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An Innovative Human Machine Interface for UAS Flight Management System

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LIST OF ACRONYMS

ACARS	Aircraft Communication Addressing & Reporting System
ACL	Autonomous Control Level
ADF	Automatic Direction Finder
ADIRU	Air Data Inertial Reference Unit
ADR/IR	Air Data Reference / Inertial Reference
ADS-B	Automatic Dependant Surveillance-Broadcast
ADT	Air Data Terminal
AGL	Above Ground Level
AMP	Autopilot Modes Panel
AOA	Angle Of Attack
AOO	Area Of Operation
ARINC	Aeronautical Radio Incorporated
ASRS	Aviation Safety Reporting System
ATC	Air Traffic Control
ATM	Air Traffic Management
ATO	Along Track Offset
ATSU	Air Traffic Service Unit
AV	Air Vehicle
BIT	Built In Test
BIT	Build In Test
BLOS	Beyond Line Of Sight
C2	Command and Control
C4I	Control Communication Computer Information
CAS	Calibrated Air Speed
CCD	Cursor Control Device
CCI	Command and Control Interface
CCISM	Command and Control Interface Specific Module
CG	Center of Gravity
CI	Cost Index
COMINT	Communication Intelligence
COMM	Communications
CPC	Cabin Pressure Controller
CPDLC	Controller Pilot Datalink Communication
CS	Certification Specification
CUCS	Core UCS
DB	Database
dB	decibel
dBi	isotropic decibel
dBW	decibel Watt
Deg	Degrees
DLI	Data Link Interface
DMD	demand

DME	Distance Measurement Equipment
DTED	Digital Terrain Elevation Data
ECAM	Electronic Centralized Aircraft Monitor
EFIS	Electronic Flight Instrument System
ELINT	Electronic Intelligence
ELOS	Equivalent Level Of Safety
ENAC	Ente Nazionale Aviazione Civile
EO	Electro Optical
ETP	Equal Time Point
FAA	Federal Aviation Administration
FADEC	Full Authority Digital Engine Control
FCMC	Fuel Control & Management Computer
FCS	Flight Control System
FCU	Flight Control Unit
FIR	Flight Information Region
FMGC	Flight Management & Guidance Computer
FOV	Field Of View
FOV_H	Horizontal Field Of View
FOV_V	Vertical Field Of View
ft	feet
g	Acceleration divided by the gravity acceleration
G/S	Glide Scope
GDT	Ground Data Terminal
GLS	GPS Landing System
GRD	Ground Resolvable Distance
GS	Ground Speed
GUI	Graphical User Interface
h	hours
HALE	High Altitude Lon Endurance
HCI	Human Computer Interface
HDD	Head Down Display
HF	High Frequency
HF	Human Factor
hh:mm:ss	Hours : Minutes : Seconds
HOTAS	Hands On Throttle And Stick
HSC	Human Supervisory Control
HSI	Horizontal Situation Indicator
HUD	Head Up Display
IAS	Indicated Air Speed
ID	Identifier
IDD	Interface Definition Document
ILS	Instrument Landing System
ILS	Instrumental Landing System
IMINT	Image Intelligence
in	inches
IR	Infra Red
IRS	Inertial Reference System

ITO	Indium Tin Oxide
JCGUAS	Joint Capability Group On Unmanned Aerial System
kg	kilogram
kts	Knots
LAT	Latitude
LED	Light Emission Diode
LGCIU	Landing Gear Control Interface Unit
LNAV	Lateral Navigation
LOI	Level Of Interoperability
LON	Longitude
LOS	Line Of Sight
M	Mach Number
MALE	Medium Altitude Long Endurance
mbar	Millibar
MCDU	Multifunction Control Display Unit
MCE	Mission Control Element
MFD	Multi Function Display
MLS	Microwave Landing System
MLS	Microwave Landing System
mph	miles per hour
MSG	Message
MSL	Mean Sea Level
MSZ	Mission Zones
MTOW	Maximum Take Off Weight
N.A.	Not Applicable
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Theatre Organization
NAVAID	Navigation Aid (radio)
NED	North East Down
NFZ	No Fly Zone
NGA	National Geospatial-intelligence Agency
NIIRS	National Imagery Interpretability Rating Scale
NIMA	National Imagery and Mapping Agency
NM	Nautical Mile
NMS	Navigation Management System
NVD	Night Vision Device
OEI	One Engine Inoperative
OEW	Operative Empty Weight
OODA	Observe Orient Decide & Act
OVR	Override
PB	Polar Bearing
PBD	Polar Bearing Distance
PC	Personal Computer:
PFD	Primary Flight Display
PNR	Point of Non Return
PPOS	Present Position

Pt	Points
PTT	Push To Talk
px	Pixels
RA	Radio Altimeter
rad	radian
RAFIV	Reformulate Access Forma Insert Verify & Monitor
RNAV	Area Navigation
RNP	Required Navigation Performance
RT	Real Time
RTCA	Radio Technical Commission for Aeronautics
SAR	Synthetic Aperture Radar
SATCOM	Satellite Communication
SEAD	Suppression Enemy Air Defense
SESAR	Single European Sky ATM Research
SFCC	Slat Flap Control Computer
SID	Standard Instrument Departure
SIGINT	Signal Intelligence
SNS	Slaved Navigation to Sensor
SSR	Sub System Rig
STANAG	Standard Agreement
STAR	Standard Terminal Arrival
SUA	Special Use Areas
SW	Software
TALS	Tactical Automated Landing System
TAS	True Air Speed
TCS	Tactical Control Station
TLX	Task Load Index
TSD	Touchscreen Display
UAS	Unmanned Aerial System (also Unmanned Aircraft System)
UAV	Unmanned Aerial Vehicle
UCAS	Unmanned Combat Aerial System
UCAV	Unmanned Combat Aerial Vehicle
UCD	User Centered Design
UCS	UAV Control System
UHF	Ultra High Frequency
USAF	United States Air Force
USAR	Unmanned aerial vehicles Systems Airworthiness Requirements
UTC	Universal Time Coordinated
VHF	Very High Frequency
VNAV	Vertical Navigation
VOR	VHF Omni-directional Range
VS	Vertical Speed
VSM	Vehicle Specific Module
W	Watt
WGS 84	World Geodetic System 84
yds	Yards

INTRODUCTION

Unmanned Aerial Systems (UASs) – also named "Unmanned Aircraft Systems" – have gained a significant importance in recent years due to their operational effectiveness and efficiency with respect to manned aircraft, becoming a relevant part of the current aviation world. UAS role is destined to further increase considering the challenge of their integration in civil airspaces, that would open a new range of missions with a consequent broad diffusion of UASs. In order to reach this goal, however, a series of improvements shall be brought to the current systems, that suffer of a poor reliability with respect to manned aircraft. At this purpose, analyzing the past mishaps, one of the main causes is the poor Human Machine Interface (HMI). The Human Factor is in fact particularly critical in unmanned systems, due to the physical separation between human and vehicle, and to the different function allocation between user and automation. Therefore proper solutions shall be adopted in order to keep adequately the human operator inside the control loop, providing a high situational awareness and an affordable workload.

At this purpose, the doctorate – done jointly by the "Politecnico di Torino" and "Alenia Aermacchi" – has regarded the study of an innovative HMI relatively to a Flight Management System (FMS) for a MALE UAS Ground Control Station (GCS). FMS can be thought as the "brain" of a manned aircraft, since it is responsible to manage several functions: navigation, trajectory prediction, flight planning, performance computation/optimization, guidance, communication and aircraft configuration. Many of these functions are already performed on current UASs, but with a lower level of integration and performances with respect to that offered by a FMS. A FMS for unmanned system, introduces some peculiarities with respect to classical manned implementations, both in terms of architecture (due always to the physical separation between operator and vehicle) and performed functions (e.g. autonomous replanning). In any case the critical element is again the Human Machine Interface, since also in airliner operations the great quota of FMS related incidents is due to human factor problems.

As design constraints for the FMS development, the civil certification and interoperability requirements have been considered. In particular, the interoperability is always more required for UAS in order to reduce the operative costs and enhance the mission effectiveness in terms of exploitation, dissemination and analysis of gathered data. To implement it, the STANAG 4586 has been followed as reference standard to define the communication protocol between GCS and vehicle. As a consequence of this requirement and taking into account also the need to realize and easily upgrade system for future improvements, a Graphical User Interface (GUI) has been implemented, with an as much as possible parametric and modular structure. In particular, a significant innovation is represented by the adoption of touchscreens, that provides a more instinctive interaction and high flexibility to the interface.

Put together UAS HMI issues, current manned FMS HMI problems, design constraints and touchscreen issues, the development of an innovative interface has been very challenging. More in detail, the work on the HMI formats has not been limited to the design of the GUI, but has involved the definition of the operative concept of the FMS, the decision of the functions to include in the new system, their allocation between user and system, and finally the link between graphic controls and STANAG 4586 protocols. Besides the studied GUI has been integrated in a real GCS, following a test process involving different environments with an incremental level of integration: GCS sub system rig, UAS system rig, ground tests on the real system and finally the flight tests.

Enlarging the HMI concept to the human-automation interaction, some advanced mission planning algorithms have been designed and integrated in the GCS. Mission planning is a FMS function, and for UASs it acquires particular relevance since it is one of key factors in the determination of system Level Of Automation (LOA). Planning a mission is in fact a complex task due to the number of involved parameters – especially for mission replan – and hence a system support in terms of automatic options during manual planning or autonomous replanner represents a significant added value in reducing the operator workload and increasing the operational performances. These algorithms, in particular, have been studied from the operative and functional standpoints: which functions shall be performed, the paradigms and parameters to consider in each computation, or how the human operator interacts with these algorithms are examples of treated items and of considered standpoint in the research activity.
The thesis structure follows the work approach, starting from a preliminary analysis of the involved issues and then presenting the developed interface. More in detail, “Chapter 1” introduces the concept of UAS, providing the relative definition, history, assigned missions, an introduction to the different ways with which an unmanned vehicle can be controlled, certification and operator role issues. It is a sort of introduction to the world of unmanned, and it provides the key concepts to understand the operative and normative context in which the research activity has been performed.
“Chapter 2” presents the manned aviation FMS, providing a description of each performed functions, of FMS interfaces in the cockpit and finally of current systems problems, due essentially to HMI lacks. The chapter is concluded with an analysis of how a traditional FMS can be adapted for an UAS, providing in particular a function allocation between ground and airborne segments. Linking to the FMS problems, “Chapter 3” presents the UAS HMI deficiencies, analyzing their contribution in past mishaps and to the lower UAS reliability with respect to manned aircraft. The general concepts of workload and situational awareness are introduced as starting base from which analyzing each UAS specific human factor issues (the different role of the automation included).
“Chapter 4” is an extending of “Chapter 3” relatively to the human automation relation, crucial for UASs. Starting from definition of automation, automatism, autonomy and artificial intelligence, the concept of Level Of Automation and the relative measuring scales are presented, passing then to the paradigm of Human Supervisory Control and to the most critic human-automation interaction issues. References to their occurrence in manned aircraft are included. The chapter is concluded with the presentation of the RAFIV model - chosen representation of human-FMS interactions at cognitive level – from which practical considerations about improvements of current interfaces are drawn.
“Chapter 5” explains the STANAG 4586, the adopted reference standard for the interoperability implementation. It results therefore a sort of bridge between the preliminary analytic part of the work and the practical implementation. Starting from the Level Of Interoperability (LOI) concept, the system architecture to adopt in order to realize the desired LOI, the standard protocol message structure and the suggested STANAG implementation of guidance-planning-navigation-trajectory prediction functions are presented. The chapter ends with a list of current STANAG 4586 limitations and possible future improvements emerged during the work.
“Chapter 6” introduces the second part of the thesis relative to the new HMI development. The chapter starts with a detailed work scope about the research activity and the relativant flow chart (linking to UAS FMS function allocation of Chapter 2), passing then to a presentation of high level requirements from which the study is started and the consequent new HMI architecture. In particular, the choice of touchscreens as FMS input devices and resistive technology as touchscreen type are motivated, presenting advantages and disadvantages of each available options.

"Chapter 7" is relative to the HMI style guide, that is the followed guidelines in the GUI development. Starting from the definition of User Centered Design (i.e. design philosophy in which the final user is at the center of the system development), generic HMI heuristics derived from technical literature and specific rules of our project are presented. Particularly relevance is given to specific graphical solutions for touchscreens.
"Chapter 8" presents the HMI design of vehicle control related functions, that is: guidance, navigation (included trajectory prediction), vertical profile, communications and system configuration. Operative, functional and graphics issues are treated in detail for each format.
"Chapter 9" is relative to the mission planning. Starting from the basic definition provided by the STANAG 4586, the concept of mission is exploited adding also elements non relative to the communication protocols, passing then to the analysis of different planner/replanner types and to present general planning algorithm issues. The chapter is concluded with the presentation of functional and graphic design of the GCS embedded mission planner and the navigation format on TSD map.
"Chapter 10" is relative to the planning algorithms. Starting from an algorithm work scope, each function is then presented.
"Chapter 11" concludes the research activity presentation, reporting the process of testing and integration. In particular, the peculiarities of each test environment are presented.
At the end, the thesis conclusions are reported.

1 UNMANNED AERIAL SYSTEMS

1.1 Definition

Although the most visible element is the Unmanned Aerial Vehicle (UAV), it is more correct to consider an Unmanned Aerial System (UAS). In particular, according to the STANAG 4586 (standard for UAV interoperability), the following elements (see Fig.1) can be distinguished in a UAS [1]:

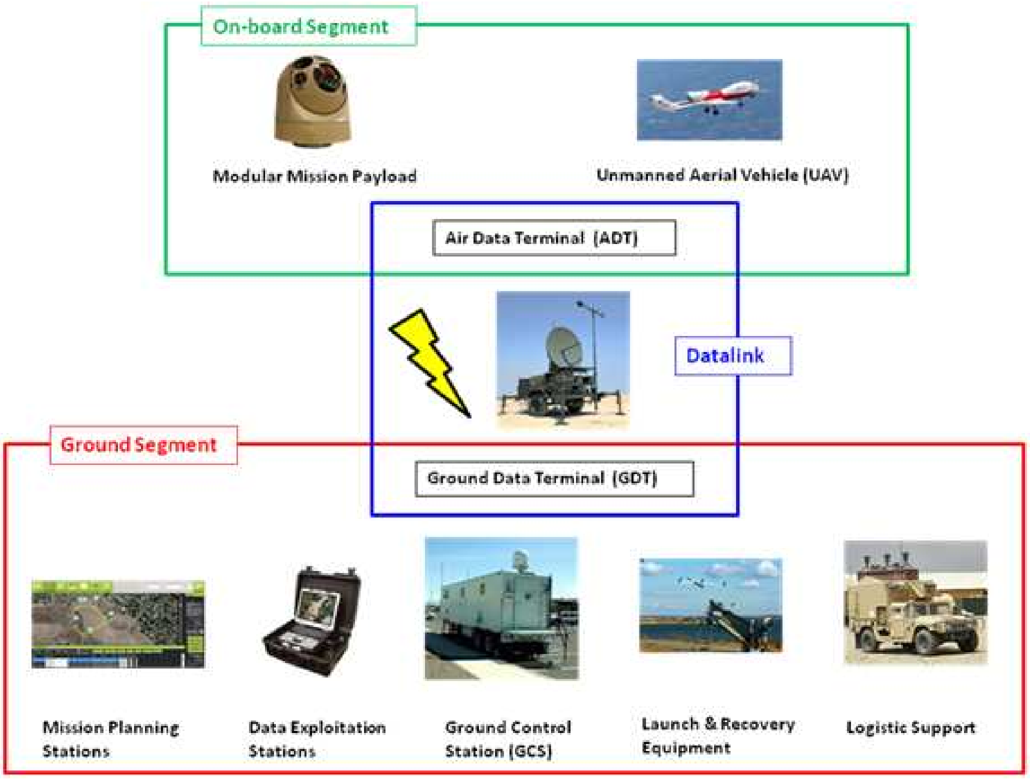


Figure 1. UAS Elements

Main distinction is between the ground based elements and the airborne (on-board) ones, linked together by the datalink. Entering more deep in the Ground Segment, the core is the Ground Control Station (GCS), from which the operators control one or more vehicles. GCS can be situated in a room, integrated in a shelter, put on a carrier (e.g. a cross country vehicle, a ship or a manned aircraft), or hosted on a laptop, according to the specific UAS. Besides, there are stations from which it is possible to control only the payload and not the vehicle, and vice versa. Mission Planning and Data Exploitation stations are “optional”, but they are usually provided for advanced systems. Launch & Recovery equipment are typically feature of “little” UAVs that are not able to perform conventional take off and landing or as provision for short take off and landing. Logistic support is fundamental for the system operability, and it means for example the ground power unit.

Airborne segment, instead, is made up basically by an UAV and the relative payloads, with the provision to control more vehicles from a single GCS. In particular, a UAV must not be confused with ballistic vehicles, cruise missiles, and artillery projectiles, also if many technologies are common [2]. In fact, according to the STANAG 4586 [1] and the "Unmanned Aircraft Systems Roadmap 2005-2030" [2], there is the following definition for an UAV:

A powered, aerial vehicle that does not carry a human operator, uses aerodynamic forces to provide vehicle lift, can fly autonomously or be piloted remotely, can be expendable or recoverable, and can carry a lethal or non lethal payload.

Finally, datalink subsystem is divided in Ground and Air Data terminals. Many times there are two datalinks for the Line Of Sight (LOS) communication: one for the Vehicle Command and Control (C2) functions and the other for the payloads (control and data streaming). In case of Beyond Line Of Sight (BLOS) operations, instead, there are two possible solutions: radio relay or satellite communication (most used). Independently by the datalink case the following two channels are distinguished for each link:

- uplink: commands sent on-board from the ground segment,
- downlink: data sent by the airborne segment to the ground.

Each of UAS recognized element, off course, varies in size, capability and characteristics according to the UAS category, but the general system description is the one previously reported.

1.2 History

Origin of unmanned flight arose from the experiments of the Montgolfier brothers balloons in 1782. First practical recorded application was the use of aerostats by Austrian army to attack Venice on August 22, 1849. Aerostats were loaded with explosive and launched from the ship "Vulcano", but many of them failed the mission due to a wind change that deviated the balloons back over the Austrian lines [3]. Similar use was done by the Northern Union in the America Civil War in 1861-1865, when incendiary devices where put on aerostats and released toward the Confederate forces [4]. Although these applications were far from current idea of UAS, they represent a first attempt to use an unmanned flying objects in military applications.
A further step were the steam powered propeller driven model aircraft built by John Stringfellow and William Henson from England in 1848-1868 [4], [5]. Models were wire guided, but during a display in the Crystal Palace of London in 1868, a large model triplane was managed to leave the wire and flew for a distance [5] (see Fig.2).

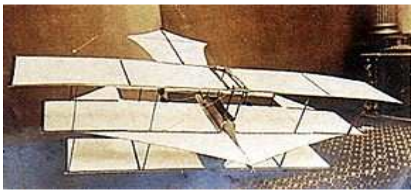


Figure 2. Steam Engine Powered
Large Model Triplane On Display At The Crystal Palace, London, England – 1868 [5]

Another steam model - called Aerodrome Number 5 – was built by Samuel Langley (USA) in 1896, and flew for 0.75 mile along the Potomac river [4].

In 1883 the first aerial photograph was taken using a camera mounted on a kite and controlled by a long string attached to its shutter. Six years later (1889), this technology was practically used in the American-Spanish war [6].
In the aviation age, during the World War I, two prototypes of flying bombs (a sort of forerunner of today's cruise missiles) were developed in USA: the Hewitt-Sperry Automatic Airplane (1916) and the Kettering Bug (1918) [3] (see Fig.3).

Figure 3. Kettering Bug [7]

Although they were not real UASs, they permitted an improvement in the automatic control technologies applied to the aircraft. Control system was based on gyroscopes, barometric altimeter, pneumatic/vacuum system ad an electric system. A mechanical device tracked the distance flown in order to hit the assigned target [7]. These two aircraft were tested in flight, but they were not used in war. In particular the Kettering Bug flew for 50 miles on a preset course in 1918 [4].
Between the two World Wars, the research on unmanned vehicles went on. In particular, in UK a DH-82B "Queen Bee" were transformed in a radio controlled aircraft, becoming the first reusable and returnable UAV. "Queen Bee" was able to fly up to 17000 ft, at over 100 mph for 300 miles [8] (see Fig.4).

Figure 4. DH-82B "Queen Bee" [8]

In 1930s, radio controlled model where diffused for fighter and anti-aircraft artillery training [3]. In particular, in1936, the term "drone" was created in order to indicate a radio controlled aerial target by US Navy researchers.
During World War II, unmanned vehicle use grew. Germany develops the famous V1 (see Fig.5) and V2 (1944), first real cruise missiles in the history. Like the Kettering Bug, they are not UAVs in the current meaning, but they involved a further and important growth in automatic control capability, besides to be a milestone in the missile technology development. They were able to hit London starting from their launch sites in France [4].

Figure 5. Fiesler FI 103 V1 [4]

Germany also developed two radio controlled glide bomb: the Henschel Hs 293 and the Fritz X. They were launched from a mother aircraft and steered toward the target by an operator. Two Fritz X, in particular, were used to sank the Italian battleship “Roma” on September 9, 1943 [4].
On the Allies front, USA developed aerial “torpedo” like the Interstate BQ-4 (see Fig.6), converting manned aircraft.

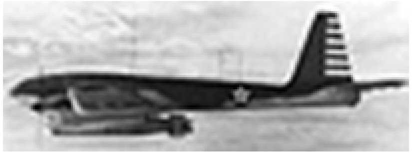


Figure 6. Interstate BQ-4 [4]

They were used in real operations resulting in 18 hits on Japanese targets [4]. They were radio controlled and TV camera guided.
After the war, converted manned aircraft (prop bomber B-17, prop fighter F-6 and jet fighter P-80) were used to monitor nuclear test (1946, 1947, 1951) in order to gather samples in the nuclear cloud [3].
During Vietnam war, the Ryan Model 147 “Lighting Bug” (see Fig.7) performed 3435 reconnaissance missions over North Vietnam and China with 554 UAV lost [3]. It was launched in flight and then controlled by a mother C-130 “Hercules”.

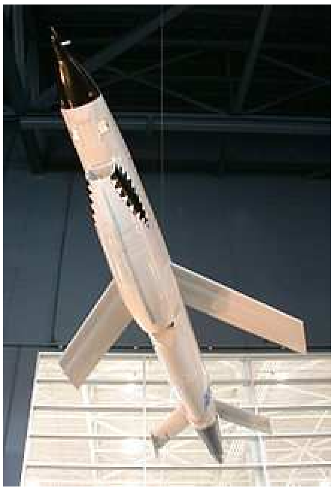


Figure 7. Ryan Model 147 “Lighting Bug”

In 1970s, greater performances reached by satellites, momentary slowed down the UAS development in USA (and more general in Occident), limited to few prototypes. Unmanned rebirth happened during the Israeli operations in Lebanon in 1980s, where the Scout and Pioneer (see Fig.8) UAS were used [9]. They represented the evolution toward the current glider-type UAV model [10].

Figure 8. Pioneer

Starting from that years, the role, number and complexity of UAS have increased continuosly, with a peak in the last ten years after the Twin Towers attack in 2001. Noteworthy the achievement of 1,000,000 flight hours by the General Atomic Predator in 2010 (see Fig.9), especially considering that in 2006 the flight hours were 80,000 [11]. Very recently also the aim of 2,000,000 flight hours has been reached.

Figure 9. General Atomics Predator A

Currently UASs have reached a good level of maturity, both in terms of operational capability and performances, also if the reliability is still lower than manned aircraft. This issue, in particular, is very important for the integration of UAS in the civil air traffic, one of the primary milestone of the expected UAS roadmap. Another and related point is the increment of automation level of UAS. Current UASs have been already developed in order to rely on less on remote manual human control, but the trend is to confer more and more authority to the system, especially when a quick reaction is required.

1.3 UAS classification

Several UAS classification have been created according to different parameters and criteria, without reaching a universal accepted standard. In particular, the NATO Joint Capability Group On

Unmanned Aerial System (JCGUAS) classification has been chosen. It proposes an UAS classification in which three different classes have been individuated according to the UAV mass [12]. Each class is further divided in different categories according to the following parameters:

- employment,
- operative altitude,
- mission radius,
- primary supported commander in military operations.

UAV CLASSIFICATION TABLE						
Class	Category	Normal Employment	Normal Operating Altitude	Normal Mission Radius	Primary Supported Commander	Example Platform
CLASS III (more than 1320 lbs/600 kg)	Strike/ Combat	Strategic/National	Up to 65,000 ft	Unlimited (BLOS)	Theatre COM	
	HALE	Strategic/National	Up to 65,000 ft	Unlimited (BLOS)	Theatre COM	Global Hawk
	MALE	Operational/Theatre	Up to 45,000 ft MSL	Unlimited (BLOS)	JTF COM	Predator B, Predator A, Heron, Heron TP, Hermes 900,
CLASS II (150 kg to 600 kg)	Tactical	Tactical Formation	Up to 10,000 ft AGL	200km (LOS)	Bde Comd	SPERWER, Iview 250, Hermes 450, Aerostar, Ranger
CLASS I (less than 150 kg)	SMALL >20 kg	Tactical Unit (employs launch system)	Up to 5K ft AGL	50 km (LOS)	Bn/Regt, BG	Luna, Hermes 90
	MINI 2-20 kg	Tactical Sub-unit (manual launch)	Up to 3K ft AGL	25 km (LOS)	Coy/Sqn	Scan Eagle, Skylark, Raven, DH3, Aladin,Strix
	MICRO <2 kg	Tactical, Pl, Sect, Individual (single operator)	Up to 200 Ft AGL	5 km (LOS)	Pl, Sect,	Black Widow,

Table 1. JCGUAS UAV Classification table [12]

Following chapters are directly referred to the Class III, and in particular to the Medium Altitude Long Endurance (MALE) UASs, but many considerations can be applied also to the Class II and in part also to Class I.
In particular, for strike/combat category (Class III) we talk about Unmanned Combat Aerial Vehicle (UCAV), while the relative system is named UCAS.

1.4 Missions

Unmanned vehicles have been historically conceived in order to replace humans in the execution of the so-called “3D missions”, where the three D are: Dull, Dirty and Dangerous. Dull missions are typically represented by long endurance flights and/or repetitive tasks execution. Examples can be surveillance mission or long roundtrip phases. In these cases, psycho-physiologic human limitations can affect the achievement of mission goals and the effective endurance of the system. With an UAS, instead, there are not these problems, since the persistence of the vehicle on the mission area

depends only by the aircraft endurance, while the operator turnover in the Ground Control Station guarantees correct level of operator vigilance and workload.
Dirty missions are characterized by operating in a dangerous environment for the operator health, characterized for example by radiation, pollution, chemical or biological threats. Example of these missions were the nuclear cloud sampling performed by the radio controlled B-17 and F-6 between 1946-1948, or the recent monitoring activities of the Global Hawk over the Fukushima reactor in 2011 [13].
Finally, Dangerous missions are defined in a military context, where there are several threats to the pilot life. In particular the original idea at this purpose was to substitute manned fighter/bomber with unmanned vehicles only for the most dangerous tasks like for example the Suppression of Enemy Air Defense (SEAD) or reconnaissance over highly defense target, but the future trend is to increase the role of unmanned aircraft for other missions. At this purpose, 3D concept has been enlarged in military field, arriving to define the following mission types:

- Intelligence
    - Image Intelligence (IMINT),
    - Communication Intelligence (COMINT),
    - Electronic Intelligence (ELINT),
    - Signal Intelligence (SIGINT),
- Surveillance.
- Reconnaissance.
- Unexploded artillery detection.
- Battle Damage Assessment.
- Combat mission (generic).

Besides military field, however, UASs are expected to be used ever more for civil applications. Several civil missions in which UASs can provided a significant aid, in fact, have been individuated [14], [15]:

- Security
    - border surveillance,
    - law enforcement,
    - smuggling fighting,
    - big event monitoring.
- Territory monitoring (e.g. after an earthquake).
- Searching Task (e.g. shipwrecked or missing persons).
- Agricultural industry support
    - fertilizer dispersing,
    - pesticide dispersing,
    - crop monitoring.
- Fisheries support.
- Environmental control /weather research.

- Scientific research support (generic).
- Mineral Exploration.
- Coast Monitoring.
- Pollution detection/monitoring.
- Telecommunication relays.
- News broadcasting.
- Air traffic control over busy airports.
- Ground traffic control.
- Sea traffic control.
- Terrain mapping.
- Pipeline monitoring.
- Firefighting.

1.5 UAV Control

According to the system Level Of Automation (LOA), an UAV can be controlled in several ways. The problem to define the LOA is complex and it will be discussed in Chapter 4, but just to give an initial idea the following vehicle control ways can be identified in Fig.10:

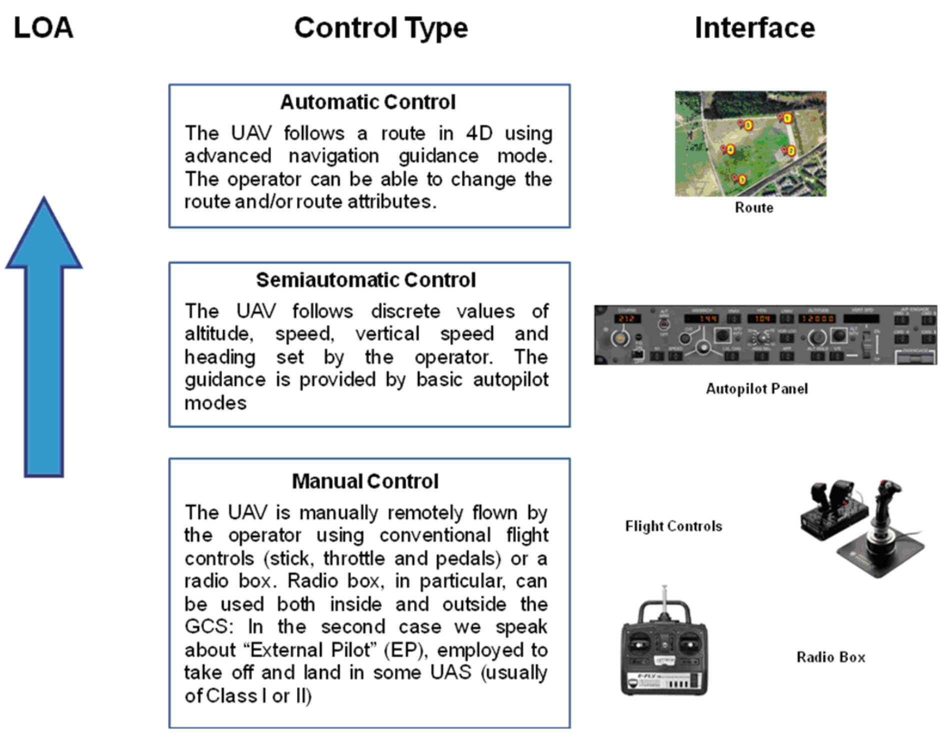


Figure 10. UAV Control Types

In practice, the distinction is not so clear, since an UAV can have the capability to be controlled in different ways according to the selected guidance mode, and plus there can be hybrid modes (e.g. an automatic guidance to follow a route in the horizontal plane, while the altitude and speed are controlled in semiautomatic way by the operator). Each control type involves specific Human Machine Interface issues. Autonomous UAVs behave in the same way of automatic ones from the standpoint of vehicle control. Automatic and Autonomous behaviors are distinguished by the allocation of higher level decisions between human and system. These concepts will be better treated in Chapter 4.

1.6 UAS Certification

Since UAS have been initially developed for military applications, there is not a defined and universally accepted set of rules for civil certification. This lack shall be solved in the future in order to integrate the UAS in the National Airspace Systems. This integration is based on three main principles [16], [17]:

1. Equivalence: UAS shall demonstrate an Equivalent Level Of Safety (ELOS) with respect to manned aviation.
2. Compliance: UAS shall operate in compliance with the existing aviation regulation in terms of operative and flight rules.
3. Transparency: UAS shall be transparent to other airspace users, i.e. other aircraft do not perform extraordinary procedure due to the presence of an unmanned vehicles.

These macro requirements need a regulation infrastructure analogous in form to that existing for manned aircraft. In particular the following aspects shall be certificated:

- system airworthiness,
- operator certification,
- operating and flight rules,
- vehicle registration and marking,
- maintenance.

Currently these is a broad series of regulation proposals for the previous issues, derived by several researches involving civil authorities, air traffic control authorities, air forces, industries and universities. Developing the new regulation framework, the basic approach is to start from the existing manned aviation regulation in order to reuse as much as possible the well proven manned rules. However several researches have demonstrated that this way is not completely pursuable. In fact, it has been estimated that only the 30% of current rules are directly applicable, while the 54% may be reused with some modifications, and finally the 16% is not usable [18]. UAS in fact are characterized by many features not contemplated on a manned aircraft like for example the GCS, the datalink or the greater level of automation.

In particular, for the airworthiness the STANAG 4671 “Unmanned Aerial Vehicles Airworthiness Requirements” (USAR) has been adopted [19], since it is considered applicable as certification basis by the EASA Policy Statement Airworthiness Certification of Unmanned Aircraft Systems (UAS) E.Y013-01 [20]. STANAG 4671 refers mainly to fixed wing UAV system with a maximum take off weight between 150 and 20,000 kg. It has been derived directly by the EASA Certification Specification (CS) 23, i.e. the European rule relative to general aviation and commuter aircraft. More in detail, the STANAG 4671 is divided in 7 sections (see Fig. 11): sections from A to G are directly derived from the CS-23, while the subparts H and I have been properly created for UAS [19] (see Fig.11).

		UAV System				
		UAV	Command and control data link	Communication system	UAV control station	Other ancillary elements
A	General	X	X	X	X	X
B	UAV Flight	X				
C	UAV Structure	X				X
D	UAV Design and Construction	X				X
E	UAV Powerplant	X				
F[3]	Equipment	X				
G	Operating limitations and information	X	X	X	X	X
H	Command and control data link Communication system		X	X		
I	UAV control station				X	

Figure 11. STANAG 4671 structure [19]

About the software, the STANAG 4671 considers the RTCA DO-178B/EC-12B “Software considerations in airborne systems and equipment certification” as reference.

1.7 UAS Operators

STANAG 4671 does not provide information about the UAS Operator qualification. When we speak about UAS crews, it is more correct to refer as a generic “operator”, since it is not obvious that he/she is a pilot. About the professional qualification and background of UAS operators, in fact, there is not a clear and univocal position: each user adopt a particular solution according to the specific case (UAS type, cultural influence, previous experience, etc.). Considering always a Class III UAS, the following possible operator figures can be identified:

- UAV operator: responsible of vehicle control. He/she can also coincide with the payload operator.
- Payload operator: responsible of one or more payloads control. He/she can also coincide with the UAV operator.
- Mission Commander: crew leader and final responsible of the UAV. This role can be assigned to a dedicated figure or to an another operator.
- Data analyst operator: operator assigned to the real time detailed analysis of the collected data (e.g. images) and their exploitation.
- Communication specialist: operator dedicated to the communication with other actors in the operative scenario. In case, he/she can be also responsible of the management of some GDT functions.

According to the specific UAS, only a subset of the previous roles are usually present in a GCS. In particular, in this section only UAV operator role is considered – identified for simplicity as generic “operator” – since he/she is charged to control the FMS. A representation of the differences between a manned cockpit and an unmanned Ground Station is reported below in Fig.12.

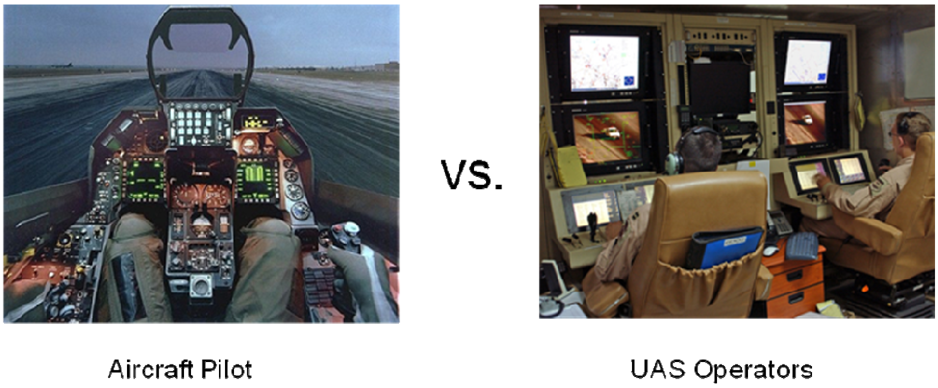


Figure 12. Aircraft Pilot versus UAS Operators

As UAS operators, basically, it is possible to distinguish between who has a previous rated flight experience (as pilots or flying officers) or not. This is not a trivial issue, since it involves consequences not only from the regulation standpoint and in the training process, but also in the design of the Human Machine Interface (HMI) in the GCS.
Consider a rated pilot can be easier from several standpoints: the pilot figure, in fact, is well regulated, and the UAS qualification can be translated in a type-rating like on manned aircraft with an ad hoc training. However this choice has some disadvantages: first of all the cost, since the flying training is really expansive. Besides a pilot could not appreciate to work “on ground” – missing the phase of flight – and this can involve a performance detriment. Finally, a pilot could not be the proper figure to manage an advanced autonomous UAS, both for mentality and professional background. These considerations are valid also for flying officers, usually employed as payload operator.
A generic operator, instead, could be potentially more oriented to control an autonomous UAS via high level commands, and his/her training will be less expansive. In any case having to control an aircraft (also if unmanned), they need at least an airmanship theoretical training. The issue is to evaluate the need also for a minimum practical flying training (i.e. basic pilot training). Without a real experience in controlling an aircraft, in fact, an operator could have more difficulties to understand the UAV state/behavior. Besides, if the considered UAV can be also remotely piloted through traditional flight controls (i.e. stick, throttle and pedals), this experience could be a fundamental step.
About this issue, it is interesting to consider the experience of the greatest UAS user in the world: the United States Air Force (USAF) [21], [22], [23], that in 2011 has trained more UAS operator than fighter and bomber pilots combined [24]. In order to satisfy the increasing demand of UAV operator, in fact, the USAF has opened the UAS career also to undergraduate pilots and not flying duty officer, developing a proper training syllabus. Previously, this role was accessible only to rate pilots. In particular, this has been done for the Predator/Reaper systems, that have the possibility to be manually controlled, and so a basic flying training has been considered for duty officers. After

the first training cycles, the amount of provided flying hours have been increased from 18 to 35 hours, remarking the importance of flying background in the UAS training. Probably this need will decline in the future with the UAS level of automation increase, but now it is still required, especially when the remote manual control is available.

Italian Air Force, instead, employs only rated pilots, but the it has a very limited numbers of UASs and so it has not problems in finding operators.

The trend however is to move toward a greater employment of non pilots operators, especially in order to reduce the operational cost of the UASs. The definition of a dedicated set of rules to certificate this role, in particular, is a milestone for the unmanned system diffusion, especially for civil application.

The design of the HMI is drawn by the operator background, since a rated pilot is more confident with a cockpit like symbology/controls. A generic operator, instead, probably is more prone to learn the use of a different type of interfaces – more similar to a computer – having not a previous “imprinting” on manned aircraft.

In any case, independently to have a pilot or an operator, controlling an UAS is a particular demanding task that involves several issues in terms of Human Factors due to the physical separation between the operator and the vehicle. This challenges will be described in Chapter 3.

2 FLIGHT MANAGEMENT SYSTEM

2.1 Introduction

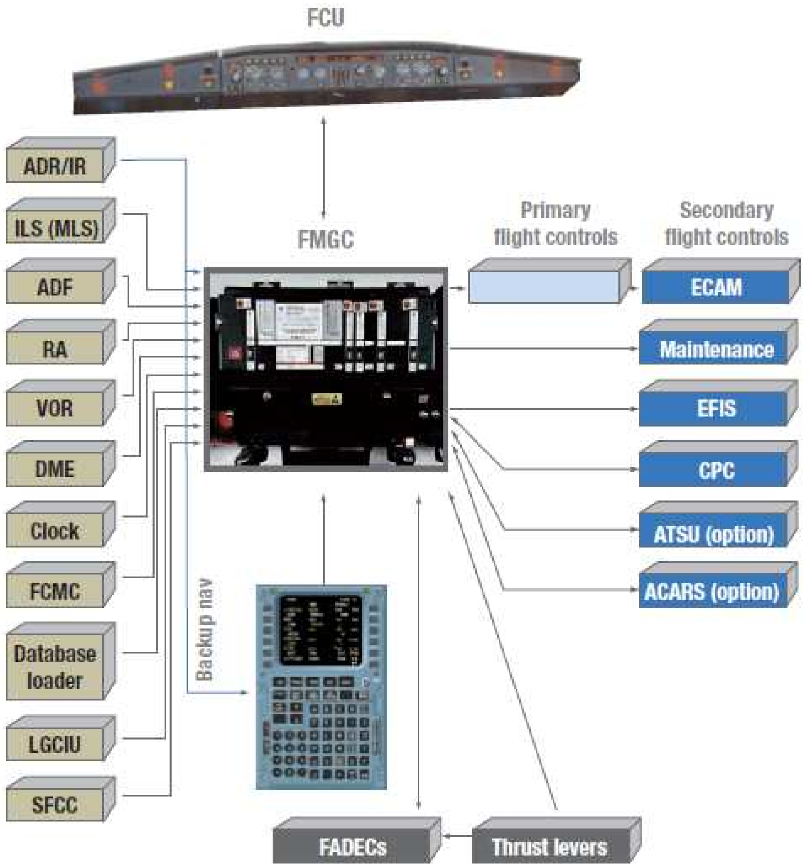
Flight Management System (FMS) can be though as the “brain” of modern airliners [25], and it is devoted to the management of the following functions:

- navigation,
- flight planning,
- trajectory prediction,
- performance computation/optimization,
- guidance,
- FMS initialization,
- communication.

Historically it derives from the Navigation Management System (NMS) [26], introduced in the 1980s in order to reduce the pilot workload to plan the flight and then navigate the aircraft. Significant commercial flights increase, in fact, has involved the need for airliners to follow strict rules in all flight phases. So flight planning before take-off and management of any possible deviation in flight have become very demanding tasks for pilots [25]. The NMS has automated some functions and provided a better interface for some others, reducing the pilot workload and increasing their situational awareness. In particular the NMS has permitted the introduction of the Area Navigation (RNAV), that is a navigation concept in which an aircraft follows a 3D path defined by waypoints, instead of standard routes determined by the radio navigation aids (NAVAIDs). The FMS derives from the merge of the NMS with aircraft performance database and autothrottle system, obtaining the capability to optimize the flight plan and following in automatic way the computed speed schedule. FMS introduction, in particular, has contributed to remove the role of the flight engineer for the long range flights, reducing the crew size from three to two. This automation increase in the cockpit, however, has not been introduced without problems, since it has involved a shift of pilot role from aircraft manual controller to system supervisor, with several issues about the human-automation integration. Some accidents have occurred due to these problems. In recent years, the FMS has further increased its capability adding new functions and taking into account the future of the Air Traffic Management (ATM).
The idea to integrate a FMS into an UAS is very attracting, since it will enable an improve in navigation, planning, communication and 4D trajectory control capabilities, needed for an integration of unmanned vehicles in the National Airspace System (NAS) [27].

2.2 Architecture

Flight Management System is made up basically by two macro-elements: a Flight Management Computer (FMC) and the relative HMI. FMC is redounded for safety, and is linked to several aircraft sensors and equipments. Fig. 13 represents a typical FMS hardware architecture for an airliner, providing an idea of the system complexity.



ACARS	Aircraft Communication Addressing & Reporting System	**FCMC**	Fuel Control & Management Computer
ADF	Automatic Direction Finder	**FCU**	Flight Control Unit
ADR/IR	Air Data Reference / Inertial Reference	**FMGC**	Flight Management & Guidance Computer (equivalent to a FMC)
ATSU	Air Traffic Service Unit	**ILS**	Instrument Landing System
CPC	Cabin Pressure Controller	**MLS**	Microwave Landing System
DME	Distance Measurement Equipment	**LGCIU**	Landing Gear Control Interface Unit
ECAM	Electronic Centralized Aircraft Monitor	**RA**	Radio Altimeter
EFIS	Electronic Flight Instrument System	**SFCC**	Slat Flap Control Computer
FADEC	Full Authority Digital Engine Control	**VOR**	VHF Omni-directional Range

Figure 13. FMS Architecture [25]

For the HMI, instead, the main data entry interface is the Multifunction Control Display Unit (MCDU), while the navigation status is monitored on the Navigation Format. In order to permit the datalink communication with the Air Traffic Control (ATC), further formats (considered part of the FMS) have been added to the flight-deck. However, the FMS strictly interacts also with other interfaces like the autopilot mode panel (FCU) - from which the guidance of the FMS is enabled – or the display control unit, from which for example is controlled the navigation format (orientation, declutter, etc.). In Fig. 14, an example of the Airbus A-330 cockpit is presented.

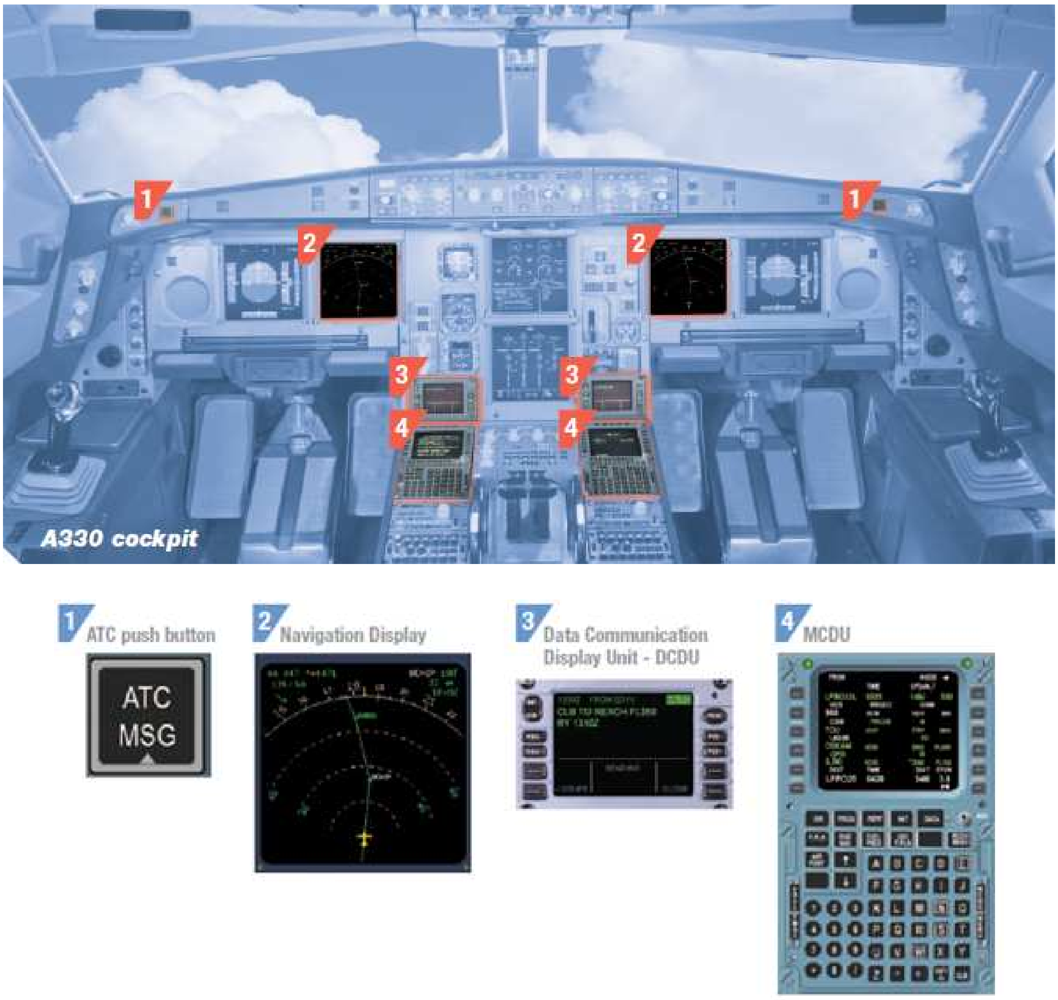


Figure 14. FMS HMI

2.3 Functions

In the following paragraphs the main FMS functions will be discussed. Each of them is presented alone, also if they are strictly related each other in the FMS.

2.3.1 Navigation

The navigation is responsible for determining the best estimate of the current aircraft state (best data) by the fusion of navigation data provided by several autonomous sensors or receivers. Aircraft state is provided by the following parameters [28]:

- three dimensional position (latitude, longitude and altitude),
- velocity vector in NED reference frame (i.e. Ground Speed – GS – in the horizontal plane and Vertical Speed – VS),
- track angle,
- heading angle,
- drift angle,
- wind vector (speed and direction),

- Estimated Position Uncertainty (EPU).

A typical navigation sensor suite for an airliner is made up by [28]:

Autonomous Sensors	Navigation Receivers
• Air Data Reference • Inertial Reference	• DME • VOR • ADF • Global Positioning System (GPS) • Differential GPS

Table 2. Navigation Sensor Suite

Navigation receivers are managed by the FMS. In particular there is an auto-tune function that permits to select the proper NAVAID frequency according to the aircraft position and the flight plan. Different navigation data sources can be combined together to determine the best estimate with three possible criteria [26]:

1. Prioritization: only the best system is used according to an established merit classification.
2. Weighted Average: available sources are combined, weighting the relative data according to the sensor characteristics.
3. Kalman Filter: optimal recursive data processing algorithm, used to estimate the aircraft state taking into account the input noise.

In practice – being the most accurate criteria – the Kalman Filter is actually used on airliners, although its development is expansive. Prioritization and Weighted Average criteria were used in the past, and now they are available in some cheap applications for general aviation. The crew is however able to force the best data source to a desired sensor.
In any case, the precision relative to the aircraft position computation (EPU) is calculated and displayed to pilots. It is compared with the Required Navigation Performance (RNP) in order to determine if the aircraft is able or not to perform the RNAV. RNP varies with the airspace according to the DO-206 standard [28]:

Airspace definition	RNP (NM)
Departure	1.0
Enroute domestic	2.0
Enroute oceanic	12.0
Terminal	1.0
Approach	0.5

Table 3. Required Navigation Performance

Current trend is to use the differential GPS combined with the inertial data as primary navigation data source [29], reaching RNP lower than 0.3 NM (also 0.1 NM).

2.3.2 Flight Planning

Flight Planning function is relative to the creation, modification and activation of the flight plans. Usually for an airliner a primary flight plan is specified from the departure airport to the destination one. Some secondary flight plans are available in order to permit an aircraft diversion to other airports in case of problems (e.g. bad weather or a failure). A flight plan consists in the aircraft route, plus other related information like the radio/NAVAID frequencies. A route is specified linked together several elements present in the aircraft navigation database [28]:

- Standard Instrument Departure (SID) procedures,
- Standard Terminal Arrival (STAR) procedures,
- approach / missed approach procedures,
- holding patterns,
- airways
- fixes (waypoints, NAVAID, airport reference points, runway thresholds, etc.).

Procedures and patterns, in general, are coded by the path and terminator concept [29], according to which a route leg (i.e. the segment joining two fixes of the route) is defined not only specifying the ending point, but also the path that the aircraft shall follow to reach it. At this purpose, 23 leg types are reported in the standard ARINC 424. These legs translate in computer language procedure originally created to be manually flown with compass and clock [29].

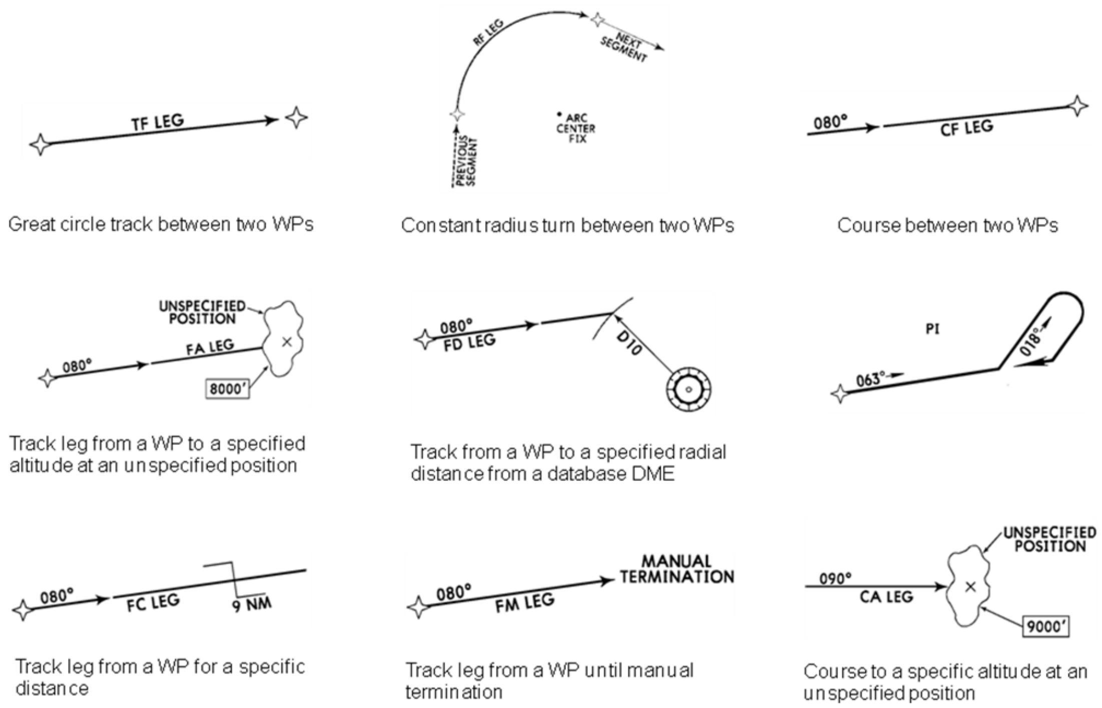


Figure 15. ARINC 424 legs

According to the DO-206, non determinist legs – like course legs or legs ending at an unspecified position – should be avoided, since they could involve problems for air traffic separation and added complexity to the FMS path construction being dependent to the aircraft performance. DO-206 suggests to use track legs with a specified terminator. In particular, track legs are advantageous with respect to course legs, since they not depend by wind condition and avoid problems related to magnetic variation.
Among the deterministic terminators, the most relevant are the waypoints. In particular, the users can define the WP position on horizontal plane in several ways [28]:

WP determination	Description
PBD	Polar coordinates (bearing and range) from an another fix.
PB/PB	Intersection of bearings from two defined WPs.
ATO	Specified by an Along Track Offset (ATO) from an existing flight path fix.
LAT/LON	WP is defined entering the relative Latitude/Longitude.
LAT/LON Crossing WP	The WP is placed at the intersection of a specified point (LAT/LON) with the active flight plan.
Airways Intersection	First point at which two given airways crosses.
Runway extension WP	WP is placed at a given distance from the runway threshold along the runway heading.
Abeam WP	When a direct to function is activated toward a fix, abeam WPs are created at their abeam position on the direct to path.
FIR/SUA Intersection WP	WP is placed at the cross between the active flight plan and the Flight Information Region (FIR) or Special User Areas (SUA) boundary.

Table 4. WP creation methods

A WP can be of two different types, according to the way with which the round between the relative legs is flown:

- Fly-By (also named short turn): the WP is not overflown and the aircraft links the two legs with a turn.
- Fly-Through (also named fly-over): the WP is overflown and then the aircraft returns on the leg.

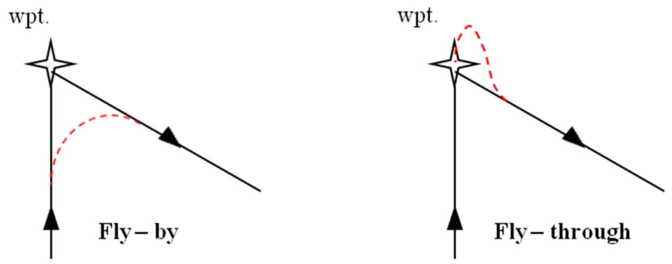


Figure 16. WP types

DO-206 prefers the Fly-By type, since the Flight Through trajectory is not predictable. Overshoot due to the WP overflight, in fact, depend by several factors like the aircraft speed, aircraft bank limitations and wind. With the Fly-By, instead, there are not these problems, since the roll-in points (starting point of the turn between the two legs) is properly determined according to the aircraft characteristics and wind condition.
Above issues about the WP creation methods and the WP types are relative to the Lateral Flight Plan (i.e. Latitude / Longitude plane). Regarding to the Vertical Flight plan, instead, at each WP it is possible to associate altitude, speed and time constraints. The following constraint types are usually available [28]:

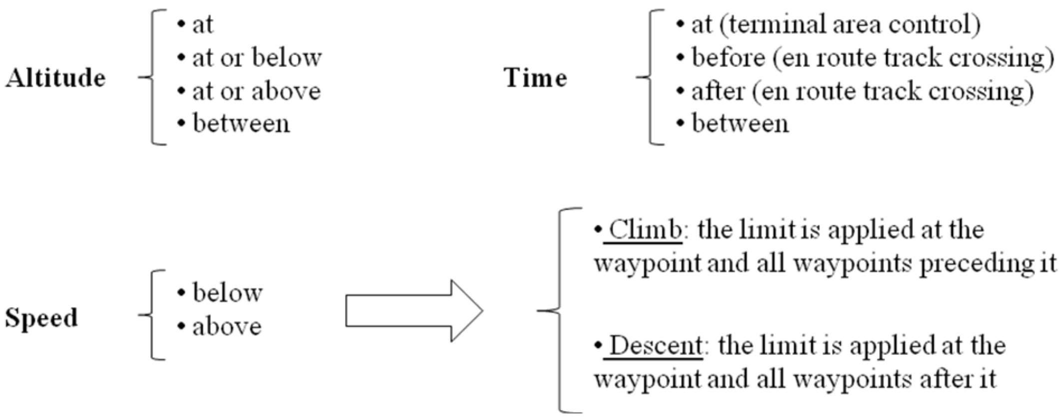


Figure 17. Vertical Flight Plan Constraints

In particular, DO-206 suggests to not use the altitude “at” constraint in order to avoid undesired climb/descent paths. Analogously, also speed “at” constraint is not typically considered, since speed is normally varied by the FMS in the feasible range in order to optimize the performance according to the selected criteria. An example of vertical flight plan profile is reported in Fig. 18.
Apart the characteristics presented above, a WP is identified by an alphanumeric string in order to facilitate its recognition by the pilots.
According to the presented paradigms/rules, the Flight Plans are created. Creation can be performed both in the MCDU and in an external planning station. In the last case, the flight plans are upload on the FMS by a proper memory card.
Only a flight plan can be activated at time (as default the primary flight plan is activated). Crew is able to modify the active flight plan during the flight, changing any WP attribute or adding new WPs.

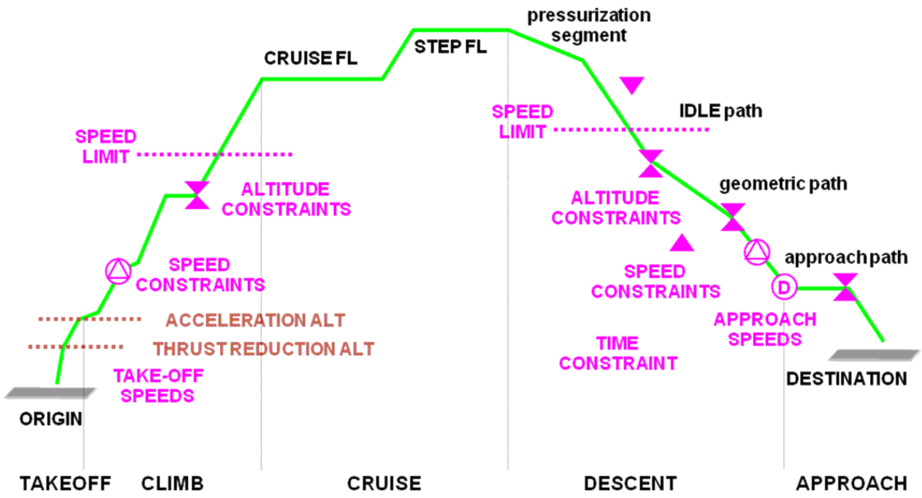


Figure 18. Vertical Flight Plan profile

In particular, there are the following two functions that permits a change in the active flight plan [28]:

- Direct to: the aircraft flies toward a given fix from its current position. If the selected fix belongs to the active flight plan, the prior WPs are deleted; while if the fix is a new point, a discontinuity is inserted after it and current flight plan is conserved.
- Direct/Intercept: equal to the Direct to, but the pilot specifies also the course with which the selected fix shall be reached.

2.3.3 Trajectory Prediction

Trajectory Prediction function computes the predicted four dimensional flight profile (both in lateral and vertical planes) [28] according to the active flight plan (constraints), weather conditions, aircraft performance and selected mode of operations.
Numerically integration on the aircraft energy balance equations is performed in order to calculate for each WP the following variables:

- lateral path (e.g. cross track error and track angle error with respect to the current leg, roll-in point and turn radius for fly-by WP, path to intercept a WP, etc.),
- predicted fuel consumption,
- arrival time,
- distance to travel,
- altitude,
- speed.

An initial prediction is performed before take off, but then the prediction is continuosly updated considering the best estimate of the aircraft state calculated by the navigation function, taking into account any possible diversion [28].

In particular the following two points are calculated during the flight:

- Point of Non Return (PNR): point along the flight plan where the fuel to reach the destination is less than the fuel to return to the departure airport.
- Equal Time Point (ETP): point along the flight plan where the time to go back to the origin is the same as the time to continue to the destination.

In order to obtain an accurate prediction, weather conditions – in terms of wind (speed and direction) and air temperature – are very important. During the planning wind and air temperature data are entered for the different flight phases. For take off and landing prediction, wind and temperature are provided for the considered airports (departure, destination and alternates). For climb and descent, instead, wind is usually entered for different intermediate altitudes, while the air temperature is only provided for a given altitude. Finally, for the cruise phase, wind and air temperature are provided for the desired altitude. Besides it is usually possible entering further value at each cruise WP. In any phase, a linear propagation of wind and temperature data is provided. During the flight the measured wind and air temperature values are used to update the initial forecast, always applying a linear propagation. Pilots, in any case, are however able to modify the previously entered forecasts.

2.3.4 Performance Computation/Optimization

Performance function has enabled the evolution of the NMSs in the current FMSs, providing the computation of several performance parameters previously manually calculated by pilots, and so making possible an optimization of the flight plan according to several paradigms. The computation takes into account the aircraft performance database, engine performance database, airport database and weather condition. The optimization occurs in the vertical flight plan, and in particular on the speed schedule computation for each flight phase, taking into account however the fixed constraints. The following possible criteria are considered for each phase [28]:

Climb	Cruise	Descent
• economy (lowest cost), • steepest (max climb angle), • fastest (max climb rate), • required time of arrival.	• economy (lowest cost), • max endurance, • max range, • required time of arrival.	• economy (lowest cost), • fastest (max descent rate), • required time of arrival.

Table 5. Performance Optimization Criteria

The criteria to use is selected by the crew for each phase or portion of phase. Some criteria are common to all phases, like the economy and the required time of arrival. Economy criteria determines the optimal speed to minimize the overall cost of operation, according to a Cost Index (CI) entered by pilots in the FMS (see Eq.1). Cost Index is determined by each company according to the current economy state, especially considering the oil cost. Required time of arrival, instead, varies the speed in order to minimize the overall cost (CI), guarantying the achievement of the required time of arrival at the considered WP.

$$CI = \frac{Flight\ Time\ Related\ Cost}{Fuel\ Cost}$$

Equation 1. Cost Index [28]

Speed is defined in terms of Calibrated Air Speed (CAS) or Mach number (M) according to the cross-over altitude (i.e. the altitude for which CAS and M are equivalent). In particular: when altitude is lower than cross over altitude the CAS is used, while for greater altitudes the Mach number is considered. This distinction is done in order to avoid compressibility and aeroelastic effects at high altitudes. In any case, the crew is able to perform a manual override of the speed schedule both in terms of CAS and M. Besides, for climb and descent is also possible to manually edit a vertical speed.
Regarding the altitude, the following data are calculated [28]:

- Cross over altitude: altitude for which CAS and M are equivalent.
- Optimum altitude: altitude for which the ratio between the ground speed and the fuel consumption is maximum.
- Ceiling altitude: max altitude reachable with a residual climb rate available.
- Trip altitude: compromise between the optimum altitude and the specific flight profile. It is considered for short range flight, when the aircraft has not the possibility to reach the calculated optimum altitude.

Optimum or trip altitude can not be usually reached directly after the climb phase due to the heavy weight of the aircraft. The FMS computes the optimal point to execute a step climb and the new altitude to achieve. The same happens for the descent. This is very important especially for the long range flights in order to reduce the fuel consumption.
Another feature of the performance function is the computation of the take-off and landing data in terms of characteristic speeds and altitudes.

Input	Output
• runway slope, • runway length, • runway threshold coordinates and altitude, • runway stopway, • runway clearway, • flap setting, • air temperature, • wind, • aircraft weight, • aircraft Center of Gravity (CG) position.	• V_1 = max speed at which the take off can be aborted, • V_R = rotation speed, • V_2 = take off speed, • V_{FR} = flap retract speed, • V_{SR} = slat retract speed, • V_{CL} = final segment climb speed (also V_3), • engine thrust reduction altitude (from take off to climb value), • acceleration altitude.

Table 6. Take off performance computation

Input	Output
• runway slope, • runway length, • runway threshold coordinates and altitude, • runway stopway, • runway clearway, • flap setting, • air temperature, • wind, • aircraft weight, • aircraft Center of Gravity (CG) position.	• V_{APP} = approach speed (the pilot is usually able to do an override of this value), • V_{REF} = landing reference speed at an height of 50 ft above the runway threshold, • Minimum maneuvering speed in clean configuration, • Minimum maneuvering speed with slats extracted, • Minimum maneuvering speed with flaps extracted, • Landing weight.

Table 7. Landing performance computation

Another considered condition is the performance computation with One Engine Inoperative (OEI), relative in particular to the following parameters:

- maximum climb rate,
- maximum cruise speed,
- ceiling altitude,
- take off data,
- landing data.

In general, for any performance computation, the thrust limit is considered in order to prevent unexpected maintenance and to extend the engines life. In particular, several limits are calculated according to many parameters:

Input to calculate the Thrust Limits	Computed Thrust Limits
• aircraft characteristic, • engine characteristic, • engine bleed setting, • air temperature, • altitude, • speed.	• Take-off thrust, • Climb thrust, • Cruise, • Maximum continuous thrust, • Go Around.

Table 8. Computed thrust limits

Finally, a performance factor entered by the crew is considered in performance computation to make worse the computed values in order to take into account the aircraft age. Performance factor is usually expressed as a percentage increment to predicted fuel flow. It is equal to zero for new aircraft.

2.3.5 Guidance

Starting from the outputs of the previously presented functions, the guidance lets the aircraft to fly the active flight plan. Generally guidance function provides input to the Flight Control System (FCS), but in modern aircraft FMS and FCS can be strictly coupled each other, and so the guidance function provides directly the control surface/engine commands. Apart basic autopilot modes (e.g. altitude, speed, vertical speed, heading hold/acquire functions), three different navigation related guidance modes (specific of FMS) are usually provided:

- Lateral Navigation (LNAV),
- Vertical Navigation (VNAV),
- automatic landing.

LNAV provides the following of the active route in the LAT/LON plane. Altitude and speed are not considered in this mode. Output of guidance function for LNAV is usually the roll command to follow the flight plan.
VNAV, instead, is the opposite mode: it considers the altitude and speed/time assigned to the WP, but not the lateral path of the route. It provides pitch axis and thrust command. VNAV mode can be only activated if the LNAV mode is already active and involves typically also the autothrottle engaging. Activating together LNAV and VNAV an aircraft is able to perform a 4D navigation.
Automatic landing function takes the aircraft to land annulling the deviations from the approach path. Advanced systems executes also the final flare that brings the aircraft to the touchdown. Deviations from approach path are traditionally determined by the Instrumental Landing System (ILS) or the less diffuse Microwave Landing System (MLS). Improvements in navigation precision – due both to the sensor suite (e.g. augmented GPS) and the FMS computation functions – permits however to perform precision like approaches with guidance both in lateral and vertical planes. In practice the descent path is determined by FMS computed WP beam starting from the airport data and previously stored procedures in the FMS database. In this way it is possible to optimize the descent path, reducing the flight time, fuel consumption, pollution and acoustic impact on ground. Besides in this way it is also possible performing automatic landing on airport for which previously it was not possible due to the orography that prevents a straight alignment of the aircraft for the ILS use, requiring hence a manual execution (possible only with good weather conditions). Currently these precision like approaches are cleared for visibility conditions higher than that of ILS, but in the future probably these differences will expire considering the estimated precision increase of the differential GPS with airport local augmentation.

2.3.6 FMS Initialization

Initialization function permits to initialize some FMS parameters and to check some other data. This is a very specific function of each system. Example of parameters that can be set are:

- aircraft weight (in particular fuel weight),

- IRS initialization (if the IRS is available),
- Cost Index,
- Performance Factor,
- preferred altitudes for cruise,
- default air temperature and wind for cruise,
- departure, destination, and alternate airports (this data can be entered in the flight plan creation or initialization phase according to the system).

Possible data to check are the FMS software part number or the databases (navigation, performance, engine, etc.) release dates. This is important since for example the navigation database shall be updated each 28 days.

2.3.7 Communication (Radios, Transponder, Datalink)

Basic communication function for a FMS is relative to the tune (also automatic according to the active flight plan and the navigation database) of the NAVAIDs. Current trend in avionics however is to integrate navigation, communication and identification (transponder) functions together. Some FMSs, so, are able to manage also radio communications and transponder. In particular Satellite Communication (SATCOM) is managed through FMS. In any case, a dedicated panel to manage communication functions on the cockpit is however provided as back-up interface.
Another fundamental feature is the datalink communications. Two different types of datalink communications are distinguished:

- Controller Pilot Datalink Communication (CPDLC),
- Aircraft Communication Addressing & Reporting System (ACARS).

The former is relative to the ATC functions, and in particular to the exchange of request/authorization or information between the controller and the pilots. It was introduced in order to reduce the use of voice radio communication, that was becoming overloaded with the increase of air traffic. Practically it consist in the exchange of textual messages (like a mobile phone SMS) that correspond to standard voice phraseology used in radio communications. Currently, CPDLC is used on oceanic routes and in upper airspace (above Flight Level 245) of Belgium, Germany and Netherlands [31], but there are several researches that aim to extend the use of CPDLC to other airspaces like the terminal areas (e.g. Single European Sky ATM Research – SESAR).
ACARS, instead, is a system to exchange textual messages not relative to ATC between aircraft and ground station with a standard protocol. It is used for several purposes like for example:

- aircraft automatic maintenance report to the airline maintenance staff,
- dispatch exchanges with the airline administration,
- weather report updates.

Some of the ACARS messages are automatically sent/received, while others are directly entered by pilots through an alphanumeric keyboard like for CPDLC. In any case, in practical applications CPDLC and ACARS are strictly related applications. In Fig. 19, a list of CPDLC and ACARS combined functions are reported according to the flight phase.

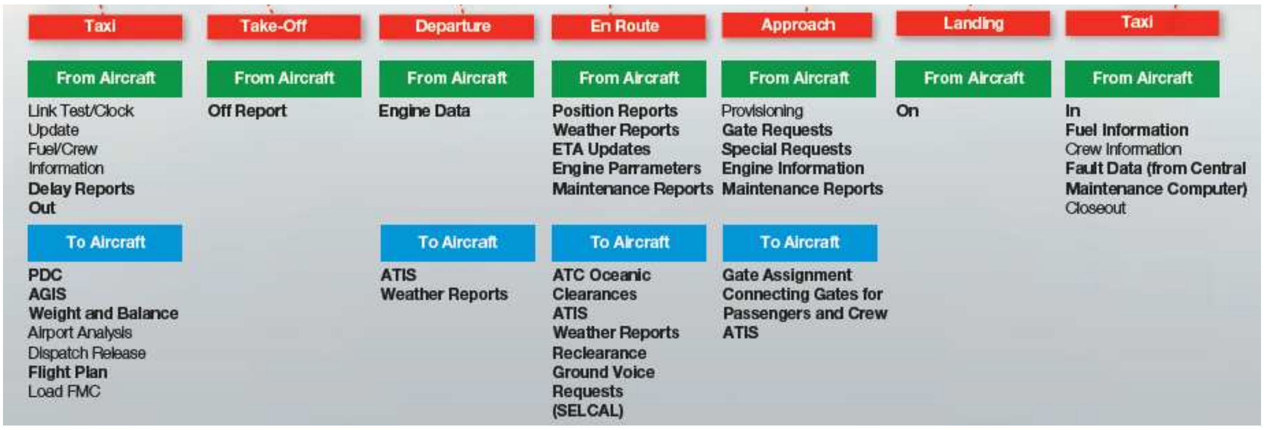


Figure 19. CPLDC and ACARS functions for phase of flight [32]

2.4 Human Machine Interface

In this section, the main Human-Machine interfaces of the FMS will be examined, starting from the traditional layout (see Fig. 20), and then presenting the most recent operative solutions that introduce some innovations with respect to the classic systems (see Fig. 21, 22). Datalink communication interfaces are not considered.

2.4.1 Multifunction Control Display Unit

MCDU has a hierarchical organization in which, starting from the top menu, there is a sort of "folder" for each macro function, composed at its time by one or more pages. Pilots have to navigate in these pages in order to access all available data/controls.

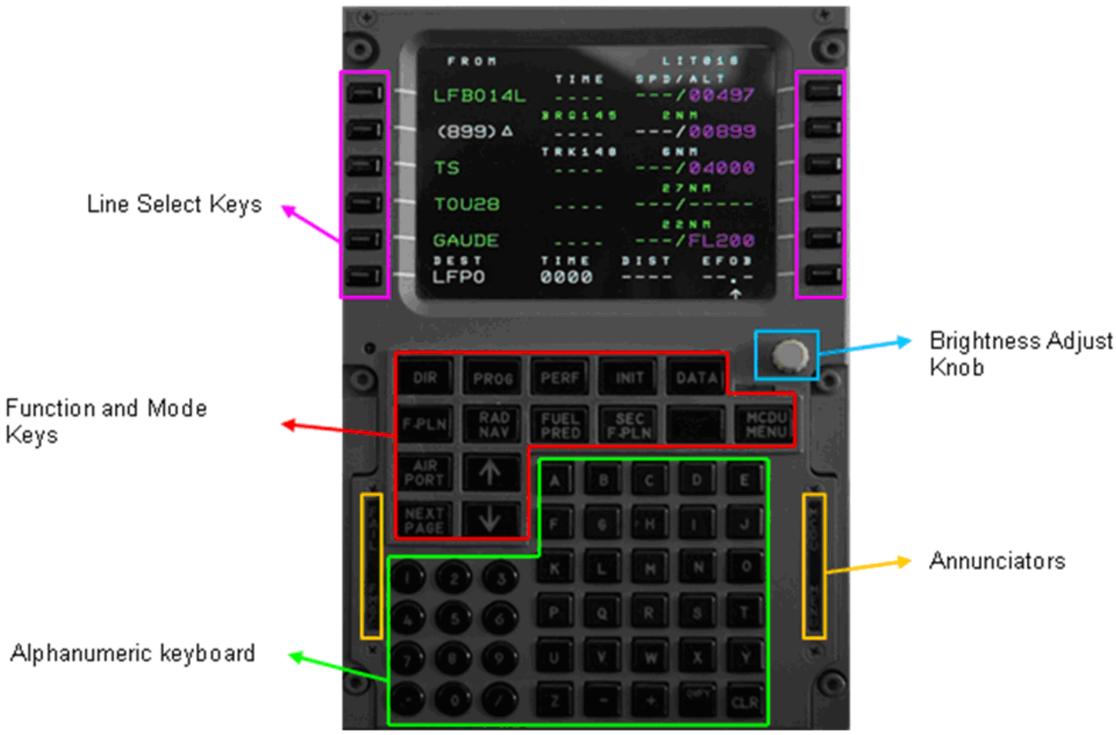


Figure 20. Classic MCDU elements

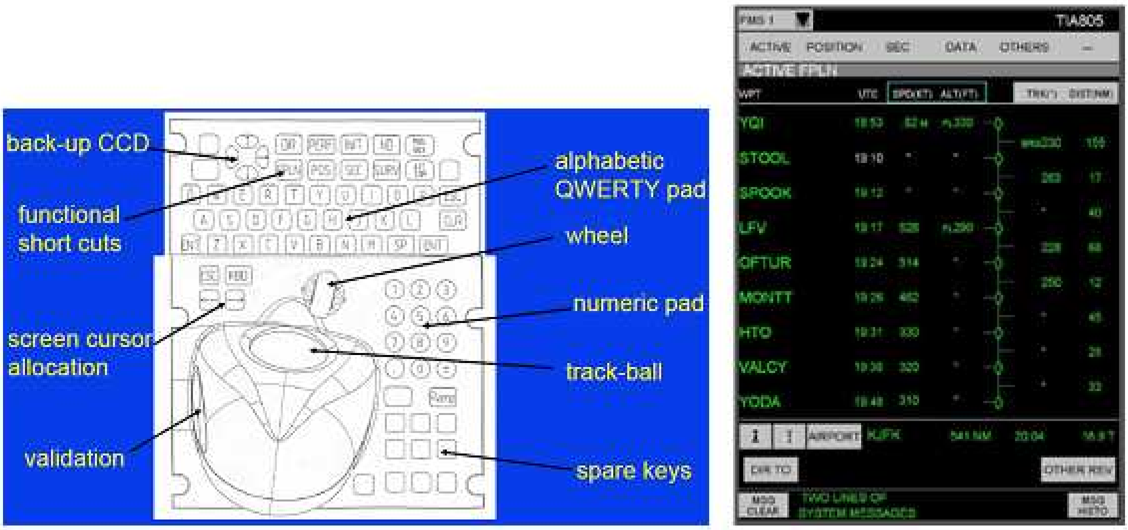
Classic MCDU is made up by the following macro elements:

- Line Select Keys: permit to interact with the current MCDU page selecting the available items.
- Function and Mode Keys: permit a quick access to the main FMS functions without passing from the MCDU menu. Besides they enable the navigation between the possible several pages of the current selected function. Number and type of function keys depend by the specific FMS: there is not a standard.
- Alphanumeric Keyboard: data entry interface for the pilots. It is usually organized in a numeric pad and in a characters keyboard organized in alphabetical order. A Clear key is also provided.
- Annunciators: convey urgent messages to the crew, like for example a MCDU failure or the reception of a datalink message.
- Brightness Adjust Knob: permit to regulate the display brightness according to the lightning condition. If the MCDU has an automatic brightness regulator, this control permit a manual override of the brightness.

In classical interfaces, the Navigation format has only a monitoring function and the crew is not able to provide command through it.
In most recent airliners like the Airbus A-380 and the Boeing B-787, instead, the MCDU configuration is changed, since there is a bigger display without Line Select Keys, on which the crew acts through a Cursor Control Device (CCD), that is a trackball or a trackpad. In this case, it is possible to interact with the CCD directly on the Navigation Format. With this implementation, it is possible for example to command a “direct to” toward a WP with a simple “point and click” interaction on the Navigation Format, without moving in the pages hierarchy of the MCDU.

Figure 21. Airbus A-380 cockpit

In particular, the control devices (CCD and keyboard) have the following layout:



CCD and Keyboard MCDU Display

Figure 22. A-380 FMS Interfaces [33]

2.4.2 Navigation Format

Navigation format provides the situational awareness about the aircraft position in the horizontal plane. Core of this format is the aircraft symbol, around which some concentric circles/arc of circles are displayed at indicated radial distances from it. In particular, the external circle reports the compass rose with respect to the North, that gives the name to the entire symbol (external and inner circles). There are usually two possible layouts of aircraft symbol/compass rose:

- <u>center (also named “rose”) mode</u>: the aircraft symbol is displayed at the center of the navigation format, with the whole Compass Rose around it.
- <u>offset (also named “arc”) mode</u>: the aircraft symbol is displayed at the bottom of the navigation format, with only a circular sector of Compass Rose displayed.

Aircraft symbol is fixed in position on the display, while the beneath world runs according to the aircraft position. The entire navigation format can have several orientation: North Up, Track Up or Heading Up. In the first case the aircraft symbol rotates according to aircraft heading/track, while for others two orientations it is fixed in upright position, and it is the format that rotates when the aircraft turns. Therefore offset layout is not available for North Up orientation.
Besides aircraft symbol and Compass Rose, other symbology is displayed on Navigation format: active flight plan, navigation database fixes (e.g. NAVAIDs, airport, etc.), wind indication, autopilot/FMS demands, navigation parameters (e.g. distance and time to reach a WP, aircraft Ground Speed), NAVAID frequencies, etc.
Other information can be displayed on Navigation Format background, like for example the images coming from the weather radar or the terrain orography.
Recent Navigation Format includes also a Vertical Profile that provides situational awareness about the VNAV.

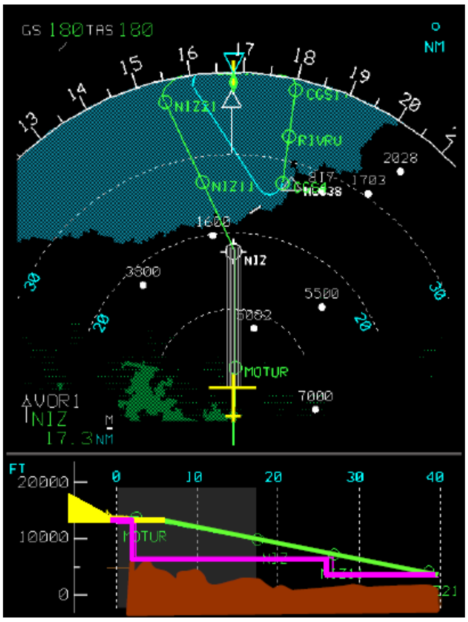


Figure 23. Airbus A-380 Navigation Format in Offset mode [33]

Especially for regional aircraft, there is also the Horizontal Situation Indicator (HSI), used especially for radio navigation. It can be also be integrated in the Primary Flight Display (PFD).

Figure 24. ATR-600 PFD

2.4.3 Autopilot Modes Panel

Autopilot Modes Panel (AMP) is the interface with the guidance function of the FMS. Considering in fact the always greater integration between FMS and FCS, the AMP can be considered a part of the FMS HMI, also if historically it has been developed early as separate interface to control basic autopilot mode. In general, from the AMP it is possible to perform the following actions:

- activate/deactivate the Flight Director,

- activate/deactivate a guidance mode,
- select the guidance mode demand,
- activate/deactivate the autothrottle.

Advanced FMS guidance modes differs from the basic autopilot ones in the level of automation, that is higher in the first case where the aircraft follow an entire horizontal/vertical profile instead of holding/acquiring discrete values entered by pilots.

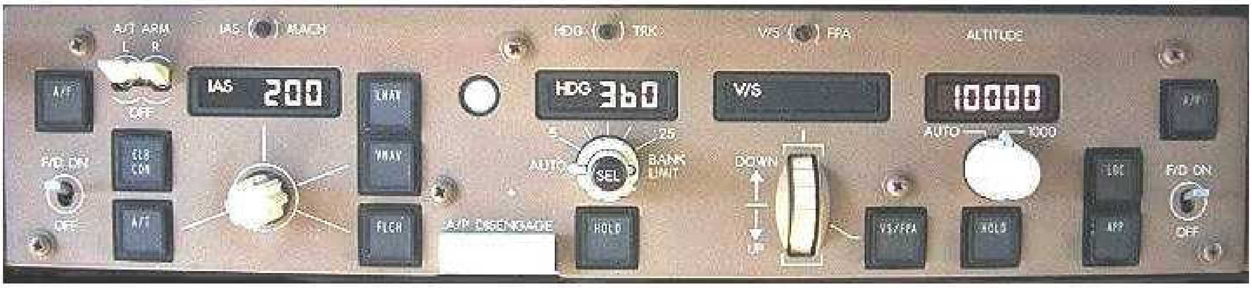


Figure 25. Boeing B-777 autopilot modes panel

The indication of the active autopilot modes is usually displayed on the PFD.

Figure 26. Autopilot mode data on Airbus A-380 PFD

The moding of autopilot mode pushbuttons on the AMPs, instead, is different from an aircraft to another one. In particular, some mode pushbuttons illuminate or otherwise show they have been selected regardless if the mode has been actually engaged or not [34]. The active mode, in fact, is always displayed on the PFD. This different indications, however, can be misleading for the crew, especially since the pilots usually expect to check the mode on the relative control panel. Problems relative to the AMP will be detailed in chapter 4.

Finally, autopilot/autothrottle disconnect pushbuttons are also present on stick/control wheel and throttles in order to permit a quick recovery in manual control by pilots.

2.5 FMS Problems

Introduction of FMS in the airliner cockpits has enabled an improvement in aircraft performances, crew situation awareness and safety, supporting the increase of the air traffic. Nevertheless these advantages, the new level of automation to manage has involved several incidents/accidents. Pilots, in fact, sometimes are in difficulty to understand the system behavior and to choose the proper level of automation to use. These troubles are related both to the FMS algorithms and to the Human Machine Interface. In particular, the following issues have been risen in an investigation performed by the USA Federal Aviation Administration (FAA) through the Aviation Safety Reporting System (ASRS) [35], that is a voluntary and anonymous pilots/ATC operators reports about incidents occurred in flight:

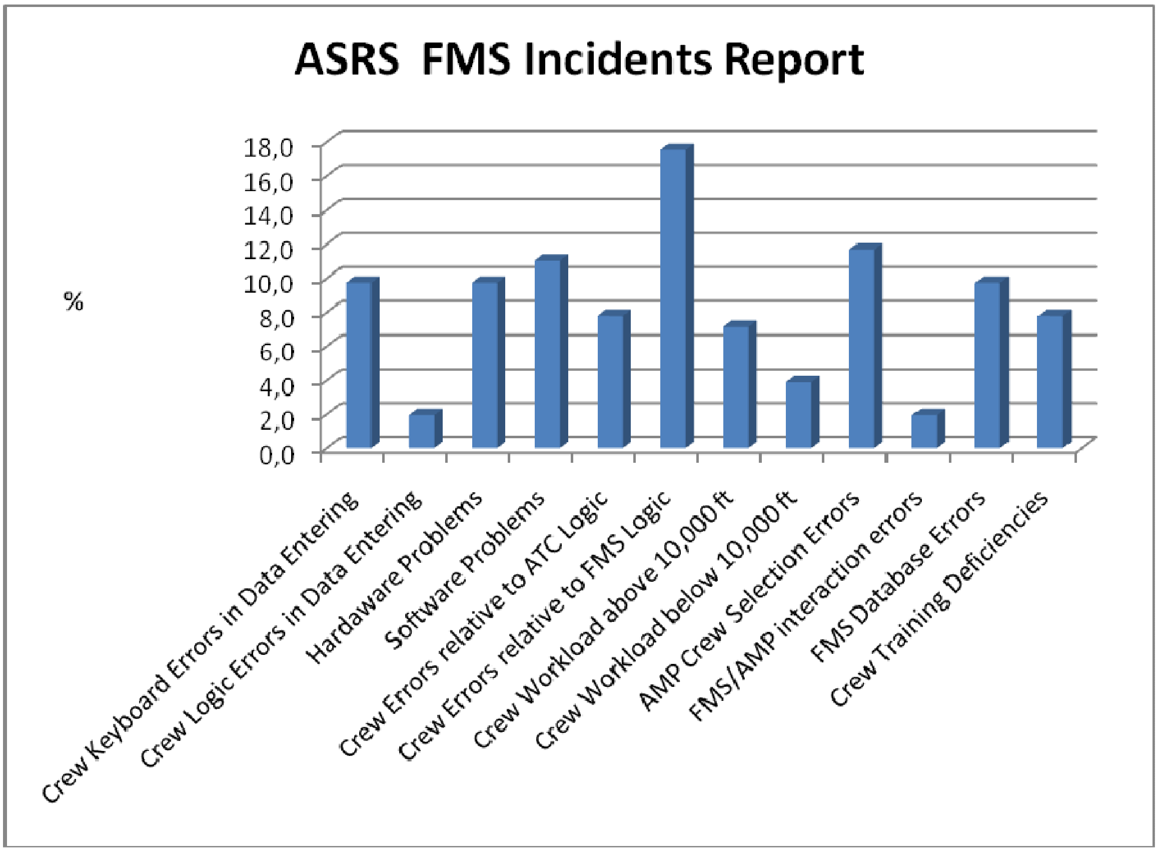


Figure 27. ASRS FMS related problems

Several problem have been reported, with comparable percentages of occurrence. In particular, the most diffuse type is relative to crew errors about the comprehension of the FMS logic. Second position, instead, is relative to troubles about the selection of the guidance mode. More in detail, it is possible to distinguish between two categories: problems directly related to FMS algorithms/components, and that relative to the interface with the crews.

FMS Algorithms and Components	FMS Human Machine Interface
• Hardware problems. • Software problems. • FMS/AMP interaction problems. • FMS Database Errors.	• Crew Keyboard Errors in Data Entering. • Crew Logic Errors in Data Entering. • Crew Errors relative to ATC Logic. • Crew Errors relative to FMS Logic. • Crew Workload above 10,000 ft. • Crew Workload below 10,000 ft. • AMP Crew Selection Errors. • Crew Training Deficiencies.

Table 9. FMS problems categories

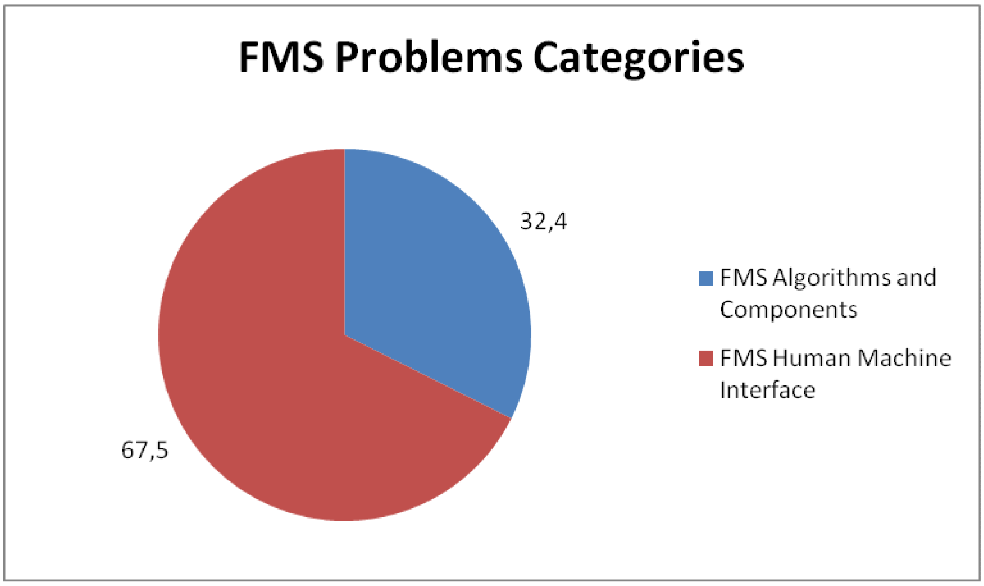


Figure 28. FMS Problems Categories

As reported in Fig. 28, the HMI issues are preponderant with respect to the FMS elements problems. Logic errors – about the FMS moding, ATC constraints implementation in the FMS or guidance mode selection/awareness – are responsible of a generic poor comprehension of how the automation works and what the automation is doing by the crew. FMS interface, in particular, does not provide an adequate feedback about the automation state and requires a complex interaction to modify the flight plan/guidance mode. This complexity contributes also to increment the pilot workload, especially below the 10,000 ft of altitude where the air traffic is particularly congested, with consequent high time pressure on the crew to perform flight plan/guidance changes. The workload is also due to the mnemonic effort required at the pilots by the MCDU menu structures (i.e. number of pages and relative navigation logic). At this purpose, the FMS has been originally conceived for the long-term control of the aircraft, and so when a suddenly flight path change is needed the use of a lower level of automation (i.e. basic autopilot mode/flight director) or manual control is preferable. Many companies, in fact, suggests to avoid FMS re-program below 10,000 ft. For more details, a deepen analysis about human automation interaction will be reported in Chapter 4.

Data entering errors, instead, are related both to the FMS complexity (in particular to the sub-menus/pages structure) and to a poor interface that does not guide the pilot in the task execution alerting for possible erroneous entering.

Finally, there are the crew training deficiencies, particularly relevant in the first years after the adoption of the FMS, when the new pilot role related to the higher level of automation to manage was not well comprised, with consequent poor training relative to the FMS. This issue, however, is still relevant, since the difficulty to train adequately the pilots to manage all possible automation failures. Training necessity, in any case, shows how the automation does not provide a complete assistance to the operator, and requires a detailed training to be successfully and safely managed.

Analyzing the occurrence of ASRS reports per phase of flight (Fig. 29), we find that the greatest number of incident is relative to the vertical flight plan, and in particular to the violation of crossing restrictions (in terms of altitude, speed or time constraints) and to the climb management (altitude to reach, desired climb rate, etc.). This result is due to the complexity of vertical route profile (see Fig. 16 for an example), and to the low situational awareness provided by the HMI. The introduction of Vertical Profile in recent navigation formats has been just done to alleviate this problem.

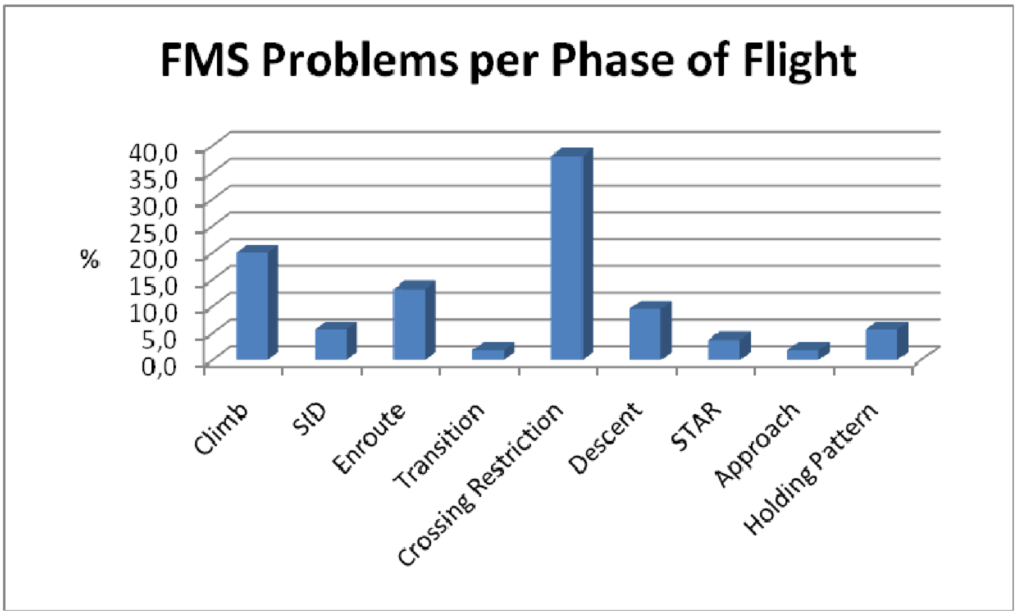


Figure 29. FMS problems per phase of flight

To summarize, the current FMS Human Machine Interface suffers of the following lacks:

- poor situational awareness about the automation state (especially about the guidance mode);

- complexity of MCDU interface – in terms of number of pages, linkage between them and navigation logic – with consequent high workload and difficulty to timely re-program the FMS;
- poor information/data arrangement in each screen;
- information sources are split in several formats (e.g. a complete situational awareness about the VNAV is obtained combined the information present on AMP, MCDU PFD and navigation format), with consequent visual/cognitive workload;
- no graphic FMS assistance (e.g. pop-up, prompt, etc.) in the task execution with consequent possible errors/high workload;
- no erroneous data entered alerting;
- poor situational awareness about the vertical flight plan management.

ASRS investigation is relevant to first FMS generations, and in fact the new models (e.g. A-380, B-787, ATR-600 FMSs) provides some innovations to mitigate the HMI problems, like for example the Vertical Profile in the navigation format, or the bigger size of MCDU screen with a Graphical User Interface (GUI) controllable with a cursor. The previous considerations, however, are still applicable and shall be considered in the design of new interfaces, especially considering the foreseen greater role that the FMS should have in the future ATM scenario.

2.6 Flight Management System for UAS

Main FMS functions are usually performed by current UASs, but with a lower level of integration and performances with respect to that offered by a traditional manned Flight Management System. Therefore the improvement obtained integrating a FMS into an UAS is fundamental, not only to increase the operational capabilities of unmanned systems, but also for a future UAS integration in the civil air traffic.
Unfortunately, a traditional certified FMS can not be taken and installed on an UAS without any care. A Flight Management System for a UAS, in fact, is different in terms of architecture and functions with respect to an airliner one. Starting from the architecture, the equivalent of FMCs are split between on-board and ground segments, according to the performed functions (see Fig. 30). Referring to UAS elements (Fig. 1), on the ground segment the FMS regards only the GCS, while on the airborne part only the airframe is involved. More in detail, the HMI and all functions requiring direct and frequent interactions with the operators are hosted in the GCS (high level control loop). On the vehicle, instead, are allocated the inner control loop functionalities (e.g. navigation, guidance, etc.). Besides the common functionalities, on a UAS there are also other functions not performed by a manned FMS (e.g. autonomous replanning on the vehicle).
Generally speaking, in terms of functions a FMS for an UAS is simpler with respect to that of a manned aircraft for some aspects (in particular for that directly related to the airframe), while it could be considerably more complex for other functions, especially that relative to the mission planning and the vehicle autonomy. A possible functional division between GCS and UAV has been defined starting from typical airliner functions (see Fig 31). In any case, also if a function has been mainly allocated to a segment, there will be often a part also to the corresponding element (e.g. the navigation function is performed on-board, but the aircraft position is displayed on the Navigation format in GCS). As UAV reference, a Class III MALE has been considered. The

payload type, instead, is not relevant in a general context, since the FMS does not interact directly with it. In the FMS, in fact, the payload can be considered only during the planning or in the selection of related guidance modes.

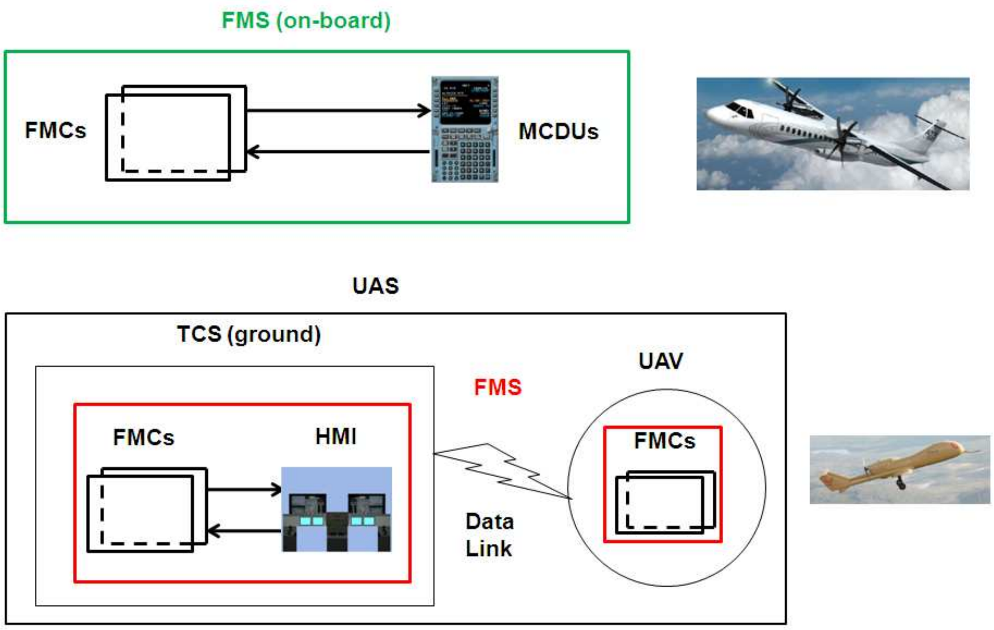


Figure 30. Architectural differences between manned and unmanned FMSs [27]

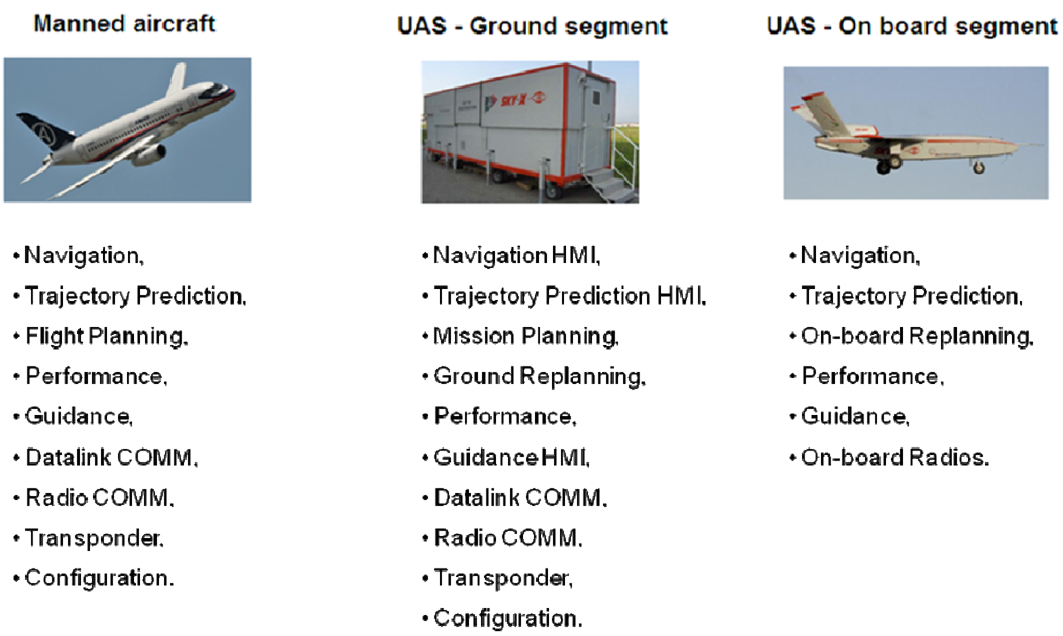


Figure 31. Functional differences between manned and unmanned FMSs [27]

Entering deeper in the functional analysis, in the following table the characteristics of the considered functions are detailed, providing their main features.

Function	GCS	UAV
Navigation	Navigation output are displayed to the operator in the Navigation Format (HMI) in order to provide situational awareness about the vehicle state. Manual override of the best data source can be available for the crew.	It is usually based only on IRS/GPS sensors, with a Kalman filter as best estimate criteria. Use of NAVAIDs would be considered as provision for a future integration in the NAS if they will be required by the civil authorities. In any case, also for manned aviation the trend is to rely on less on NAVAIDS.
Trajectory Prediction	Trajectory Prediction outputs are displayed to the operator in the Navigation Format. From the HMI standpoint, navigation and trajectory prediction can be merged.	Analogous to the manned FMS, with in addition possible calculation relatives to mission parameters (datalink coverage, target visualization, etc.)
Mission Planning	At difference of airliners, for UAS the concept of mission is considered and not a basic flight plan, with all the related issues (mission zones, targets, emergency routes, etc.). Other peculiarities regard the Loiter WPs and the contingency WPs/Routes, terminating usually on safe crash points. Besides, since UAVs are not yet integrated in the civil air traffic, the routes usually have less restrictive speed and altitude constraints.	
Autonomous Replanning	It is a very specific UAS functionality. Ground replanning is preferable for medium Level Of Automation, and it is simpler to certify.	On-board replanning is a very specific feature of UAS. Basically it is relative to emergency conditions, but it can be also consider the operative context (e.g. autonomous route replanning if a new target has been detected). It is suitable for high Level Of Automation, with the relative certification issues.
Performances	Performance calculation is essentially relative to the planning. Typically MALE UAVs are propeller driven and single engine (reciprocating or turboprop), and so the computation is simpler than an airliner.	Performance calculation can be involved in the autonomous replanning, trajectory Prediction and in the guidance.
Guidance	Selection of guidance mode and parameters (HMI).	Aircraft control algorithms. In general guidance has a greater role than on a manned aircraft, since it is the main (or the only) way to control the vehicle. A greater automation level is usually provided with respect to manned aircraft.
Datalink COMM	Intended as communication with ATC and other operative scenario actors, and not between GCS and UAV.	
Radio COMM	Radio management (e.g. frequency selection/storing). Distinction is done between GCS, on-board and satellite radios.	On-board radios are used to avoid Line OF Sight limits in the communications (especially with the ATC).
Transponder	Management of the transponder (mounted on-board).	
Configuration	Setting of some configuration/initialization parameters of the UAS.	

Table 10. UAS FMS functions

3 HUMAN FACTOR ISSUES FOR UAS

3.1 HMI Deficiencies

Developing a Flight Management System for an UAS, specific Human Factor (HF) issues have to be considered together with the HMI problems of manned aviation FMSs. In particular, these issues have a considerable impact on the UAS reliability. UAS, in fact, are still "young" with respect to manned aircraft, and so they have a significant lower reliability, as reported in the following table [27], [36]:

UAS Mishaps	Manned Aircraft Mishaps
Predator – 32*	F16 – 3
Pioneer – 334*	General Aviation – 1
Hunter – 55*	Regional Commuter – 0.1
* much less than 100,000 flight hours (2004)	Large Airliners – 0.01

Table 11. Class A Mishap Rates Per 100,000 Flight Hours

These data are relatively old (2004) and probably the situation is in part get better, due to the greater experience obtained in the last years with the flight hours increase, but the UASs still remain a step below with respect to manned aviation. This is however a problem of system maturity: comparing the F-16 mishap rate with those of Predator and Global Hawk at the same amount of flight hours, in fact, the values are nearly the same [36].

The Pioneer has a greatest mishap rate with respect to the other two systems, but it is the oldest model and it is characterized by a particularly unreliable engine. Analyzing the mishap factors, in fact, the airframe failures are the main accident causes, as reported in the following figures relative to the USA (194000 flight hours) and Israeli (100000 flight hours) fleets in 2005 [2].

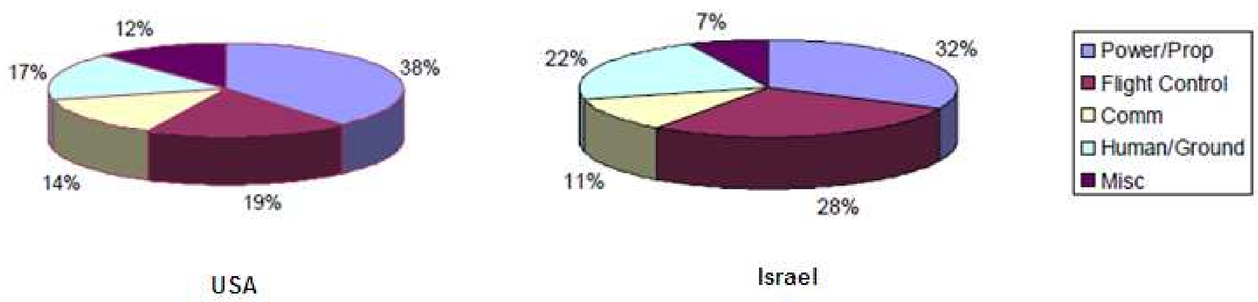


Figure 32. Mishap Causes in USA fleet

Summing the Flight Control and Power/Prop failures, in both cases an airframe percentage of nearly 60% is reached. This is due in part to the use of non qualified/low quality components in order to

reduce the UAS cost. This choice reflects the standpoint according to which a UAV is an expendable vehicle due to the human absence. This consideration however is no longer applicable considering both the UAS integration in the civil air traffic and the cost of modern UAVs, that is increased due to the more complex payloads.
The second voice, instead, is relative to the Human Factor, settled at nearly 20%. Analyzing the causal factors for some US UASs, the percentages oscillates according to the considered system. In particular, the HF varies from the 21% (Shadow 200) to the 67% (Predator). In Fig. 31, Human Factor causes are broken down for each UAS [37].

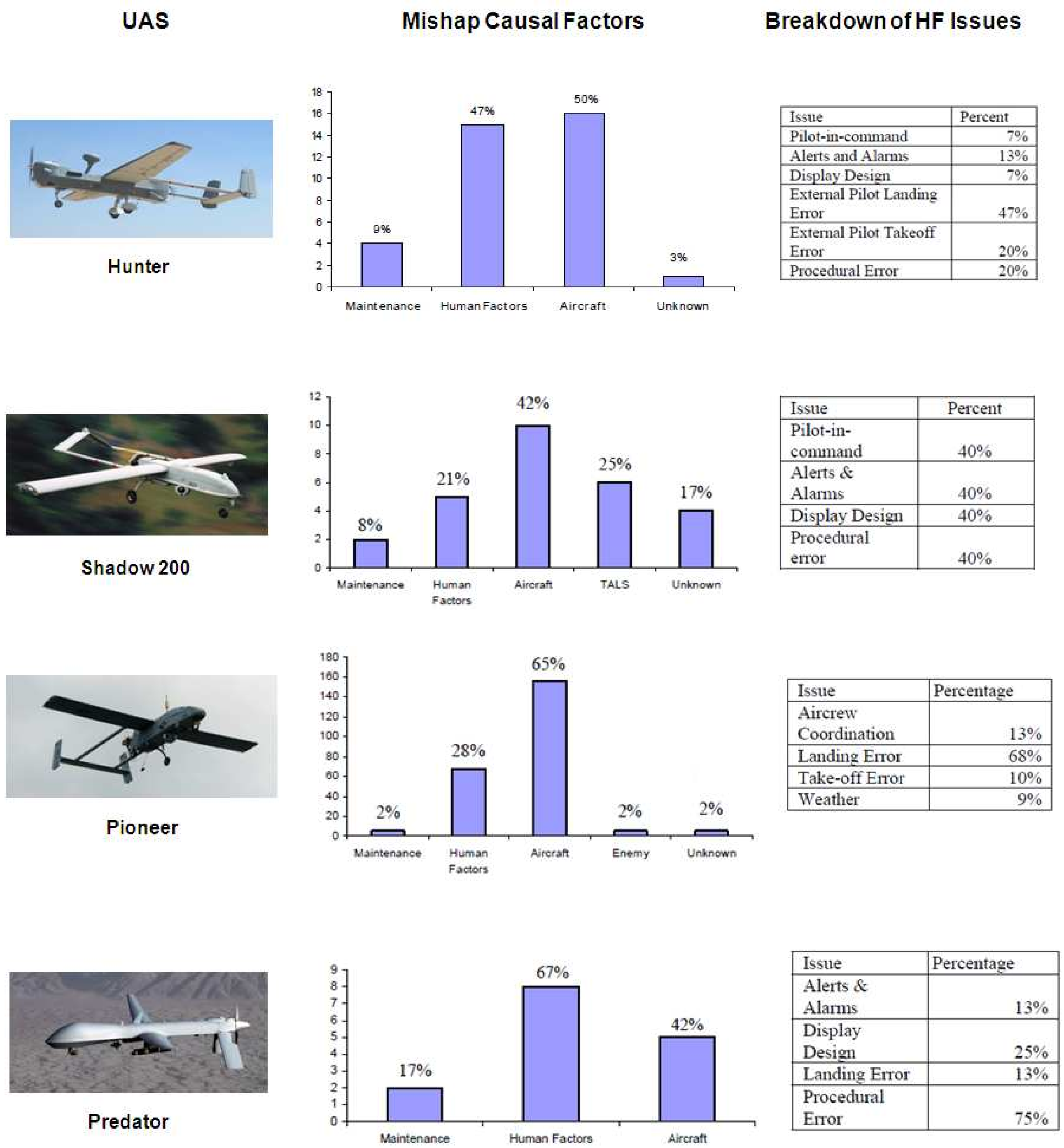
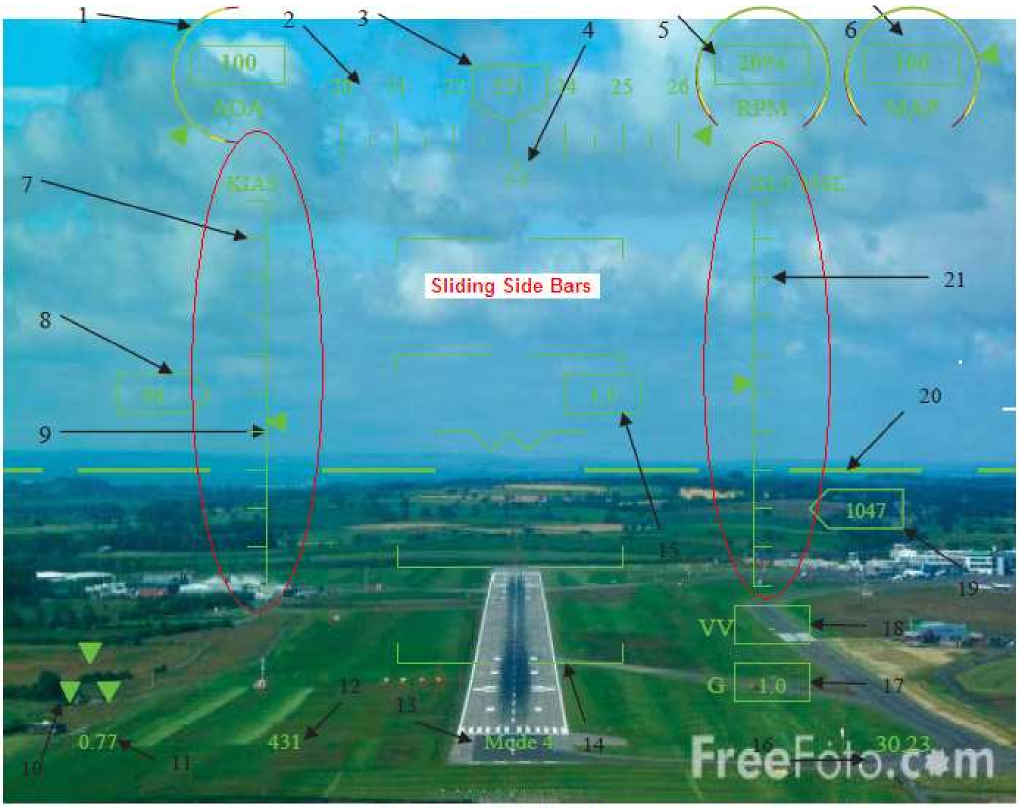


Figure 33. HF Mishap Causes

On the vertical axis of previous histograms there is the accident number. Summing the percentages of the histograms, the total is more than 100%, since some accidents have been classified in more categories.
Analyzing the breakdown – apart from the mishaps due to the presence of an external pilot (i.e. an operator that controls the UAV with a radio flight-control box during take off and landing) or to crew coordination/procedure violation – we can note the presence of display design and alert & alarm deficiencies. Considering the Predator – one of the most diffuse UAS in the world – that has the worst percentage, in particular, several HMI design errors have been identified [38], [39]:

- Sliding side bars in the HUD are not intuitive.



Predator HUD Mock-up

Boeing B-777 PFD

Figure 34. Predator HUD sliding side bars compare with B-777 PFD [39], [40]

- HUD read graphic on sky blue background involves chromostereopsis (i.e. difficulty to focus on an image that combines two colors because each colour is fuzzy when the other colour is in focus) and eye fatigue.

Figure 35. Chromostereopsis example [38]

- Insufficient field of view provided by the guidance camera for manual landing (30°).
- In the Head Down Display (HDD) there are too many levels in the page structure (e.g. in order to change the autopilot mode, the operator must navigate through 4 submenus, spending nearly 7 s [38]).
- In the HDD the information are displayed in a non optimized way.
- In the HDD the operational value ranges are inconsistent within the display.
- Critical commands are not protected.
- In the keyboard, functional keys are next each other (e.g. the keys to control the lights and to cut off the engine), with consequent possible errors.
- Alerts do not provide attention.
- Audio warnings are not sufficient or absent.
- Alerts do not provided enough situational awareness about the real problem.
- Alerts are not correctly prioritized.
- Data to be compared are not displayed in the same display (this is a problem especially in case of failures).
- Engine cut-off and weapon release commands are co-located on the throttle, are similar in shape (i.e. similar tactile feedback) and require the same confirm: an error is so possible.
- The stick can not be long hold by the grips, since this involves an unsupported arm fatigue.

As reported above, the HMI lacks are not only relevant to display design or alert logic, but also to ergonomics aspects.

Figure 36. Predator GCS

Analogous conclusions have been reached in an operative evaluation of the Global Hawk HMI for the Mission Control Element (MCE) station in 2001, with a low global rating on a discrete scale where the possible values are in order: Unacceptable, Poor, Adequate, Good or Excellent [41].

Question	Median Rating
Rate the mental effort workload during task completion with the Global Hawk (GH) UAV system.	Poor to Acceptable
Rate the physical workload during task completion with the GH UAV system.	Acceptable
Rate the time pressure during task completion with the GH UAV system.	Acceptable
Rate the work backlog during task completion with the GH UAV system.	Acceptable
Rate the adequacy of the physical arrangement of the workspaces in the MCE.	Unacceptable to Poor
Rate the lighting in the MCE facility.	Acceptable
Rate the heating and cooling facilities in the MCE.	Poor to Acceptable
Rate the level of noise in the MCE.	Acceptable
Rate the freedom of motion within the MCE	Poor
Rate the utility of the status displays and indicators in the MCE.	Unacceptable
Rate the utility of the controls and menus in the MCE.	Unacceptable
Rate the ease of access to displays, indicators, and controls in the MCE	Unacceptable

Figure 37. Global Hawk MCE HMI Evaluation

3.2 HMI Parameters

In order to discuss the UAS specific Human Factor issues, it is important to fix the main parameters considered in the evaluation of a Human Machine Interface: Situational Awareness and Workload.

3.2.1 Situational Awareness

The Situational Awareness has been defined by Endsley (1988) as three increasing levels of operator comprehension about the operational scenario [42]:

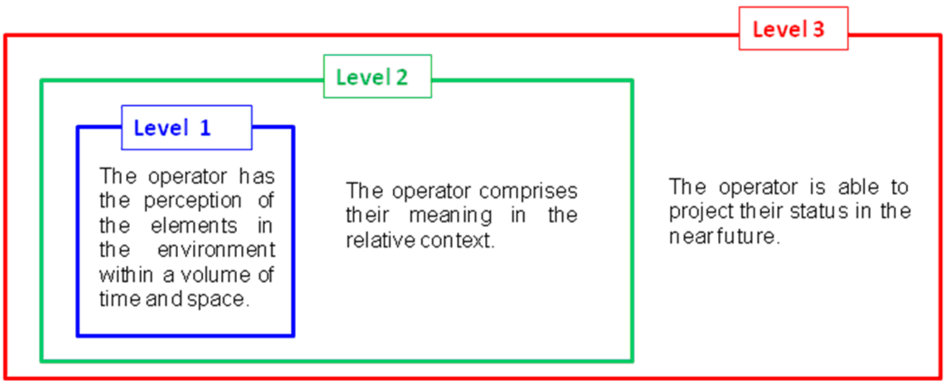


Figure 38. Situational Awareness

In particular, for the UAS context the Situational Awareness is relative to the operator understanding of the following relationships/elements [43]:

- UAV position with respect to:
  - relevant fixes (e.g. waypoints, airports, etc.),
  - terrain (in order to avoid collisions),
  - other aircraft (for mission purposes and in order to avoid collisions),
  - targets.
- Future projection of the previous UAV spatial relationship.
- Weather in the mission area (e.g. wind, air temperature, clouds, turbulence, ice conditions, etc.).
- UAV Health.
- UAV Status (e.g. attitude, speed, fuel level, airframe configuration, payload state, etc.).
- UAS logic (i.e. operator mental model about how the system works, used to predict the UAS responses to various conditions).
- Operational threats (e.g. anti-aircraft defenses, fighters, etc.).
- UAS Mission (i.e. operator understanding of the assigned mission goals and environment).
- Mission Progress (i.e. operator mental model about the mission accomplishment progress).
- Degree to which an UAS Trust can be trusted (i.e. operator evaluation about the probability that his/her commands are received by the UAV and correctness of UAV data).

Original Endsley definition assumes that the human operator is the only intelligent part of the system. Considering UAVs with a high level of autonomy, however, the concept of situational awareness can be extended also to the vehicle. In order to execute an autonomous replanning, for example, an UAV requires detailed information about its position, status, health, replan pre-programmed laws, threats, etc.

3.2.2 Workload

Workload is a very complex meaning and it is relative to the load felt by the operator in the execution of a task. Basically it is possible to distinguish between physical and mental workload components. In our analysis the second – relative to the human cognitive process load – has been mainly considered, since it is the more relevant in UAS context. According to Hart and Staveland, there is the following definition [44]:

Workload is defined as a hypothetical construct that represents the cost incurred by a human operator to achieve a particular level of performance.

This definition is human centered rather than task centered, since it involves several subjective parameters in addition to the objective task demand [44], like for example the operator training/experience or his/her psycho-physical stress level at the considered time. In particular, considering the workload subjective rating scale NASA-TLX (Task Load Index), there are the following workload causes:

Figure 8: NASA-TLX RATING SCALE DEFINITIONS

Title	Endpoints	Descriptions
MENTAL DEMAND	*Low/High*	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
PHYSICAL DEMAND	*Low/High*	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
TEMPORAL DEMAND	*Low/High*	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
PERFORMANCE	*good/poor*	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
EFFORT	*Low/High*	How hard did you have to work (mentally and physically) to accomplish your level of performance?
FRUSTRATION LEVEL	*Low/High*	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Figure 39. NASA TLX Workload Parameters [44]

Regarding the relationship between workload and performance, as the workload increases, performance keeps oneself at maximum value until the task demand is lower than the operator psycho-physical resources (zone "A" in Fig. 40). When the demand exceeds the available resources, instead, the performance starts to decrease (zone "B" in Fig. 40), until it reach a minimum asymptotic value (zone "C" in Fig. 40), maintained independently by further workload increase. A positive difference between resources and demand represents a pool of spare capacity that permits to the operator to face possible unexpected events like a failure. Designing a HMI, in particular, it is very important to guarantee this margin. In Fig. 40 for simplicity operator resources has been considered constant to their maximum value. In real life, however, they vary according to several parameters (e.g. personal motivation, stress, etc.), and in particular they decrease in time due to the fatigue. Therefore operator shifts in GCS shall be properly defined in order to guarantee always the safety, in terms of positive spare capacities.

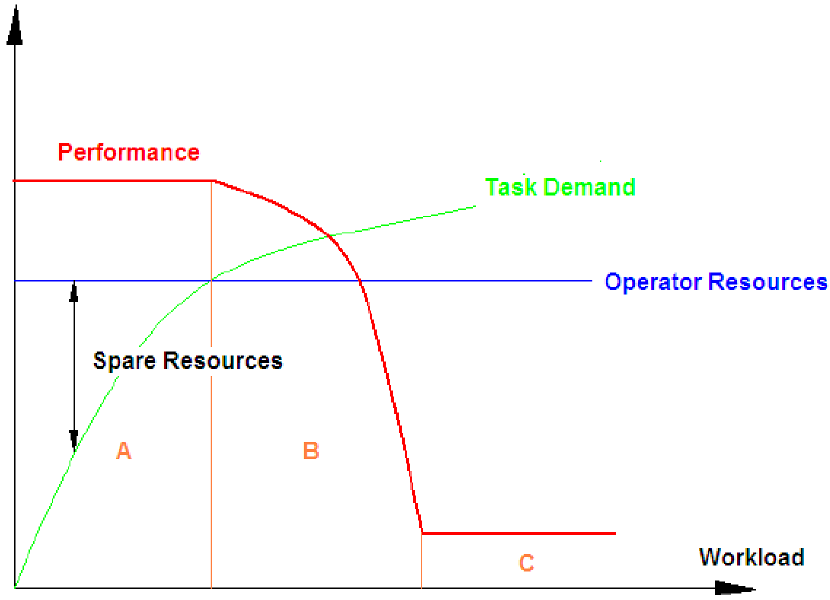


Figure 40. Workload and Performance Relationship

3.2.3 Situational Awareness and Workload Relationship

Situational Awareness and Workload are characterized by a complex relationship:

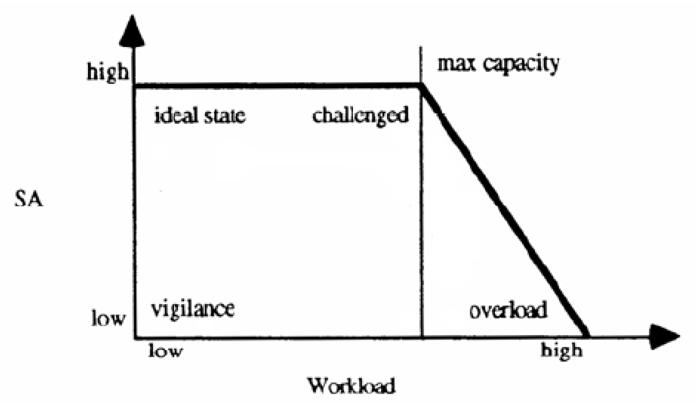


Figure 41. Situational Awareness and Workload Relationship [45]

Although related, Situational Awareness and Workload are however independent constructs. About their relationship, four fundamental states can be identified:

1. Vigilance: both Situational Awareness and Workload are low. This state is typical of monitoring task and can involve operator inattentiveness or low motivation.

2. Ideal State: optimum condition in which the operator achieves a high Situational Awareness with a low Workload. It corresponds to the HMI design goal.
3. Challenged State: the operator is able to maintain a high Situational Awareness, although the workload is increased.
4. Overload: task demand exceeds the operator resources, and hence the workload is so high that the operator is not able to maintain the Situational Awareness.

3.3 UAS Specific Issues

After having drawn attention about the current UAS HMI lacks and having defined the concepts of Situational Awareness and Workload, the specific UAS Human Factor issues due to physical separation between operators and vehicle will be analyzed in details. These issues make the design of a GCS HMI very challenging with respect to a manned aircraft cockpit, and the poor consideration received in the past has contributed to make the Human Factor one of the main UAS mishap causes.
An improvement in this direction is so needed: just to do an example the NASA has recently started (2010) a broad research activities about this problem in the ambit of UAS integration in the civil airspace [46].
In the following paragraphs, each issue is discussed in detail [27].

3.3.1 Different Functional Allocation between Human and Automation

In an UAS the functions allocation between automation and operator is different with respect to manned aircraft. In fact not only the level of automation is usually greater on a UAS, but also the functional division is different, with in general more functions assigned to the automation in an unmanned aircraft. This involves a shift in the operator role from a "traditional" pilot figure charged of vehicle manual control, to a supervisor that monitors the automation behavior and controls the aircraft through high level commands. A similar pilot role changes has been also verified on airliners when the FMS was introduced, but on a UAS the shift is enhanced. The increasing automation authority is needed due to the physical separation between operator and UAV, to the latency that makes difficult (especially in BLOS) the remote manual control and to the possibility to control more vehicles from a single GCS. Besides on an UASs it is also possible to perform actions usually not allowed on a manned aircraft, like for example the capability to wipe out the on-board computer memory on Predator [37], [42].
This different human-automation interaction of course involves several issues in the design of the HMI – that shall always guarantee an adequate situational awareness about the automation state with a low workload – and to the automation logic, that shall be transparent as much as possible to the operator. Unlucky, this issue has not been adequately taken into account in current UASs, that have several problems about it. A detailed discussion of human-automation interaction will be provided in Chapter 4.

3.3.2 Huge Disparity in Level Of Automation

An UAV can be usually controlled with different Levels Of Automation, ranging from the remote manual control to advanced full automatic/autonomous modes. In particular this disparity is greater than on manned aircraft. Since the HMI is strictly related to the considered LOA, having different levels can complicate the design. According to the level, in fact, the information presented to the operator, the available controls and the system feedbacks vary. It is very different in fact providing high level commands like the route to fly or the target to observe, rather than direct control surface/engine commands with stick, pedals and throttle. Adding this huge disparity in LOA to the others UAS specific HF issues, it is not obvious optimizing the interface, with consequent influence on the operator performances. This issue, in particular, is critical for an interoperable GCS able to control different types of UAV.

3.3.3 Lack of Sensory Cues

Since the operator is not physically on the aircraft that controls, he/she suffers of a lack of sensory cues, like ambient visual input, kinaesthetic (experience of bodily position, weight and body movement provided by tactile sensors), vestibular (sense of balance and equilibrium provided by the inner ear) and auditory information [27]. The resultant sensory isolation reduces the operator situational awareness, increasing the probability of a hazard.

This is especially a problem for remote manual control of the vehicle, for which the determination of aircraft state (attitude, speed, engine status, etc.) can be difficult for the operator, since it is based only on the information provided by the instruments and not also to the physical feeling directly experienced by the operator (e.g. accelerations, engine sound, etc.). In particular, for manual flying it is very important to have a visual reference of the external environment, but usually an UAS operator can rely only on the image provided by a guidance camera mounted on the vehicle nose, limited in terms of field of view, resolution and refresh rate due to communication bandwidth constraints. Among the limitations, this absence of a peripheral vision makes manual landings hard, with increasing mishap rates (e.g. Predator [38]).

In order to compensate these lacks, there was in the past the tendency to provide a lot of information to the operator about the aircraft status, generating a possible overload. Processing more data, in fact, can generate a high cognitive effort to the operator, especially when the response time is critical, with a consequent workload increase. Besides due to a bad display design, these information are spread in different formats that can require several steps to be visualized, with a further workload augmentation caused by the operator frustration.

An another way to mitigate the problem is to consider a greater automation, removing all problems related to manual flying of the vehicle. In this case it is not needed neither the video provided by the guidance camera. It is not easy however to reach the same flexibility provided by the manual control.

In any case the HMI shall be designed taking carefully into account the lack of sensory cues, presenting to the operator in a feasible way all the needed information for the achievement of a correct mental model about the aircraft state. For manual control, in particular, the displays (e.g. the Head Up Display – HUD – superimposed over the guidance camera video) have specific symbols not present on analogous manned aircraft formats, like for example a dedicated Angle Of Attack (AOA) indication (see Fig. 34).

3.3.4 Latency

The datalink (uplink and downlink channels) introduces a latency in the control loop that – added to the lack of sensory cues – makes more difficult an UAV control with respect to a manned aircraft. In particular, this is a problem for satellite BLOS control, for which the latency is greater than 1 s, making manual control of the vehicle impractical. This is true also for the payload control (e.g. EO/IR camera orientation through manual input on a stick). So a LOA increment for BLOS operation is mandatory in order to shift the operator role to a supervisory figure. More in detail, the latency effects are [38]:

- compensatory tracking performances deterioration for latency of about 300 ms,
- "move and wait" operator control strategy when the latency is greater than 1 s,
- placement task performance deterioration when latency is above 82 ms,
- over actuation problems when the system delay is unpredictable.

3.3.5 No Shared Fate

Being separated from the vehicle, the operator does not share its fate. This point, together with the sensory isolation and the latency effects, increases the separation feeling in the operator mind. In particular, this issue becomes relevant in case of hazard conditions (failures and/or threats), since the operator could manage the situation with a greater risk-taking tendency than on a manned aircraft where he/she shares the vehicle fate.

3.3.6 Long Duration Mission

"Dull" missions typically assigned to UASs (e.g. searching, monitoring, communication relay, etc.) are characterized by a long persistence on area of operation. This requires a proper crew turnover in GCS in order to maintain an adequate level of performances. Humans, in fact, present poor performances on prolonged vigilance tasks. At this purpose, several studies have demonstrated a vigilance decrement after only 20-35 minutes from work initiation, with a decline in correct responses and/or an increment in reaction times [47]. In particular, analyzing the Predator" operator community, an increment of 7.1 – 17.8 % in reaction time have been found on a course of an 8-hour shift, associated to an increased fatigue subjective rating and decreased alertness ratings. More 92% of operators have also reported moderate to total boredom [47].

3.3.7 Control Migration

UASs are characterized by the possibility to transfer the UAV and/or payload control between different stations. This procedure is named "handover". In particular, the handover is possible between two different GCSs, two stations in the same GCS, external and internal operators or finally between two operators in the same internal station (crew turnover). This procedure is complex and in the past it caused several mishaps due to procedural errors. A specific HMI is required in order to guarantee an adequate situational awareness during the control passage.

3.3.8 Lack of Standardization

Manned aviation has well established standards for the HMI (e.g. standard "T" for the instrument/formats arrangement in the cockpit), consolidated after the experience of millions of flight hours and mishap lessons learned. UAS are still young and so an analogous standardization has not been reached in the past. The recent increment of flight hours, however, permits to define a standardization for UASs. This is a quite difficult task, since the disparity in the Level Of

Automation and the peculiarity of each system (developed in a military context and so with poor attention to these aspects) make complex to define a common line. There can be in fact systems that require an external pilot, others with conventional flight controls (stick, pedals and throttle) or station with a desk station controlled with mouse and keyboard, and finally a mix of the previous solutions. A first attempt has been done with the STANAG 4671, that in the section relative to the Control Station defines some generic requirements about the control types, the mandatory information to display and so on. But a more detailed activity is needed in order to integrate the UASs in the civil airspaces. In particular, the definition of common guidelines for the HMI design and implementation – that takes into account the previous issues – can lead to a reduction in the hazards due to Human Factor. Besides this harmonization will be useful also in an interoperability context in which a GCS is able to control different UAVs/payloads.
Generally speaking, however, therequested standardization goes beyond the simple HMI aspect, since for example also possible Level Of Automation constraints (e.g. mandatory manual control as safety back up) or operator qualification (see section 1.7) are not clearly specified. At the end this problem is responsible to the general rule lack about UASs (see section 1.6).

3.3.9 Lack of Application of Manned Cockpit Know-How

Current UASs consider marginally the traditional manned aviation know-how. In particular, from the HMI standpoint, a GCS is not an aircraft cockpit due to all previously exposed issues, but the HF principles establish in more than a century of flight are not to be rejected a priori, since they can increase the usability and hence the safety of the system. Some of design errors of current GCS, in fact, could be avoided if HMI standards accepted for manned aviation were be considered(e.g. MIL-STD-1472G or DEF-STD-0025). Like for rules (see section 1.6), in fact, only a part of standards can be used without any change, while an another can be considered with some modifications and finally there is a not applicable part. This poor re-used of aeronautics know-how is also due to the fact that in the past the main UAS manufacturers were not aeronautical industries (e.g. General Atomics for the Predator). The optimum is to merge the traditional aviation background with the UAS specific issues/knowledge in order to define the new standards mentioned in section 3.3.8.

4 HUMAN AUTOMATION INTERACTION

4.1 Definition of Automation

Automation has been introduced to reduce the operator workload and to increase the safety, replacing humans in the execution of prolonged/repetitive or critical tasks. An example is the FMS that relieves pilots from the boredom task to keep the aircraft in route during the cruise phase, or the advanced autolanding guidance modes that permit to land in poor/null visibility conditions without loss in safety. More formally there is the following definition [48]:

The automation is defined as the execution by a machine agent (usually a computer) of a function that was previously carried out by a human.

Current automation in aeronautics concerns essentially physical functions – like the previous examples of navigation and autolanding guidance modes – freeing humans from time-consuming and laborious tasks. Automation of cognitive functions like decision making and planning processes (normally devoted to the operator), instead, is rarer [48]. At this purpose, speaking about automation it is possible to distinguish between the two macro concepts of automatic and autonomous systems, having the following definitions [49]:

Automatic systems are fully pre-programmed and act in the same manner regardless of the situation and whether the solution is the most favorable.

Autonomous systems optimize their behavior in a goal-directed manner in unforeseen situations (i.e. in a given situation, the autonomous system finds the best solution).

Today's Flight Management Systems belong essentially to the first category, since they act from external inputs according to fixed laws. For example, given deviations in azimuth/elevation from the landing path and the aircraft state, the guidance will react according to an establish control algorithm to annul the errors. But the mode activation and validity conditions check are assigned to the pilot. Autonomy, instead, is a wider concept, since it provides automation also in the decision making/planning activities, besides to the automatism in the execution of the taken decisions. Just to do an idea: a current FMS follows the route planned by the pilot, while an autonomous system first determines the optimum route according to the mission objectives and then follows it. In manned aviation this concept is not implemented due to the presence of pilots on-board, but for the UASs it is a fundamental characteristic in order to enhance the system capabilities, especially for BLOS operations and the control of multiple vehicles from a single GCS. Autonomy, in particular, sometime is confused with intelligence, but they are not the same thing. Intelligence in fact is defined as [50]:

The Intelligence is the capability of discovering knowledge and using it to do something.

To resume, an automatic system performs actions exactly as programmed without any degree of freedom, an autonomous system is able to choice the actions to perform according to the assigned objectives and fixed decision/planning rules, and finally an artificial intelligence is able to modify the decision/planning rules according to the knowledge learnt by mission environment. In any case, there is not an universally accepted distinction between automatism, autonomy and intelligence, and these concepts can overlap.

4.2 Level Of Automation

In practice, it is not easy to classify a system as automatic, autonomous or intelligent – that is to determine the Level Of Automation (LOA) – since there are many intermediate conditions. Considering for example the performance optimization function of the FMS, it has the capability to determine the optimum altitude and the step climb points, but the acceptance of these suggestions is however delegated to the pilot. Comparing this situation with the previous definitions of automatic and autonomous systems, thus there is a middle situation in which the system is able to propose a decision to the operator if he/she requires it, but not to activate it without an authorization. Level Of Automation, in fact, can not be represent by three discrete categories, but it evolves along a continuum. Therefore in order to determine actually the LOA of a system several measure scales have been defined, discretizing the automation continuum with different criteria. One of the most diffuse scale has been created by Parasuraman, Sheridan et al. dividing the LOA in ten values according to the allocation of the decision making task:

LOA	Meaning
10	Computer ignores the human.
9	Computer reports only if it wants to.
8	Computer only reports if asked.
7	Computer executes, then reports to human.
6	Human can veto computer decision within timeframe.
5	Computer executes suggestion with approval.
4	Computer suggest one alternative.
3	Computer chooses a set of alternatives.
2	Computer computes complete set of alternatives.
1	Human makes all decisions.

Table 12. Parasuraman, Sheridan et al. LOA scale

Although extensively diffused, this scale has some limits, since it is limited to the decision making phase, that it is the core of automation, but does not represent the whole “cognitive” process performed by the automation. Besides it is more suitable to evaluate a single function than a complete system, and it does not consider the specific context. More details are provided by the

Autonomous Control Level (ACL) scale, developed by the USA Air Force Research Laboratory. It was developed specifically for UAS and it based not only on the analysis/decision making process, but also to perception/situational awareness and communication/cooperation features. Considering more parameters, it is able to distinguish better between the different UAS categories. At difference of Parasuraman and Sheridan scale, it provides eleven levels, ranging from the remotely piloted vehicle (level 0) to the human like UAS (level 10).

Level	Level Descriptor	Perception/Situational Awareness	Analysis/Decision Making	Communication/Cooperation
10	Human-Like	/	/	/
9	Multi-Vehicle Tactical Performance Optimization	Detection & Tracking of other air vehicles within airspace.	Full decision making capability on-board. Dynamically optimize multi-ship group for tactical situation.	Distributed cooperation with other air vehicles. On-board deconfliction and collision avoidance. Fully independent of supervision/control if desired. No centralized control within multi-UAV group.
8	Multi-Vehicle Mission Performance Optimization	Detection & Tracking of other air vehicles within local airspace. OK to operate in controlled airspace w/o external control.	Continuous mission/trajectory evaluation & replan – optimize for current mission situation. Avoid collisions and replan/optimize trajectory to meet goal, etc.	External supervision – abort/recall or new overall goal. On-board deconfliction & collision avoidance. Distributed cooperation with other air vehicles.
7	Real-Time Multi-Vehicle Cooperation	Detection of other air vehicles in local airspace. Multi-threat detection/analysis on-board.	Continuous flight path evaluation & replan. Compensate for anticipated system malfunctions, weather, etc. – optimize trajectory to meet goals, manager resources, avoid threats, etc.	On-board collision avoidance. Uses off-board data sources for deconfliction & tracking. Hierarchical cooperation with other air vehicles.
6	Real-Time Multi-Vehicle Coordination	Detection of other air vehicles in local airspace. Single threat detection/analysis on-board.	Event-driven on board. RT flight path replan – goal driven & avoid threats. RT health diagnosis. Ability to compensate for most failures and flight conditions – inner loop changes reflected in outer loop performance.	On-board collision avoidance. Uses off-board data sources for deconfliction & tracking. Assumed acceptance of replan. External supervision – rejection of plan is an exception. Possible close air space separation (1-100 yds).
5	Fault/Event Adaptive Vehicle	Automated Aerial Refueling & Formation sensing. Situational Awareness supplemented by off-board data (threats, other air vehicles, etc).	Event-driven on board. RT trajectory replan to new destination. RT Health Diagnosis. Ability to compensate for most failures and flight conditions and to predict onset of failures. On-board assessment of status vs. mission completion.	On-board derived vehicle trajectory "corridors". Uses off-board data sources for deconfliction & tracking. External supervision – accept/reject of replan. Possible close air space separation (1-100 yds) for automated aerial refueling, formation in non-threat conditions.
4	Robust Response to Anticipated Faults/Events	Threat Sensing on-board.	RT Health Diagnosis. Ability to compensate for most failures and flight conditions. Automatic trajectory execution. On-board assessment of status vs. mission completion.	Secure within LOS electronic theater to nearby friendlies. Offboard derived vehicle "corridors". Medium vehicle airspace separation (100's of yds). Threat analysis off-board.
3	Limited Response to Real Time Faults/Events	/	RT Health Diagnosis. Ability to compensate for limited failures. Automatic trajectory execution.	Health Status monitored by external supervision. Off-board replan/WP plan upload. Wide airspace separation requirements (miles).
2	Pre-loaded Alternative Plans	/	RT Health Diagnosis. Automatic trajectory execution (via WPs). Preloaded alternative plans (e.g. abort).	External commands – alternative plans, approvals, aborts. Report status on request or on schedule. Wide airspace separation requirements (miles).
1	Execute Preplanned Mission	Situational awareness via Remote Operator Flight Control and Navigation Sensing	Robotic/Preprogrammed. Pre/post Flight BIT.	External control via low level commands. Reports status on request. Wide Airspace separation requirements (miles). No on-board knowledge of other air vehicles-all actions are preplanned.
0	Remotely Piloted Vehicle	Flight Control (altitude, rates) sensing. Nose Camera. Situational Awareness via Remote Pilot.	N/A	Remotely Piloted. Vehicle status data via telemetry.

Table 13. Initial ACL metrics chart [50]

Nevertheless the greater provided details with respect to the previous scales, the initial ACL metrics have some problems [50]:

- the metrics are not broad enough to cover UAS acting on strategic knowledge: they are limited to the tactical level,
- the cooperation ("what") is mixed to the communication ("how") in the same metric.

In order to improve the scale resolution, a new version of the ACL metrics has been developed:

Level	Level Descriptor	**Observe** Perception/ Situational Awareness	**Orient** Analysis/Coordination	**Decide** Decision Making	**Act** Capability
10	Fully Autonomous	Cognizant of all within Battlespace	Coordinates as necessary.	Capable of total independence.	Requires little guidance to do job.
9	Battlespace Swarm Cognizance	Battlespace Inference – Intent of self and others. Complex/intense environment on-board tracking.	Strategic group goals assigned. Enemy strategy inferred.	Distributed tactical group planning. Individual determination of tactical goal. Individual task planning/execution. Choose tactical targets.	Group accomplishment of strategic goal with no supervisory assistance.
8	Battlespace Cognizance	Proximity Inference – Intent of self and others. Reduced dependence upon off-board data.	Strategic group goals assigned. Enemy tactics inferred ATR.	Coordinated tactical group planning. Individual task planning/execution. Choose targets of opportunity.	Group accomplishment of strategic goal with minimal supervisory assistance.
7	Battlespace Knowledge	Short track awareness. History and predictive Battlespace data in limited range, timeframe and numbers. limited inference supplemented by off-board data,	Tactical group goals assigned. Enemy trajectory estimates.	Individual task planning / execution to meet goals.	Group accomplishment of tactical goal with minimal supervisory assistance.
6	Real Time Multi-Vehicle Cooperation	Ranged awareness – on board sensing for long range, supplemented by off-board data.	Tactical group goals assigned. Enemy location sensed/ estimated.	Coordinated trajectory replanning – group optimization.	Group accomplishment of tactical goal with minimal supervisory assistance. Possible close air space separation (1-100 yds).
5	Real Time Multi-Vehicle Coordination	Sensed awareness – Local sensors to detect others, fused with off-board data.	Tactical group plan assigned. RT Health diagnosis. Ability to compensate for most failures and flight conditions. Ability to predict onset of failures. Group diagnosis an resource management.	On-board trajectory replanning – optimize for current and predictive conditions. Collision avoidance.	Group accomplishment of tactical plan as externally assigned. Air collision avoidance. Possible close air space separation (1-100 yds) for air refueling, formation in non-threat conditions.
4	Fault/Event Adaptive Vehicle	Deliberate awareness – allies communicate data.	Tactical plan assigned. Assigned rules of engagements. RT health diagnosis. Ability to compensate for most failures and flight conditions – inner loop changes reflected in outer loop performance.	On-board trajectory replanning – event driven self resource management deconfliction.	Self accomplishment of tactical plan as externally assigned. Medium vehicle airspace separation (100's of yds).
3	Robust Response to Real Time Faults/Events	Health/status history & models.	Tactical plan assigned. RT health diagnosis. Ability to compensate for most control failures and flight conditions.	Evaluate status vs. required mission capabilities. Abort/RTB insufficient.	Self accomplishment of tactical plan as externally assigned.
2	Changeable Mission	Health/status sensors.	RT Health diagnosis. Off-board replan (as required).	Execute preprogrammed or uploaded plans in response to mission and health conditions.	Self accomplishment of tactical plan as externally assigned.
1	Execute Preplanned Mission	Preloaded mission data. Flight Control and Navigation Sensing.	Pre/Post flight BIT. Report status.	Preprogrammed mission and abort plans.	Wide airspace separation requirements (miles).
0	Remotely Piloted Vehicle	Flight Control (altitude, rate) sensing. Nose camera.	Telemetered data. Remote pilot commands.	N/A	Control by remote pilot.

Table 14. Final ACL Chart [50]

Since the final objective of the automation is to replace humans (level 10 of the initial chart), the idea that has driven the development of the new ACL scale is to consider a human effectiveness metric to evaluate the UAS Level Of Automation: the "Observe Orient Decide & Act" (OODA) loop. OODA – originally developed to model the human behavior in problem solving task – has been interpreted for the UAS context, associating each issue to the corresponding UAV step (e.g. observation phase is considered as the achieving of the situational awareness by the vehicle thanks to its sensors). Although developed for military context, the scale can be however used for civil UASs, since the capability to perceive the environment and to analyze the collected data is equivalent independently to be in a battlespace or in a generic operative scenario. Only the words change.
Generally speaking the ACL charts is futuristic, since current UASs reach only a low LOA.

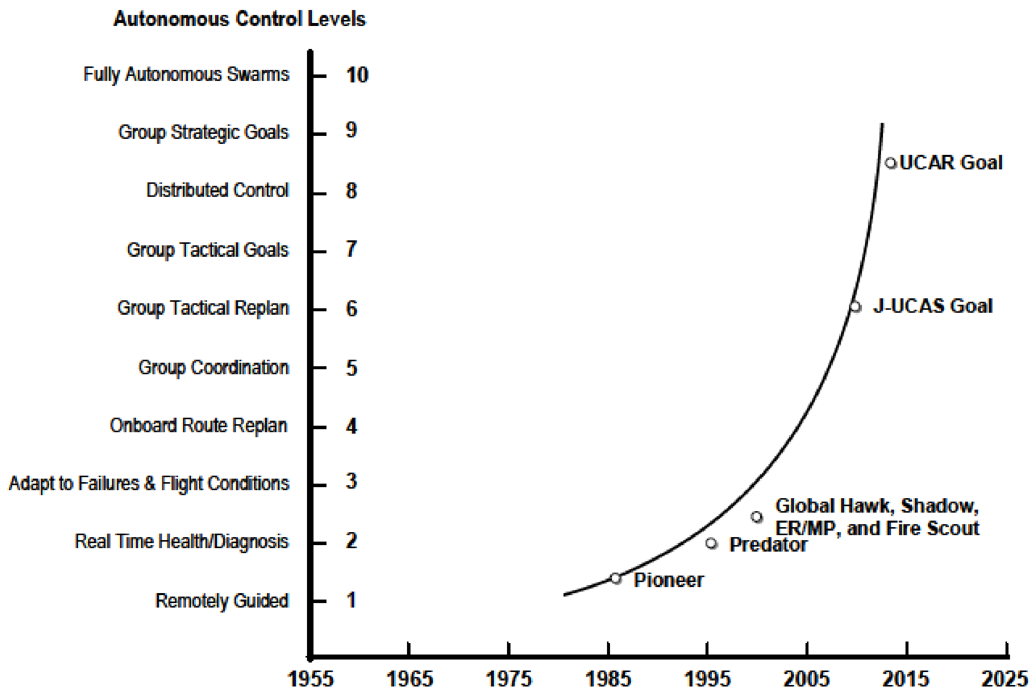


Figure 42. Trend in UAS Level Of Automation [2]

As reported in the previous figure, the Predator has an ACL of 2, while the more advanced Global Hawk reaches about 2.5. The curve in Fig.42 is relative to 2005, but the foreseen trend has not be realized since now there are not operative UASs with an ACL of nearly 7 (at least in MALE, HALE and UCAV categories). Develop an high Level Of Automation, in fact, is not a trivial task, due to the difficulty in the implementation of the relative algorithms, especially considering also the certification standpoint. In any case, as the LOA increases, the type of interaction between human operator and automation changes. In particular, the following types can be distinguished:

- Direct manual control: the automation has no or very little role.
- Assisted manual control: the automation helps the operator that keeps however the manual control of the system (e.g. Flight Director).
- Shared control: automation and operator share the control of the vehicle (e.g. basic autopilot modes in which the operator set a demand, that is reached and kept by the system).

- Management by delegation: the operator delegates the automation to perform some tasks (e.g. advanced navigation guidance modes in which the vehicle follows automatically a path defined by the operator or the autolanding). The automation can not take the initiative.
- Management by consent: automation proposes an action that will be executed only after the operator approval (e.g. new route proposed by the system according to a change in the operative scenario, first evaluated by the operator and then in case accepted).
- Management by exception: automation proposes an action that will be executed if no stopped by the operator within a time frame (e.g. on-board route replan in case of emergency). Human approval is not mandatory.
- Autonomous Operation: further advanced levels in which the automation decides autonomously to act, reporting or not the decision to the operator.

Comparing these interaction types with the LOA and the Human involvement, there are the following situations:

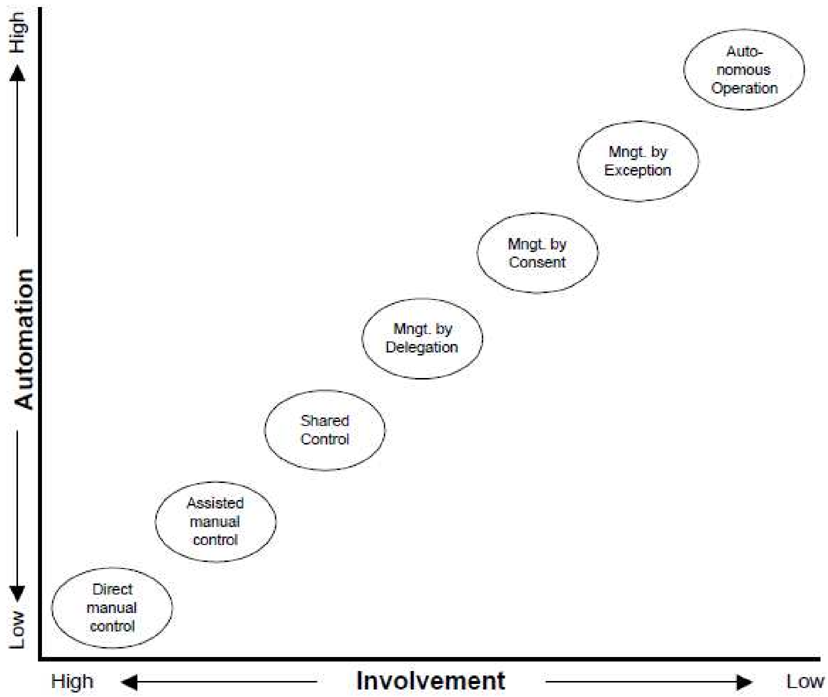


Figure 43. Human Automation Interaction Levels [42]

It is quite easy to correlate the previous interaction types with the Parasuraman and Sheridan scale, since it considers only the decision-making allocation that is just the parameter used to discriminate the several human-automation relationships. For the ACL chart, instead, the correlation is more complicated, due to the fact that it is relative to the global system and do not consider explicitly who takes decision between human and automation. Besides, in a UAS there can be functions with different Levels Of Automation, and the ACL does not discriminate this situation. In any case, a possible classification of human-automation interactions for the ACL and Parasuraman-Sheridan scales is provided in Tab. 15. From the comparison between these scales, the futuristic vision of the ACL is reconfirmed, since more than half levels are relative to autonomous operation. Operative

UASs reach in fact only a Management by Delegation interaction, and so they can be classified as automatic system.

LOA	Parasuraman-Sheridan et al.	ACL
10	Autonomous Operation	Autonomous Operation
9	Autonomous Operation	Autonomous Operation
8	Autonomous Operation	Autonomous Operation
7	Autonomous Operation	Autonomous Operation
6	Management by Exception	Autonomous Operation
5	Management by Consent	Autonomous Operation
4	Management by Consent	Management by Exception
3	Management by Consent	Management by Consent
2	Management by Consent	Management by Delegation
1	Direct, Assisted or Shared control, or Management by Delegation	Management by Delegation
0	N.A.	Direct, Assisted or Shared control

Table 15. LOA scales vs. Human-Automation interaction

4.3 Human Supervisory Control

According to the Human-Automation interaction type, the operator role changes. In particular, starting from the Management by Delegation strategy (i.e. automatic system), there is a shift from a direct controller figure to a supervisor role. As the automation increases further, the supervision switches to higher command levels. In particular between human and vehicle there are some computers as intermediates. This form of computer mediated control is named Human Supervisory Control (HSC), and it is particularly suitable to describe the control of an UAS

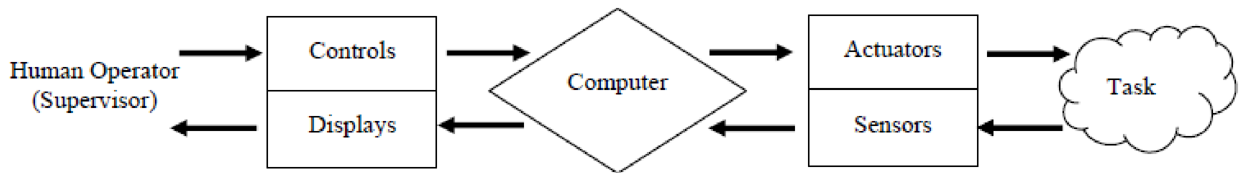


Figure 44. Human Supervisory Control [51], [52]

More in detail HSC can be represented by four nested control loops.

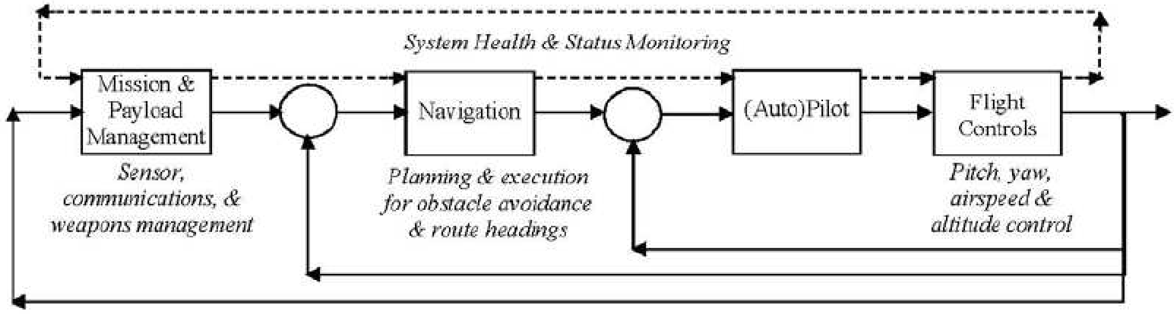


Figure 45. HSC nested control loops [51], [52]

The inner loop is relative to the motion control/guidance of the vehicle, and it is directly related to the dynamics of the specific UAV. It comprises the management of autopilot (basic modes). The second loop extends the control to the navigation, that is vehicle position determination, route planning and its execution. Practically it involves many FMS functions. Finally outer loop considers the management of the mission and payload. In this case the operator provides only high level commands to the vehicle. Parallel to these three control loops, there is the system health and status monitoring loop, that is transversely to the previous ones.

Each control loop can be allocated partially or totally to human or automation. According to this allocation there are all the possible LOA. In particular different LOA there could be also inside the same loop: for example the planning can be manual while the route execution is automatic.

The reduction of human involvement in low level tasks execution permits to allocate the limited human resources to the more demanding knowledge based processes of monitoring, situation analysis and decision making. As the LOA increases, also part of these processes are allocated to the automation. This permits a quick system reaction in time pressure situations (e.g. a failures or new target detection), reducing further the operator workload. Besides automating the first two control loops is a fundamentals step in order to achieve the multi vehicle control.

4.4 Automation Problems

It is apparent that rather than eliminating human error; some of the new technology has simply resulted in creation of entirely new opportunities and entirely new categories of human error to occur" (Lauber, 1987). [38]

Nevertheless the automation has been introduced to augment the system capabilities and safety, the poor attention to the HMI perspective has raised new Human Factor issues. In particular, in the last decades this matter has received greater attention for manned aviation after some catastrophic accidents that have thought over the way in which the automation has been integrated in the cockpit. This knowledge pool is directly applicable also on UAS, for which these issues are more critical due to the greater LOA. Some UAV losses, in fact, have been just caused by human-automation interaction problems. In the following sections, the several Human Factor issues related to the automation are discussed.

4.4.1 Mode Awareness

On 20th January 1992 an Airbus A-320 crashed during the landing to the Strasburg-Entzheim Airport in France due to an erroneous crew autopilot setting. The crew inserted 3.3 intending to fly with a 3.3 degree glide scope on the landing path convinced to be in autolanding mode, but at the moment the active autopilot mode was the vertical speed, and so the command resulted in a descent rate of 3300 ft/min with the consequent crash [52].
This is only an example of one of the accidents caused by a poor crew situational awareness about the automation state and the way in which it works. This issue is named “mode awareness” (sometimes also “mode confusion”), and it is one of the main problems in human-automation interaction.
A mode is defined as a system state that corresponds to an unique behavior [27]. The operator interacts with them in order to accomplish the assigned task. Comparing task description, user mental model about how automation work and feedback provided by the automation interface, the following diagram is obtained:

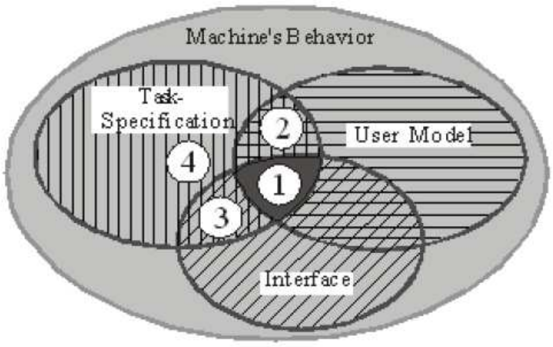


Figure 46. Mode Awareness factors [53]

Referring to Fig.46 the optimal situation is in the zone 1, where all factors are adequate. In order to keep a good mode awareness, in fact, three conditions shall occur simultaneously: the task shall be clearly specified (e.g. ATC constraints), the user shall have a comprehensive knowledge about the automation functioning and finally the interface shall provide an unambiguous feedback about the automation state. Current systems are improvable in all these aspects. Starting from the task specification, it depends only in part to the system, but having modes that permit to satisfy directly the assigned tasks helps. Unfortunately autopilots/FMSs are very complex systems and the pilot often has to reformulate the task in several steps that he/she has to perform. Complexity is related directly to the big number of available modes on airliners (in average 25 [54]) and to the transitions between them. Just to give an idea: in average the 80% of control laws code consists of logical statements [53].
Modes are usually classified in three categories: pitch modes (i.e. modes relative to vertical plane motion through pitch commands), roll modes (i.e. modes relative to lateral plane motion through roll commands) and thrust modes (i.e. modes relative to vertical plane motion through autothrottle commands). In Fig. 47 it is reported an example relative to the Boeing B-747 400, that has 21 different modes. The proliferation of guidance modes is due to the attempt to reproduce with automation the same flexibility provided by the pilot manual control, but this has complicates considerably the management of the system. Besides to the difficulty to choose the proper mode

combination to perform the assigned task on the three control channels (pitch, roll and autothrottle), there are other conditions that shall be monitored by the pilot. Each mode in fact is characterized by a set of conditions relative to [55]:

- engagement,
- arming,
- disengagement,
- control properties (subsystem involved, set of parameters controlled, control moding),
- pilot overrides allowed.

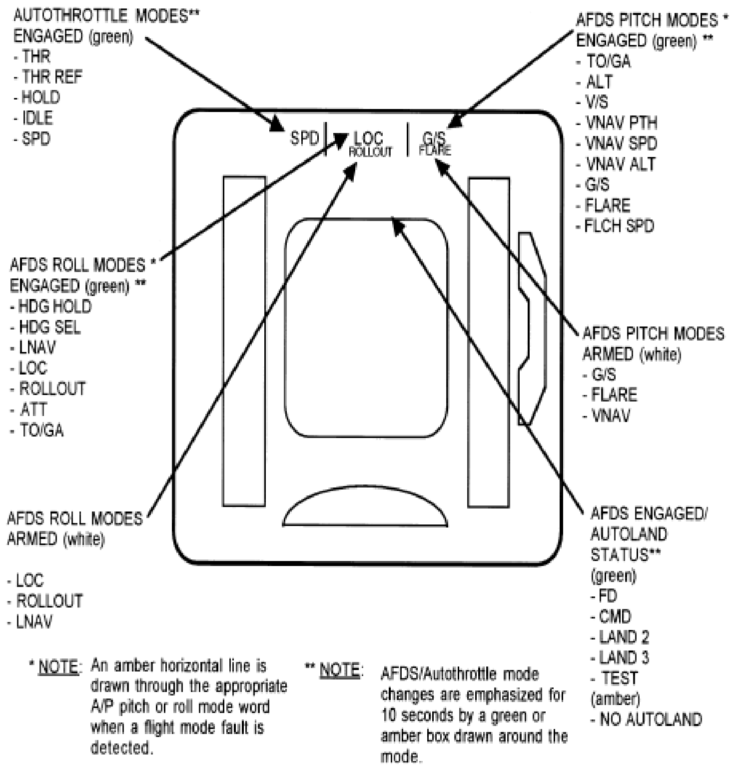


Figure 47. Boeing B-747 400 modes representation on PFD [34]

Further complication is provided by the fact that some tasks can be performed in several ways: for example the speed can be controlled with a pitch mode or the autothrottle, and still the demand value can be taken from the flight plan or set by the pilot (eventually overriding the planned demand). Although pitch/thrust are the same parameters used in manual flight to control the speed, the pilots have shown difficulty to translate these concepts in relation to automation.

Besides not all the available modes can be commanded by the pilot, since some of them are submodes used by the system to achieve the assigned task. For example the pilot usually activates the autolanding, and then the system passes automatically from the Glide Scope (G/S) during the descent phase to Flare before the touchdown. G/S and flare modes can not be activated directly by the crew. This automatic mode changes are very frequent and they are critical for the crew situational awareness. Researches on pilot community in fact have demonstrated as 30-40 % of these changes go undetected with an increasing mishap probability [53], as occurred in some catastrophic events in the past.

All previous considerations explains why it is difficult for the pilots to keep an adequate mental model about how the automation works. “What is the system doing?” and “What will the system perform?” are typical questions pondered by pilots. This has an impact also on training, since currently nearly 40% of an aircraft type rating course is devoted to learn the use of autopilot/FMS guidance [54].

Also the poor Human Machine Interface contributes to decrease the mode awareness. The indication of active and armed modes is reported on the PFD (see Fig.47), but the automatic changes are not particularly highlighted. Besides the Autopilot Mode Panel on which the crew interacts directly with the guidance system often provides less information than PFD, and this can be misleading. As consequence the pilot is not assisted adequately by the system to understand what the automation is doing, and this could be dangerous.

To resume: the poor attention to Human Factor perspective in the design of guidance laws (both in term of functional moding and HMI) has leaded to an issue about crew mode awareness, identified as main cause of several catastrophic accidents.

4.4.2 Trust in Automation

The reduced mode awareness can draw the operator trust in the automation. This is critical especially in cases where the automation is optional, and so the trust is one of the main factor affecting the decision whether use or not the automatisms. If the operator has a poor awareness about how the automation works and what it is doing, in fact, he/she can thinks that a so complex system is very reliable also if little transparent, or at the contrary he/she can maturate a poor trust in a system for which it is difficult to understand and predict the behavior. In any case an incorrect trust can be dangerous, because in a critical situations an operator could react in a wrong way due to his/her biases. An excessive trust in fact could lead the operator to blindly use the automation also if it is in fail or if it is more appropriate to take manual control, while a too low trust at the contrary could lead the operator to ignore system alerts (considered false) or to disengage the automation at the first demanding situation, also if it is safer. In the first case there is the so-called complacency phenomenon (also named automation misuse), while in the second case we speak about automation disuse. Complacency, in particular, is dangerous coupled to poor human vigilance capabilities, with consequent huge reaction time in case of sudden critical events.

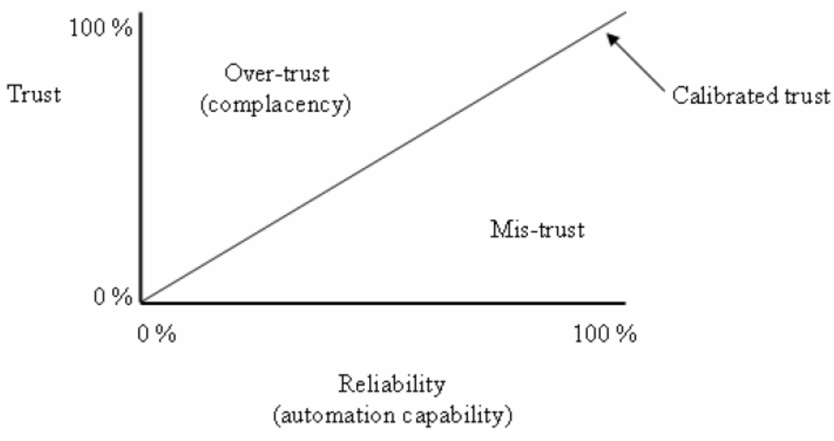


Figure 48. Trust-Automation Reliability relationship [42]

It is so very important for humans developing a calibrated trust level in the system. Assuming an adequate training of the operator, the trust in automation is directly proportional to its reliability, as reported in Fig. 48. Human Machine Interface however concurs to reach a correct trust. If the automation state, action feedbacks and health alerts are adequately presented to the operator, in fact, a greater mode awareness is provided and so he/she is more prone to develop an adequate trust. This issue is particularly critical for advanced UASs in which there is not the possibility of manual control.

4.4.3 Switch from Physical to Cognitive Workload

Passing from manually controlled to automated system, the cognitive workload component has gained relevance with respect to the physical one. This has involved a change in the cockpit design due to the new supervisor role of the operator. In particular the monitoring, planning and decision making activities can lead to a cognitive saturation of the operator (i.e. a very high workload) – especially when there is the need to process many information in a little time – with consequent detriment of performance and the safety. This problem is in particular applicable for the UASs, in which the operator is not physically on-board the vehicle. Therefore the automation and its relative interface shall be properly designed in order to aid the operator in these tasks.

4.4.4 Unbalanced Workload

Although automation has been introduced with the objective to reduce the operator workload, sometimes it provides an unexpected effect in which the workload is reduced when it is already low and increased when it is high.

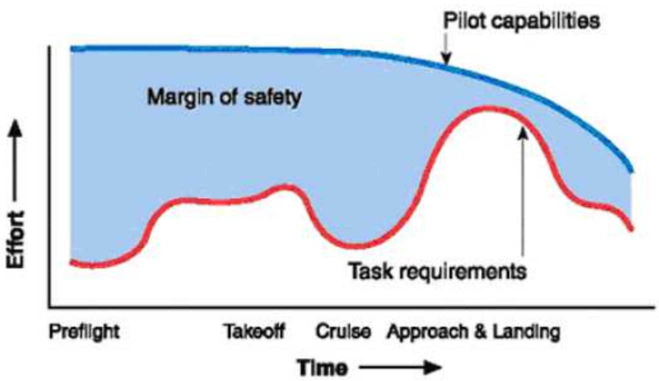


Figure 49. Workload distribution per phase of flight

Considering the cruise phase for example, the introduction of the FMS has reduced further the workload in a low effort phase, automating some functions previously performed by pilots (e.g. NAVAIDs tuning). Therefore pilots are relegated to system monitoring tasks, falling in the vigilance case where humans perform poor. The resultant low attention can negatively affect the pilot reaction time to a sudden event (e.g. collision avoidance or failure).
In the opposite case, in time critical situation interacting with automation could augment considerably the workload due to the poor HMI and to the system complexity. A NASA research about the FMS induced workload in the Terminal Area operations (evaluated with the NASA TLX

scale) [56], in fact, has demonstrated as the FMS is the more demanding way to control the aircraft, considering a route change and the communication with the ATC as reference tasks (see Fig. 50). In particular, in these cases the basic autopilot modes have been considered the less demanding controls by the pilots, and it is preferred with respect to manual control. In other words, an intermediate Level Of Automation has been considered more suitable by the interviewee crews to manage a quick aircraft path change in stressful conditions.
For the UASs this is a crucial issue, especially for the most advanced systems that do not have the possibility to be manually controlled. In particular, due to the physical separation between vehicle and operator, for UASs the opposite solution to adopt a higher LOA can be a better solution. Off course a proper Human Machine Interface is needed to support this solution.

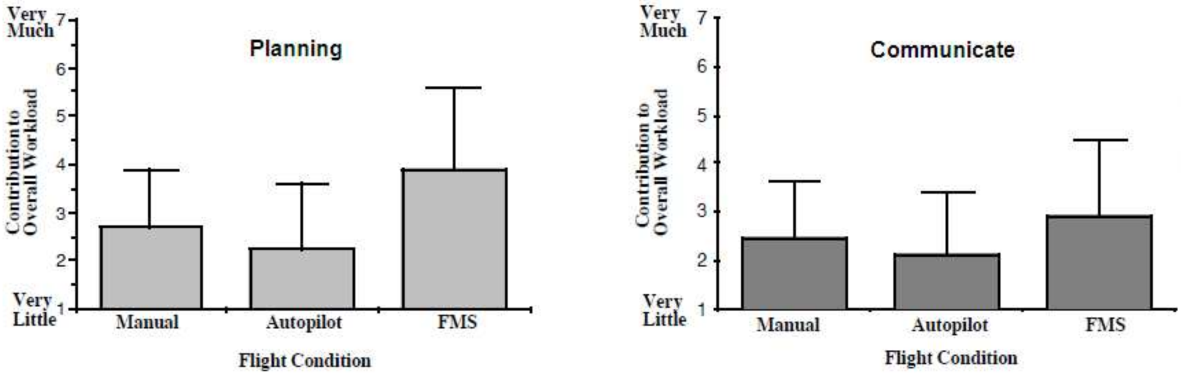


Figure 50. Workload vs. LOA in Terminal Area operations [56]

4.4.5 Increased Crew Coordination demand

Due to the poor transparency provided by highly automated system, a greater crew coordination is required in order to provide an adequate situational awareness for the operators. If a pilot, in fact, reprograms the FMS without informs the other crew member, probably the second will not be aware of the change and so he/she will develop an incorrect mental model about what the aircraft will do. This situation has caused several mishaps in the past. Comparing the time required to share a FMS change with those relative to autopilot and manual control, it is in fact evident a clear disadvantage for the first due to its complexity.

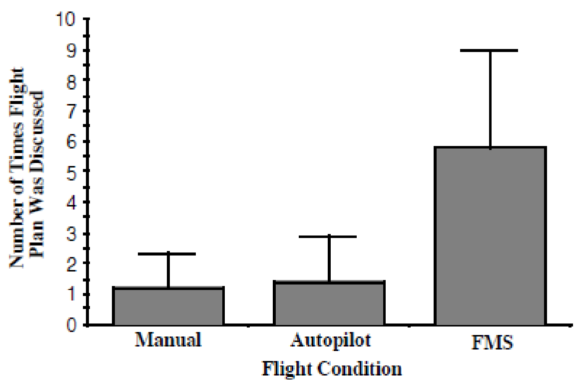


Figure 51. Crew Coordination Time vs. LOA in Terminal Area Operations [56]

Although this issue can be solved with a proper training and procedures, the interface can however help the crew providing a greater transparency about automation moding and notifying any performed change. For a UAS this is critical for the coordination between the several GCS operators, especially between UAV and payload operators.

4.5 RAFIV Model

In the previous sections the general Human Factor issues relative to automation have been presented, but the description of how exactly an operator interacts with automated system has not been provided. This knowledge is useful, since it provides many practical indications about the Human Machine Interface design.

Among the several models present in literature the RAFIV model has been chosen, developed by a partnership between Honeywell (company active in the FMS design and production), the University of Colorado (Institute of Cognitive Science) and the NASA Ames Research Center [27], [57], [58]. RAFIV means “Reformulate Access Format Insert Verify & Monitor”, i.e. the five steps in which the human-automation interaction is broken down. Although RAFIV has a general validity, it has been specifically developed for the interaction with the MCDU of the FMS. Therefore it is particularly suitable for our purposes.

Basic idea of the RAFIV models is that the efficiency and the robustness of the interface is function of the volume of actions memorized by the operator.

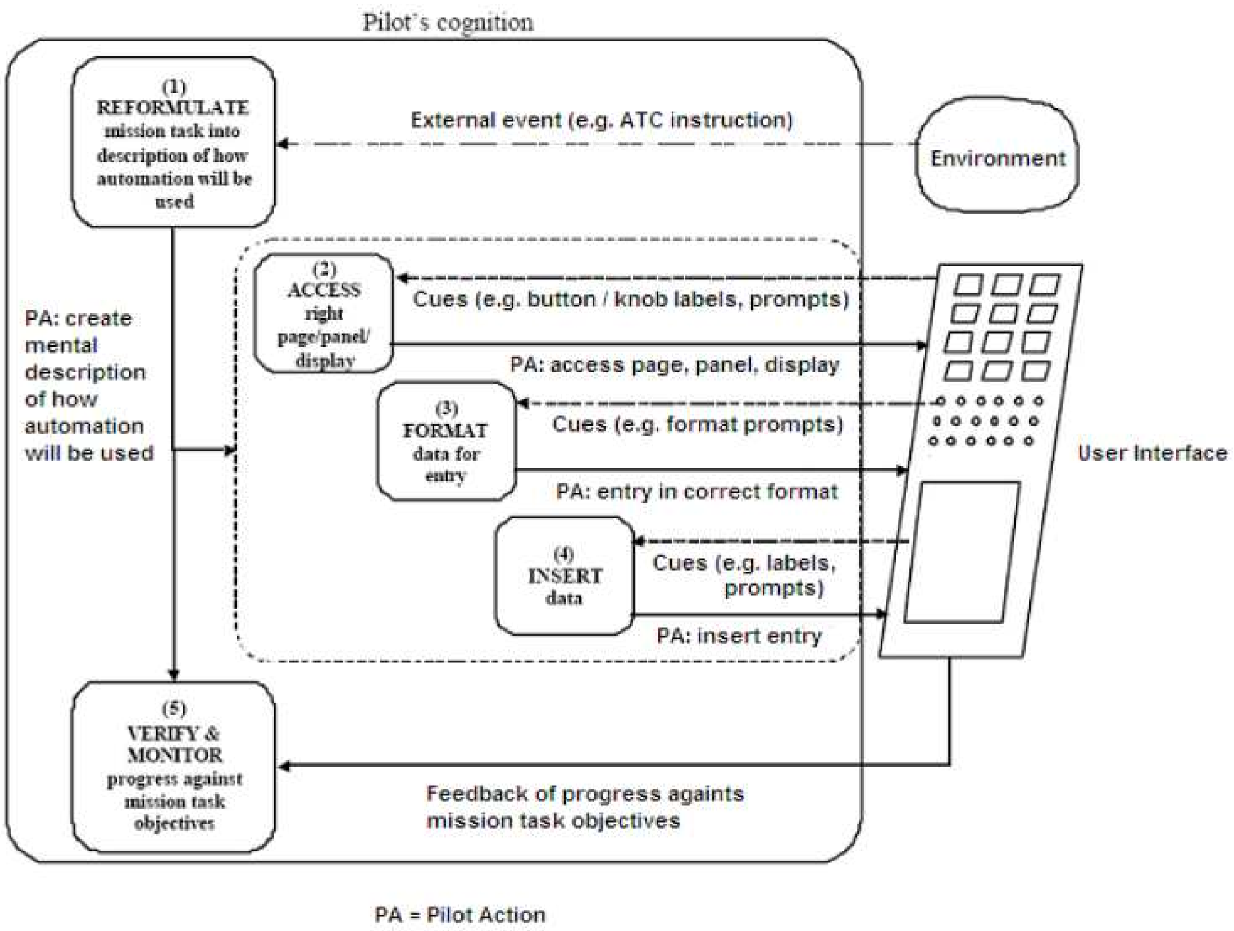


Figure 52. RAFIV Model [57]

At each step corresponds the following operator actions [27], [57], [58]:

1) Reformulate: the assigned task shall be reformulated in terms of data to communicate to the automation. In other words, in this phase the operator creates a mental model about how the system shall be used. For example an ATC altitude clearance is converted into the set of data to enter in order to modify the current VNAV profile.
2) Access: once a mental description of the automation use has been defined, the correct interface (i.e. hierarchy of pages, format, panel, etc.) shall be accessed by the operator. This step corresponds to the operator mental orientation toward the correct interface to use, and to the identification of the required actions to display the field for the data entry.
3) Format: identified the interface the operator enters the data with the proper format (e.g. L0.5 for a left route offset, or N4515.345 for the latitude).
4) Insert: once the data have been entered, the operator shall insert them in the proper field. This step is very typical of traditional MCDU in which the data are entered in a scratchpad and then inserted in the correct field acting on the line select keys. In case a data is directly entered in its field, the phases 3) and 4) can be joined in a single step.
5) Verify & Monitor: finally the operator shall monitor that the command has been accepted by the automation, that the system performs correctly and that the command is appropriate to accomplish the assigned task.

Each step can be accomplished by the operator recalling the appropriate actions from the long term memory or recognizing them from the visual cues provided by the interface [27]. Relying on too much on memory is not an advantageous strategy, especially for infrequent tasks. In these cases, in fact, it has been demonstrated that the success probability is lower than 50%, with consequent operator skills deterioration due to the low frequency of tasks execution and an increased complexity perceived by the crew [57]. Besides also the training time is 2-10 time greater [57]. Unlucky current MCDUs are poor from this standpoint, especially in terms of not adequately task support (with consequent needed reformulation) and poor guide provided by the interface in the data entry.

Tasks Supported by the MCDU/FMS
• Alignment of ADIRU Position • Flightplan/Route Planning • Aircraft Performance Computations • Direct To • Holding Patterns • Lateral Route Offset • Missed Approach/Go Around • Descend Direct • Descend Now

Tasks <u>not</u> Supported by the MCDU/FMS
• Climb through intermediate altitude constraint • Descend to crossing restriction • Change departure/arrival runway • Adjust climb speeds to achieve desired climb gradient • Crossing radial with altitude restriction

Figure 53. Example of tasks directly supported/not supported by a FMS [58]

To aggravate the situation many tasks are not frequent: considering for example the Boeing B-777 MCDU and a sample of 102 tasks, the74% of them of them need memorized action sequences and the 46% occurs infrequently [27].
Therefore the weak human-automation interaction is due to the way in which the automation functions have been implemented and to the poor HMI. Display size and device layout are not considered as causes.
From this analysis some guidelines for a new FMS interface can be derived [27]:

- the interface shall support directly (as much as possible) the mission task execution to reduce the workload related to the reformulate step,
- the operator shall be guided in the interface interaction with visual cues like labels, prompt, dialog boxes, pop up and so on,
- the step of verity & monitor can be simplified displaying to the operator a visual representation of automation state.

In particular for the second and third points, the adoption of a Graphical User Interface seems the solution (in fact the modern FMSs have it as reported in Fig. 33), but it is not enough alone. It is the careful design of the automation functions in support of mission tasks that makes the difference.

5 STANAG 4586

5.1 Introduction

The STANAG 4586 is a NATO standard for the UAS interoperability that provides interfaces for the communications between GCS/UAV and GCS/C4I (Command Control Communication Computer Information center). External mission Planning stations and logistic support are included in C4Is. Today's many UASs have been designed as systems with specific interfaces and unique software/hardware architectures, that do not permit the achievement of an adequate interoperability with different UASs. Considering that usually there are several UASs that cooperate to reach the mission goals, there could be a proliferation of GCSs and difficulty to share the collected mission data to the C4Is.

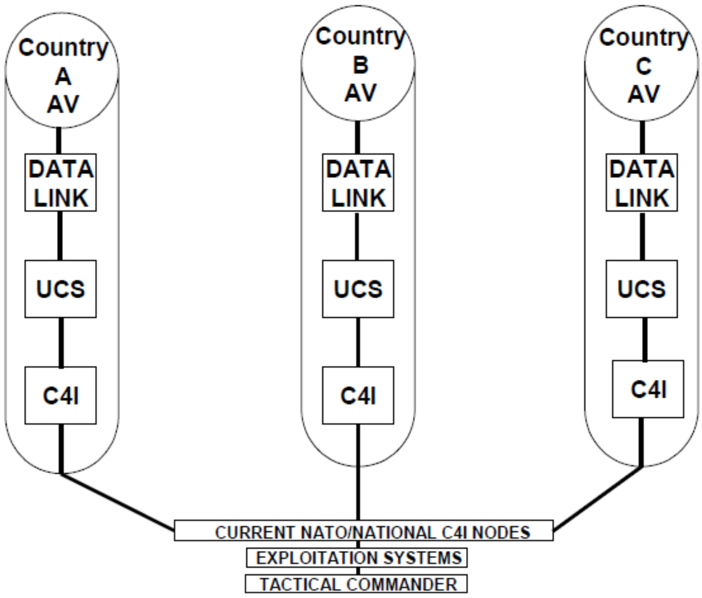


Figure 54. Current UAV System Operation Example [1]

In order to reduce the operative costs and enhance the mission effectiveness in terms of exploitation, dissemination and analysis of gathered data, a proper standard for UAS interoperability is therefore needed. At this purpose, the STANAG 4586 has been developed. According to it, a compliant GCS would be ideally able to control each compliant UAV/payload and exchanging information with compatible C4Is. In practice this is not directly possible due to the need of some specific modules, with the relative problems of integration and qualification (critical for the civil certification). Actually a GCS will be able to interact with all UAVs and C4Is for which it has been integrated and qualified. Following a standard, however, the processes of integration and qualification should be shorter and easier with respect to starting from zero with a specific solution.
Although the STANAG 4586 has been conceived for military applications, it is directly applicable also to civil missions, since they have the same requirements of interoperability. The matter of UAS integration in civil air space however is not treated in the standard.

Currently the STANAG 4586 is still not very diffused in operative UASs, but it is adopted as reference in the design of many new systems, and therefore it is a very good candidate to become the universal standard in the near future.
At the moment, there are two published editions of the STANAG 4586, and the third has been diffused in draft. In any case, due to the complexity and the broad of the subject, and to the early maturity of the standard, in practice the STANAG 4586 is difficult to implement since many design choices and solutions can be adopted. In order to help the designers, therefore, a relative Implementation Guide has been developed [59]. The guide however provides only suggestions to be compliant to the standard, but not mandatory requirements.
The second edition has been adopted as reference for the FMS design, especially in terms of interface protocols. This differentiates further a FMS for UAS with respect to that for an airliner, since the STANAG 4586 philosophy is quite different from traditional manned aviation concepts due to many peculiarities of unmanned systems. Besides, nevertheless the STANAG 4586 provides directly only a guide to define the system internal interfaces, it affects as consequence also the design of the system architecture, functionalities and the relative HMI. Considering the interface between GCS and UAV (or better a specific module of the UAS control system as it is reported next), in fact, the STANAG 4586 provides a series of standard messages in both the link directions (uplink and downlink) plus the possibility to create new specific messages (private messages). However the use of a protocol (with the relative message structure and data) inevitably affects the design of the system functions and architectures especially considering the requirement to reduce as much as possible the vehicle specific elements in order to reach the greatest possible interoperability.

5.2 Level Of Interoperability

According to the STANAG 4586 there is the following definition of interoperability [1]:

The ability of Alliance forces and, when appropriate, forces of Partner and other nations to train, exercise and operate effectively together in the execution of assigned missions and tasks.

This is a generic definition that does not discriminate the possible intermediate situations. At this purpose, the STANAG 4586 has created the concept of Level Of Interoperability (LOI) for the communication between GCS and UAVs. In particular there are the following five levels [1]:

- LOI 1: indirect receipt of UAV related payload data.
- LOI 2: direct receipt of UAV payload data.
- LOI 3: control and monitoring of the UAV payload in addition to direct receipt of other data.
- LOI 4: control and monitoring of the UAV, less launch and recovery.
- LOI 5: control and monitoring of the UAV (level 4), plus launch and recovery functions.

Note that higher levels do not necessarily include previous levels: for example it is possible to have the full control of the vehicle (LOI 5), without the payload control (LOI 3). Payload control (LOI 3), instead, comprises the direct reception of relative data (LOI 2).
Besides the LOI concept considers only the interoperability between GCS and UAV, and not between the GCS and C4Is. A GCS can implement different levels of interoperability for the same

UAV or for different vehicles (e.g. a GCS can be able to control the UAV “A” and its relative payload, or to control the payload of the UAV “B” and to have a direct receipt of UAV “C” data). For a FMS, the LOI 5 has been considered since the payload control is not demanded to it. In particular, fifth level permits to include also the autotakeoff and autolanding modes for the guidance function. Interoperability with the C4I is not treated, since it is not a FMS function.

5.3 System Architecture

In order to implement the interoperability requirement, a proper system architecture shall be adopted. In particular referring to the UAS definition provided in the Chapter 1, it is possible to distinguish the elements reported in Fig. 55. The communications between them are defined by several standards. In particular the STANAG 4586 is applicable to the Unmanned Control System (UCS), for which it specifies the requirements for the definition of the architecture and the interfaces.

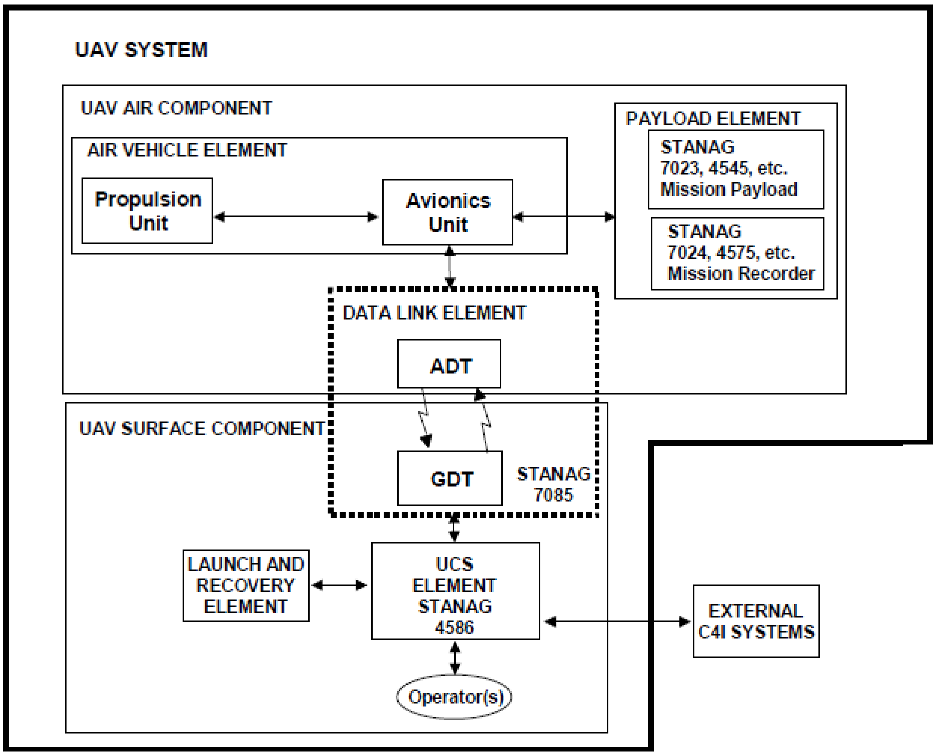


Figure 55. UAV System Interoperability Architecture [1]

The UCS is composed by the following elements [1]:

- Core UCS (CUCS),
- Human Computer Interface (HCI),
- Data Link Interface (DLI),
- Command and Control Interface (CCI),
- Vehicle Specific Module (VSM),

- Command and Control Interface Specific Module (CCISM).

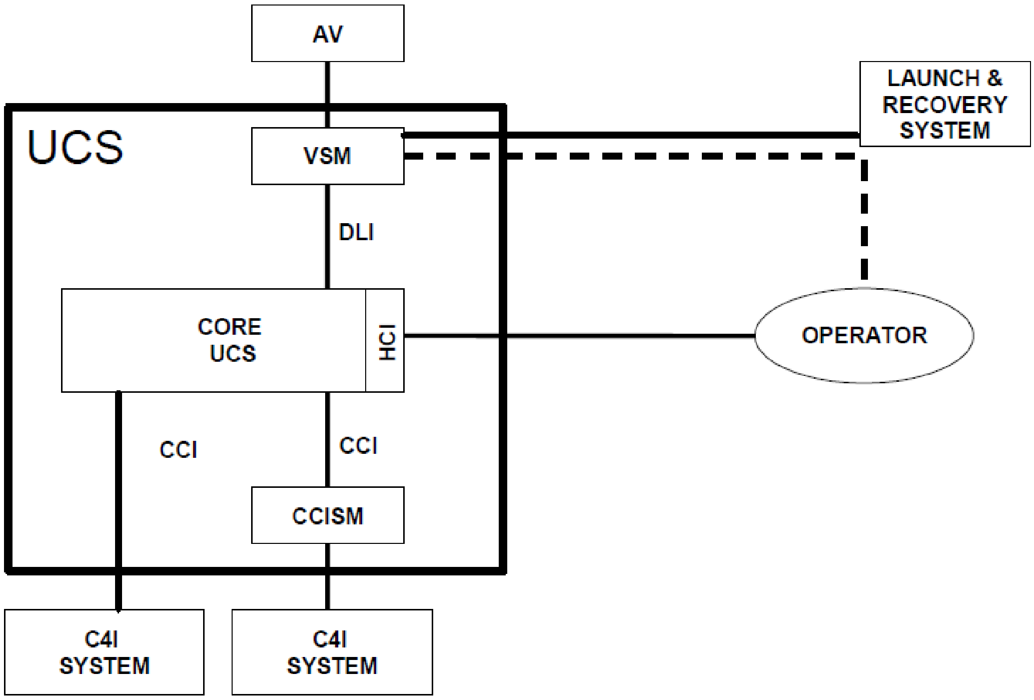


Figure 56. UCS Functional Architecture [1]

CUCS is the "core" of the control system and it is responsible to provide the control functions according to the implemented LOI. In case an UAV has not been fully developed according to STANAG 4586, a VSM is added to the system. Vehicle Specific Module is mainly responsible to translate the standard STANAG protocol into unique/vehicle proprietary native language and vice versa, with the relative interface timing and data format conversions. The VSM is the key of the STANAG 4586 interoperability philosophy, since in order to enable the control of a new UAV/payload by a GCS it is sufficient to integrate the relative VSM with no changes or minor changes to the CUCS (due to specific messages in STANAG format and relative visualization on the HCI). Besides the "translator" role, the VSM performs other functions like [1]:

- acting as repository for UAV specific information and functions,
- optimizing datalink transmission bandwidth,
- managing the interfaces to monitor and control the datalink,
- managing the interfaces for the control of the Launch & Recovery Systems (specific of each UAV).

Communications between CUCS and VSM are implemented by the Data Link Interface, with UAV proprietary interfaces between VSM and air vehicle elements (e.g. Flight Control Computers or Payload Control Computers). VSM can be hosted in the GCS, on the UAV or split in a ground VSM plus an airborne VSM (see Fig. 57). In the first case, the Data Link Interface is not actual connected to the datalink terminals, since it is relative to intra ground segment communications. Basically hosting the VSM in the GCS simplifies the design, but in order to increase the vehicle

Level of Autonomy it should be hosted on-board. Intermediate solutions are also possible, especially to control specific launch & recovery elements for which the airborne VSM has an excessive latency. Noting that in a GCS there could be more VSMs for many vehicles/payload or to implement different LOIs for the same vehicle (e.g. payload and vehicle control). In case of a ground VSM, it can be practically realized with the same, different or remote hardware with respect to the CUCS [1].

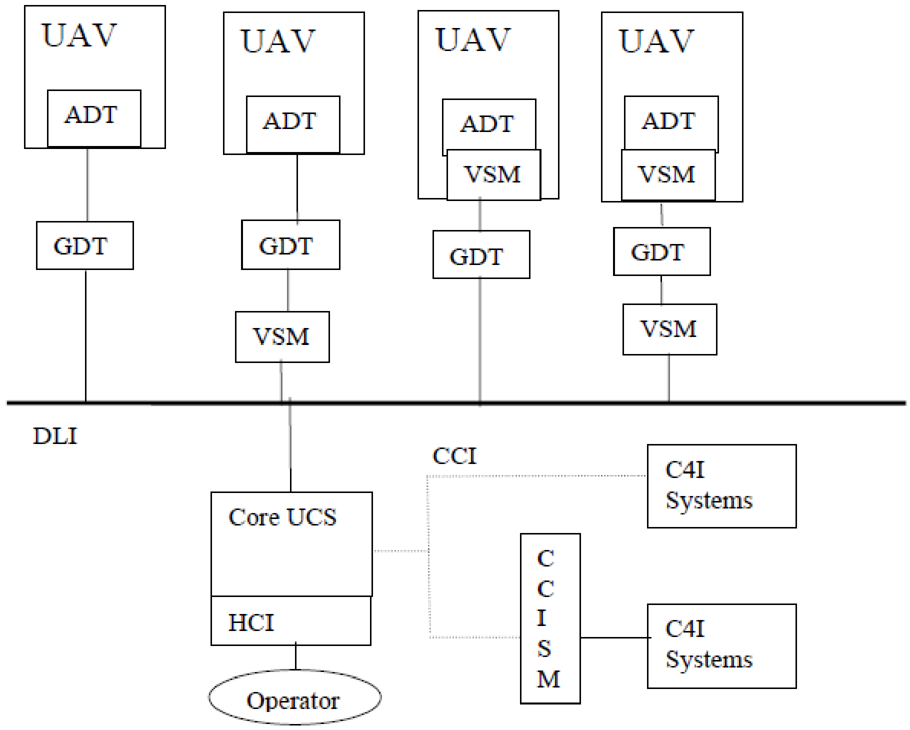


Figure 57. VSM allocation in the UCS [1]

The Human Computer Interface (HCI) receives inputs directly by the CUCS. Vehicle specific data are displayed using the private messages. The STANAG 4586 specifies macro requirements about the HCI functionalities that the CUCS shall support for different LOIs, but it does not provide any impositions about the human factors (e.g. display layout) and ergonomics (e.g. physical arrangement of displays) standpoints. Therefore the issues presented in the previous chapters are not considered by the STANAG 4586. For the LOI 5, in particular, the following functions shall be provided to the operator [1]:

- configuration,
- mission planning,
- air vehicle control,
- operator control and monitoring,
- communication management,
- alert visualization and management.

The first five points are more or less directly related to the Flight Management System.
Considering the Implementation Guide, it suggests some possible HMI standards to follow and provides a general guide to the design process that have been considered in our work [59]. As HMI standard, in particular, the MIL-STD-1472 has been adopted, considering that is a common diffused standard for several applications both in military and civil fields.
To conclude the examination of the STANAG compliant system architecture, there are the CCI and the CCISM, that are the equivalent of the DLI and the VSM for the communications between a GCS and a C4I.

5.4 Message Wrapper Structure

STANAG 4586 defines a wrapper structure common to the standard and private messages, as reported in Fig. 58.

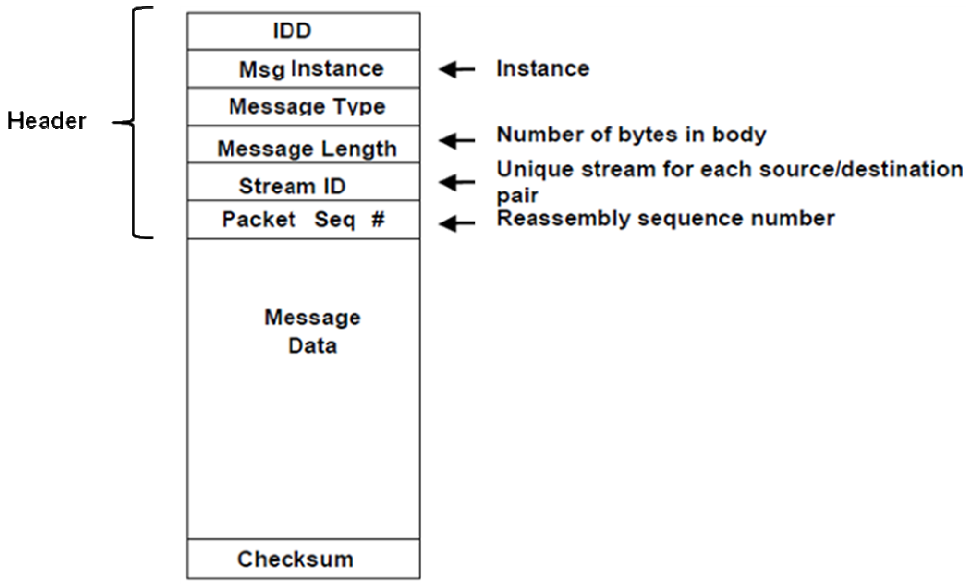


Figure 58. STANAG 4586 Message Wrapper Structure [1]

Three main areas can be distinguished: the header, the message data (message body) and the checksum. The header is composed by several fields [1]:

- Interface Definition Document (IDD): number relative to the implemented STANAG 4586 edition (e.g. 2.0 for the second edition).
- Message Instance: progressive uniquely numerical identifier of the message instance (e.g. 101 for the 101th message type "X" sent by the CUCS),
- Message Type: numerical identifier of the type of message (e.g. Message 2100). Number under 2000 are reserved to the standard messages, while the greater ones are available to create private messages.
- Message Length: number of bytes in the message body.
- Stream Identifier (ID): reserved for future capabilities.

- Packet Sequence: not used and set to "-1".

Message body is the core of a message and contain different data according to the type. Unique common information are the time at which the message has been captured, and the ID of vehicle and CUCS. Finally the checksum is a bit sequence introduced in order to verify the message data integrity. In practice transmitter and receiver calculate this parameters with the same algorithm and so it is possible to detect an error comparing the calculated theoretical value with that actually received. As reported in Fig. 58, a private message is distinguished from a standard one only from the message type and the typology of contained data.
For each message, the STANAG 4586 provides the detail of the contained data, the conditions relative to the message sending and a guideline to implement the relative moding. In particular each data is characterized by the following information [1]:

- Unique ID,
- Field in the message body (progressive number),
- Data name and description,
- Type (e.g. double, float, integer, unsigned, char, etc.),
- unit of measure (in general the international system is considered),
- admissible range of value.

Unique ID	Field	Data Element Name & Description	Type	Units	Range
0044.01	1	**Time Stamp**	Double	Seconds	See Section 1.7.2
0044.02	2	**Vehicle ID**	Integer 4	None	See Section 1.7.5
0044.03	3	**CUCS ID**	Integer 4	None	See Section 1.7.5
0044.04	4	**Set Lights** When a bit is set the lights are commanded on, when the bit is cleared the lights are commanded off.	Unsigned 2	Bitmapped	0x0001=Nav 0x0002=NavIR 0x0004=Strobe 0x0008=StrobeIR 0x0010=NVD 0x0020=reserved 0x0040=landing 0x0080=landingIR

Figure 59. Example of STANAG 4586 message body [1]

In general, the STANAG 4586 philosophy considers that for each message sent by the CUCS, there should be the relative response from the VSM (translation of the vehicle response in its native language), in order to be aware of the parameter actually active on the UAV.

5.5 Guidance Implementation

Guidance function is implemented by the CUCS and the VSM with the standard messages reported in Tab. 16. The moding foresees that the CUCS sends to the VSM the operator demand, and then the VSM responses to the CUCS according to the air vehicle states. An exception is relative to the loiter demand message (MSG #41), for which no standard response has been implemented by the STANAG 4586.

Object	CUCS Demand	VSM Response
Guidance mode selection	MSG #42	MSG #106
Guidance mode demands selection	MSG #43	MSG #104
Guidance mode demand source (database/override)	MSG #48	MSG #109
Loiter parameter demands	MSG #41	
From-To WPs State		MSG #110

Table 16. Guidance related messages

MSG #42 contains the guidance mode demanded by the operator. The following standard modes are considered by the STANAG 4586 [1], [59]:

Mode	Means
No mode	No guidance mode active.
Flight Director	Manual near real time UAV control using MSG #43 with autopilot disengaged.
Waypoint	Automatic steering in order to follow a WPs sequence. Equivalent to the sum of LNAV and VNAV modes of a manned FMS.
Loiter	Loiter around a point defined by MSG #41, #43.
Autopilot	Autopilot engaged (general terms) with a possibility of a near real time manual override by the operator using the MSG #43.
Terrain Avoidance	Autopilot engaged plus terrain avoidance with a given height safety margin.
NAVAID navigation	Slaved navigation with respect to NAVAID beacons.
Autoland	Engaging of automatic landing.
Wave Off	Automatic go around in case of aborted landing.
Launch	Engaging of automatic take off.
Slave to sensor	Slaved navigation with respect to the active payload (e.g. with respect to the observed point with an electro optical camera).

Table 17. STANAG 4586 standard guidance modes

As reported in Tab. 17, these are very general modes adaptable to several UAV types. The STANAG 4586, however, foresees the possibility for the operator to define vehicle specific modes using always the MSG #42 through an enumerative fields.
Guidance mode relative demands, instead, are specified in the MSG #43. This messages contains many parameters, but only a subset of them are used according to the mode selected in MSG #42 and to the considered vehicle capability. In particular the following standard demands are available:

- altitude,
- vertical speed,
- altitude + vertical speed to achieve it,
- heading,
- course,
- heading rate,
- turn rate,
- roll rate,
- roll angle,
- speed,
- destination waypoint (DWP) for the waypoint mode or other vehicle specific navigation mode (provided as an univocal numerical identifier as explained later for MSG #802),
- loiter point coordinates for loiter guidance mode or other vehicle specific navigation mode.

For vertical plane (altitude, vertical speed, altitude + vertical speed) or lateral (heading, course, heading + course, roll) demands, in particular, the MSG #43 specifies which is the parameter to consider between the available options. Besides it is possible to specify the type of altitude (pressure altitude, barometric altitude, GPS altitude or height) and speed (indicated, true or ground speed). For the barometric altitude is provided also a field to set the altimeter reference pressure.
MSG #48 is used for waypoint and loiter modes in order to determine the source of altitude, speed and course/heading demands between the planned value (database – DB) or an override (OVR) value specified by the operator (sent through MSG #43).
Finally MSG #41 contains the loiter parameters for the loiter guidance mode in terms of geometric characteristics of loiter path, altitude planned value and type, speed planned value and type. More details about the loiter waypoints is providing in the next paragraph. Loiter types and relative geometric characteristics will be explained later for the MSG #802 (Mission Concept paragraph).
VSM responses (when available) are a copy of the CUCS messages, with the exception of the MSG #104 that contains less parameters with respect of the MSG #43. In particular no VSM echo about the vertical speed demand is provided. Another exception is the MSG #110, that is the VSM report about the Next/To Waypoint state when the UAV is in waypoint mode or about the loiter coordinates in loiter mode. MSG #110 can be also used for periodic report during navigation.
The set of standard guidance messages therefore are flexible and adaptable to many different systems, with more options and a greater LOA with respect to a manned aircraft. No standard messages for remote manual control, in fact, are provided.

How using in detail each message and what data writing in them is left to each vehicle specific implementation and it depends also by the considered guidance mode. The STANAG 4586 Implementation Guides limits oneself to suggest that CUCS sends required message for the relative mode, with the VSM that responds at each of them. Besides, for the scheduling, the guide suggests that CUCS and VSM send messages only when there is a mode/demand change in order to save communication bandwidth (i.e. asynchronous implementation) [59]. Just to clarify the moding, the paragraph is concluded with some examples relative to a possible guidance mode implementation. Other data contained in the involved messages and not specified below are not considered, since not applicable to the considered cases.

Mode	**CUCS Messages**	**VSM Messages**
Altitude Hold at 5000 ft (1524 m)	• MSG #42→mode: autopilot. • MSG #43: - altitude demand = 1524 m - altitude type: GPS - demand type: altitude.	• MSG #106→mode: autopilot. • MSG #104: - altitude demand = 1524 m - altitude type: GPS - demand type: altitude.
LNAV + VNAV (route already loaded)	• MSG #42→mode: waypoint. • MSG #43→DWP: 1157. • MSG #48: - altitude DMD source = DB - speed DMD source = DB - course DMD source = N.A.	• MSG #106→mode: waypoint. • MSG #110→DWP: 1157. • MSG #109: - altitude DMD source = DB - speed DMD source = DB - course DMD source = N.A.
Direct to Loiter	• MSG #42→mode: loiter. • MSG #43: - altitude demand = 1524 m - altitude type: GPS - demand type: altitude - speed demand = 55 m/s - speed type = IAS - loiter latitude = 0.77 rad - loiter longitude = 0.131 rad • MSG #48: - altitude DMD source = OVR - speed DMD source = OVR - course DMD source = N.A. • MSG #41→loiter type and geometric characteristics.	• MSG #106→mode: loiter. • MSG #104: - altitude demand = 1524 m - altitude type: GPS - demand type: altitude - speed demand = 55 m/s - speed type = IAS • MSG #109: - altitude DMD source = OVR - speed DMD source = OVR - course DMD source = N.A. • MSG #110: - loiter latitude = 0.77 rad - loiter longitude = 0.131 rad • Private message to respond to MSG #41.

Table 18. Example of guidance mode selection according to STANAG 4586

5.6 Mission Concept

5.6.1 STANAG 4586 Mission Structure

An UAS shall extend the traditional flight plan of manned aircraft FMS to the concept of mission, due to the particular tasks assigned. The STANAG 4586 defines a mission as [1]:

The route planning, payload planning, datalink planning (including frequency planning), and UAV emergency recovery planning (rules of safety) for an UAV flight.

More in detail, plans composing the mission concern the following items [1]:

Plan	Means
Route Plan	Set of waypoints defining the path of the UAV. Other than 4D attributes, at each waypoint it is possible to define airframe actions. Taxi Plan can be included with the same form.
Payload Plan	Details about the sensor to use, the relative operative mode, image resolution, configuration and the associated target. It can be linked to the route plan through payload action specified at each waypoint.
Datalink Plan	Details about the bands and frequencies to use. It can be associated to the route plan through specific action specified for each WP (e.g. handover from a LOS datalink to a BLOS satellite link).
Emergency Recovery Plan	Details about the recovery actions that the UAV shall automatically perform in case of failures (e.g. link loss) according to the rule of safety defined during the mission planning. Typical examples of these actions are reaching contingency WPs or following contingency routes starting from the current active route. Emergency WPs/Routes are linked to the Route Plan.

Table 19. Plans composing a mission according to the STANAG 4586

In general, the STANAG 4586 does not consider the planning itself, but it rules the process of upload/download of a mission to/from a VSM. Data present in the relative standard messages however influences the concept of mission and its architecture. According to the involved standard messages, in particular, the STANAG 4586 mission is made by one or more routes, each of them composed by a sequence of waypoints (see Fig. 60).

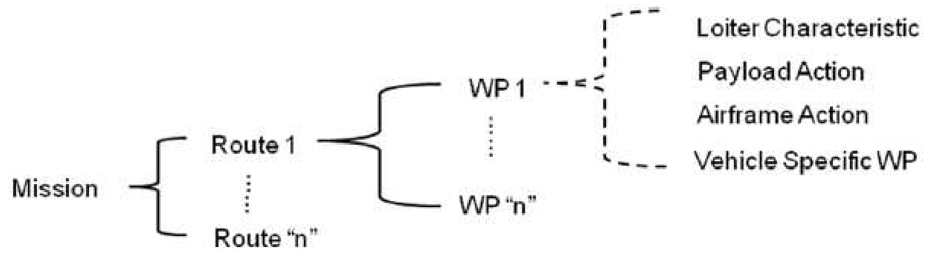


Figure 60. STANAG 4586 Mission Architecture [17]

Routes, in particular, represent the UAV path in a 4D space through broken lines (see Fig. 61), having the waypoint as vertexes. Fourth dimension is specified assigning a speed or a temporal demand to each WP. This is quite different from the ARINC 424 concept, since STANAG 4586 specifies only the terminator (i.e. the waypoint) and not the mode in which a leg is flown, that depends by the specific implementation of the UAV navigation laws. Typically however the legs are flown in track mode. The track is determined considering the azimuth of each route segment with respect to the North. Besides at each WP can be added airframe, payload or other specific actions in order to increase the system LOA. This is a further difference with respect to manned FMS flight plans.

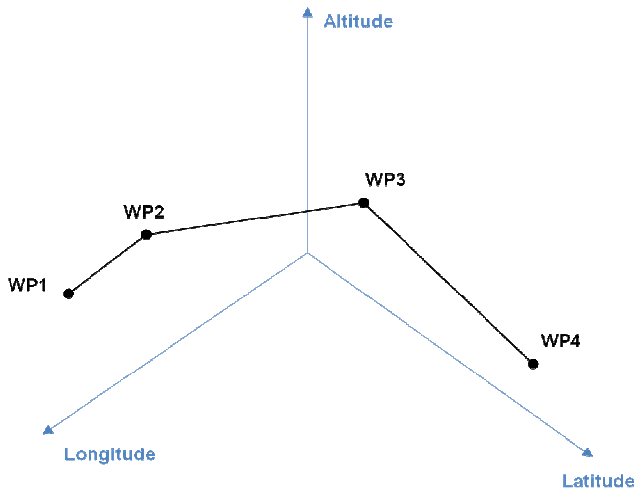


Figure 61. Example of route

Considering the communication protocol, apart the Datalink plan that is not directly relative to the FMS, there are the following standard messages for the other plans [1]:

Message	Object	Affected Plan	CUCS Use	VSM Use
#800	Mission Upload Command	Mission level	X	
#801	Route definition	Route / Emergency Recovery Plans	X	X
#802	WP definition	Route / Emergency Recovery Plans	X	X
#803	Loiter definition	Route / Emergency Recovery Plans	X	X
#804	Payload action definition	Payload Plan	X	X
#805	Airframe action definition	Route / Emergency / Datalink Plans	X	X
#806	Vehicle Specific Action	Mission Level	X	X
#900	Mission Upload/Download Status	Mission Level		X

Table 20. STANAG 4586 standard messages related to the Mission Upload/Download

5.6.2 MSG #800

Examining more in detail the messages, the MSG #800 permits to execute the following actions [1]:

- clear a mission on the VSM,
- load a mission on the VSM,
- download a mission from the VSM,
- download a single waypoint from the VSM,
- cancel upload/download process.

Each mission is univocally identified by a string of 20 characters. Although the number of missions that can be uploaded on a VSM is not specified, it is logic that there is only a mission at time on the VSM (and therefore on-board the UAV).

5.6.3 MSG #801

Message #801, instead, defines a route, identified by a string of 33 characters. In particular, the following route types are distinguished [1]:

- launch (i.e. take off route),
- approach,
- flight,
- contingency A,
- contingency B.

Apart from the take off and landing specific routes, all other normal routes are categorized as “flight”, independently if they are related to a transit or to a mission phase (e.g. searching of a target in a given area). Contingency routes are relative to the emergency plans and are distinguished between A and B, since at each normal route WP can be associated two contingency WPs from which it is possible to define the relative routes. Contingency WPs assignment is done in MSG #802. Finally in MSG #801, it is specified the first WP of the route, that permits to rebuild the WP sequence composing the route.

5.6.4 MSG #802

MSG #802 defines a basic WP and it is the core of the STANAG mission protocol. It contains the following information [1]:

- Waypoint number (univocal identifier of a WP),
- 2D position:
    - Latitude/longitude data (WGS 84),
    - X, Y coordinates with respect to a relative reference frame.
- altitude (third dimension),
- altitude type:

  - pressure altitude,
  - barometric altitude,
  - GPS altitude (WGS 84),
  - height.
- speed type (fourth dimension):
  - Indicated Air Speed (IAS),
  - True Air Speed (TAS),
  - Ground Speed (GS),
  - Arrival time.
- speed value (set only if speed type is equal to IAS, TAS or GS),
- arrival time value (set only if speed type is equal to arrival time),
- turn type:
  - short turn (i.e. Fly By WP),
  - flyover (i.e. Fly Through WP).
- next WP number (data used to construct the routes),
- Contingency “A” WP number,
- Contingency “B” WP number.

The WP number is used as univocal identifier and it is the key that permits to build the routes (plus Initial WP number in the MSG #801 plus next WP number in the MSG #802), to associate Contingency WP/route or a generic action to a WP. There shall not be two different WPs with the same number in a mission. WP number ranges from 1 to 65535. “0” indicates the end of route. Considering for example a route composed in order by the waypoints “WP1”, “WP2”, “WP3” and “WP4”, it is constructed by the following messages:

MSG	Instance	Route	Type	Initial WP Number
#801	1	Route 1	Flight	1157

WP	MSG	Instance	WP Number	Next WP Number
WP1	#802	1	1157	1158
WP2	#802	2	1158	1159
WP3	#802	3	1159	1160
WP4	#802	4	1160	0

Table 21. Example of route construction from MSG #801, #802

Although the WPs are identified by a number in the protocol, the operator usually identifies a WP through a short text (e.g. "WP1"). This data however is not needed to the VSM. The CUCS therefore performs the association between the text identifier and the WP number (not displayed to the operator). WP identifiers are managed differently by the Mission and Route ones, due to the fact that they are not only used by the VSM to distinguish an item, but also to actually construct a route with the relative actions associated from the series of received messages. For these operations a numerical ID is more efficient from the software standpoint with respect to a string.
From the attributes standpoint, a WP is always defined in all four dimensions. Lateral position can be specified with Latitude and Longitude with respect to the WGS-84, or by Cartesian coordinates (X and Y values) with respect to a Relative reference frame. This is defined with the MSG #47, not reported here for simplicity. For the altitude, no info about how the altitude is reached on the leg is provided. The climb/descent laws are vehicle specific and so they are not treated by the STANAG 4586. If a user wants to specify them, a dedicated private message shall be created.

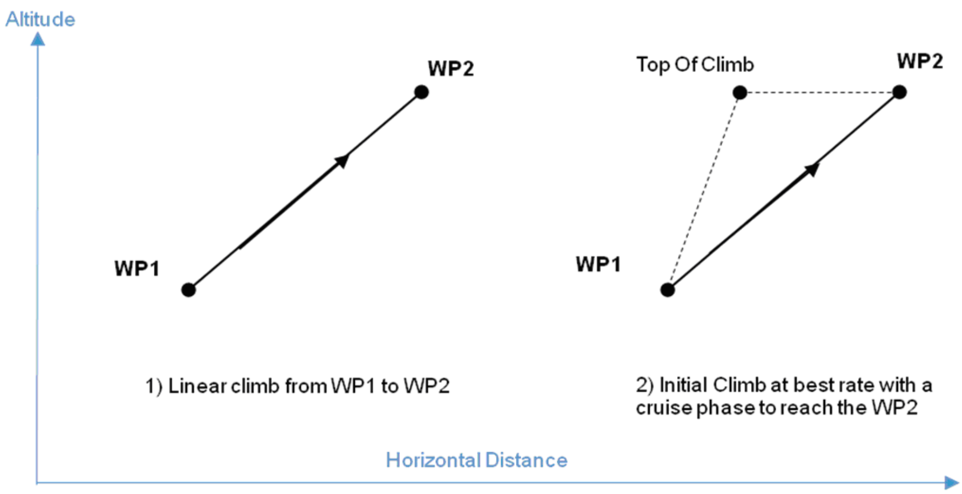


Figure 62. Examples of possible climb laws

As fourth dimension on a WP, a speed demand or an arrival time are considered alternatively (i.e. a speed and a time can not be assigned together). The more common speed type is the IAS (considered as reference by the ATC), but also TAS and GS demands are available. GS, in particular, is used for mission purposes (e.g. sensor pointing) or to reach a certain time for UAVs that have not the capability to process time demand. Arrival time is an absolute value (e.g. 15:59:25), expressed as number of seconds from the 1st January 1970 in order to provide info about the relative date.
STANAG 4586 does not provide directly the possibility to assign altitude, speed or time constraint to a WP, at difference of traditional FMS.
As WP type, instead, are considered only Fly By and Fly Through. Loiter path can be introduced through the MSG #803.
Finally, contingency WPs/Routes are another differences with respect to manned aircraft flight plans, since for the UAV is needed to plan safe paths to be automatically flown by the vehicle in case of lost link condition (i.e. loss of uplink communication between the GCS and the UAV) or when some failures occur [17]. Contingency WPs or last Contingency Route WP can be also safe

crash points for the UAV termination if no recovery actions are possible, in order to reduce as much as possible damage to people and infrastructures. At this purpose, the STANAG 4586 foresees for each normal route WP the possibility to assign two Contingency WPs, named “A” and “B”. From them it is possible to define a Contingency Route as said before. Having two WPs permit to define different path according to the considered emergency: for example the path A can be relative to the lost link, while the “B” to a termination point due to a major failure of the vehicle. According to the STANAG philosophy many implementations are possible:

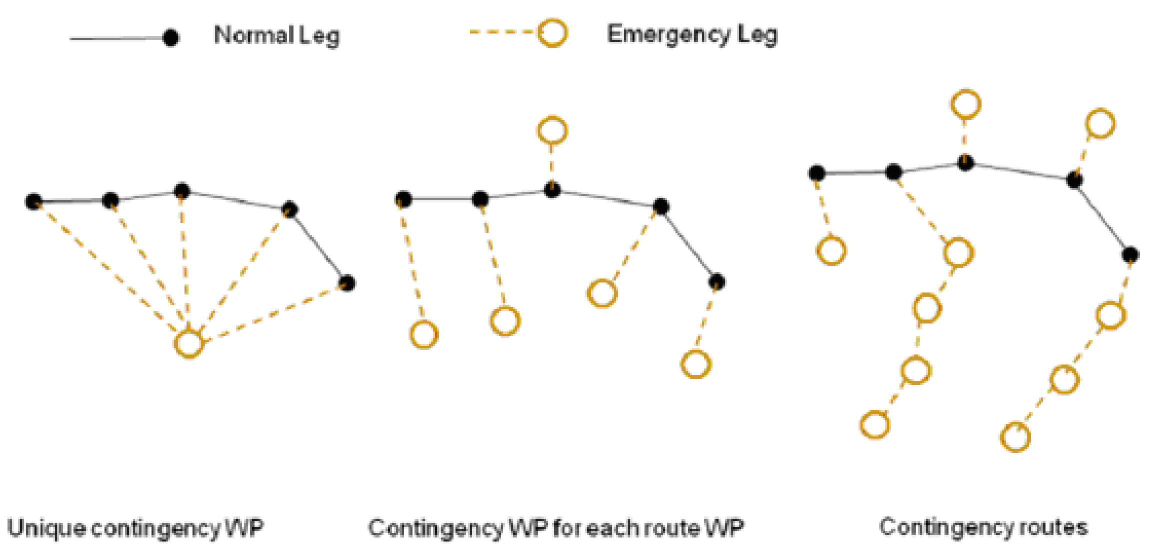
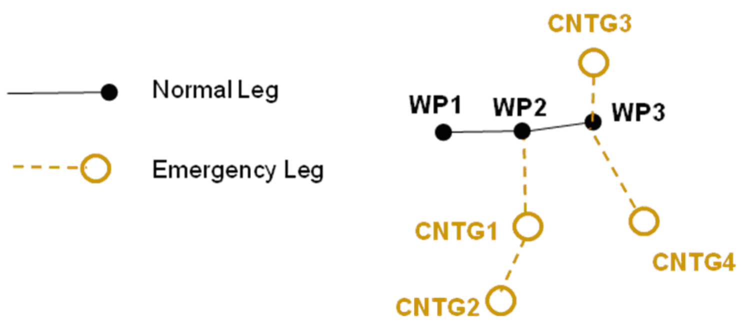


Figure 63. Examples of Contingency WPs/Routes [17]

Although advised for safety, it is not mandatory for STANAG protocol to have two Contingency WPs for each normal waypoint. Contingency WPs are always defined by a MSG #802. As example of Contingency route upload, the following example is provided:



MSG	Instance	Route	Type	Initial WP Number
#801	1	Route1	Flight	203
#801	2	CNTG Route	Contingency A	207

WP	MSG	Instance	WP Number	Next WP Number	Contingency A Number	Contingency B Number
WP1	#802	1	203	204	0	0
WP2	#802	2	204	205	206	0
WP3	#802	3	205	0	208	209
CNTG1	#802	4	206	207	0	0
CNTG2	#802	5	207	0	0	0
CNTG3	#802	6	208	0	0	0
CNTG4	#802	7	209	0	0	0

Table 22. Example of Contingency WPs/Routes upload

5.6.5 MSG #803

Message #803 specifies a loiter pattern for a WP. In particular, the STANAG 4586 considers four types of loiters:

- Circular,
- Racetrack,
- Figure 8,
- Hover (applicable only to rotorcraft or tilt-rotor vehicles).

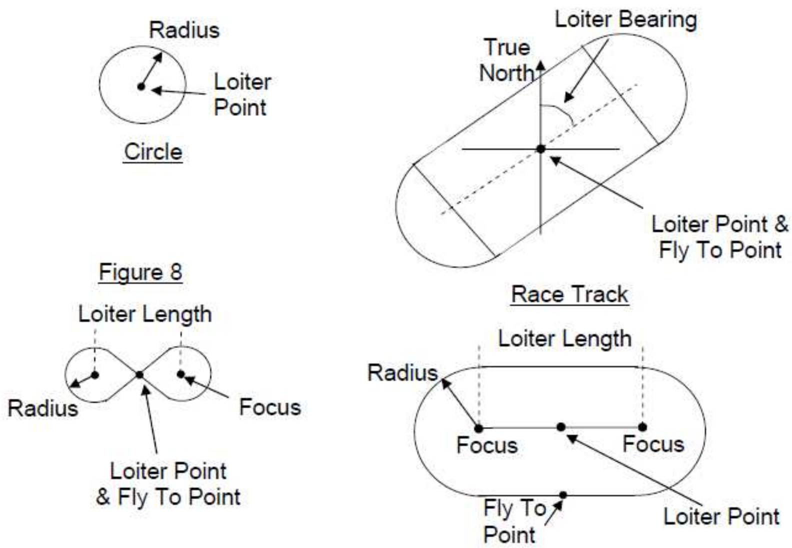


Figure 64. STANAG 4586 Loiter Patterns [1]

Loiter Center is defined by the relative WP coordinates (MSG #802), while the pattern type and the relative geometric characteristics are defined in the MSG #803 (see Fig. 64 and Tab. 23).

Parameter	Meaning	Circle	Racetrack	Figure 8	Hover
Radius	Dimension of the circle or semi-width for Racetrack and Figure 8	X	X	X	
Length	Length of pattern in the bearing direction for Racetrack and Figure 8		X	X	
Bearing	Azimuth with respect to the North of the Racetrack/Figure 8 greater axis.		X	X	

Table 23. Loiter Pattern Geometric Parameters [1]

MSG #803 considers also the loitering direction between the following options [1]:

- clockwise,
- counter-clockwise,
- into the wind,
- vehicle-dependent.

Although the direction is assigned, the way with which the UAV enters in loiter from the relative leg is not considered, since it is specific of the UAV navigation laws. As loiter exit condition, instead, is considered the expiring of a loitering time, reported in the MSG #803 as relative time from the loitering starting.

5.6.6 MSG #805

Relative to the Route, Emergency and Datalink Plans, at each normal and emergency WP can be associated an airframe action with the MSG #805. In particular, this message consider some standard actions for a series of vehicle functions:

Action	Functions
• Turn Off • Turn On • Go to Standby • Receive Only • Transmit Only	• Navigation/Strobe Lights, • Primary/Secondary Datalink, • Navigation/Strobe IR Lights, • NVD Compatible, • Landing, • Landing IR, • Vehicle Specific Action.

Table 24. MSG #805 data

5.6.7 MSG #804

For the Payload plan, it is possible to associate to a WP an action relative to a certain payload (identified by the relative station number) by the MSG #804. More in detail, the following options are available [1]:

- set sensor 1/2 mode:
  - turn off,
  - turn on,
  - stand by.
- sensor output:
  - sensor 1,
  - sensor 2,
  - both.
- set sensor pointing mode:
  - nil,
  - angle relative to the vehicle,
  - slewing rate relative to the vehicle,
  - slewing rate relative to the inertial,
  - LAT/LON slaved,
  - target slaved,
  - stow,
  - line search start location,
  - line search end location.
- set starepoint coordinates:
  - latitude,
  - longitude,
  - altitude,
  - altitude type (barometric, pressure, GPS altitude or height).
- payload azimuth with respect to the vehicle,
- payload elevation with respect to the vehicle,
- payload sensor rotation angle.

5.6.8 MSG #806

Finally, the STANAG 4586 provides the MSG #806 to implement the execution of vehicle specific action. For each action – identified by a string – is possible to command the start and the end.

Actions specified by the MSGs #804, #805 and #806 are started when the relative WP is the current DWP. In other word, they are performed along the leg relative to the associated WP.
At each WP is possible to associate more additional messages #803, #804, #805, #806, always using the field WP number.

5.6.9 MSG #900

As last message relative to the mission there is the #900, used by the VSM in order to provide feedback about the upload/download status (in progress, complete or aborted/rejected) and the complete percent.

5.6.10 Mission Upload Protocol

To conclude the section, in case of mission upload, the protocol starts with a MSG #800, followed by a #801 and relative WP MSGs (#802, #803, #804, #805, #806) for each route of the mission. The VSM responds with the #900 for the upload status.

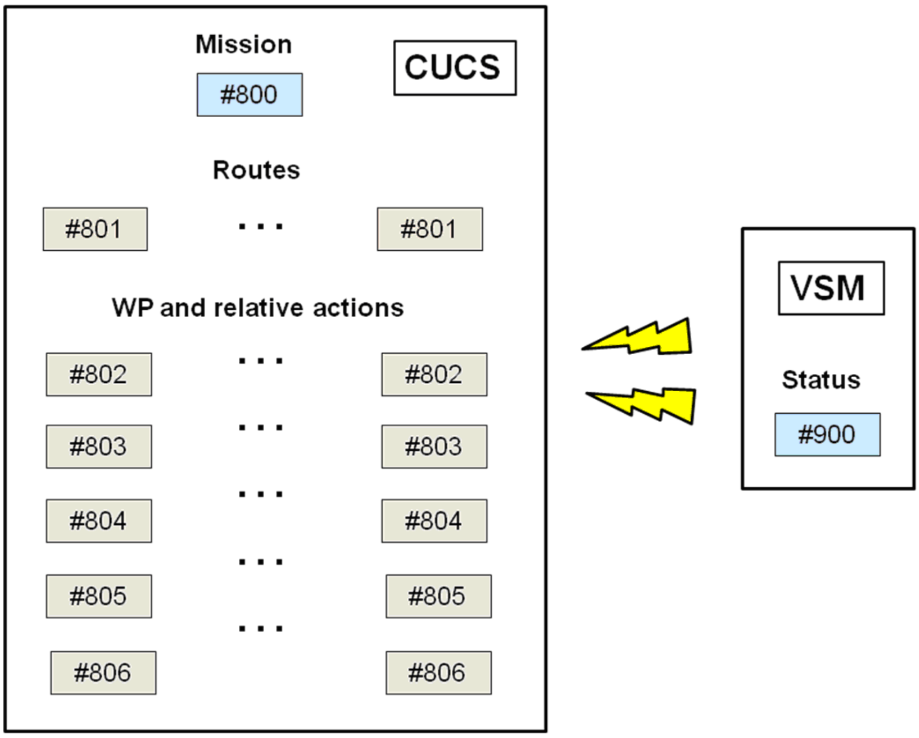


Figure 65. Mission upload according to STANAG 4586

5.7 Navigation / Trajectory Prediction Related Messages

In Chapter 2 some parameters relative to the "Navigation" and "Trajectory Prediction" functions of a traditional manned aircraft FMS have been identified (see section 2.3.1). They are perfectly applicable also to UAS, and being calculated on-board they are affected by the STANAG 4586 protocol. Unlucky not all of these data are present in the common messages. In some case, it is possible to calculate the data from other parameters (e.g. the Ground Speed and the Track from the North and East speed components), but in others the data is missing. In Tab. 25 it is reported an analysis about the data availability, considering a sample of typical FMS parameters. As reported in Tab. 25, only the UAV position is directly presented in the common messages, while other data can be determined by the NED vehicle and wind speed components. Greater part however is not available, forcing the designer to use private messages since many of the missing data shall be displayed to the operator according to the STANAG 4671. Some of missing parameters could be calculated, but it is more correct that they are determined on-board as output of the navigation/trajectory prediction algorithms. For example cross track and track angle errors can be calculated by the CUCS comparing the current UAV position and track with respect to the planned leg (i.e. geometric segment joining two WPs). This however could introduce some errors, since the navigation/trajectory prediction laws can consider some virtual leg during the flight, not known on ground.

Data	Present	Calculable from other standard data	Not Present & Not Calculable
UAV Position (Latitude, Longitude, Altitude)	X		
Ground Speed		X	
Track Angle		X	
Drift Angle		X	
Wind Speed/Direction		X	
Estimation Position Uncertainty			X
Source of Best Data (i.e. sensor used to determine the Navigation data)			X
Cross Track Angle			X
Track Angle Error			X
Predicted Fuel Consumption			X
Arrival time at WP			X
Distance to travel at WP			X
Point of Non Return			X
Equal Time Point			X

Table 25. Navigation and Trajectory Prediction data availability

5.8 STANAG 4586 Limitations

The STANAG 4586 represents an admirable effort in order to develop an universal interface protocol that permits the control from a single GCS of different types of UAVs. Taking into account for example the differences from a tactical rotorcraft UAV and a turbojet HALE, the complexity to define an unique standard interface can be understood, with the relative system architecture and message structure that enable also to add private messages.
Despite its merits, the STANAG 4586 presents several limitations that complicate its adoption as design reference. These issues are probably due to the early maturity of the standard and to its limited diffusion, with the consequent poor data and practical experience about its implementation. Besides STANAG 4586 suffers of “aeronautical culture” lacks, since many practices well established in the manned aircraft have not been considered in the development of the standard, with consequent problems especially in terms of operational effectiveness. However these limitations are not critical and in many cases they can be solved adopting a private message. Anyway in order to enable a further greater interoperability this is not a good solution, since private messages should be ideally limited as much as possible. It is desirable that future editions of the STANAG 4586 remove these problems. Unlucky the edition 3 draft does not solve the whole list [60]. Below the main issues discovered implementing the STANAG 4586 in our work are reported.

5.8.1 Remote Manual Control

Remote manual control is not considered by the STANAG 4586 standard messages, with the absence of the relative mode in MSGs #42/#106 and demands (pitch, roll, yaw, engine commands) in MSGs #43/#104. Roll command is present in MSGs #43/#104, but it is relative to a semiautomatic autopilot mode and not to a remote stick input of the operator. Besides also the autothrottle activation/deactivation is not provided. STANAG 4586 philosophy (although not roundly reported) considers a good level of automation for the compliant vehicles (at least ACL = 2) in order to reaching a high LOI. There are however many UAVs that although fully automatic, can be also manually flown, and more generally this type of basic control should be considered to be as interoperable as possible. Besides is not cleat at the moment if the capability of remote manual control will be mandatory (at least for emergency operations) to operate in civil airspaces. Adding these information in the standard interface requires to distinguish between aircraft and rotorcraft control surfaces commands, and between different engine types (piston, turboprop, turboshaft, turbojet/turbofan).

5.8.2 Guidance Messages Implementation

Guidance implementation with eight asynchronous messages (#42, #43, #48 and #41 from the CUCS, and #106, #104, #109 and #110 from the VSM) complicates the software design and integration, due to the risk that one or more messages of protocol will be not received by the CUCS/VSM, especially when they communicate through datalink. In other words although efficient from the bandwidth saving standpoint, it is more difficult to make it robust. In any case, also with the asynchronous solution, the messages could be reformulated in a more efficient way. For example, for the loiter mode it is not optimized having the loiter point coordinates in the MSG #43 and the geometric characteristics in the MSG #41.

5.8.3 Guidance VSM Responses

VSM standard messages do not provide full response to the CUCS demands. In particular MSG #104 does not contain the feedback to the commanded vertical speed, while the CUCS MSG #41 does not have a standard response (added in the edition 3 of the standard [60]).

5.8.4 Fourth Dimension Definition at WP

MSG #802 assigns at each WP an arrival time or a speed. It is not possible to not define the 4D attributes. This can be a problem in some operative cases, where there is an assigned time on target on a given WP, with no rigid constraints to the previous time. In this case a manned aircraft typically adjust the Ground Speed on the previous legs in order to satisfy the time on target. According to the STANAG view, instead, in order to reach the assigned time, at the previous WPs a compatible time or speed should be assigned, complicating the planning phase. Differences between aeronautical traditional implementation and STANAG 4586 are reported in Fig. 66. A possible way to bypass the problem could be consider a certain speed/time value in the MSG #802 (e.g. the speed lower limit of 0 m/s) as indication of no 4D demand. However this could rise an other problems in case of checks of admissible planned value by CUCS or VSM, that will reject the zero value. Optimum solution could be adding a new type of speed type: “system commanded GS”, leaving to the system the responsibility of the 4D management for a part of route. In this way however the predictability of the actual route path/state is reduced.

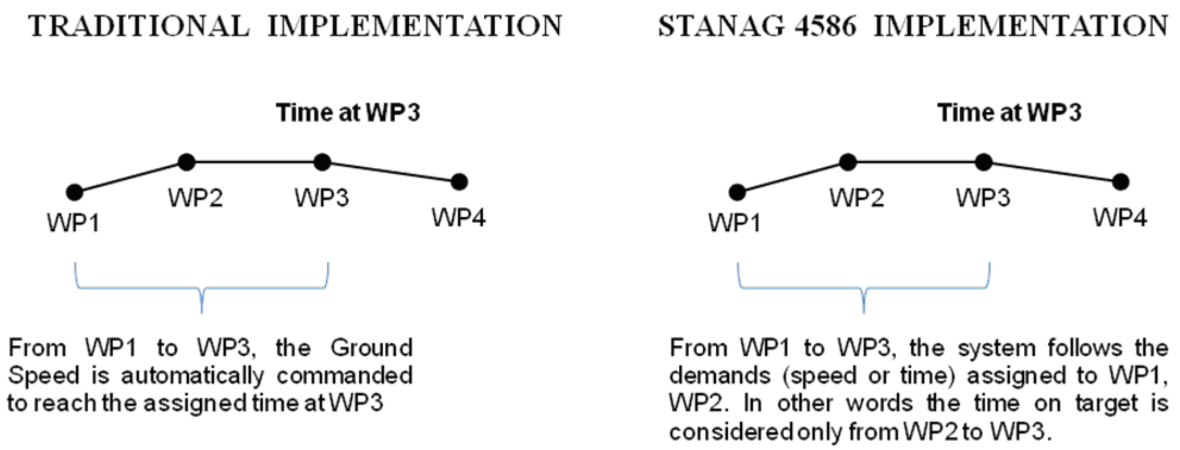


Figure 66. Traditional vs. STANAG 4586 Time On Target Implementation

Besides, there is not the possibility in MSG #43 to perform a manual override of an arrival time, forcing the operator to modify the WP attributes and then upload again the route if he/she wants to modify a time.

5.8.5 Additional Attributes/Action to WP

Actual implementation of MSG #803, #804, #805 and #805 is not robust, since it considers only the WP number as link to the relative MSG #802. On the MSG #802, however, there is not an indication that it will be followed by other related messages. Therefore, in case one of the additional messages is lost during the mission upload/download, this will not be detected by the VSM/CUCS with consequent incomplete routes construction. In order to solve this issue, the edition 3 proposes to add this info to the MSG #802 [60].

5.8.6 Loiter Attributes in MSG #803

MSG #803 does not provide the capability to enter a loiter speed different from the speed or time assigned in the relative #802. Therefore, at least of automatic aircraft speed change to a predefined value or manual operator command, the UAV flies the loiter with the same speed used in the relative leg, and this is not an optimum solution since usually a loiter is flown with the best endurance speed in order to save fuel. Besides as loiter exit condition is specified only the time, and therefore the actual UAV path is not predictable during the planning if a navigation/flight control laws model is not used to check the route. In some practical cases, in fact, it is requested the possibility to specify the exit radial from a loiter, especially considering the future integration in the civil airspace. Another not considered exit condition could be the number of loiter rounds.

5.8.7 No Contingency WPs/Routes for All Guidance Modes

The STANAG 4586 provides definition of UAV emergency paths in case of Waypoint guidance mode. No general definition of contingency WPs/Routes is provided for other modes. Although the vehicle behavior in these cases is usually specific of each system, a standardization is required especially for future civil certification.

5.8.8 No Standard Target Characterization

No common messages for the target upload are provided by STANAG 4586. This lack limits the Payload plan detail and definitively the achievable LOA.

5.8.9 No Mission Zones Characterization

Analogously to the previous point, the upload of Mission Zones (e.g. area of operation or No Fly Zones) has not be foreseen by the STANAG 4586. This can be an interoperability limitation for more autonomous vehicles having replanning or navigation algorithms that check the respect of these zones, since a private protocol would be implemented.

5.8.10 Route/Waypoint Repetition Attribute

In MSG #801 there is not an attribute that define the number of route repetitions, i.e. the number of times that a route is flown. The same for the MSG #802, in order to implement the repetition function only for a route portion. This attribute would be useful for an UAV involved in monitoring or searching task along a planned path. Without it, it is needed an operator’s command or the creation of a private message to repeat the route.

5.8.11 Navigation / Trajectory Prediction Parameters

As reported in the section 5.7, standard messages do not consider all navigation / trajectory prediction data. In any case the problem can be easily bypassed through private messages, although it would be more desirable the definition of common messages in order to reach a greater level of interoperability.

5.8.12 Differences between STANAG 4586 and ARINC 424

STANAG 4586 route format is quite different from traditional manned aviation flight plan. In particular there are not comprised the instrumental flight procedures (SID, STAR, holding pattern, NAVAID approach, etc.), as defined for example by the ARINC 424. Besides common messages do not consider the possibility to specify altitude, speed or time constraints to the WPs. A study with the civil aviation authorities would be performed in the future – when the UAS integration in Common airspaces will be closer – to evaluate the needed to add these items to the UAS route concept. In positive case, the STANAG 4586 should be accordingly modified. This issue affects especially the UAVs of Class III.

6 NEW FLIGHT MANAGEMENT SYSTEM HMI

6.1 Work Scope

Research activity has been practically concretized with the study of an innovative HMI for a Flight Management System relatively to a MALE UAS. Referring to the FMS functional allocation reported in Tab. 10, a subset of GCS macro functions on which concentrating the work has been identified:

- guidance,
- merging of navigation and trajectory prediction,
- radio communication,
- configuration,
- mission planning,
- autonomous replanning,
- performance.

For each of these macro functions a new HMI solution has been designed in order to be compliant to the STANAG 4586 and to reduce UAS mishap rate due to human factor, taking into account the problems/limitations of current interfaces exposed in the first four chapters of the thesis. HMI development cycle will be presented in detail in the next section 6.3, but just as introduction it has not been limited to the symbology standpoint, since the Graphical User Interface (GUI) design derives from an analysis of the related operative concept and the definition of the functions to provide at the operator (linked to the messages of STANAG 4586 protocol). More in detail, design activity has been concretized in the realization of an interface prototype that has been integrated in a real GCS to validate the proposed concepts, arriving to the flight tests. As test bench the Alenia Aermacchi MALE UAS Sky-Y has been considered.

6.2 Alenia Aermacchi Sky-Y

The Alenia Aermacchi Sky-Y is a MALE technological demonstrator used to validated key enabling technologies for a surveillance UAS [61]. It is characterized by the following data [61]:

Dimensions	**Weights**	**Performances**
• length = 9.725 m,	• MTOW = 1200 kg,	• LOS radius = 100 NM,
• wing span = 9.937 m,	• OEW = 850 kg,	• Range = 500 NM,
• wing area = 10.785 m^2.	• Fuel = 200 kg,	• Ceiling Altitude = 25000 ft,
	• Typical Payload = 150 kg.	• Endurance = 14 h

Table 26. Sky-Y Characteristics

Figure 67. Alenia Aermacchi Sky-Y

6.3 HMI Development Process Cycle

The following design process has been followed for the development of the new Human Machine Interface:

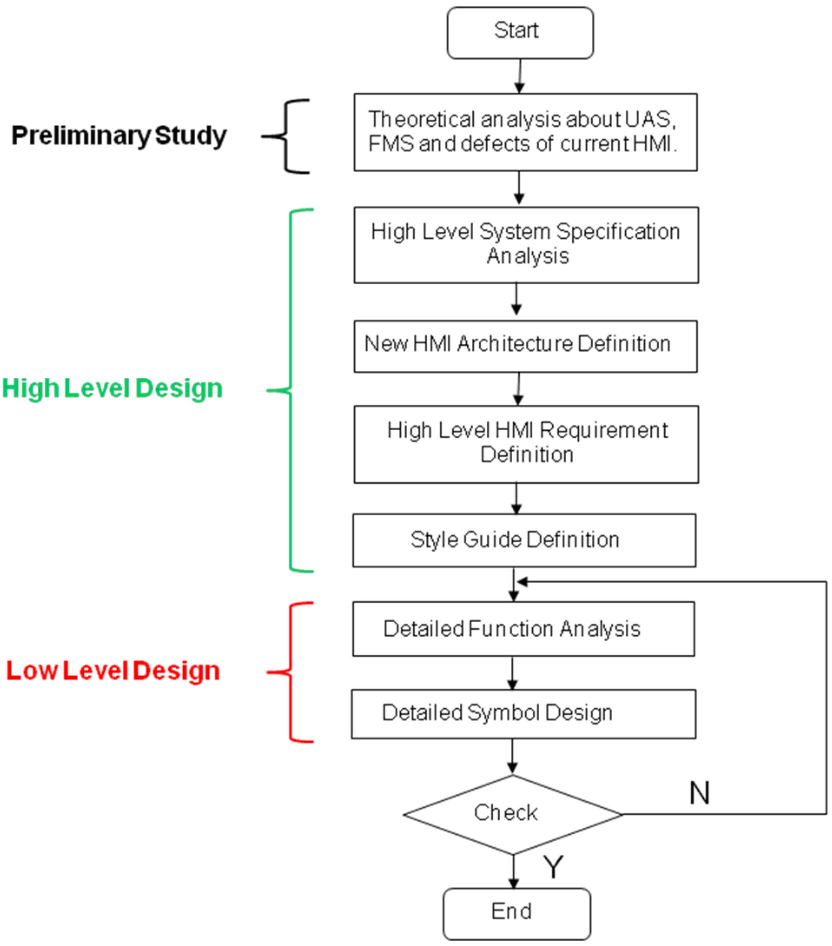


Figure 68. HMI Design Process

First phase coincides with a preliminary study about the subject, the in service systems and the relative defects/problems. Obtained results have been presented in the first five chapters. Passing to the practical realization, the high level design involves the definition of the HMI architecture, the macro functions that shall be performed by the system and the style guide according to which the symbology will be developed. In other words, in this phase the frame around which actually developing the interface is built, starting from the initial considerations and the analysis of the assigned system high level requirements. Defined the frame, it is possible to do the detailed functional and symbol design for each considered format. Link between GUI elements and STANAG messages is done in this phase. In particular, to realize the format draws, the free drawing software "Inkscape" has been used.
Detailed design output then is checked, and if the results are negative it is modified until reaching a complete system validation and integration. Testing and integration, in particular, has been an iterative process involving several environments with an incremental level of integration. The iterative characteristic is due to the fact that if an integration problem is found after a test, a design

change that solving it is done, and hence a new test that verifies the bug absence of new software is needed.
In particular the following items are verified:

- correct GUI functioning according to the design,
- GUI integration in the real GCS and with other UAS elements,
- operator evaluation.

Testing & Integration process will be detailed presented in Chapter 11.

6.4 High Level System Specifications

Design activity starts with the analysis of the high level system specifications, that is a series of assumption – done before starting the design – about the operative environment and reference UAS for which studying the new FMS interface. An interface, in fact, can not be created independently by the context and the specific system in which it will be used.

6.4.1 Mission

A generic MALE UAS designed to perform monitoring, surveillance and searching missions has been considered. Typical operative tasks, therefore, are characterized by a long endurance.
In terms of flight permission, currently only operations into reserved areas are considered, due to the absence of rules to fly in common airspaces. At this purpose, the concept of Area Of Operation (AOO) – i.e. an area in which the UAV is free (or near free) to move in order to satisfy the assigned tasks – has been considered, joined to airports by safe corridors. Particular areas for which an overfly is prohibited by the Authority (e.g. high populated areas) are identified as No Fly Zones (NFZs). NFZs can be also present inside corridors and AOO. It is also possible the case in which there are more AOOs connected by corridors.
Finally, for the mission range, currently only LOS operations are considered, but many considerations are perfectly applicable also to the BLOS case.

6.4.2 Crew

A crew made up by a pilot and a payload operator has been assumed. Pilot operator is responsible of the vehicle control and he/she is usually the mission commander, while payload operator is charged of payload control. FMS HMI, in particular, is only relative to pilot station.
For the operator qualification, the Italian civil aviation authority (Ente Nazionale Aviazione Civile – ENAC) requires rated test pilot/navigator as crew. According to this, rated test pilots have been considered as main stakeholders for the development. In the following part of the thesis, the terms “operator” and “pilot” will be considered equivalent. Finally, a provision to extend the new interface to enable a single operator to control both vehicle and payload have been considered.

6.4.3 Civil Certification

As critical design constraints, the civil certification for the FMS has been considered according to the STANAG 4671. The DO-178B has been followed for the software certification. In particular, using certifiable hardware, operative system, programming language and graphic libraries makes more difficult the realization of safety critical interfaces. Seeing section 1.6 for more details.

6.4.4 Interoperability

Together with the certification, the second key assumed design constraint is developing the FMS in order to reach the LOI 5 according to the STANAG 4586 Edition 2.

6.4.5 HMI Upgradability

Having realized a subset of full FMS functions and considering the Interoperability requirement, the new HMI shall be developed with an open structure in order to have the possibility to easily add new specific functions in the future keeping a format commonality. In other words, the interface shall be realized modular and parametric as much as possible.

6.4.6 Level Of Automation

Having as goal the development of a new interface that overcomes many human factor issues of operative UASs, we have assumed as reference Level Of Automation an ACL of 2, that is the best reached value of current systems. In particular, the possibility to control the vehicle in several ways has been considered (i.e. manual, semi and fully automatic). Manual control capability has been included also because it is not clear if future civil regulations will require or not a manual mode as emergency backup in order to operate in common airspace (at least for LOS operations).
A provision to increase the LOA to an ACL of 3 has been considered relatively to the autonomous replanning function. Seeing section 4.2 for further details about ACL.

6.5 HMI Architecture

The two considered operators (see section 6.4.2) have been assumed to be sit in two stations disposed side by side like on manned cockpit. Usually pilot sits in right seat in order to have the stick in right hand for manual control.

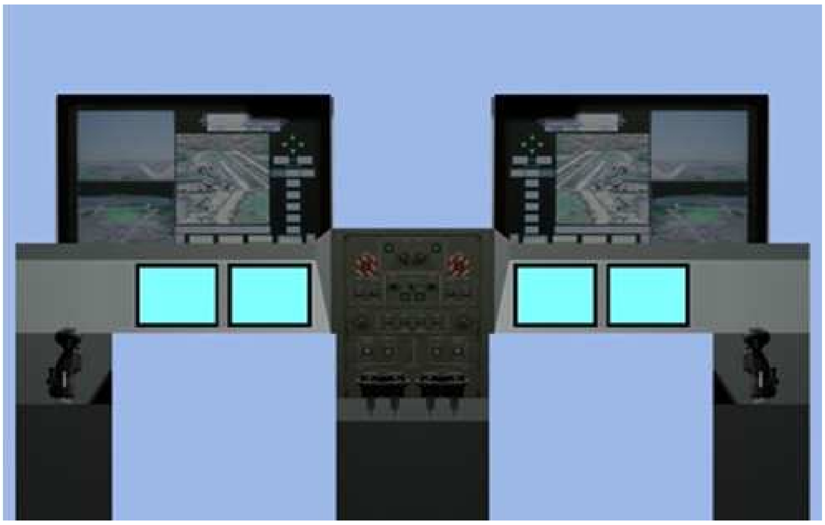


Figure 69. New GCS general layout

More in detail each operator station is made up by the following elements:

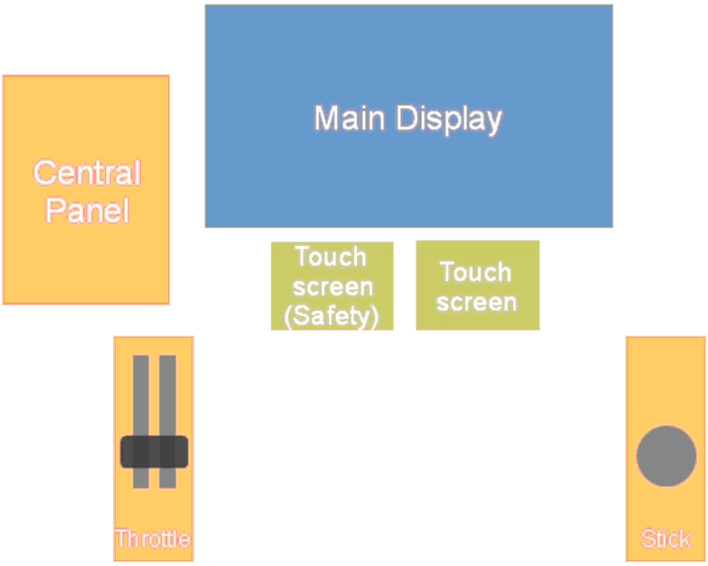


Figure 70. Station Layout [27]

Referring to the pilot station for which the FMS is developed, the studied interface philosophy is to display all information about the current UAV status on the Main Display (26”), and using two 10” Touchscreen Displays (TSD) as data entry interfaces. Besides touchscreens have also a secondary role of displaying information about the future state of the vehicle. No data, instead, are entered through the Main Display. A TSD and the Main Display are considered Safety Critical (SC), while the other TSD is dedicated to the Non Safety Critical (NSC) functions [27]. In particular, all functions involving a communication between GCS and UAV or other actors (e.g. ATC) have been assumed as safety critical. SC touchscreen has been considered in the opposite side with respect to the stick, in order to permit actuations on it during manual flight.

The use of TSD as input device enables the adoption of a Graphical User Interface (GUI), that is the natural solution considering the requirements of HMI upgradability and the complexity of the involved functions. Adopting a GUI, in fact, it is possible to host more software formats/controls in the same hardware device, with high flexibility in adding new items or modifying others. Besides the interface is able to support the operator during the execution of mission tasks, through for example prompts, pop-up and other visual cues. Finally also the operator workload due to the visual searching of the control to actuate is reduced.

Central panel contains hard switches relative to the safety critical functions for which a quick access shall be provided, and hence interacting with the GUI menu is not suitable.

Flight Controls (i.e. stick, throttle and pedals) are used for manual control. Besides some switches on stick and throttle – Hands On Throttle And Stick (HOTAS) concept – enables the operator to execute some actions in a quick way (e.g. change the display zoom or the autopilot demands), avoiding the possible workload related to TSD page change to perform frequent operations.

Finally, from the STANAG 4586 standpoint the VSM has been assumed on-board, and therefore the HMI (HCI in STANAG language) has been considered speaking directly with the vehicle.

6.6 FMS Input Device Selection

Touchscreens have been selected after a comparison with other possible solutions, taking into account operative and certification aspects. Input device choice is not a trivial issues, since it significantly affects the SW design and realization. In particular, common GCS solutions adopt only a keyboard, but it has not been judged as completely satisfactory by the operators for the following reasons:

- Quick selection of a function could be difficult (although time critical functions are not controlled through keyboard, but by panel switches).
- Keys are very close each other and so errors are possible.
- In order to avoid errors, keys combination (e.g. CTRL + A) are used, with consequent mnemonic load for the operator and further difficulty to perform quick actions.

The following two alternative options have been considered, assuming in both cases to have always one Main Display and the Flight Controls:

1. touchscreens,
2. keyboard plus a Cursor Control Device (CCD) acting on the Main Display.

Traditional MCDU has not been taken into account for the reasons reported in the Chapter 2, while innovative MCDU (like that of A-380) conceptually relapsing into the second case.

Figure 71. Alternatively FMS Input Devices

In the following tables, advantages and disadvantages of each solution with respect to the others are presented. In particular, for the CCD three different types have been taken in exam.

Advantages	Disadvantages
• More Instinctive Interactions. • Operator verifies the results of his/her actions in the same interface where the inputs are entered. • Possibility to adopt new types of interaction like for example the scroll movement on the sliders. • Alphanumeric keyboards are displayed only when necessary. • Greater display dimension with respect to a traditional MCDU, due to the absence of line select keys and fixed keyboards. • Possibility to have a back-up of the Main Display in case of failures. • Main Display is devoted only to the monitoring, without input interactions on it (i.e. there are not pop-ups or windows that cover the UAV status information). • Current UAV state is always displayed in the Main Display, giving the capability to see on the Touch Screens other information about the mission (e.g. future UAV status). • No size issues related to the keyboard and CCD positions, particularly critical due to flight control presence.	• Touchscreens are more expensive than keyboard and CCD. • For prolonged interactions the TSD is not the best interface, especially considering the arrangement due to the presence of the flight controls. • Input entering happens at "head down", that is with a temporary loss of visibility on main display. • Touchscreen use in aviation is at the beginnings, and therefore there is very limited know-how, especially in terms of reference standard and civil certification. • Finger size limits the number of controls in a page, and the interaction quality when an accurate pointing is required. • Fingers could obstruct the display view.

Table 27. Touchscreen Advantages and Disadvantages [27]

Advantages	Disadvantages
• More cheaper than touchscreens. • Writing with a hard keyboard is more ergonomic than use the virtual one. • More controls on a page and a greater interaction quality in case of accurate pointing can be obtained due to the smaller size of a pointer with respect to the finger. • GUI can potentially have greater dimensions, since it is allocated on the Main Display, compatibly with the current UAV status info.	• Potential Situational Awareness reduction when the operator enters inputs on Main Display. • Less information are provided to the operator, since there is only a display. • It is difficult placing keyboard and CCD taking into account the flight controls. • No Main Display backup is available. • Keyboard is used essentially to writing and so it is very little used.

Table 28. Keyboard + CCD Advantages and Disadvantages

Figure 72. Possible CCDs

Device	Advantages	Disadvantages
Mouse	• It's a very common device: high acceptance from the operator.	• It is difficult to use in GCS, since the lack of a proper space.
Trackball	• Smaller than a touchpad. • Fixed device.	• More difficult to use than a mouse. • Not much usable in a big display.
Touchpad	• More instinctive than a trackball. • Usually present in notebooks: more acceptance from the operator with respect to a trackball. • Fixed device.	• Not much usable in a big display.

Table 29. CCD Comparison

Comparing the two solutions, the most suitable for our case is the touchscreens, due to its flexibility, instinctively and further information provided with respect to the keyboard plus CCD. Besides the touchscreen modularity permits to reduce the number of interfaces on which the operators controls the vehicle, lowering in this way the workload and increasing the operator performances. An example of overmuch controls is reported in Fig. 73, relative to the Predator GCS, for which there are two Multi Function Displays (MFD) controlled by a keyboard and a CCD, two main displays (not present in the figure), plus other optionally displays.
Examining the touchscreen disadvantages, the assumption that the operator does not interact continuosly on them, but only when a system state change or a specific information is required, has been done, especially considering that common operations can be performed on HOTAS. In this way, there are not ergonomic problems (e.g. arm fatigue) or situational awareness losses due to "head down" operations. This assumption has been then confirmed by simulator and flight tests.
Regarding the limited know-how, currently there are very few examples of touchscreen in aviation, like the cockpit of the F-35, the Garmin G-5000/G-3000/G-2000 MCDU for business jets and general aviation, and some IPad ®and IPhone ® tools for general aviation and sailplane pilots. However the fast growing rate of the relative technologies – in terms of performance, size, weight and reliability – makes really interesting the use of touchscreen on manned cockpit, and in fact there are several research activities about that (e.g. ODICIS and ALICIA at European level). It is

therefore natural extending their use at the GCS, especially since in this case there are not vibration, sun reflection and ergonomics (due to aircraft maneuvers and glove use) problems.

Figure 73. Predator Pilot Control Station

Figure 74. Examples of Touchscreen in Aviation

With respect to a traditional cockpit, a GUI on touchscreens represents a significant change in the interaction way for pilots, but the instinctively of touchscreens plus their diffusion in everyday life (e.g. smartphone, tablet, cash dispenser, satellite navigation device, etc.) reducing the training time and increasing the operator feeling about them. HMI design standards and certification rules, however, are still lacking on these issues, and new rule editions will be required in the future as TSD use for safety critical applications increases.
Finally, the number of controls in a TSD page is limited by the finger size, but a proper design and the reduced required inputs due to the system automation make this issue not critical for us. Besides an accurate symbol/formats arrangement in each page permits to avoid also the problem of critical page view obstruction by the operator finger/hand.
This input device analysis was performed in the Spring of 2010 and its results have been confirmed by a new issue of the MIL-STD-1472 (edition G) in the January 11, 2012 as reported below:

Advantages	Disadvantages
No separate input device	Slower alphanumeric data entry
Programmable interface	Arm fatigue
Fast access	Finger may obstruct view
Direct manipulation of targets	Fingerprints or other debris may obscure screen
Input/output in same location	Larger buttons required for finger use
Intuitive	Pointing is not very accurate
Natural pointing action	User must be within reach of screen
Generally no additional desk space required [1/]	No tactile feedback provided [3/]
Generally no training required [2/]	Unable to rest finger on target without actuation [3/]
	Accuracy degraded by vehicle movement and vibration.
	Gloved operation may be incompatible with some touch-screen technology.
	Controls must be deactivated for cleaning.

NOTES:
[1/] If incorporated as part of an existing primary display.
[2/] Application-dependent.
[3/] If a tactile feedback membrane is not incorporated.

Table 30. Touchscreen Advantages and Disadvantages According to MIL-STD-1472G [63]

In particular, MIL-STD-1472G suggest to use touchscreens for intermittent actions, and not when continuous data entry is required[63].
In any case, a GUI on touchscreen permits also to reduce the number of interfaces with respect to a manned cockpit, since in a single device can be concentrated several controls, that are usually separated on a traditional cockpit (e.g. MCDU, radio and autopilot panels).

6.7 Touchscreen Type Selection

Touchscreens can be realized with different technologies, affecting the type of control supported and in general the interaction quality. Therefore as second step of input device selection, there have been the choice of TSD type. In the following sections the common touchscreen technologies are presented with the relative advantages/disadvantages in order to justify the final choice.

6.7.1 Touchscreen Elements

Figure 75. Example of Touchscreen Elements [64]

Each TSD – independently by the type – is made up by the following three elements:

1. Sensor: device joined to the screen that detects the operator touches in terms of display coordinates (X,Y). It is the element that discriminates the different touchscreen types.
2. Controller: electronic interface between the sensor and the computer at which the touchscreen is connected.
3. Drivers: firmware enabling the interaction between touchscreen and computer.

6.7.2 Resistive Touchscreen

Resistive touchscreen is the most common type. Practically, it is realized with two layers each coated with a transparent resistive material (Indium Tin Oxide – ITO). Bottom layer is rigid and it usually made in glass, while the upper is flexible and made in plastic. They are separated by spacing dots and run by an electric current. When the operator touches the screen, he/she pushes in contact the two layers closing the circuit. From the electric current variations, the touching point coordinates are detected. Several variants can be realized according to the way in which the coordinates are measured. In other words, this type of TSD is based on electric resistance property. In Tab. 31 the relative advantages and disadvantages are reported.

6.7.3 Capacitive Touchscreen

A capacitive touchscreen is basically made up by an insulator like a glass layer coated with ITO, at which a potential difference is applied. In this way a uniform electric field on the screen is obtained, and in general the display acts as a capacitor. When the operator touches the screen, it alters the electric field, since the human finger has very different dielectric properties with respect to the air.

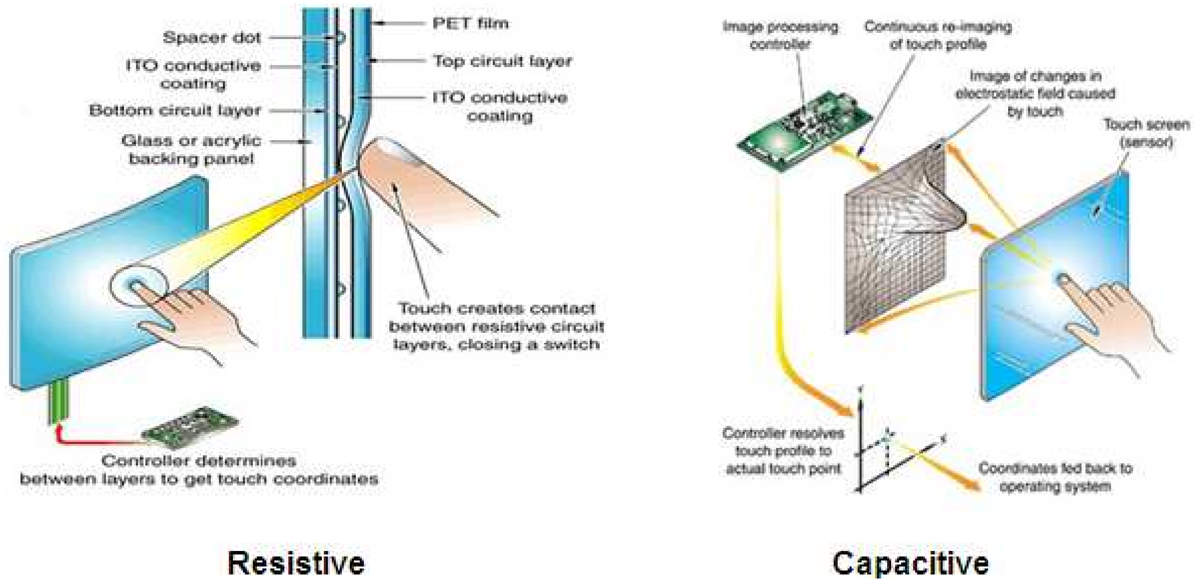


Figure 76. Resistive and Capacitive Touchscreen Working Principles [65]

Advantages	Disadvantages
• It is cheaper with respect to the other types. • It can be used also with fingernails, gloves or a pen stylus. • It can work with a wide temperature range: from -15° to 45° in average. Besides there are no humidity constraints. • External layer is resistant to crash. • It is not affected by grease, moisture, liquids or other contaminants.	• Precision is strictly correlated to the pointing device. In case of hand actuation, it is limited to the finger size. • Poor image contrast in some lighting conditions (especially in external environment) due to the flexible layer. • External layer can be liable to damage or wearing by sharp object • Multi-touch is not supported, unless to do a re-engineering of the device. • The reactivity is lower with respect to other types (e.g. capacity TSD) due to the need to press down the upper layer. • Quality interaction is lower than capacity types, especially in sliding movement or double click interactions.

Table 31. Resistive Touchscreen Advantages/Disadvantages

Electric field distortion is measured in terms of capacitance variation and permits to determine the touching point coordinates. According to the way with which the capacitance is measured and to the glass/conductive layer structure, there are different variants of capacitive TSD. In Tab. 32, the relative advantages/disadvantages are reported.

Resistive and capacitive touchscreens, in particular, are the most diffused types.

Advantages	Disadvantages
• It has a better reactivity and in general a greater interaction quality, since it is sufficient to accost the screen: no pressure is required. • Multi-touch is directly supported. • Greater image quality due to the absence of external layer (glass layer usually transmit almost the 90% of the display light). • It is resistant to wear.	• It is expansive with respect to the other types (also 50% more than a resistive TSD). • It can not be used with a non conductive material, like fingernail, glove or pen stylus. • It is easier to be damaged by crashes. • It works in a little temperature range (typically from 0° to 35°), and it requires at least a humidity of 5%. • It can be affected by moisture, grease, liquids or other contaminants. • Precision is limited by the finger size.

Table 32. Capacitive Touchscreen Advantages/Disadvantages

6.7.4 Surface Acoustic Wave Touchscreen

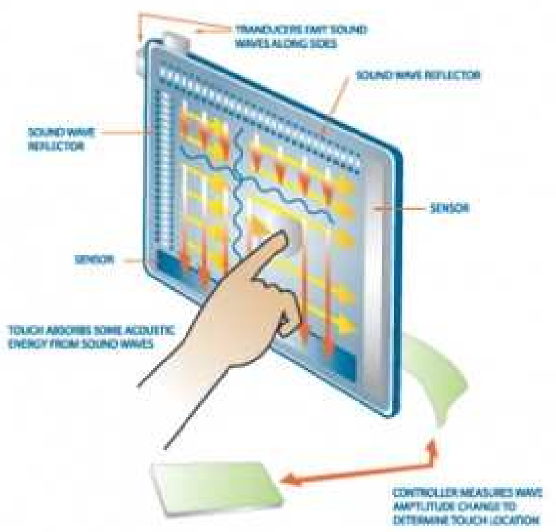


Figure 77. Sound Acoustic Wave Touchscreen Working Principle [66]

Surface Acoustic Wave touchscreen is based on sound wave properties and not on electric ones. Practically it is realized placing two transducers (a transmitter and a receiver) on each screen axis (X and Y), plus a reflector on the glass. TSD controller generates electric signals that are converted in ultrasonic waves (not perceived by human hearing) by the transmitter and emitting toward the receiver through the reflector. Waves are reflected by the receiver to the transmitter, that converts them again in electric signals sent to the controller. In other words a web of ultrasonic waves is created on the screen. When the operator touches the screen, the wave beam is interrupted and part of its energy is absorbed. The controller detects the touching point coordinates measuring the variation in the sound wave amplitude due to the energy reduction. Peculiarities of this touchscreen are reported in the table below:

Advantages	Disadvantages
• It provides a very good image quality (100 % of display light transmitted) due to the absence of a metallic conductive layer. • It supports the multi-touch. • It can be used with fingernails, gloves or in general soft tip stylus.	• It is very expensive with respect to the other types. • It can not be used with hard tip stylus. • It can be affect by dirt, dust, liquid and other contaminants. • Precision is strictly correlated to the pointing device. In case of hand actuation, it is limited to the finger size. • Glass can be damaged by crashes.

Table 33. Surface Acoustic Wave Touchscreen Advantages/Disadvantages

6.7.5 Infrared Touchscreen

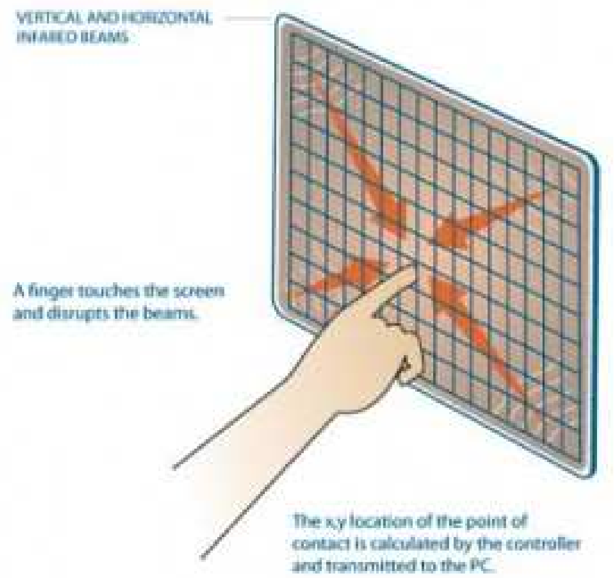


Figure 78. Infrared Touchscreen Working Principle [66]

This type of touchscreen detects the operator touches by the interruption of an infrared beams grid over the screen. The grid is obtained by two arrays on the screen sides of Light Emission Diodes (LEDs) and photodetector pairs.
Relative advantages/disadvantages are reported in the table below:

Advantages	Disadvantages
• It provides a very good image quality (100 % of display light transmitted) due to the absence of a metallic conductive layer. • It supports the multi-touch. • It can be used with fingernails, gloves or any stylus.	• It can be affected by dirt, dust or other contaminants that interrupt the beams. • It can suffer of parallax in curved screen. • There can be an accidental pressure when the operator hovers his/her fingers over the surface while searching the correct control to push.

Table 34. Infrared Touchscreen Advantages/Disadvantages

6.7.6 Touchscreen Selection

Comparing the previous types, the resistive touchscreen has been chosen for the following main reasons:

- It has the better environmental properties in terms of operative temperature, humidity and contaminant resistance. Although the GCS is a closed space with an environmental control system, in fact, it is a mobile shelter and therefore can operate in different climatic zones.
- MIL-STD-1472 requires a resistance to the TSD actuation, and therefore the unique compliant type is the resistive (see section 7.2.4 for more details).
- It is cheaper with respect to the others.

Reactivity and in general quality interaction reduction does not significantly affect the system operability with respect to others types (e.g. capacitive). In any case, the lower reactivity could be a further protection from undesired inputs by the operators, more probably for example with a capacitive touchscreen in which it is sufficient to approach the screen to actuate a command. This issue, in particular, is critical for the touchscreen use in a mobile vehicle (aircraft, ships, etc.), but it could be also considered in a static GCS. The multi-touch absence is not critical and can be substituted by other types of interaction/graphical formats.
Besides, working in a close environment with a properly lighting, there are no problem of image contrast due to the external flexible layer. Finally, the TSD is manually actuates by the operator, without using gloves (not required due to the GCS environmental control system) or stylus (not practical for operative use), and therefore all types have the same limitation of finger size in the GUI design.

7 HMI STYLE GUIDE

7.1 General Principles

A GUI is usually developed according to a set of general guidelines defined before to start the detailed format design. Some of these rules are common to every GUI and present in literature, while others are specific design choices that derive in part from the firsts and in part from the application context. The whole of these rules defines the “HMI Style Guide”. In particular, the design process (see Fig. 68) is compliant to the “User Centered Design” (UCD) principles (Woodson, 1981) [67]. UCD puts the user at the center of design in order to be sure that the developed product satisfy as much as possible his/her needs. In other words, the human is not considered as the final element with which verifying the product compatibility, but at the contrary the core around which the system shall be designed since the early stages.
Standards, rules and guidelines present in literature help to design a good GUI providing some advices to the designers, but they are not rigid “checklists” that guarantees the achievement of a good interface. More in detail, the following heuristics have been considered for GUI design[67]:

- Display the data in a usable and consistent form in order to avoid reformulations/transpositions by the operator with consequent workload increase (see also section 4.5).
- Maintain a display layout commonality for different formats in order to reduce the mnemonic operator load, the error possibility and the training time.
- Use simple and natural dialogue.
- Use the operator language (i.e. aeronautic language).
- Minimize the mnemonic load (see section 4.5).
- Provide feedback about the given commands and system status.
- Provide clear way to exit from a format.
- Prevents error (e.g. asking confirm for relevant actions).
- Provide adequate error messages.
- Design the interface as simple as possible.
- Optimize the visibility, conspicuousness (ability to attract attention and distinguishability from other symbols/background interference and distraction) and legibility.
- Compatibility of data display with data entry.
- Standardize abbreviations.
- Present only data useful to the operator.
- Present information in analog (i.e. graphic symbology) and/or digital (i.e. numerical value or string) way according to the specific case and not with fixed rules.
- Involve directly the operator in the design.
- Use an underlying layout grid.

- Standardize the screen layout.
- Related element should have similar format and should be grouped. Vice versa for not related elements.
- Provide an initial focus for the operator attention, directs attention to important, secondary or peripheral items and assist in navigation (see section 4.5 for the assistance).
- Use clear and unambiguous symbols and icons.
- Use familiar references when possible (taking into account the operator culture and training).
- Colors shall be used in a clear and unambiguous way, focusing the operator attention on critical information and respecting cultural and professional usage. In other words, colors are information and not decors.
- Adopt a color coding with the minimum possible number of color (considering the human cognitive limitations in the short memory, at maximum 7 ± 2 color should be adopted).
- All the information required during a transaction should be available on the current display.
- When display are partitioned in pages/folders, related information should be displayed together.
- Feedback should be provided to indicate that an input has been correctly received and that the system performs as intended by the operator.
- Display should be designed in order to minimize eye movements.
- The information to display should be prioritized so that the most critical are always displayed, while the others are available upon operator request.
- User should always feel in control of the system.
- Make all available objects accessible at all times.

7.2 Specific Design Issues

In this section, the specific choices of the style guide are reported. In particular, the touchscreen adoption has risen several peculiar issues that have requested a particular care in the design. As reference to tailor the GUI design for the TSD, the MIL-STD-1472F has been considered (1999) [68]. In January 2012, the edition G was published, but it does not modify the data presents in the previous edition.

7.2.1 Types of Controls

Apart specific cases, the following generic types of touchscreen controls have been considered:

- <u>Pushbutton</u>: used to select functions/system modes. Several types of pushbuttons are provided, different in terms of size and color.
- <u>Data Entering Field</u>: used to display a function parameter or a mode demand. Several types are provided, different in terms of size, color and active area. Pushing on an active field, the

relative alphanumeric/numeric keyboard is opened in order to modify the parameter/demand.

- Radio button: used to select a parameter/item when different fixed options are available.
- Slider: used to select an item between variable lists.
- Scrollbar: coupled to sliders with many possible rows (i.e. possible options for the operator), when a quick navigation is required.
- Alphanumeric/Numeric keyboard: used to enter parameters/demands. Several types are provided, with specific pushbuttons for the relative functions. Each of them is made up by some pushbuttons and a not interactive parameter field (i.e. the keyboard scratch pad).
- Combo Box: used to open a submenu with fixed options relative to HMI setting and not to the communication with the VSM.

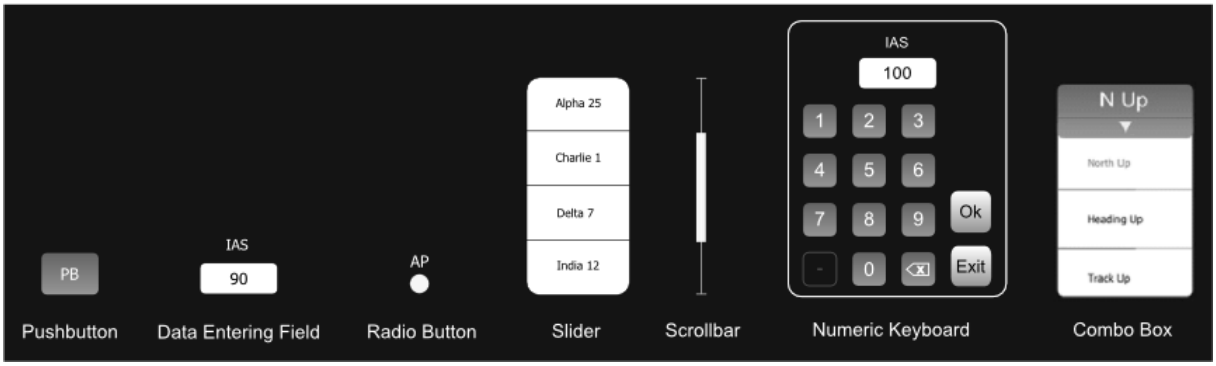


Figure 79. TSD Control Types

7.2.2 Symbol Definition

Apart the assigned functions and specific moding that vary in each case, the following set of information have been chosen to graphically describe a symbol:

- Position with respect to the format in terms of display X, Y coordinates.
- Active Area (only for TSD symbols).
- Type and Range of Movement.
- Resolution (the step changes for continuous variable data).
- Default Color.
- Change Color.
- Text Size.
- Layout.
- Line Thickness.
- Occult (conditions for which the symbol is occulted).
- Window Required.

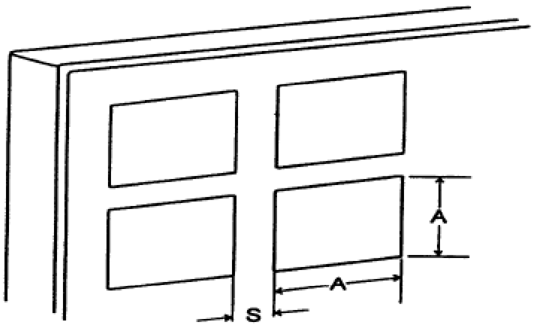
- Priority (i.e. order with which displaying the symbol in case of superimposition with other symbols).
- Flash Rate.
- Update Rate (i.e. rate with which the symbol status shall be updated).

7.2.3 Modular and Parametric Interface

In order to satisfy the interoperability (STANAG 4586) and upgradability requirements, macro control categories have been defined as much as possible (e.g. pushbutton type 1, numeric keyboard type 3, and so on), in order to use them for several purposes. For example, considering the equivalent of the autopilot mode control panel, all mode pushbuttons are of the same type, also if they controls different guidance modes. Besides the same pushbutton can be used for different purposes. This parametric structure of the design is then reflected in the software.

7.2.4 Touch Area Dimensions

First critical issue in the GUI design for a touchscreen is the sizing of the controls, particularly critical since they are virtual. Having no a physical pushbutton, in fact, may increase the error possibility and operator frustration if the controls have not a sufficient active area (i.e. the area in which the operator touch triggers an effect) or if they are not adequately separated. At this purpose, the MIL-STD-1472 proposes possible values, distinguishing between virtual alphanumeric/numeric keyboard or other functions related pushbuttons.



	ALPHANUMERIC / NUMERIC KEYBOARDS		
	A (Actuation Area)	S (Separation)[1]	Resistance
MINIMUM	—	0	250 mN (0.9 oz)
PREFERRED	13 x 13 mm (0.5 x 0.5")	—	—
MAXIMUM	—	6 mm (0.25")	1.5 N (5.3 oz)

	OTHER APPLICATIONS		
	A (Actuation Area)	S (Separation)[1]	Resistance
MINIMUM	16 x 16 mm (0.65 x 0.65")	3 mm (0.13 in)	250 mN (0.9 oz)
MAXIMUM	38 x 38 mm (1.5 x 1.5")	6 mm (0.25")	1.5 N (5.3 oz)

[1]For touch screens that use a "first contact" actuation strategy, separation between targets should be not less than 5 mm (0.2"). For touch screens that use a "last contact" strategy, separation between targets may be less than 5 mm (0.20"), but not less than 3 mm (0.12") for applications other than alphanumeric/numeric keyboards.

Figure 80. MIL-STD-1472 TSD Active Area Dimensions [68]

As reported in Fig. 79, the standard considers only square active area. For the separation, different values are considered according to the actuation strategy (see section 7.2.5). Noting the presence of a column relative to the control resistance, that is minimum and maximum admissible loads that the operator shall apply to activate the TSD. This could prevent the use of some touchscreens. According to these issues, the MIL-STD-1472 is quite restrictive, and in fact some adjustments have been done in practice. First of all also rectangular active area have been considered, respecting always the standard limits for the two sides. This is related to the fact that when the dimensions were sufficient, an active area equal to the pushbutton geometrical area has been implemented, in order to simplify the interaction with the operator. When this is not possible, the active area is however centered with respect to the control. An example of this solutions is reported below, with the active area is represent in red.

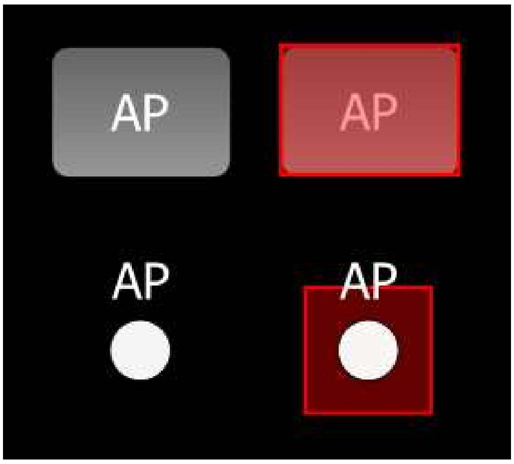


Figure 81. Active Area vs. Control Dimension

As regarding the separation for generic pushbuttons and similar controls (e.g. radio buttons or data entered fields), when possible the maximum separation has been used both for alphanumeric keyboards and other applications, in order to reduce the possibility of an erroneous selection. Some exceptions have bee done for the Mission Planners due to specific layout constraints. In any case this concerns specific functions not frequently actuated (e.g. the creation of a new route in a mission) in a not safety critical application.

The problem arises for the sliders, that are not considered by the standard. Trying to match the MIL-STD-1472 with these controls, it is obtained a situation in which each slider row has an active area smaller than the geometric one. This case is to avoid since it can create confusion to the operator when he/she pushes on a not active part of the control obtaining no effect. Besides, the operator can be habituated to use sliders on smartphones, and differences can generate further confusion. Adding the consequent frustration to the cognitive load due to the need to recognize each time the active part of the slider, as result there is a workload increment and a minor feeling of the operator with the interface. Finally, adopting rigidly the MIL-STD-1472 brings to a global active area on the touchscreen little smaller than the geometric area, and therefore there is not a real advantages in terms of control separations. Therefore taking into account the previous considerations, the whole slider area has been considered active.

Different, instead, the situation of a scrollbar, for which only the moving part is active.

Test pilots have rated positively these solutions.

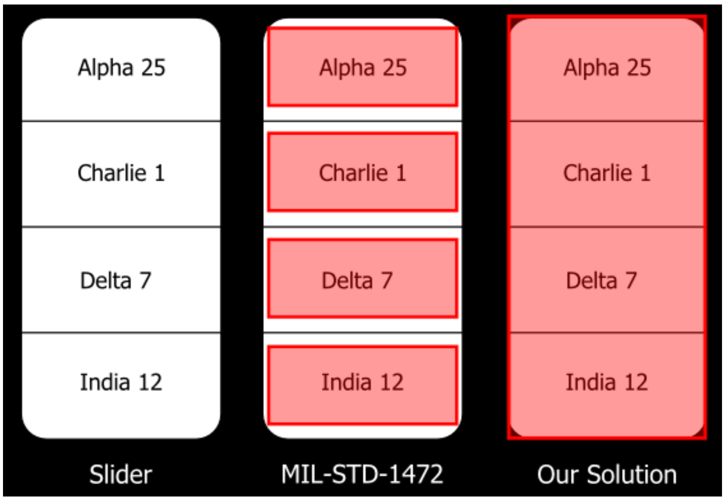


Figure 82. Slider Active Area

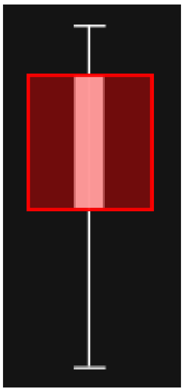


Figure 83. Scrollbar Active Area

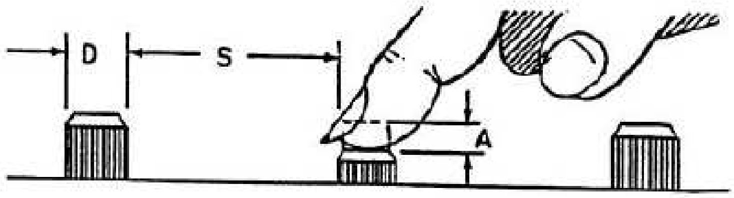
Unlucky Sliders are not taken into account also by the recent Edition G and therefore a new issue considering also this type of control is needed in the future. Besides also the actuation resistance requirement can be discussed, since in some application can be interesting to adopt a capacitive or a sound acoustic wave touchscreen. A similar reasoning has been done for Combo Box rows.

To conclude, a diffused touchscreen critic is the greater required virtual control size to avoid errors with respect to traditional control panel. At this purpose, it is interesting a comparison with hard pushbuttons, considering the case of fingertip actuation in analogy to the touchscreen. As reported in Fig. 84, the dimensions are lower, but the separation is greater with respect to the TSD. Therefore it is possible concluding that there are no real disadvantages adopting virtual controls with respect to hard ones in terms of interface sizing.

7.2.5 Touchscreen Type of Contact

Second issue of touchscreen use is the choice of the type of contact strategy required to active a control. Generally speaking the two following types can be distinguished:

- First Contact: the control is actuated when the operator pushes the TSD.
- Last Contact: the control is actuated when the operator release the pressure from the TSD.



	DIMENSIONS (Diameter, D)						RESISTANCE		
	Fingertip		Thumb		Palm				
	Bare hand	Gloved hand	Bare hand	Gloved hand	Bare hand	Gloved hand	Single Finger	Different fingers[1]	Thumb/ Palm
MIN	10 mm (0.4")	19 mm (0.75")	19 mm (0.75")	25 mm (1.0")	40 mm (1.6")	50 mm (2.0")	2.8 N 10 oz	1.4 N (5 oz)	2.8 N (10 oz)
MAX	25 mm (1.0")	—	25 mm (1.0")	—	70 mm (2.8")	—	11 .0 N (40 oz)	5.6 N (20 oz)	23.0 N (80 oz)

	DISPLACEMENT (A)	
	Fingertip	Thumb or Palm
MIN	2 mm (0.08")	3 mm (0.12")
MAX	6 mm (0.25")	38 mm (1.5")

	SEPARATION (S)				
	Single Finger		Single Finger Sequential	Different Fingers	Thumb or Palm
	Bare	Gloved			
MIN	13 mm (0.5")	25 mm (1.0")	6 mm (0.25")	6 mm (0.25")	25 mm (1.0")
PREF	50 mm (2.0")	—	13 mm (0.5")	13 mm (0.5")	150 mm (6.0 ")

[1]Actuated at same time

NOTE: Where gloved hand criteria are not provided, minima should be suitably adjusted.

Figure 84. Hard Pushbutton Sizing Parameters According to the MIL-STD-1472F [68]

As generic rule, the last contact interaction has been adopted in order to avoid undesired commands. In particular if the operator releases the pressure out of control active area, it is considered a null command. In this way, keeping pushed a control, no effects are scheduled (apart some exceptions) and the operator has a feedback of his/her action from the color coding of the pressed control. Besides this solution is particularly suitable for airborne touchscreen.

Some exceptions have been done for alphanumeric/numeric keyboard pushbuttons, data entering fields and radio buttons, for which a first contact interaction has been adopted. For Data Entering field, in particular, the pressure feedback is given by the relative keyboard opening, and if the control was not desired it is sufficient to close the keyboard. This solution permits a quicker interaction and avoids the need to define a proper color coding for the pressed data entering field. Of course, the keyboard appears in a different position with respect to the relative field if possible, but in any case no undesired commands are possible since a new pressure on TSD is required to actuate the keyboard. For the keyboards a similar reasoning has been done, since in this case the feedback of the first contact pressure is given by the selected digit in the keyboard scratch pad. A graphic pushbutton pushed state has been however implemented as redundant information. Keyboard confirm pushbuttons however have a last contact strategy. Finally, radio buttons are usually used to choose alternative options, and therefore the selection feedback is provided by the graphic state change of the corresponding button with respect to the pushed one.

7.2.6 Touchscreen Type of Interaction

Generally all controls are activated by a single click interaction, independently if they are based on first or last contact strategy. Prolonged pressure on a control does not usually provides effects, with the exceptions of some pushbuttons for which a long pressure opens a submenu, or the alphanumeric/numeric keyboard delete pushbutton for which the long pressure deletes all the entered digits/characters. Again the problem has been raised by the sliders, for which there are two different types of interaction:

- single click and drag to move the slider,
- double click to select a slider row.

The adoption of double click has been considered in order to avoid erroneous selection when the slider is moved with a single click. This is different with respect to the classical smartphone implementation in which movement and selection are distinguished by the drag movement associated to a single click: if it is lower than a threshold the command is a selection, while if it is greater it is interpreted as a sliding command. Errors however are quite frequently with this solution. According to this, the double click has bee adopted for the selection, especially considering the use of a resistive touchscreen for which the sliding movement requires a continuous pressure on the screen. Similarly, a scrollbar is moved with a click and drag interaction.
Combo Box rows, instead, are selected with a single click since for them there is not the sliding movement.

7.2.7 Tactile Feedback

One of major touchscreen drawback is the absence of a command tactile feedback. This involves “head down” operations and a greater workload, since the sight is the unique sensorial channel that provides information to the operator about the interface status. A partial fix can be obtained adopting TSD with tactile feedback. This technology is usually realized making movable the external screen of the TSD with some actuators in order to provide a direct feedback (i.e. a vibration) that a control has been pushed. In particular, varying the vibration parameters (i.e. frequency, amplitude, wave shape, duration), it is possible to associate a specific feedback to each control. In the early phase of the research, a prototype of a sound acoustic wave TSD with this technology has been evaluated. Several vibration profiles were available, and in particular some of them reproduced the feeling of actuating the virtual equivalent of hard switches (e.g. a rotary knobs).
In a first analysis three different profiles have been identified, associated to the following three actions:

- normal operations,
- command confirmations,
- error message acknowledgement.

More in detail, the associated vibration parameters are reported in Tab. 35. In a successive analysis, involving also the test pilots, it has been recognized that providing the tactile feedback for all interactions may be annoying for the operator, since the vibration is however an artificial feedback different from the real feeling of pushing a control, and repeated frequently may frustrate the user. Therefore the decision to remove the feedback for normal operations has been taken, leaving it only for the command confirmations and error acknowledgement. In this way, the vibration is associated uniquely to critical commands, for which the operator shall be sure about their actuation.

Operation	Frequency	Amplitude	Shape	Duration
Normal	high	weak	smooth	short
Confirm	low	strong	sharp	short
Error	high	strong	sharp	long

Table 35. Tactile Feedback Vibration Parameters

Adopting last contact interactions, however, raises further issues about tactile feedback, since in this case it provides a feedback that the control has been correctly pushed by the operator, but not that the command is actually sent (it depends by the release point that shall be in the pushed active area). In any case, unlucky, tactile feedback technology is still immature for several reasons:

- it is expensive,
- the Mean Time Between Failure is lower than that of a pure TSD,
- actuator dimension makes really bigger the TSD.

According to the previous points and in particular to the third, this technology has been leaved. Format layout and a proper color coding, in fact, have been rated as sufficient by test pilots to keep a good situational awareness. In any case, tactile feedback technology will be surely to consider when it will reach an adequate level of maturity.

7.2.8 Graphic Feedback Actuation

In order to provide a feedback that a last contact or a keyboard pushbutton has been pushed, a proper color coding is adopted (background inversion, outline and text bolded):

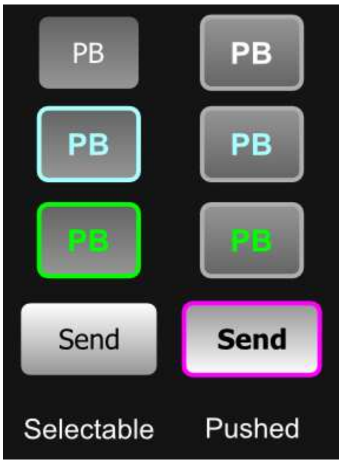


Figure 85. Pushed Graphic State

Pushbutton dimensions are sufficient to make visible the graphic change when pushed nevertheless the presence of the operator finger. Besides as further indication a marker is displayed above the touching point. On the NSC TSD the marker is the “mouse” cursor, since the screen is controlled by a “commercial” workstation. The cursor therefore is always present at the last touched position. On the SC TSD, at the contrary, there is not an analogous indication, and an apposite marker has been created. At difference of the previous case, when the operator does not touch the screen it is parked in a display corner (default position).
A further feedback is provided by the general logic of the GUI: generic selectable pushbuttons (i.e. “other functions” in MIL-STD-1472 language), in fact, when pushed change always their state (e.g. passing in active state).

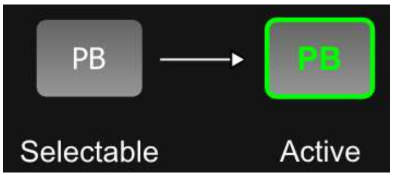


Figure 86. Pushbutton State Change

A similar moding has been also implemented for slider rows and Combo Box options selection.
In case of Confirmation Pushbuttons, they change their state while pushed, and then disappear from the page if the VSM answer is received or return in selectable state if no answer is received.
Finally for first contact controls the results of an actuation are immediately displayed (e.g. digit in the numeric keyboard scratchpad), and hence no graphic state change has been provided.
However, color coding is not used only to highlight a pressure or a state, but also to drive the operator in the selection of the correct pushbutton to push. In particular, different layout in terms of size and color is used to distinguish between a generic pushbutton and a confirmation.

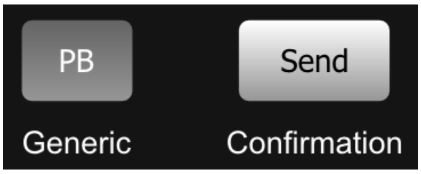


Figure 87. Generic vs. Confirmation Pushbuttons

Besides, in some cases there can be momentary not active pushbuttons, and this is communicated to the operator again with a proper color coding:

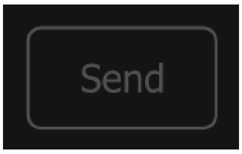


Figure 88. Not Active Pushbutton

This graphic coding, in particular, has been rated sufficient by test pilots to provide an adequate situational awareness about the system state, without adopting the tactile feedback.

7.2.9 Pushbutton Background

Besides the absence of a tactile feedback, a virtual control lacks also of depth feeling, being represented by a two-dimensional shape on the screen. In order to partially supply at this deficiency, pushbuttons have been realized with a linear color gradient as background instead of a transparent or uniform color background.

Figure 89. Different Pushbutton Background Color

As reported in Fig. 89, the linear gradient provides a sort of three-dimensional feeling, making more recognizable a control from other format element and increasing the operator feeling about the interface. Besides linear gradient permits a more distinguishable graphic layout when the pushbutton is pressed (see Fig. 85).

7.2.10 Critical Commands

Another relevant issue in the TSD use is the realization of critical commands, i.e. controls that shall be protected from a non desired actuation of the operator. In a traditional cockpit they are protected by a guard, but in a TSD this is not possible.

Figure 90. Example of covered switch

According to the MIL-STD-1472, the following two solutions to actuate these commands have been adopted:

- two pressures on different and distant pushbuttons,
- confirm pop-up.

The first solution is used to provide relevant commands to the vehicle, like for example the guidance ones. In this case a confirmation pushbutton is placed in the right bottom corner of the screen, very distant from the function selection pushbuttons. In this way the command activation requires a voluntary double action by the operator and can be difficulty the result of an error. In particular the position of confirmation pushbutton is the same in all formats.

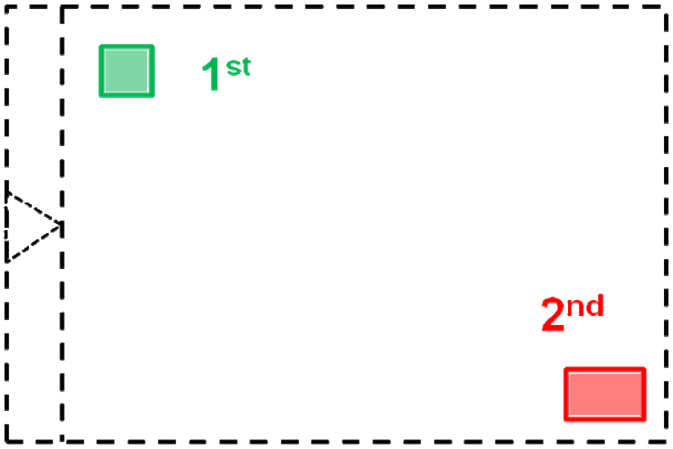


Figure 91. Example of Action Sequence to Activate a Critical Command

This solution has been preferred to the second in order to avoid a pop-up that could cover the parameters of the function to activate (not yet displayed on the Main Display), and to its higher instinctively. Confirmation pushbutton, in particular, is displayed only when a function to activate is selected and in the same position for all formats. To annul the operation, it is sufficient to deselect the relative function pushbutton.

In the opposite case – i.e. to deactivate a function – it has been instead chosen a confirm pop-up that appears when the relative function pushbutton is pressed. It is more suitable in this case, since it asks to the operator if he/she really wants to perform the selected action, without modifying the active graphic state of the relative function pushbutton. Covering function parameters it is not a problem since they are already displayed on the Main Display, and the pop-up is displayed for a short time until the operator decision. Pop-Up are made up by a text and two pushbuttons: "Yes" and "No" relative to the possible user decisions. It is automatically closed when a pushbutton is pressed.

Figure 92. Example of Confirmation Pop-Up [27]

7.2.11 Graphics Status Monitoring

In order to be sure that the graphics is not slowed down or frozen due to computational/hardware problems, the following indications have been added to each display:

- Frames per second: it is a graphic refresh rate in Hertz, and it provides an indication about possible slowdowns of the graphics.
- Cyclic counter: used to indicate to the operator a graphics frozen.

7.2.12 Alphanumeric/Numerical Keyboard Layout

For alphanumeric keyboard, the "QWERTY" format has been assumed as default since the greater operator feeling with this layout thanks to the computer and smartphone use, but it also possible to change the layout to "ABCDEF" format. Numbers are placed above the letters, just below the scratchpad. Since it is possible to enter long string, a cursor is provided in the scratchpad, with the possibility to move it along the entered data thanks to arrow pushbuttons. Also Cape Lock, minus, point and space pushbutton are provided. Alphanumeric keyboard is used only in the NSC TSD for the Mission Planner, since in other formats only numeric data are entered, and therefore it is sufficient a numeric keyboard, more practical for the operator if he/she has to enter only numbers.

Figure 93. Example of Alphanumeric Keyboard

Considering the Numeric Keyboard, instead, number pushbuttons can be arranged in two different layouts:

- telephone layout,
- adding machine layout.

In our work the first layout has been adopted, due to the greater user feeling with the mobile phone use. In particular, several types of numeric keyboard have been implemented, differing for few pushbuttons specific of their use: for example minus pushbutton for integer values, point pushbutton for real values, letters "N"/"S"/"E"/"W" for Latitude/Longitude and so on.
For data with a complex format the operator is helped in the data entering in order to reduce the required mnemonic load. Considering for example the latitude, until one between "N" or "S" is selected, the number pushbuttons are not selectable. After the hemisphere selection, when the

second digit is entered the "°" symbol and a space are automatically entered to remember at the operator that the degree field is complete and the minute have to be entered. The same for the remaining digits. A similar moding is present also in alphanumeric keyboards.

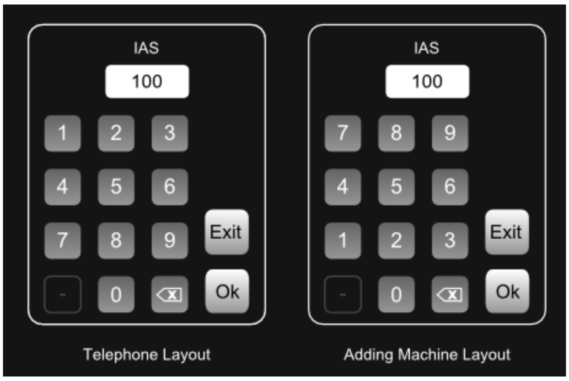


Figure 94. Possible Numeric Keyboard Layout

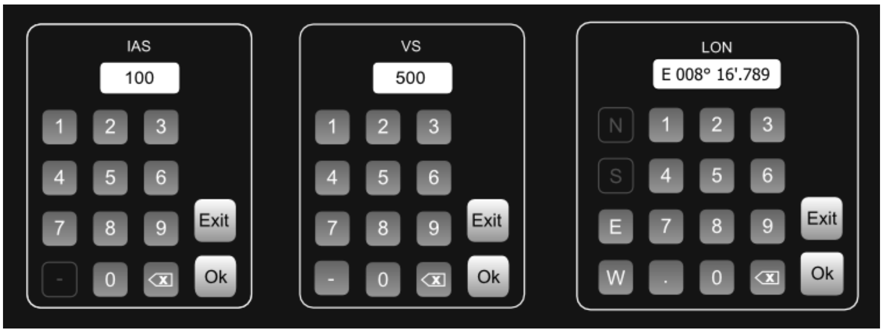


Figure 95. Examples of Different Numeric Keyboards

7.2.13 Error Protection During Data Entering

Alphanumeric or Numeric keyboards are used by the operators to enter data. In order to aid the user and preventing possible errors, a protection has been considered directly in the keyboards. If the operator, in fact, enters a value out of range or in an erroneous format, the keyboard scratchpad is showed in error state and it is not possible to confirm the entered data. Below, an example relative to an erroneous entering of Longitude Minutes:

Figure 96. Example of Numerical Keyboard in Error State

Deleting the erroneous data (in the previous example the "7"), the Error State is removed.

7.2.14 Number of Opened Windows

At difference for example of a traditional Personal Computer GUI that permits to open several windows at the same time, in our case at maximum one pop-up or keyboard can be displayed at time, in order to keep a quick access to the page control and avoiding errors.

7.2.15 Font

Many fonts are available for a GUI development, with different characteristics in terms of shape, size, character spacing, and ultimately legibility. Some examples are reported below:

Font	Lowercase Alphabet	Uppercase Alphabet	Numbers
Arial	abcdefghijklmnopqrstuvwxyz	ABCDEFGHIJKLMNOPQRSTUVWXYZ	0123456789
Calibri	abcdefghijklmnopqrstuvwxyz	ABCDEFGHIJKLMNOPQRSTUVWXYZ	0123456789
Courier	abcdefghijklmnopqrstuvwxyz	ABCDEFGHIJKLMNOPQRSTUVWXYZ	0123456789
Microsoft Sans Serif	abcdefghijklmnopqrstuvwxyz	ABCDEFGHIJKLMNOPQRSTUVWXYZ	0123456789
Tahoma	abcdefghijklmnopqrstuvwxyz	ABCDEFGHIJKLMNOPQRSTUVWXYZ	0123456789
Times New Roman	abcdefghijklmnopqrstuvwxyz	ABCDEFGHIJKLMNOPQRSTUVWXYZ	0123456789

Table 36. Examples of Possible Fonts at 10 Pt

As reported in Tab. 36, nevertheless the same dimension in terms of points (Pt), the presented fonts are quite different from each other. In particular the "Tahoma" has been chosen, developed by Matthew Carter for Microsoft in 1994 [69]. It is particularly suitable for GUI applications, thanks to its legibility with respect to dimensions. In particular, the lowercase "l" is distinguished from the uppercase "I", avoiding errors in technical texts.

As general rules of use, the uppercase has been adopted only for word fist letter and acronyms, preferring the lowercase for full text due to its greater legibility. For the dimensions, seven categories have been defined, ranging from nearly 3 mm to 6 mm of height, considering the distance at which the operator seats with respect to the screen and the different type of text to display. Bold is used to rise the attention on a text (e.g. active pushbutton name), while the italics is avoided since it is not very legible.

7.2.16 Units of Measure

In the GUI design, the following units of measure have been adopted considering the standards in aeronautics:

Parameter	Unit of Measure
Accelerations	Number of "g" (g)
Air/Ground Speed	Knots (kts)
Altitude/Height	Feet (ft)
Angles	Degrees (Deg)
Distance	Nautical Miles (NM)
Latitude Longitude	Degrees Minutes.Millesimals (Deg Min.mmm)
Mass	Kilogram (kg)
Pressure	Millibar (mbar)
Temperature	Celsius Degrees (°C)
Time	Hours:Minutes:Seconds (hh:mm:ss)
Vertical Speed	Feet Per Minute (fpm)

Table 37. Units of Measure

Noting the difference with respect to the units considered by the STANAG-4586 (International System). A conversion is therefore performed by the CUCS software.

7.2.17 Touchscreen Menu Organization

Generally speaking, Multi Function Displays – the TSD is in every respect a MFD finger actuated – had reduced the operator workload due to the visual search of the apposite format in the cockpit, raising instead the cognitive load due to the navigation in the hierarchy of pages. Hierarchy can be organized in two different ways [67]:

- Depth organization: there are more sub-menus accessible in sequence (i.e. a hierarchy tree), with few selectable items for each level. A sub-menu, in other words, can be accessed only from the node that lies above it.
- Breath organization: there are few submenus with many items in each level.

In the first case, the operator has to recall the position of the needed function and accessing it passing through the previous pages. This can increase the workload and reducing the reaction time, critical when a quick access to a control is required. However a depth structure can also provided

some advantages, especially in the cases where there are many possible options (especially if the processing time for each of them is long), and a little screen size.
Breath organization, instead, is more suitable when there are relative few possible options (with a little processing time), and a quick access is needed. In particular, it has been experimentally demonstrated that the maximum number of items per breath level should range between 4 and 13, in order to maximize the operator performance [67].
According to the previous considerations, a breath organization has been adopted, in which from a main menu is possible to select the desired page. Each page has a left blue bar in which its name is reported in order to aid the operator in the menu navigation. In case of complex function with many possible related controls, the relative TSD page is organized in folders (maximum 5). In each folders no further sub-menus are provided. Besides, from each page/folder it is always possible to return in the main menu pushing the menu button (white triangle on the blue bar). Folder navigation is provided pushing on the relative name, with a proper color coding showing the current folder. In other words, a structure with two depth levels has been realized.
At the moment, in each menu (SC and NSC TSDs) there are few pushbuttons to access to the implemented function. In the future, adding new FMS functionalities or other function controls, the number of options will increase, taking however into account the maximum suggested numbers of 13. At this purpose, the possibility to group related function pushbuttons and/or using different color coding has been considered to quicker distinguish the several menu options.

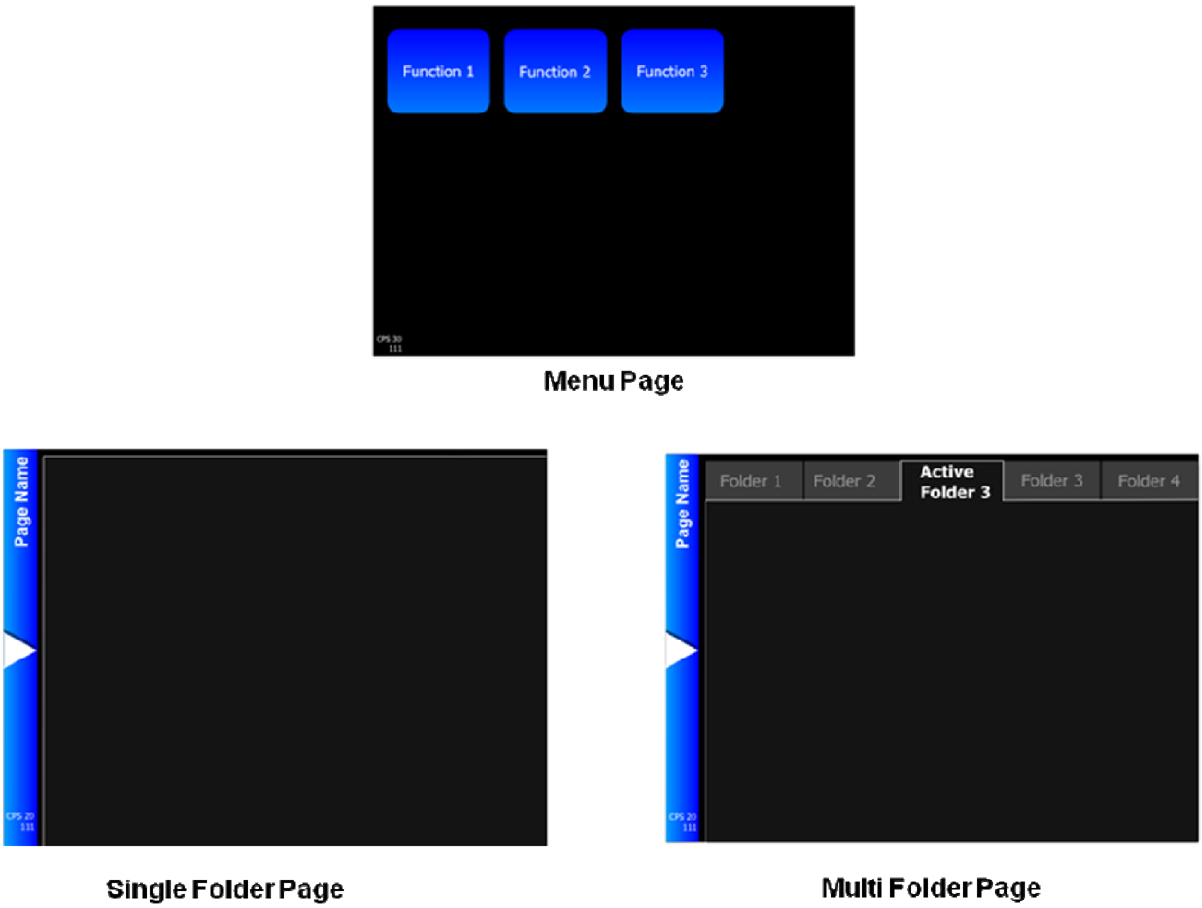


Figure 97. Menu Structure

7.2.18 Main Display Layout

Typically a GCS has two main displays for each station, like for example the Predator (see Fig. 36). In our case, adopting a single Main Display the operator visual search workload has been reduced, but the design has been complicated since there are many data to display with different priorities according to the performed task. In order to avoid an operator cognitive overload and to put greater relevance to the most used information in each context, a reconfigurable Main Display according to Phase of Flight has been studied in a previous research activity [70].

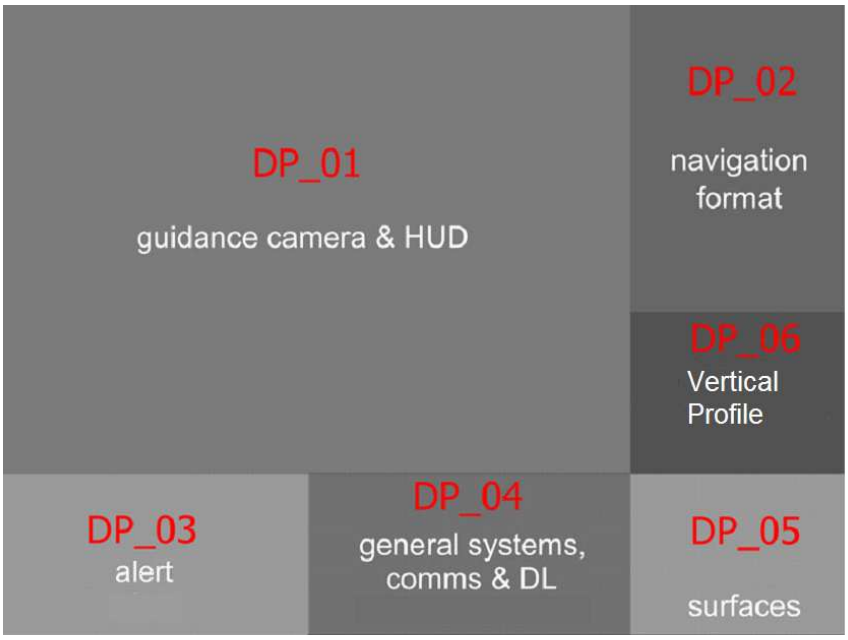


Figure 98. Main Display in Take Off and Landing Configuration

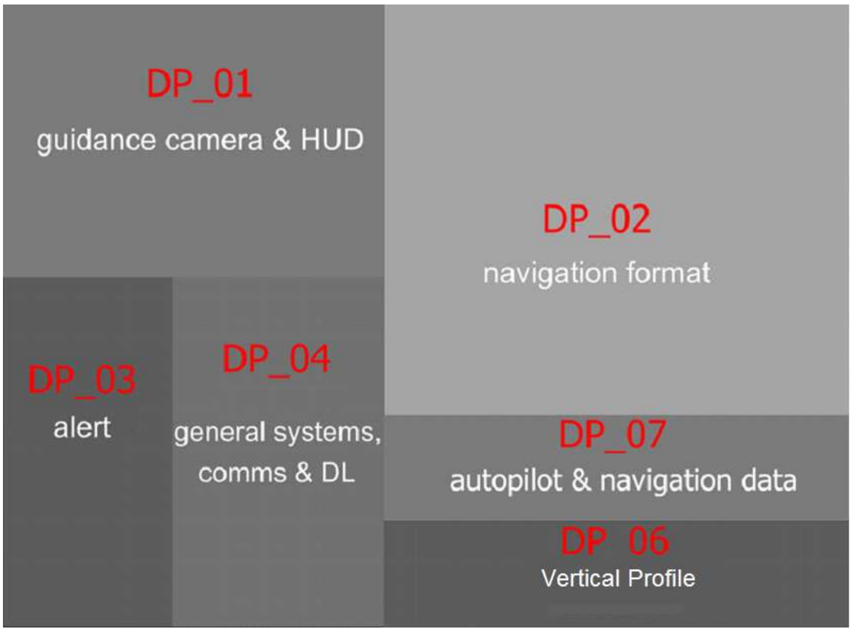


Figure 99. Main Display in Cruise Configuration

In particular the two following phases have been distinguished:

- Take Off & Landing: greater relevance to the Head Up Display (HUD) format, i.e. Primary Flight Display information (attitude, altitude, speed, heading, etc.) superimposed to the image of the guidance camera, at detriment of Navigation Format.
- Cruise: greater relevance to the Navigation Format with a little HUD.

In particular, the first layout is thought to be used for the departure and approach phases, in which it is important to have a greater image of the external world. The little navigation format it is to be used to visualize the situation at short range around the vehicle, and therefore the reduced size is sufficient. In any case, this format is most suitable when the system is manually piloted.
Cruise format, instead, would be the standard layout for the mission execution, with the aircraft controlled in automatic way and hence with greater relevance on the navigation format.

8 VEHICLE CONTROL RELATED FUNCTIONS

In this section the formats relative to guidance, navigation (extending the term to include also trajectory prediction), communication and configuration functions are presented. In particular, these formats are hosted in Main Display and SC touchscreen.

8.1 Guidance Formats

8.1.1 Operative Concept

As required by the initial assumptions (see section 6.4.6), the vehicle can be controlled in manual, semiautomatic or automatic ways (see Fig. 10). A further distinction is done between basic autopilot and navigation related modes. First are relative to semiautomatic guidance, in which the operator specifies discrete demands about the vehicle state variables (i.e. altitude, speed, heading, etc.) that are then acquired automatically by the system. Seconds, instead, involves the fully automatic following of a planned path in four dimensions. Hybrids between basic autopilot and navigation modes are possible, for example with the LNAV determined by the route and 3th, 4th dimensions assigned dynamically by the pilot like in semiautomatic guidance (see STANAG 4586 MSG #48 in section 5.5). Operatively, semiautomatic guidance permits a more flexible way to control the vehicle, with the possibility to change the vehicle state with discrete commands on a single or more parameters. Besides this type of control is the most suitable to fly under direct ATC control and therefore it shall be considered in the design for a future integration in the civil airspace. Automatic modes, instead, are thought as main guidance type along planned route or user defined loiter WPs (i.e. STANAG 4586 waypoints and loiter modes). Replanning capabilities in terms of guidance – that is the possibility to upload a new route while the vehicle is flying – is required in order to provide operative flexibility. Although foreseen by STANAG 4586, this is not a trivial capability: for example the first blocks of the Global Hawk does not have this option [41]. Further flexibility is obtained by the autopilot/navigation hybrids mentioned above.

In a second phase also a Slaved Navigation to Sensor (SNS) mode has been considered according to STANAG 4586. It is a quite different mode with respect the others, since in this case the aircraft position is determined by the sensor observation point. This involves a strict crew coordination between pilot and sensor operators, since it is the second that – although indirectly – controls the vehicle. This is a very different situation with respect to the standard way in which it is the pilot that decides where the aircraft goes according also to the sensor operator requests. Apart its operative value, the SNS mode represents also a step toward the realization of a single station that controls both vehicle and payload. In any case it has been naturally added to the interface, thanks to its modularity.

8.1.2 Functional Design

In the functional design the study of guidance functions to provide at the operator has been done. Critical issues presented in section 4.4 have been taken into account in order to realize a better interface with respect to the current ones. In particular, in order to reduce the Mode Awareness problem, the available guidance modes for the operator have been reduced only to 5 with respect to the 20 or more of an airliner, simplifying the system moding. Also considering possible new future functions, the final number will remain significantly lower than 20. At this purpose the concept of mode can be distinguished at three different levels:

- HMI: modes presented and selectable by the operator.
- System: modes at FCS/navigation laws level (e.g. modes foresee by STANAG 4586).
- Control Laws: basic control loops in flight mechanics control laws.

These three levels can coincide (e.g. in case of altitude hold function) or diverge, especially for complex mode. As example of the second case, an example is reported below about a possible division for a 4D navigation mode:

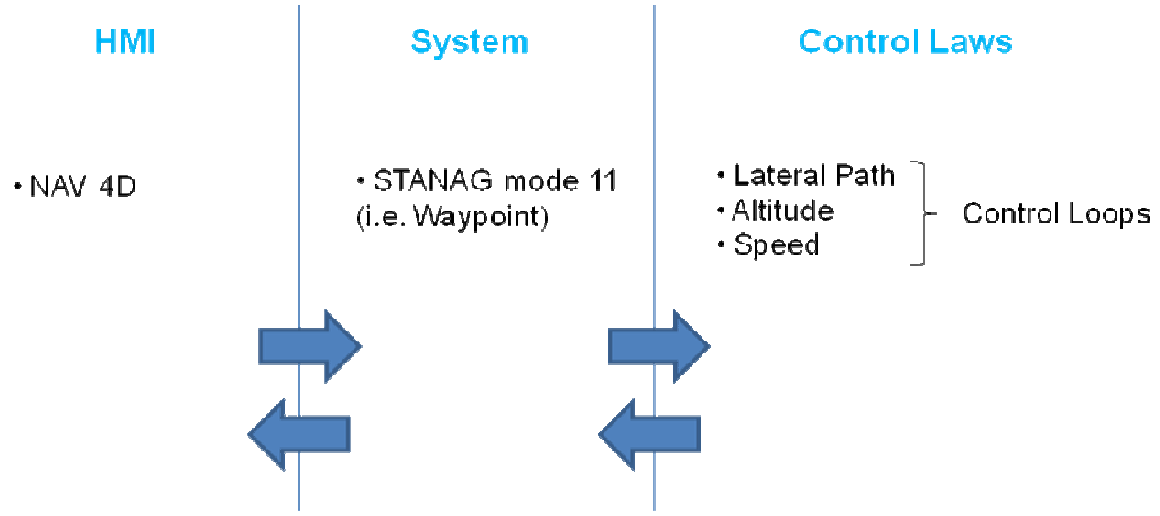


Figure 100. Example of Guidance Mode Definition At Several Levels

According to the previous example, apparently there are few differences between the HMI and system levels (just the mode name), but in many case the system discriminates from a mode to an another one using more information with a complex logic (for example considering the mode demands not reported above for simplicity). Besides the same system mode can correspond to different HMI level modes, due to the demands selected by the operator. The real differences however is with respect to the control loops, for which there could be a greater mode number than the HMI level, since there could be a mode for each of the following references: vertical plane, lateral plane, throttle/speed axis.

Instead in an airliners – always according to the example of Fig. 100 – at HMI level there would be a situation in which LNAV, VNAV and AT are reported active on the mode control panel and the PFD, reflecting the situation at the lowest level of the control laws. However having a triple indication for a single macro mode is not exactly a clear information for the operator, with a reduction in system transparency and a consequent increasing of workload. This situation is due to the need (raised when high automation was introduced on aircraft) to report at the pilots the system behavior with the greatest possible detail – like was the human to control the aircraft and not the automation – in order to have the maximum number of information about the automation state.

On a UAS, however, the same detail is not requested, especially considering the greater level of automation with respect to a classic manned aircraft. Besides realizing a system with a transparent unambiguous moding helps to reduce the detail in system feedback, simplifying the interface and reducing error possibility. In particular, modes reduction has been done at two levels: HMI and system.

Starting from the latter and considering the semiautomatic guidance, hold and acquiring functions on lateral/vertical planes and throttle/speed axis demands have been joined together in single modes. Distinction between “hold” (i.e. keeping the current vehicle state) or “acquire” (i.e. achieve the set value) functions is performed according to the mode demand. With these two modes, an operator is fully able to control the aircraft position in the space with discrete commands. It is not possible therefore activating modes on a single reference (e.g. a pure altitude hold without modes on lateral plane and throttle/speed axis). For an UAS, however, this is not a limitation, since it is not useful having an automatic control on a single plane/axis, and manual on the others. Instead to have a great flexibility, in fact, this could increase the error probability.

For the automatic guidance, it has been operated at HMI levels adopting a single mode for all the possible VNAV demand combinations reported in the MSG #48. In particular this solution has been preferred by the test pilots with respect to have different modes with relative pushbuttons and parameters.

Having coupled semiautomatic or fully automatic guidance modes, however, increases the system complexity making less predictable the vehicle behavior. Possible situations typically involve the VNAV and are relative for example to conflict between altitude/speed demands (e.g. climbing and accelerating at the same time) or to the way with which a new altitude is acquired. To solve this issue, the control laws have implemented fixed rules for climb and descent, making very easy for the operator to keep a situational awareness about the aircraft. Initially, the pilots have requested a degree of freedom in the setting of climb/descent parameters, bringing back to the familiar case of manned aircraft, but eventually they have accepted the automatic solution since it is more suitable to the unmanned contexts. Besides this implementation has permitted to avoid automatic mode changes, that are a relevant source of poor understanding about the vehicle state.

Finally 5 modes have been obtained at HMI level, 7 at system level and 7 at control laws levels. For each system level, in particular, 2 or 3 control loops are involved each time.

Another aspects affecting mode awareness are the arming and engagement/disengagement conditions. To avoid related problems, our proposal permits always to arm and then engage (if all the relative parameters have been set) a mode. If not all needed demands have been entered, in fact, the GUI prevents the mode activation. This is different from many manned aircraft, for which a mode can not be always engaged. For example many liners does not activate LNAV mode if the aircraft has cross-track and track angle errors greater than some thresholds. Automatic disengagement, instead, are not foreseen in our case: a mode change in fact is always commanded by the operator, at difference of manned aircraft. Automation disengagements, in particular, are in contrast with the UAS concept of operation that foresees an automatic/autonomous control, for which a reversion to manual remote control is meaningless.

Mode activation is therefore performed in two steps, requiring an arming before the engagement in order to enable operator demand overrides before the activation.

More in detail, arming a semiautomatic mode, default demands (equal to the current UAV values) are armed. If the mode is activated in this conditions, the “hold” function is obtained. The operator, however, is able to armed a different value for one or more demands before engaging the mode, realizing the acquire “function” for the affected values. Therefore it is possible to have hybrid in which some parameter are held and others acquired.

For the navigation management standpoint, instead, the following specific functions are available [27]:

- upload of a route (chosen from the available route list of the current mission) to the vehicle maintaining the current active guidance mode,
- route upload plus engaging from a selected WP,
- upload of a route in reverse order (useful for example during monitoring or searching tasks),
- changing of the active route destination waypoint considering both next WPs (i.e. still to be flown) and flown WPs (i.e. WP already flown),
- revert to semiautomatic control for VNAV,
- route waypoints characteristics visualization for the operator,
- realizing a direct to toward a loiter WP.

8.1.3 GUI Implementation

The STANAG 4671 requires that the active guidance mode and the relative demands are always displayed to the operator, like on the PFD of a manned aircraft. Starting from this requirements, it has been designed the GUI allocating these information on the Main Display, that is the primary monitoring interface for the operator. Noting that no information about armed modes are displayed on Main Display.

Figure 101. Example of Guidance Data on Main Display

On the SC TSD, the equivalent of the Mode Control Panel plus MCDU page to control the current route has been implemented in the same interface. The developing of this format has been very complex, since many versions have been designed in the time before reaching the final configuration. Below an examples of the final implementation is reported.

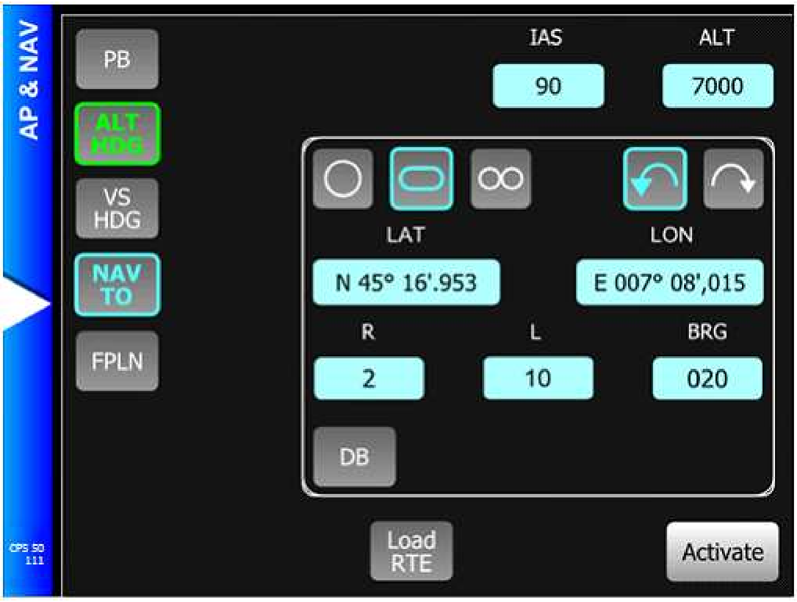


Figure 102. Example of Guidance format on TSD [27]

Having a single format requires a dynamical page reconfiguration capability. As default, the page is relative to the active mode, but when a mode is armed it is reconfigured in order to display the relative data enabling operator setting. This reconfiguration, however, is not total. Nevertheless the indication on Main Display, in fact, it has been preferred to maintain always visible the guidance mode pushbuttons in order to provide a fixed indication of armed and engaged mode also in the TSD. In this way the operator keeps an adequate situational awareness about the vehicle state during “head down” operations and can quickly modify/annul the arming selection. Besides, in the Reconfigurable Area, functional items (e.g. demand fields, numeric keyboards, navigation data pop-ups, confirmation pushbuttons, etc.) are displayed always in the same position independently by the armed/engaged mode in order to maintain a layout commonality and hence increasing the operator feeling with the interface. According to this design assumption, the adoption of two folders in this page (one for the semiautomatic modes and another for the navigation ones) has been rejected, since in this case no all mode pushbuttons are visible at the same time and the mode changing time increases. This final layout is schematically reported in Fig. 103.

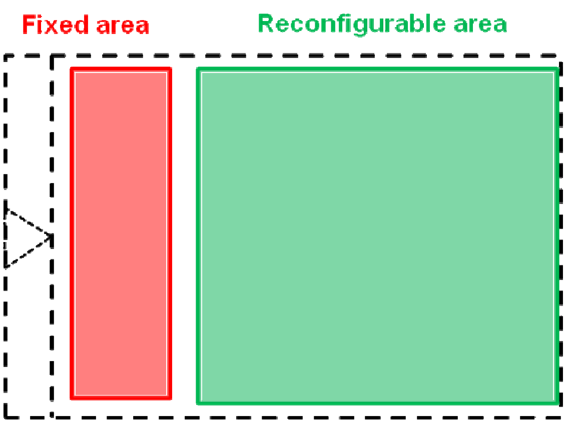


Figure 103. Guidance Format Layout on TSD

Considering the demand fields – displayed in the reconfigurable area – the initial idea was to provide indications only about armed and engaged states, but the test pilots have requested a further distinction between the engaged demands in acquisition by the system and that already achieved in order to have a greater situational awareness about the vehicle state. Besides also demands commanded by the system during altitude variation are presented to the operator with an apposite graphical layout. This information is helpful to avoid mode awareness problem. Altitude acquisition laws are fixed and hence easily predictable by the operators, but providing an indication is however preferable in order to increase the system behavior understanding. In the figure below, possible graphical states of a guidance demand field is reported. An analogous indication is also provided on Main Display (see Fig. 101).

Figure 104. Guidance Demands Layout in the TSD

Demands are aligned from left to right at the top of the Reconfigurable area, with an order that recalls the standard “T” of the traditional cockpit. This is the classical disposition of main analogical instruments adopted in all aircraft (i.e.. anemometer, attitude indicator, altimeter and directional gyro indicator). and then borrowed also on multi function display and HUD symbology for commonality with traditional analogical panels.
Apart the attitude information that are not pertinent in our case, this rule has been followed for the demand disposition in order to reduce the operator visual search workload. A pilot in fact is skilled to find information in fixed zone of the screen, and therefore he/she will find “natural” this layout.
An exception to the previous rule has been done for the demands that has not the acquisition/achieved attribute, like for example the geometric characteristics of a loiter WP. In these cases, therefore, there is not the magenta/green outline. Besides these demands are arranged into apposite box relative to the navigation function and not at the top of the screen to distinguish them by the demands relative to the UAV state.

Figure 105. Example of Standard “T” Layout in a Traditional Cockpit

In order to avoid errors during data entering, numeric keyboards are opened in a free position that do not cover the current demand values, so that the user is able to see at the same time old and the values. Besides until a keyboard is opened, it is not possible to activate a mode/demand.
For the navigation related functions, the operator can select a route from a list relative to the current mission received from the Mission Planner. No geographic or type WP attribute modifications are possible in this format. From the graphics standpoint, route and WP lists of the selected route are visualized through sliders. In particular, an indication of armed and engaged route/waypoint is provided with a color coding common to demands and modes pushbutton. Besides also a graphical indication of on-board but not active route is given. For the current armed WP – or engaged WP if no arming is done – the relative attributes are presented to increase the operator situational awareness. The possibility to change the DWP of the active route in both the route direction, in particular, provides a high flexibility to the system since the operator is able to conduct the vehicle to any route WP at difference of typical manned aviation system. In particular, it is possible to upload and engaged a new route, while the vehicle is already in navigation guidance mode, without the requirement to disengage it. Further flexibility is obtained by the possibility to revert to a semiautomatic VNAV profile control, i.e. the capability to set discrete altitude and speed demand while the LNAV is automatically followed by the system.
Engaged status of mode pushbutton, demands and slider rows is triggered by the reception of VSM response at the CUCS command and not by the upload of the command itself, since they shall present to the operator the vehicle status and not the user requests.
To conclude the presentation of the guidance interface, the possibility to change some demands through HOTAS has been considered in order to avoid the workload relative to the TSD page change is an another format is visualized, and to enable frequent operations to be performed at “head up”.
From the STANAG 4586 standpoint, the GUI has been realized with a modular structure that enables easily further updates. If a new mode has to be implement, in fact, it is sufficient to add a new standard pushbutton in the apposite free space with the relative demand, and then linking the symbology with the relative common and/or private STANAG messages to realize the function.

8.2 Navigation Format

8.2.1 General Layout

Like on manned aircraft (see Fig. 23 for an example), the Navigation Format is the main navigation interface for the operator, providing the awareness about the horizontal situation around the vehicle. In particular both navigation and trajectory prediction information are presented together in this format, named only “navigation” for simplicity. It is hosted on Main Display and therefore it has different layout according to its format. In particular, in both cases it is possible to distinguish between an upper zone in which a symbolic representation of the external environment is provided, and a lower zone in which the navigation/trajectory prediction data are displayed. Besides at the corners of the upper zone there are some fixed symbols like for example wind symbol and format scale indicator.
This format responds to the STANAG 4671 requirements about the visualization of vehicle position with respect to the mission environment, absolute time reference and wind direction/speed data. From the STANAG 4586 standpoint, the Environment Representation is applicable to any vehicle since many symbols are directly generated by the CUCS from the mission database (e.g. No Fly Zones), while vehicle position/orientation and active route are provided by standard messages. Off

course if an UAV requires the visualization of a specific symbol for its mission, a change will be needed. For the data, instead, they are usually provided by private messages and so they are vehicle related (see section 5.7 for more details). These data, however, are common to any navigation system, and so the effort to adapt the format to a new vehicle should be low.

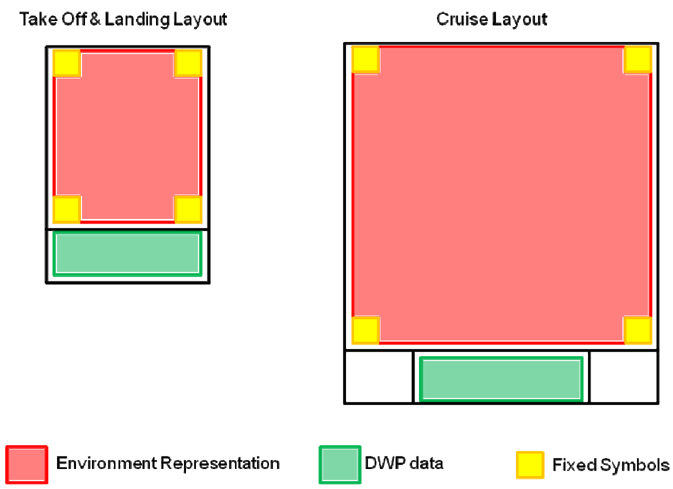


Figure 106. Main Display Navigation Format Layout

Finally, on manned aircraft also a Horizontal Situation Indicator (HSI) is present – usually integrated in the lower part of the PFD (see Fig. 24 for an example) – as further navigation reference, especially for NAVAID procedures. It has not been included, since UAVs typically do not navigate with NAVAIDs, but if needed it can be easily added to the interface in the future.

8.2.2 Environment Representation

The core of the upper zone is the aircraft symbol around which it is displayed a Compass Rose (see Fig. 107), that is a format that permits to determinate the polar coordinates in terms of range and bearing (with respect to the True North) of an object with respect to the vehicle. Compass Rose radius varies according to the zoom level of the format. With respect to classical manned aircraft implementation (see section 2.4.2 for more details), only the center configuration (i.e. rose layout) has been considered, and not the offset one. This is due to the type of mission performed by UASs – for example monitoring or searching task – that requires a 360° monitoring around the vehicle since the flight path can be complex with frequent direction inversions and for mission purposes. An airliner, instead, performs transit tasks from an airport to an another with a near straight path that does not foresee an inversion, except in case of failures or problems. Offset layout in this case is more suitable, since it provides a broader vision of the environment ahead the aircraft.
Likewise classical implementation, the Compass Rose and the external environment can be represented with different orientations: North Up, Track Up and Heading Up. In North Up, the Navigation Format is oriented with the North direction upwards. Therefore in this case the Compass Rose is fixed in the format, while the aircraft symbol rotates according to the current vehicle heading. A track symbol rotating around the Compass Rose is also displayed in order to visualize the current vehicle track, permitting to the operator an easier evaluation of the wind drift effect. In Track Up orientation, instead, the environment representation rotates to be aligned at the track, that is kept upwards. At the contrary with respect to the previous case, the aircraft symbol is fixed and it

is the external circle of the Compass Rose to rotate according to the track. No Heading symbol is provided in this case. From the operative standpoint, the North Up orientation is more useful for landmark searching or in general when the operator wants to correlate the vehicle position/orientation with respect to an external item. Track Up orientation, instead, offers an ego-centered representation of the environment to the operator, making easy a correlation between Navigation Format representation and guidance camera image.

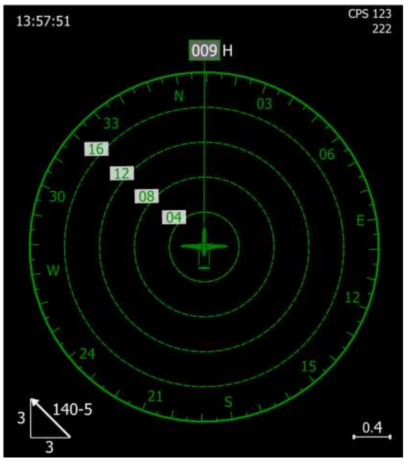


Figure 107. Example of Compass Rose

Comparing these two options, rated test pilots prefer the Track Up layout, that it is demonstrated to provide lower reaction time and workload to pilots on manned aircraft, as reported in Fig. 108. This result show the relevance of pilot skills on flying an aircraft, that are transposed to the unmanned context also when they are not completely applicable. In many missions typical of UAS, in fact, North Up orientation is more suitable, like for example to correlate vehicle, sensor footprint and targets positions. From the experience at the simulator, our opinion of no pilot operators is that Track Up format is more preferable for manual remote and semiautomatic control, while in navigation the North Up permits a greater Situational Awareness. This is an example of differences between rated pilots or operators in terms of mental model about the way to operate the system, and hence of interface type to support the user. In any case, having the possibility to choose the orientation, the HMI can be arranged to meet the expectation of each category of user, according also to the specific task to perform.

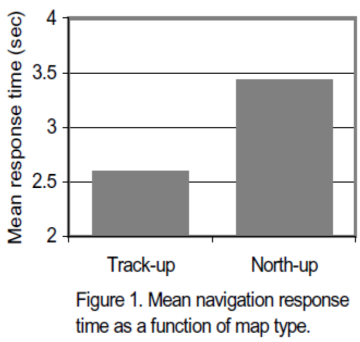


Figure 108. Track Up and North Up Orientation Comparison for Manned Aircraft[67]

Finally, the Heading Up orientation has been included (not common on manned aircraft), that could be a useful reference when the aircraft position is commanded through discrete heading demands, especially when there is a high drift angle that makes significantly different heading and track. In this last case, Heading Up orientation permits also a better correlation between guidance camera image and Navigation Format representation.

Basic Navigation Format functioning mode considers the aircraft symbol fixed at its center, with the external environment representation that slides and rotates according to the vehicle position, like on traditional implementation on manned aircraft. For monitoring or searching missions, however, can be interesting for the operator to focus his/her attention on a given zone also if the vehicle is going away from it, or still analyze a zone ahead the UAV that has not been yet reached. For this reason, it is possible to move the navigation format through apposite control on a dedicated TSD page, fixing its center in any desired position. When the Navigation Format is not centered on the vehicle, aircraft symbol and Compass Rose move according to the vehicle position, until to exit also from the screen. There is however a quick control to center again the format on the vehicle. Off course this geographic position centered mode is to use in North Up orientation, since in the other two cases at each aircraft turn the format rotates, making more difficult for the operator the analysis.

From the scenario representation standpoint, routes/WPs representation and mission relevant symbology have been implemented. As format background it is possible to display a certifiable aeronautical map. In particular, for routes/WPs it is possible to distinguish between “armed”, “on-board but not engaged” and “on-board engaged” states. These are the only armed parameters presented on the Main Display, in order to permits at the operator to evaluate the future aircraft position before to engage them. An example of Navigation Format symbols is reported in Fig. 109.

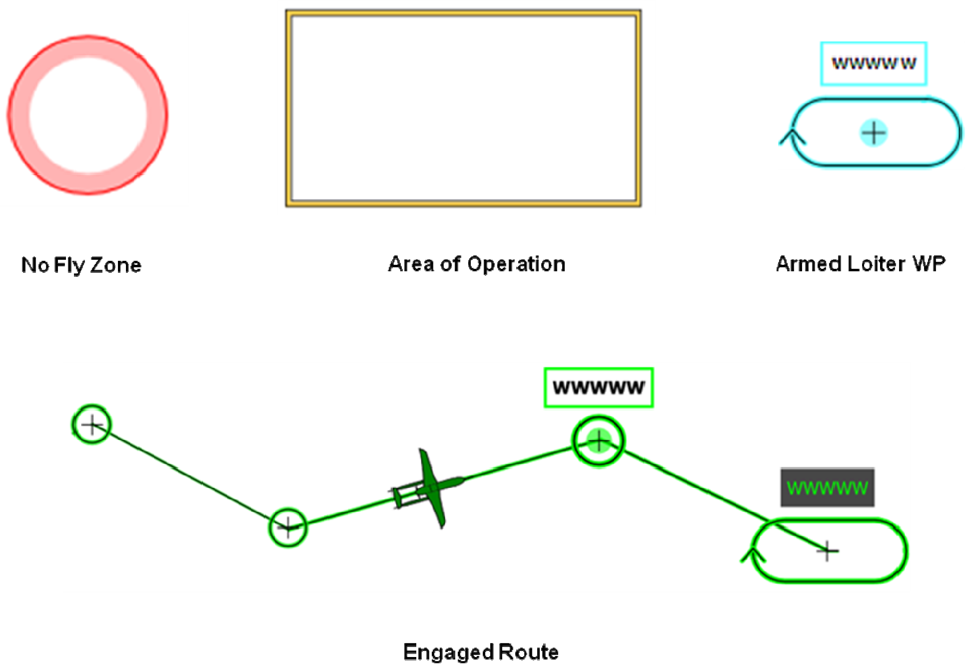


Figure 109. Example of Navigation Format Symbology

8.2.3 Navigation Format Setting

The operator is able to configure some Navigation Format setting with an apposite TSD folder, like for example the orientation, zoom level or the center moving. An example is reported in Fig. 110. Zoom level has been considered also with HOTAS in order to avoid the workload and frustration relatively to the TSD page for a very frequent operation.

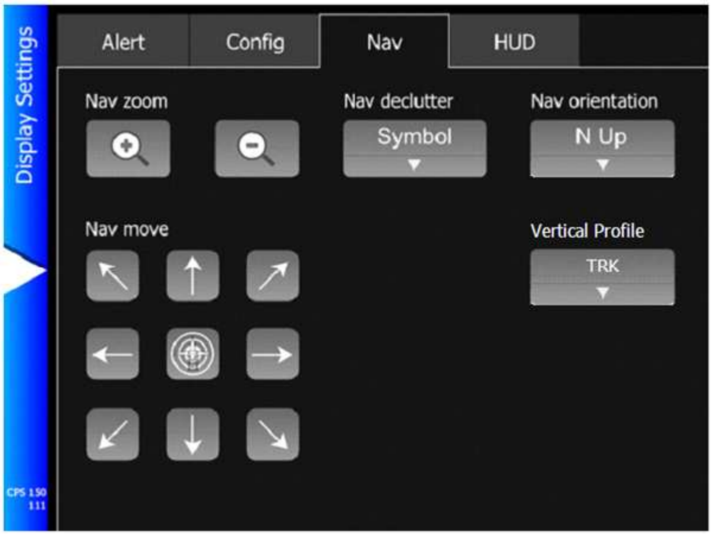


Figure 110. Example of Navigation Format Setting Folder

8.3 Vertical Profile

8.3.1 General Layout

Vertical Profile provides situational awareness about the aircraft state on vertical plane, in terms of terrain separation and route altitude profile. Basically it is a Cartesian graph with the ground distance on the horizontal axis and the altitude on the vertical one. A vehicle marker moves along vertical axis according to the current vehicle altitude. A lubber line (starting from the vehicle marker) provides an information about the current ramp angle, and hence of the future vehicle altitude. On the graph the terrain profile is displayed as background. It is generated by the Digital Terrain Elevation Data (DTED) and slides from left to right according to the aircraft position. In particular, for the profile creation the DTED are queried to get terrain altitude for some intermediate point coordinates along the considered direction. More details about DTED are provided in Appendix A. According to the considered directions for the terrain profile generation, two working modes have been implemented:

- track,
- auto route.

Like on manned aircraft Vertical Profile is displayed beneath the Navigation Format, with different dimensions according to the Main Display layout.

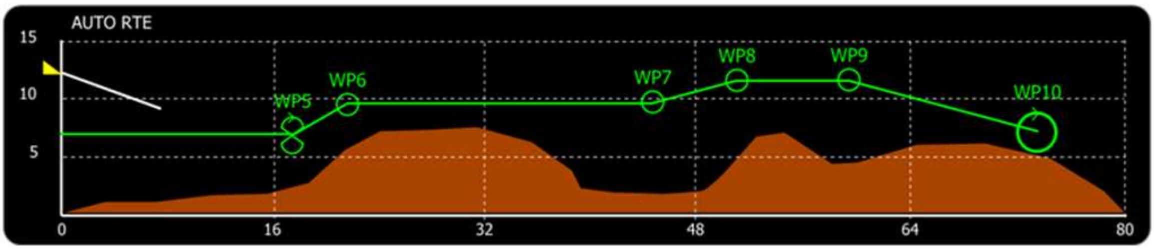


Figure 111. Example of Vertical Profile

In particular, for the terrain separation this format is an aid for the operator since it provides a prediction of the future vehicle altitude, but no collision alerts are raised. Alert generation should be allocated to a Ground Proximity Warning System on-board, that is better able to evaluate the safety margin of the vehicle from the terrain taking into account also the pull-up capability. In this way also automatic recovery action should be implemented.
Finally, STANAG 4671 does not put any statement about vertical profile, while for the STANAG 4586 this is a common format since it requires information provided by standard messages. Changes would be only required to add specific symbols.

8.3.2 Track Mode

This is the basic mode, in which the terrain profile is create considering the intersection of the terrain model with the vertical plane determined by the current vehicle track.

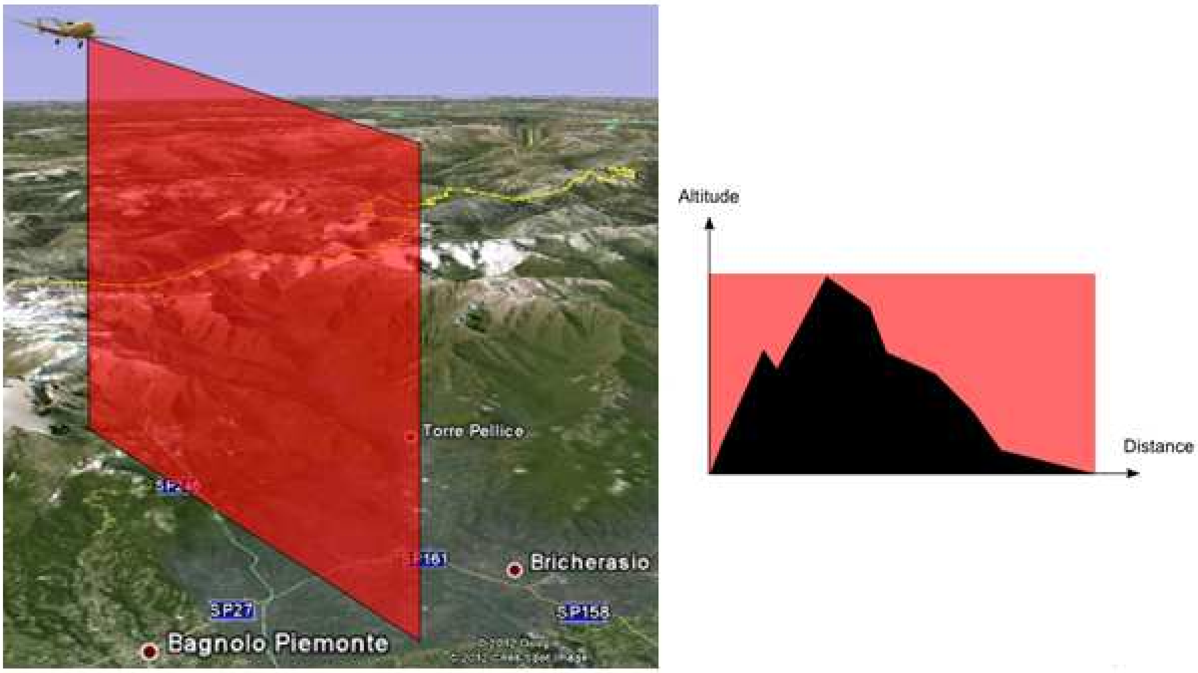


Figure 112. Terrain Profile Generation in Track Mode

To generate the terrain profile, a plane – and not the highest terrain altitudes in a volume centered on the plane – has been considered for the following reasons:

- A MALE operates typically above the terrain with a safety separation margin. Its missions in fact do not require to fly into valley or canyon.
- Terrain has not typically discontinuities and therefore the altitude values on the track plane are similar to ones of the nearest parallel planes (at least of canyons or sharp valley, not considered for the point above).
- 2D terrain information can be available on demand also on Main Display, integrating the Vertical Profile when the vehicle flies over a rough orography.

According to this implementation, the profile varies each time the aircraft turns. The effect of continuous variations present for example flying at low altitude above the Alps do not annoy the pilots, and in any case it is realistic.
In this mode the horizontal axis distances are perfectly coherent with the Compass Rose radius.

8.3.3 Auto Route Mode

This mode is automatically activated when a route is engaged in order to provide situation awareness about the VNAV and the orography along the route. Mode awareness is provided by the Vertical Profile mode annunciator at the top left of the format, and by the route visualization. At difference of the previous case, the terrain is not generated along the track plane, but arranging side by side the terrain profiles generated on the planes identified by the route legs. In case of Lost Uplink condition, Contingency WPs are considered in the generation.

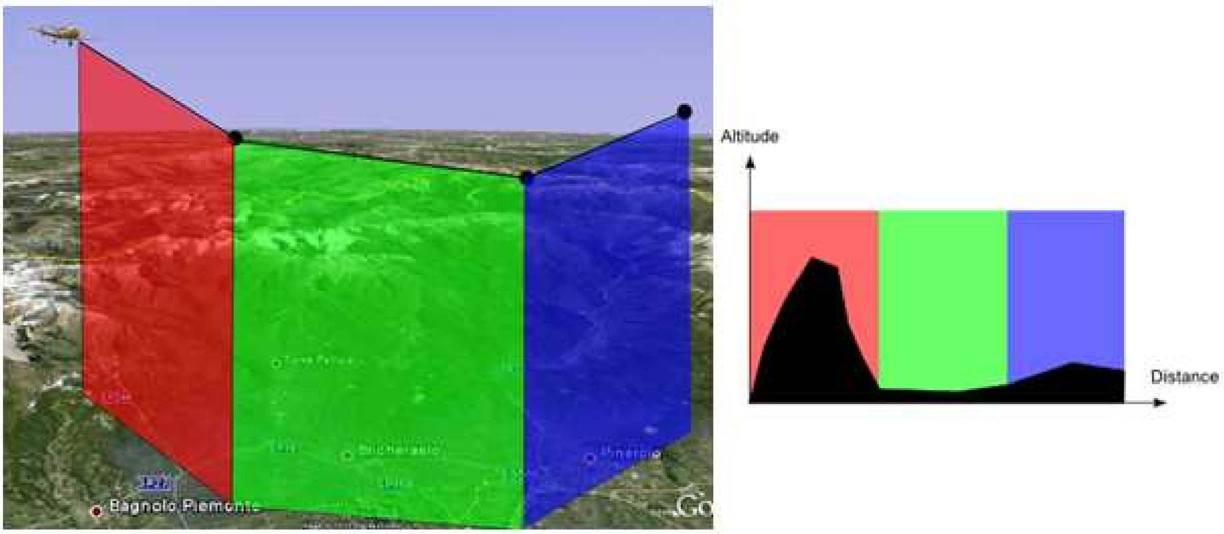


Figure 113. Terrain Profile Generation in Auto Route Mode

When a route is flown, however, the vehicle does not ever follow exactly its horizontal path: apart the engagement, in fact, there are fillings due to Fly-By/Fly Through WPs, loiters, change DWP commands and so on. In these conditions representing the terrain along the route could be misunderstand for the operator, and so the track mode is the more correct. At this purpose an automatic switching has been implemented between auto route and track modes according to distance and orientation thresholds of the vehicle with respect to the route. More in detail, if the

vehicle is within the thresholds, the auto route will be considered, while if at least a threshold is passed the profile returns in auto track. This moding is therefore valid also if the route direction is inverted. In particular, in this case the horizontal distance is relative to the leg lengths and it is not comparable to the Compass Rose radius.
Auto route implementation has been positively judged by the pilots, that have appreciated the great situational awareness provided by the format.

8.4 Radio Communications

8.4.1 Generalities on UAS Communications

Radio Communications page has been studied in order to realize a GUI for the control of the GCS radio and interphone system.
Generally speaking the Communications system of an UAS can be made up by several elements according to specific case:

- Ground Communications segment
  - GCS radios
    - LOS aeronautical radios (VHF, UHF)
    - BLOS aeronautical radios (HF)
    - Satellite Communication (SATCOM)
    - Ground radios
  - Interphone system
- On-board Communications segment
  - LOS aeronautical radios (VHF, UHF)
  - BLOS aeronautical radios (HF)
- Communication Relay (on-board payload)
- Transponder.

GCS aeronautical radios are used to communicate with the ATC – in particular with the airport tower/radar since the GCS is usually placed near them – and with other actors in the scenario. SATCOM increases the UAS operational flexibility in BLOS, enabling direct communication of the GCS with others actors (ground teams in operational areas, aircraft, etc.), without using the vehicle as repeater. Ground radios, finally, are used by the crew to communicate with the UAS ground team during airport operations.
Interphone is the manager of the ground communication segment, enabling/disabling the communications of each crew member (pilot, sensor operator or other members like mission commander, image analyst, etc.) with the others and the external users (UAS ground team, ATC, C4I, etc.), according to the selected configuration.
On-board radios, instead, permits an extension of the communication range on traditional aeronautical frequencies in BLOS operations, with the radio controls in GCS and the antennas on the vehicle, using the datalink to transfer the operator commands. In particular it is possible to distinguish between the on-board radios used by the operators to communicate with external user –

that is a part of the FMS – and the communication repeaters used by external user to extend their communication network (e.g. to replace damaged ground telephonic repeaters) – that are considered as payload and not as part of the FMS.
Transponder, finally, is mandatory to operate in controlled airspaces.
Our preliminary design has concerned the development of interfaces to control ground aeronautical radios and interphone system. STANAG 4671 does not have requirements about Communications system, while the STANAG 4586 is not affected since only ground equipments have been considered. Standard messages to control on-board radios, communication repeaters and transported are instead provided.

8.4.2 Radio Control

Radio control function has been studied considering three LOS radios. As key design driver we have considered that each operator should be able to be in reception on more channels, while obviously he/she can transmit only with a radio at time. Besides a single format to control the communication settings for both operators has been considered, like a common radio panel in a manned cockpit. This operative concept is based on the assumption that all interphone configurations enable both the operators to use the radios. More in detail, radio management involves the following functions [27]:

- transmitter setting,
- receiver setting,
- frequency setting,
- frequency storing,
- frequency loading in a DB,
- squelch enable/disable,
- Build In Test (BIT),
- Quick Emergency Frequencies Selection (121.5 MHz for VHF radios and 243 MHz for UHF radios).

For audio volume regulation and Push To Talk (PTT) – i.e. the pushbutton to press in order to transmit on the radio set as transmitter – functions, hard controls have been assumed in order to make these very frequent functions quick to executed, without forcing the operator to interact with the GUI. According to the operative concept, if the operator transmits on a channel, he/she will be also in reception on it, while on other channels the only reception can be enabled without transmission. Besides being the radios common to the crew, the GUI enables the configuration setting for both the stations. A strict crew coordination is therefore required like on manned aircraft.
Passing to the GUI study, the current status is displayed on Main Display and the controls on TSD like for other considered macro functions. An example is reported in Fig. 114.
On the SC TSD, instead, the Communication managing page is made up by two folders: one relative to the radio and the other to the interphone. In particular, the radio folder has a structure that recalls the assumed operator arrangement in the GCS. Left station controls are in fact allocated in the left part of the page, right station controls in the right part and common/other controls at the center. This solution increases user feeling with the interface, reducing the visual search workload. Some examples are reported in Fig. 115. The page has been positively rated by test pilots.

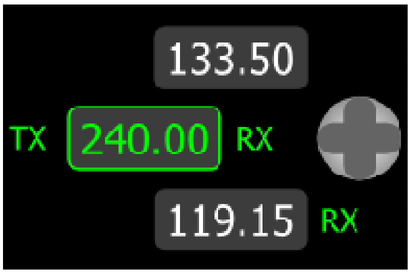


Figure 114. Example of Communication Information on Main Display

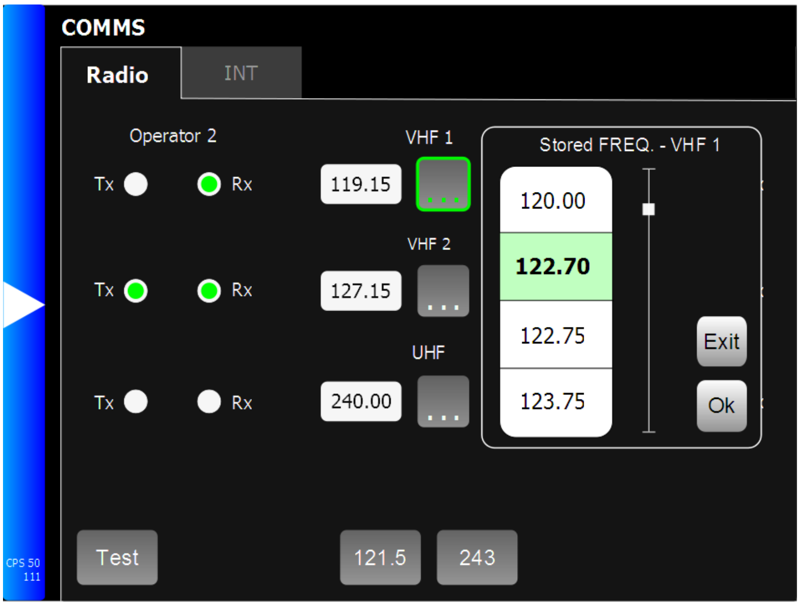


Figure 115. Example of Radio Folder

8.4.3 Interphone Control

Interphone management is strictly correlated to radio management, and hence it has been considered. Interphone folder enables the operator to arm and then engaging one of the stored configurations. A test function of the interphone is also provided. Mechanism of arming/engaging, in particular, permits to see a preview of the selected configuration before its activation. Creating a new configurations and storing it has been considered a maintenance level operation, and therefore it is not performed by the operator. An example of the folder is reported in Fig. 116.

8.5 Configuration

Configuration functions permits to set some parameters of the GCS and the On-board segments. This is a very specific function, developed essentially for flight tests. STANAG 4671, in fact, is not involved, while for the STANAG 4586 standpoint it has been realized with private messages. It is performed through a TSD page divided in five folders, each of them with a moding analogous to that of guidance and communication pages. An example is reported in Fig. 117.

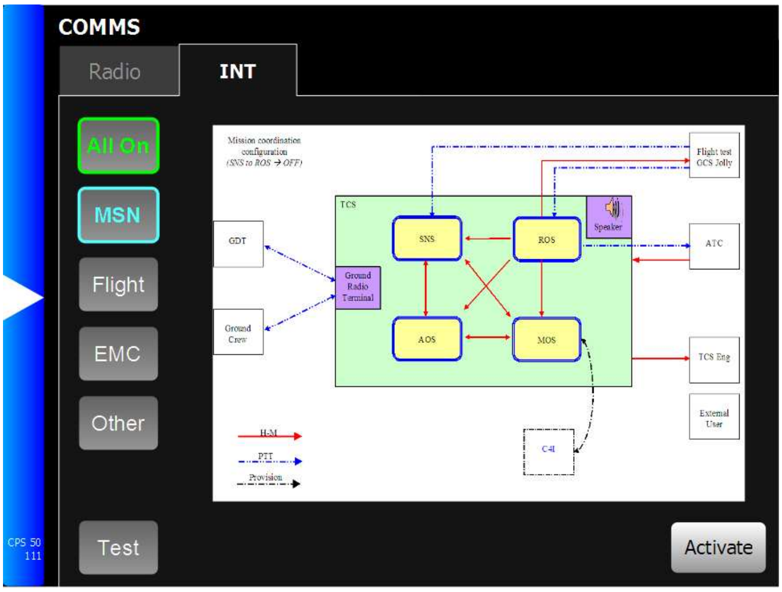


Figure 116. Example of Interphone Folder

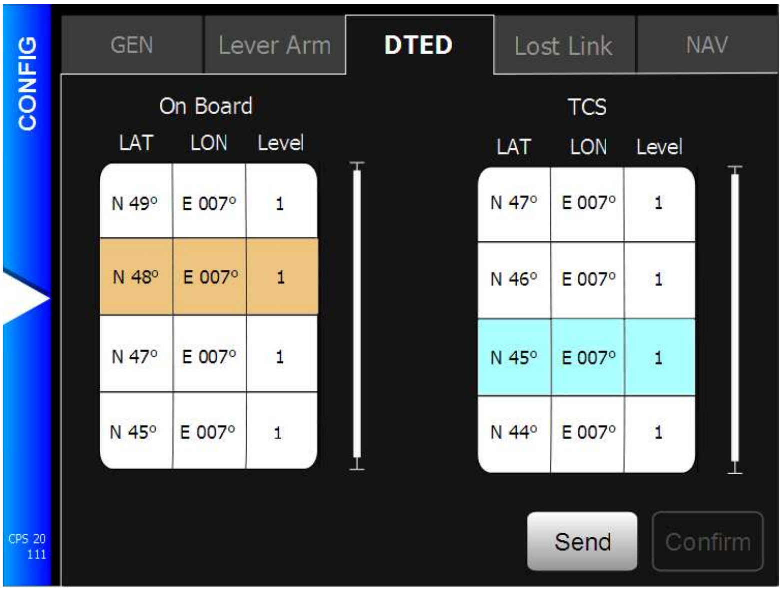


Figure 117. Example of Configuration Page

9 MISSION PLANNING

9.1 Enlarged Mission Concept for UAS

9.1.1 Mission Definition

STANAG 4586 mission concept reported in section 5.6.1 provides a mission definition based on the data exchanged between CUCS and VSM. In a broader sense, however, a mission is a collection of data comprising also information not transmitted to the VSM, like for example target images or radio frequency database for the GCS radio. According to this statement, a new definition can be:

Mission is a kind of folder containing all information needed to perform the assigned goals.

Besides, the plans considered by STANAG 4586 (see Tab. 19) are not fully exhaustive of all the possible operative conditions and needs of an advanced UAS. A more complete and general set of plans with respect to the STANAG 4586 is reported below:

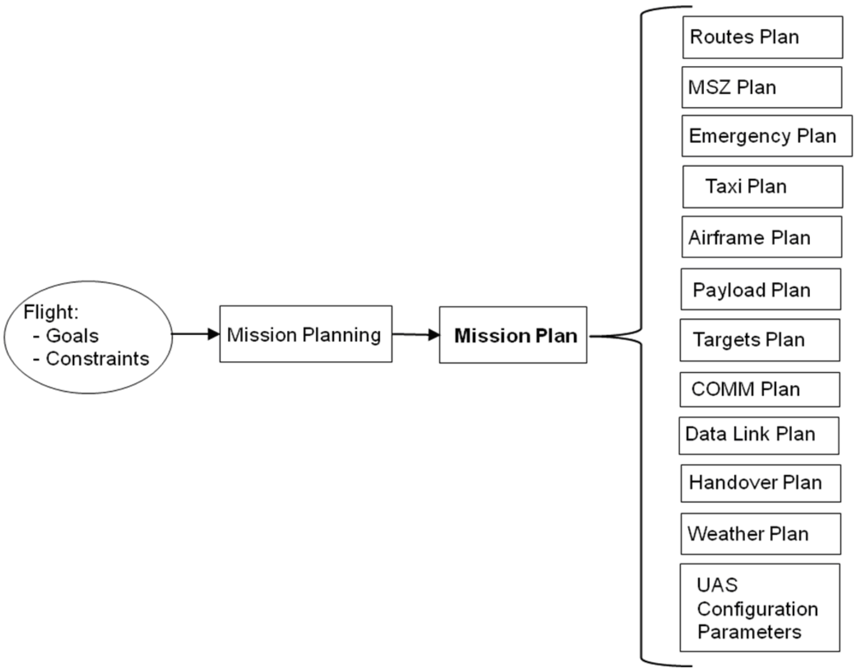


Figure 118. Mission Elements

With respect to STANAG 4585 concept, Taxi and Airframe plans have been treated as independent items, while the following plans have been added: MSZ, Targets, COMM, Handover, Configuration parameter and weather.

The number of considered items provides an idea of the mission planning complexity for an UAS with respect to a manned aircraft, due to the human-machine physical separation and the greater Level of Automation. As the LOA increases, in fact, nevertheless the system replaces the human in the execution of several tasks, the relevance of planning phase before the flight increases since the system shall be "instructed" about the mission targets, the way to reach them and relative constraints. Realizing a detailed mission plan, in particular, permits to exploit as much as possible the UAS capabilities and reduces the operative risks. This is particularly true for vehicles that can not be guided in semiautomatic or manual way. The issues can be further complicated if multiple UAV control is considered, but in our work the discussion has been limited to a single UAV. In the following sections, each plan is analyzed more in detail.

9.1.2 Route Plan

It is analogous to the STANAG 4586 concept, without the part relative to the taxi or the automatic vehicle actions. At difference of an airliner that has a transit mission from a departure airport to a destination one, for an UAS the routes profile is more complex.

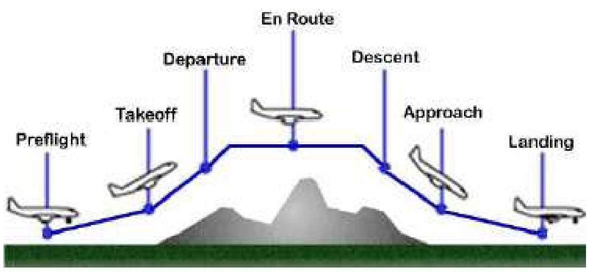


Figure 119. Classic Airliner Mission Profile [71]

Considering the assigned goals, in fact, for an UAS two different types of route plans can be realized:

- Single route that cover the whole mission from the take off to landing (in the same or different airports), plus one or more diversions toward alternate airports.
- More routes that cover all possible operative situations. Usually there are ingress/egress routes joining the airports with the Area Of Operation, and more alternative routes inside it.

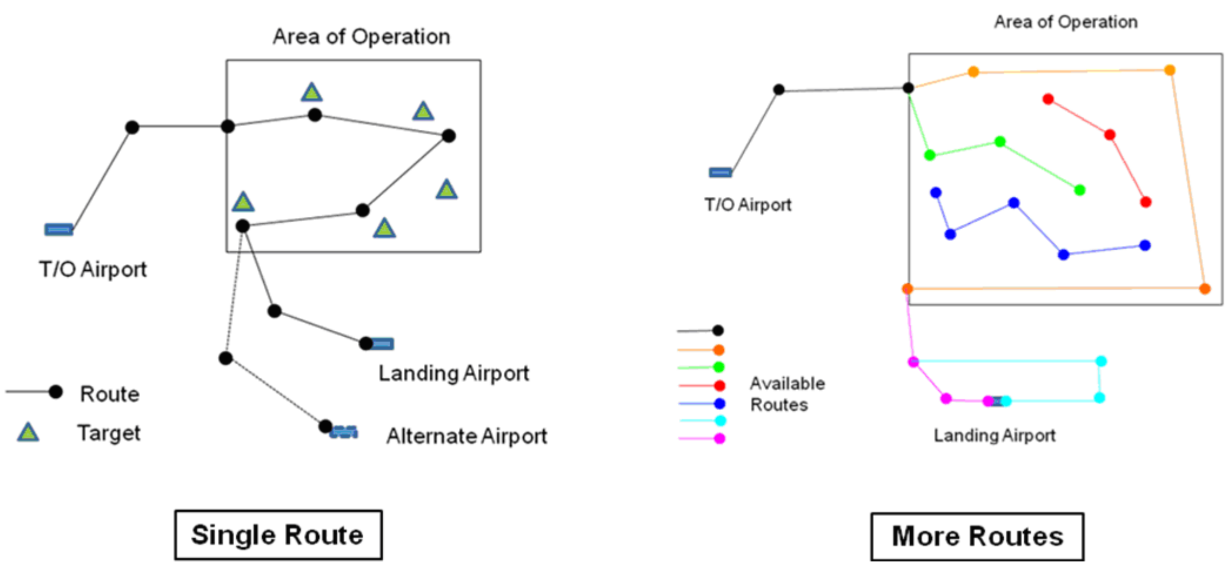


Figure 120. UAS Route Plan Profile [17]

Single Route profile is used for monitoring missions on fixed targets or searching missions along a planned path. More Route profile, instead, is more suitable when targets/searching paths are not known a priori, but depend by the operative conditions. It is near mandatory, in particular, for UAS that does not have the capability to upload a new route to the vehicle in order to provide a minimum of flexibility. A variant of the Single Route profile typical of HALE UAS – but applicable in certain conditions also to MALEs – foresees a big loiter over the Area of Operation, on which the vehicle stands to monitor an area expectant an opportunity target (i.e. a not planned target) to execute a diversion. Sensor with a quite wide range are obviously required to implement this type of operative route. In particular, this is the standard profile when the UAV acts as communication repeater for other users. An example is reported in the figure below.

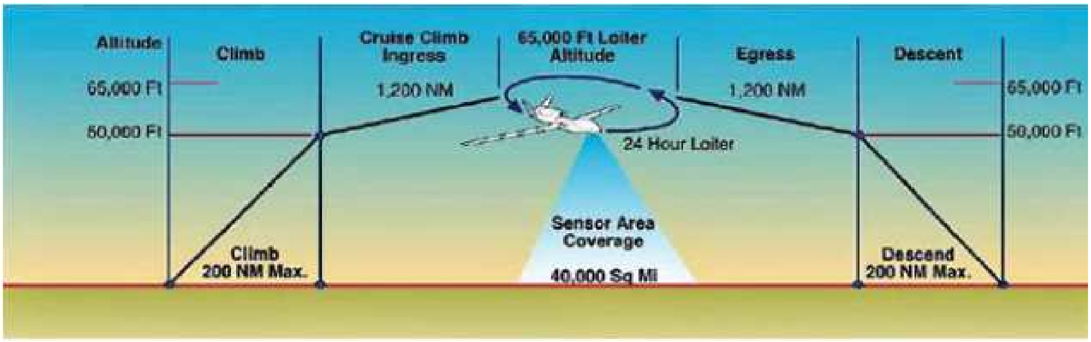


Figure 121. Loitering Route Profile [72]

Contingency Routes/WPs are included. In particular, our FMS implementation permits to realize all the three presented profiles.

9.1.3 Mission Zones (MSZ) Plan

Mission Zones are particular areas relevant to the UAV fly permission. In particular, the following items have been considered (see also section 6.4.1):

- <u>Area of Operation</u>: area in which the UAV performs its operative tasks. Currently it coincides usually with the restricted area in which the vehicle can operate safely.
- <u>Corridors</u>: safe path from the airport to the Area of Operation and vice versa.
- <u>No Fly Zones</u>: zones for which is prohibited the overfly. They can be also placed inside Corridors or Areas of Operation.

9.1.4 Emergency Plan

Analogous to the STANAG concept. Its outputs (in terms of Contingency WPs/Routes) are included in the Route Plan.

9.1.5 Taxi Plan

It is relative to the ground vehicle movements during taxi before take off and after landing. It has been separated by the Route Plan (relative to the flight path of the UAV) due to its peculiarities, at difference of STANAG 4586 that joints them. Besides automatic taxi is an advance functions, that could not be available on a vehicle. In this case, although there are not data exchange between CUCS and VSM, the operator plans however the ground path in order to have a visual reference on the displays during the manual execution.

9.1.6 Airframe Plan

Airframe Plan is relative to automatic actions performed by the vehicle at certain WP of Route and Taxi plans. It has been separated from the Route Plan, since it is an advanced function that involves specific planning logics.

9.1.7 Payload Plan

It is similar to the STANAG 4586 concept. It is strictly related to route and target plans.

9.1.8 Target Plan

Target Plan is made up by the list of potential targets to monitor during the mission. This plan shall be always included in monitoring mission, also if there is not a payload plan. In particular the following type of targets have been basically considered:

- Target Point: fix identified by its coordinates (LAT, LON, ALT).
- Target Line: broken line identified by vertex coordinates.
- Target Area: area identified by perimeter vertex coordinates.

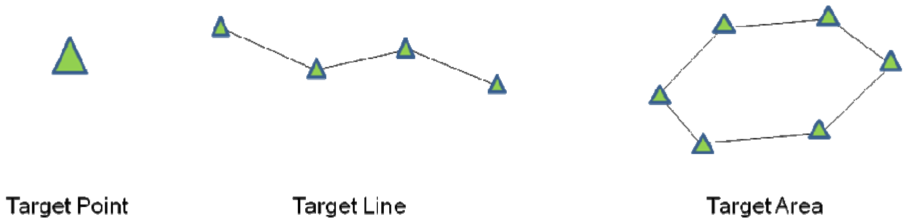


Figure 122. Considered Types of Targets [17]

Besides, each target is also characterized by a name, descriptive attributes and target images to simplify the target recognition (optionally).

9.1.9 COMM Plan

It is relative to the planning of interphone configuration, radios and relative frequencies to use in the current mission. Available frequencies on the SC TSD Communication page are defined here. A link of the available frequencies to the route plan could be considered in order to reduce the workload. Besides, a possible subset of the frequency DB could be also uploaded to the UAV for the on-board radios according to its specific implementation.
If a new interphone configuration is required for the mission execution, it will be included in this plan.

9.1.10 Datalink Plan

Datalink plan it is relative to the definition of the LOS and BLOS datalink parameters, like frequencies, code, hop pattern, channel, etc. Check about possible electromagnetic interferences on datalinks in the considered area is comprised. It is similar to the STANAG Datalink plan, with the exception that the handover is treated apart.

9.1.11 Handover Plan

Generally speaking, handover is the procedure to pass the vehicle control from an operator/station to an another. In particular the following types of handover (“old/new” controller) can be distinguished:

- GCS/GCS (both in LOS or BLOS),
- datalink/datalink with the same GCS,
- operator/operator in the same GCS station,
- operator/operator in two different operator stations of the same GCS
- LOS datalink repeater/LOS datalink repeater with the same GCS.

First case is the most typical in the UAS context, especially considering the passage from LOS to BLOS control. For long range operations, in fact, usually there is a GCS in the airport that manages the phases of departure and arrival for which low transmission latencies are required, while the en-route phase is controlled by another GCS in BLOS or another station in the same GCS (usually with a satellite datalink). The passage of control is a critical procedure that shall be carefully planned in order to avoid mishaps, and it is strictly related to the datalink plan. Another possibility is to perform the handover between two different datalink (typically from LOS to satellite BLOS) in the same GCS.

The third case is relative to operator alternation for prolonged missions in order to avoid human fatigue issues, and should be however taken into account in the planning. The fourth case, instead, can be relative to the passage from LOS to BLOS as previously exposed, or to a control handover from a failed operator station to a back up one in the same GCS.

Finally, there is the handover between different datalink repeaters. Datalink repeaters are a different way to operate BLOS without using satellite communications. Also in this case the handovers shall be accurately planned. In particular, according to the system LOA, they can be performed automatically by the vehicle when specific planned WPs are reached.

9.1.12 UAS Configuration Parameter

Finally, there is the setting of the possible configuration parameters, very specific of each system and operative context. Vehicle weight and fuel definition are comprised.

9.1.13 Weather Plan

Collection of all forecast weather data pertinent to the mission. Examples can be:

- airport air temperature and wind,
- air temperature and wind at different altitudes,

- turbulence,
- hazardous phenomenon (e.g. thunderstorms, sandstorms, volcanic ash cloud, etc.),
- cloud covering,
- rainfall,
- visibility,
- ice conditions,
- ephemeris,
- ionosphere perturbations (possible impact on datalink communication especially for satellite control).

9.2 Mission Planners

9.2.1 Classification

Mission Planner is the dedicated device to perform a mission planning – that is the process with which a new mission is created (see Fig. 118) – or to modify a previously created mission. In the second case, when the modification is done during the mission execution, we speak about mission replan. A replan typically involves a change in the route plan plus related actions. Anti collision on-board devices are considered apart and not in the replan category, since relative path is intended as a momentary deviation from the planned route and not an its permanent change. According to the previous considerations, the following planner types can be distinguished:

- external,
- embedded in a GCS,
- on-board an UAV.

9.2.2 Ground Based Planners

External and GCS embedded planners are classified as ground based. More in detail, an external planner can be hosted in a fixed workstation or a laptop, and can be a part of the UAS ground segment (according to the STANAG 4586 UAS definition presented in section 1.1) or of a C4I. It is the main device to plan a mission, since the planning of a scheduled mission is usually done some days before its execution. In any case, also for last minute planning, it is the most suitable device since it has several specific tools that enable a more detailed planning with a reduced user workload. Also from the ergonomic standpoint it is preferable, since a workstation is usually placed in an office (more comfortable than a GCS), while the laptop can be used everywhere. Beside, if an internet connection is available, the user will be able to access a lot of information and other tools (e.g. Google Maps), that simplify further the planning.

A GCS embedded planner, instead, is mainly used to import an externally generated plan and modify it just before or during the flight (i.e. to perform a replan). However it is usually possible creating a mission from zero directly in an embedded planner, also if it is not the most suitable interface to do it in terms of ergonomics and available tools/data. It is in fact integrated in the operator station displays, that have a small screen with respect to a standalone computer and require

a prolonged "head down" interaction. Besides, an internet connection is not usually present in a GCS due to security constraints. This situation is analogous to that of manned aviation, in which the flight is usually planned on external devices and then loaded in the FMS. The MCDU keeps the possibility to create a flight plan from zero, but it is a quite boring and long operation. Returning to the UAS context, it is also possible to have hybrid configuration in which an external planner is used by the user inside the GCS, but not on the vehicle/payload operator stations.
In both cases, however, creating a complete mission results a very complex and long activity, due to the amount of information to process. Just to provide an example, first "Global Hawk" blocks required nearly nine months to plan a complete mission (2000) [41]. In particular, obtaining an optimum result could be difficult. At this purpose, advanced route creation algorithms can be an aid for the operator, producing in output a route optimized according to certain paradigms (e.g. payload performance, fuel consumption, datalink coverage, etc.), that respects the assigned constraints. These algorithms however can create only a portion of the route plan. The complexity of the subject, in fact, makes really difficult realizing a single algorithm that takes into account all mission elements, mission constraints, air rules and operator expectations of how a mission (and in particular a route) should be planned. Therefore in case of mission planning these algorithms are commanded by the operator and do not run automatically.
The situation could be different for a mission replan – usually restricted to a mission portion – that can be performed both by the operator or autonomously by the system. First case is analogous to the initial planning presented above, while the second is quite different since it is a more complex function that involves also a monitoring module. Considering the OODA loop (see section 4.2 for more detail), autonomous ground replan function can be modeled as follow:

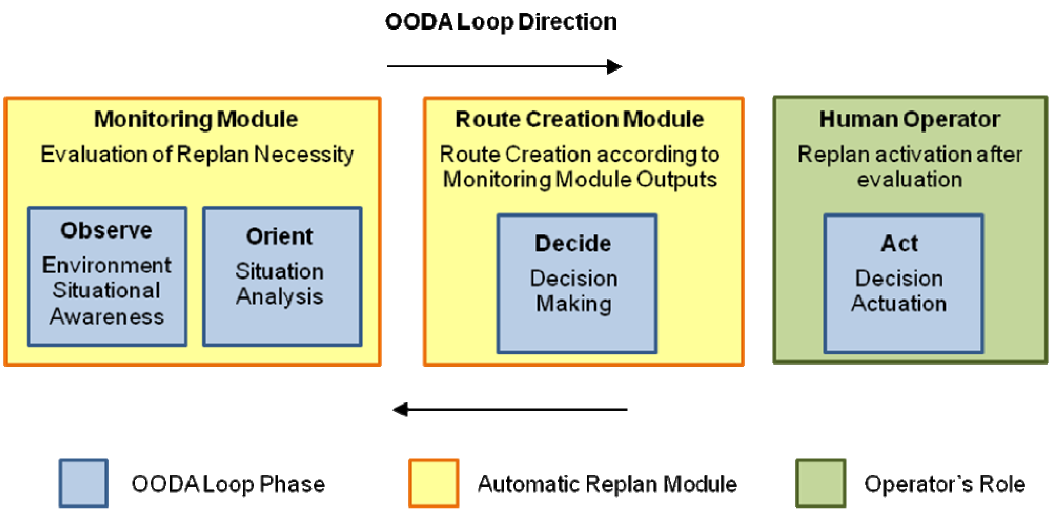


Figure 123. Autonomous Ground Replan Functional Architecture

"Decide" loop phase has been considered coincident with the route creation, leaving the operator evaluation as part of the final "Act" phase. The human remains directly in the control loop, since the operator keeps the responsibility of replan route approval. Human authority on automation is a very complex matter, especially considering operations in the civil airspace that require the plan sharing with the ATC. At the moment, the STANAG 4671 provides only a generic indication about the fact that automated mission planning calculations must not lead to unsafe conditions [19], but more detailed indications are needed. A proposal is reported in Fig. 123, with the human that has

the unique final capability to approve or not the automation proposal. In other words, an automatic ground replan module is implement with a "Management By Consent" logic (see section 4.2 for more details).
Considering a complete ground based mission planner, it can work with different LOA – according to the human selection during the initial planning and manual replanning – while advanced autonomously advanced function requires a greater value. In particular, considering the Parasuraman-Sheridan and ACL scales (see sections 4.2 for more details), the following values are applicable for ground based planners:

Planning Context	Parasuraman Sheridan et al.	ACL
• Initial Mission Planning • Manual Replanning	1 ÷ 5	0 ÷ 2
• Autonomous Replanning	5	3

Table 38. LOA for Ground Based Planners

Having a great LOA, however, makes really important adopting a HMI that keeps the operator inside the control loop, in order to avoid a "split" between user and system. At this purpose, there was a "famous" accident to a Global Hawk during taxi, due to an erroneous taxi speed of 155 kts. The misbehavior was mainly due to a bug in the mission planning software, but the operator failed in the result monitoring, not helped by the interface that presented the plan data in hexadecimal code [17], [41].

9.2.3 On-board Planner

Finally there is the possibility of an on-board replan. This is an advanced function typical of UAS that requires a vehicle with a high LOA. In particular it is adopted to provide a quick system reaction in critical conditions. It can be also needed for multi-vehicle control, not considered here. The main difference with respect to the ground based replan is that the human approval is not needed: the operator in fact has usually a timeout to stop the automatism and after it the proposed action is executed. Considering the OODA loop, the replan model is reported in Fig. 124. The automation, therefore, is controlled with a "Management by Exception" logic. This raises several issues especially in terms of civil certification and integration in the common airspace. Considering the automation scales, the following values are applicable:

- Parasuraman-Sheridan: 6,
- ACL: 4.

Higher LOA are still more complicated to be adopted, since they do not foresee a direct human control, at least to revert at lower LOA. Using "Management By Consent" logic like in ground replanners, instead, is not advantageous, since in the best case there are nearly the same number of interactions in terms of route upload/download and operator evaluation, while in the worst (i.e. the operator modifies the automatism proposal) they are greater in the on-board case. This can be critical when a quick response is required, especially considering the latencies in BLOS communications.

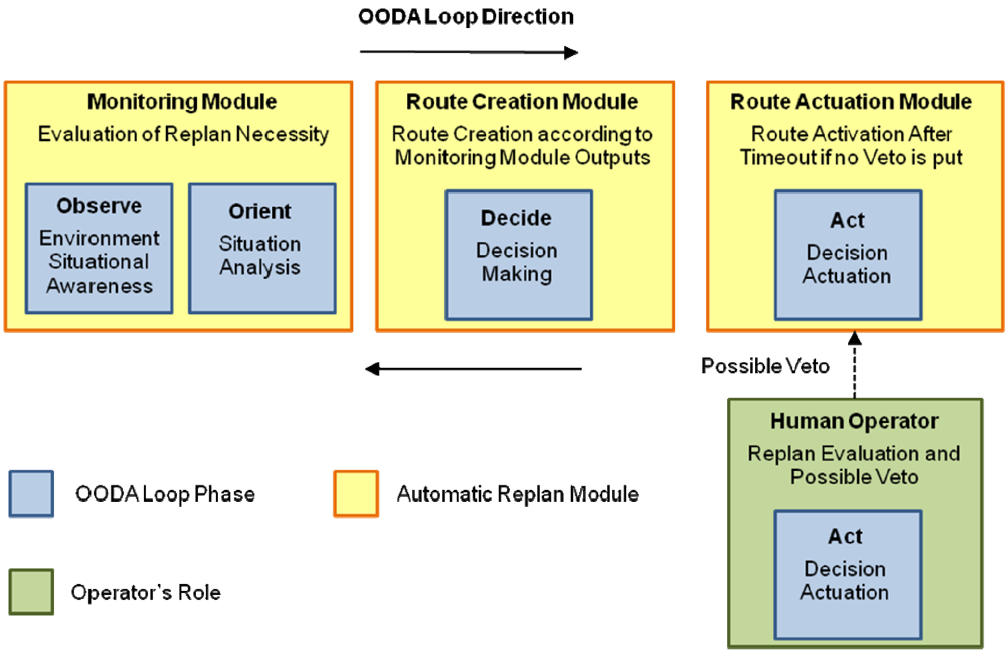


Figure 124. Autonomous On-board Replan Functional Architecture

In the next figures, two examples are reported relative to the comparison between on-board and ground based replanners with a “Management By Consent” logic.

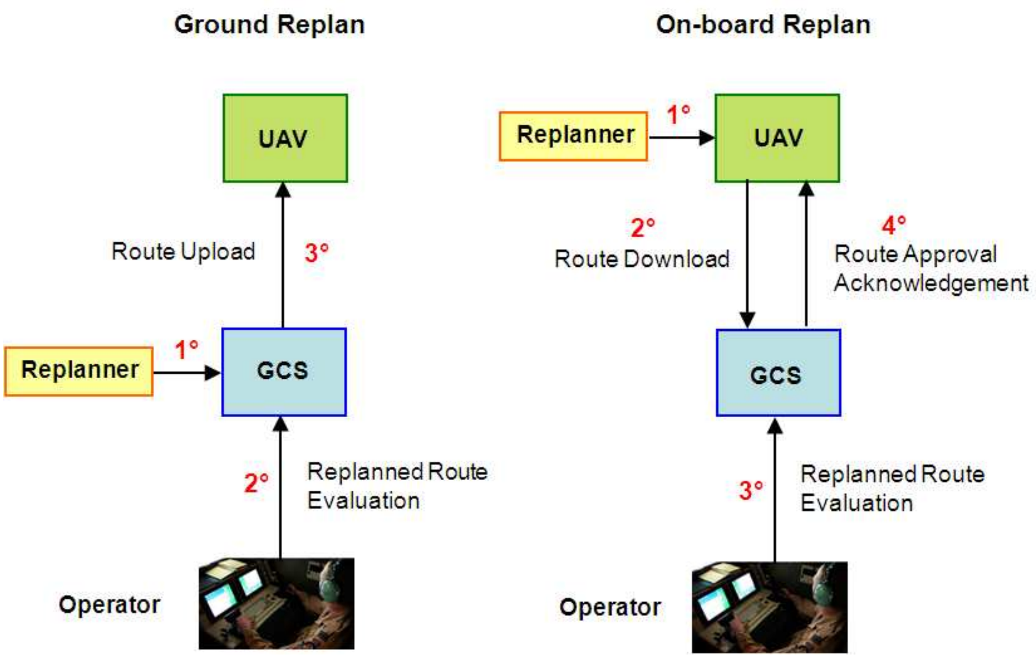


Figure 125. Ground vs. On-board Replan Without Operator Modification

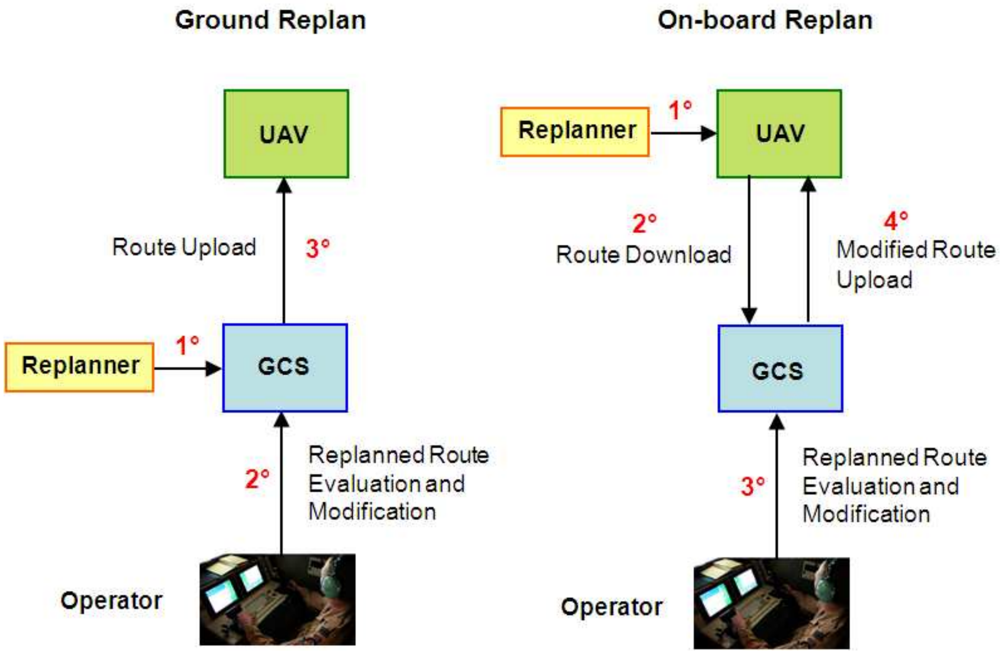


Figure 126. Ground vs. On-board Replan With Operator Modification

9.3 General Issues on Planning Algorithms

In the following sections general issues relative to the definition of route creation and validation algorithms will be discussed. These algorithms are an helpful aid for the operator in manual mission creation, and one of the two main modules of ground and on-board replanners (see Fig. 123, 124).

9.3.1 Route Creation Algorithms

Creating an optimum route for an UAV is not an easy task, since several parameters have to be considered, many time in contrast between them, with further constraints that limit the admissible solutions. When a route is manually created, the operator is responsible to weight the several aspects to obtain the global optimum, taking into account its operative experience and the specific mission context. Reproducing this knowledge based decision process with an algorithm is not a trivial issue, especially considering constraints in the computational time [17]. From the mathematical standpoint, this is a multi-objective optimization problem. To solve it, there are two possible approaches according to the desired result:

1. Identifying a main paradigm according to which optimize the result. In case of complex route, its parts can be created according to different parameters (e.g. fuel consumption for transit phase and payload performance in the operational area).
2. Running several algorithms that optimize the route according to different objectives, and then combines the result with proper weights to obtain a globally optimized final route.

In any case, also when a main objective has been identified, there can be many secondary parameters to consider, in order to obtain a result similar to a manually created routes, remaining in the case of multi-objective optimization. A list of possible parameters is reported below [17]:

- minimum time,

- minimum distance,
- minimum vehicle turns,
- minimum vehicle altitude variations,
- minimum risk considering given threats to avoid (each of them characterized by a risk probability),
- best range,
- best endurance,
- best image visualization (considering a given type of payload),
- best data-link coverage.

Besides, as reported above, the admissible solutions are further limited by mission constraints. At this purpose, it is possible to distinguish between general constraints (e.g. terrain separation) or constraints embedded in the objective (e.g. best range considering a given fuel quantity). A list of typical mission constraints is reported below [17]:

- obstacles (terrains, threats, No Fly Zones) avoidance,
- operating inside the assigned areas of operation and corridors,
- altitude limitations,
- fuel available,
- aircraft performance,
- datalink coverage,
- respect of the air rules,
- time constraints.

Practically, to solve a multi objective optimization problem randomized search methods must be used – like for example simulated annealing, evolutionary or genetic algorithms – in order to avoid the possibility to be trapped in local minimums [17]. Cost function is constructed according to the assigned objectives, and it is evaluated on the samples route, properly created taking into account the problem constraints. Apart the 3D coordinates, each WP is characterized by other attributes, and therefore some rules shall be defined in order to reduced the degrees of freedom and hence the problem complexity (e.g. the logic with which the WP type is chosen).
Finally, there are limits to the admissible computational time, especially for the GCS embedded and on-board planners due to operative needs. This constraints can be achieved for example limiting the maximum number of interactions in the algorithms, balancing the time with the risk to not find a good solution.

9.3.2 Plan Validation Algorithms

A relevant issue for all type of planners is the mission validation – in terms of goals reaching, route profile feasibility, constraints satisfaction, safety, etc. – critical due to the absence of a pilot on-board. Also in manned aviation, in fact, a flight plan is checked before the mission execution, but for UAS this aspect is more important and a detailed analysis is often required by civil aviation authority. At this purpose, route validation algorithms are included to check both manually create plans and autonomously ones with respect to the constraints reported above.

9.3.3 Algorithm Certification

Adoption of advanced route creation algorithms for the initial planning and in particular for the mission replanning raises several issues in terms of civil certification, since they are not present in manned aircraft FMS and therefore there is not specific rules. As reported above, in fact, the STANAG 4671 reports only the indication that automatic planning shall not lead the vehicle to unsafe conditions, but not further indications are provided. Considering the current manned aviation standards, there are generic requirements about mission algorithms that require deterministic results (i.e. running more times the algorithm with the same inputs, the outputs and the computational times shall be the same) and put constraints on computational time [17], [73]. Determinism, however, could be difficult to obtain, since many optimization functions are probabilistic. If the civil aviation authorities will not accept this behavior, a solution can be validating the routes with deterministic check algorithms before making them available for the engaging. In any case, dedicated and universally accepted rules shall be defined by the authorities at this purpose.

9.4 Mission Planning Functional Design

Starting from an existent initial design relative to an another research activity [70], a GCS embedded mission planner have been developed taking into account the previous considerations. Mission Planning has been considered a not safety critical applications, in order to obtain a more flexible interface being free in the use of maps and admissible software libraries to code the graphics. The main idea is to manage the whole mission in the planner and then exporting a subset of information to the safety critical guidance module of the GCS, from which the operator is able to provide navigation commands. The functional chain is reported below in Fig. 127:

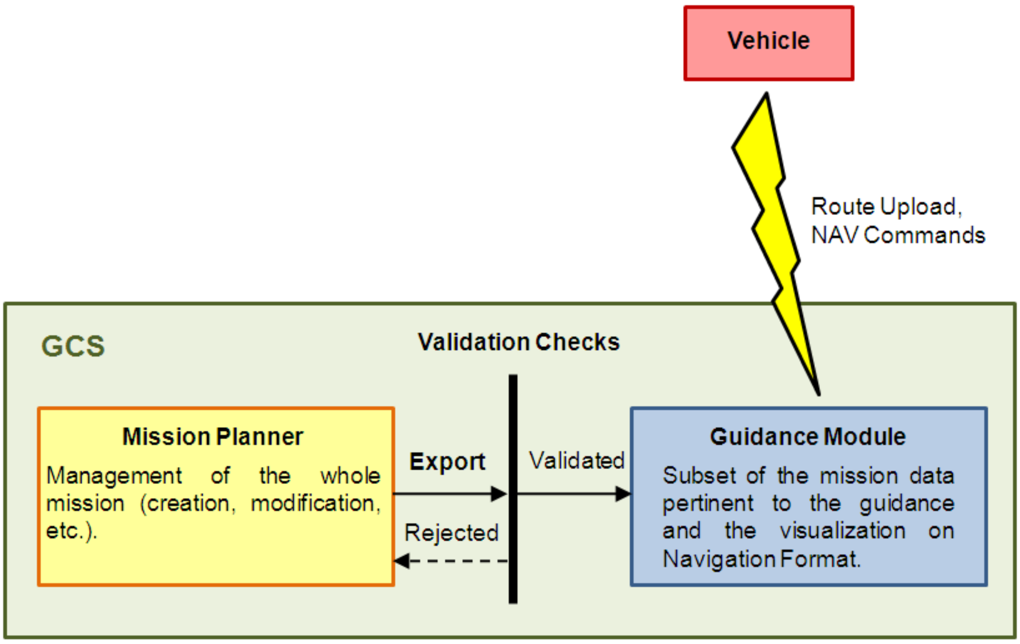


Figure 127. UAS Mission Management Functional Chain

More in detail the following macro functions can be performed on the planner:

- import of an externally created mission into planner DB,
- creation of a new mission from zero,
- import of a mission from the planner DB and modification,
- delete a whole mission from planner DB,
- export of a mission to the guidance module,
- export of a mission to an external user (e.g. a C4I or an external planner),
- mission validation.

The core of the planner is the database, that has been structured starting from the STANAG 4586 mission concept for the subset exported to the guidance module, and then adding the information not involved in the communication between CUCS and VSM. STANAG 4671, instead, does not specify requirements for the mission planning design.
Mission validation checks have been added to the planner in order to provide an immediate feedback of erroneous WP positions directly during the route creation and validating the final mission. Besides also advanced route creation algorithms have been taken into account. More details about the algorithms are provided in Chapter 10.

9.5 Mission Planning GUI Design

Mission Planner has been designed with some deviations from the common graphical layout due to its specific function and to the fact that TSD page can have a digital map and not a dark uniform color as background. The pilots have positively evaluated this design choice. Loaded map, in particular, are hosted in a specific folder of the computer and hence can be easily changed.
Any mission item (e.g. waypoints) can be entered by the operator in two different ways:

- directly on the map,
- through the alphanumeric keyboard.

In the first case, considering for example a route generation, the operator enters the Waypoint (the leg are automatically displayed for each WP couple) directly on the map defining therefore the 2D profile of the route. Symbol layout, in particular, is the same of the Main Display Navigation Format in order to increase the operator feeling with the interface, reducing the error possibility and the training time. When the WP entering is finished, other WP attributes (i.e. altitude, speed, arrival time, type, loiter attribute, etc.) are entered through an apposite sliding table. In particular from each table cell, it is possible to open the alphanumeric keyboard or a pop-up according to the selected cell. Alternatively, the entering can be directly performed on the table. Comparing the two solutions, the first is the most intuitive and easy for the operator, since he/she has a direct feedback of WP positions not only in absolute terms but also relatively to the other mission items. Besides, typing all information on the virtual keyboard could be a long an boring operation for the user. This could be a preferable solution when the coordinates are known a priori or for short new entering/modifications. While the operator enters items on the map, in particular, the interaction laws are more complicated with respect to the nominal state, as reported in the table below:

Type of Interaction	Result
Single click on a map free space.	A new item is entered in the pushed position.
Single click plus drug movement over a threshold on a map free space (threshold is used to discriminate a single click by a single click and drag movement).	Map panning.
Single click plus drug movement over a threshold on a previously entered item.	Selected item panning.

Table 39. Interaction Laws During Manual Item Entering on Map

Apart pan moving, during the manual entering the operator is also able to change the map zoom. At this purposes, in every day life – using smartphones, tablets or satellite navigators – an operator is felt to change the map zoom though a particular double touch interaction named Pinch (see the next picture for an example).

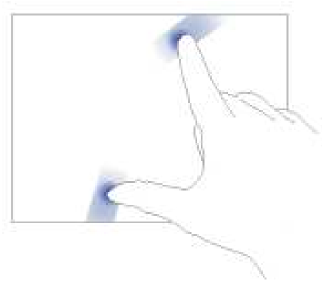


Figure 128. Pinch Interaction to Change the Map Zoom

First time that our TSD is used, every user tries to adopt the pinch interaction and this provides an idea of how touchscreen technology is diffused in few years. Using a resistive touchscreen, however, double click is not available, and therefore different solutions shall be adopted to vary the map scale , like “zoom in” and “zoom out” pushbuttons.
Finally the operator is able to delete an item from the mission, to declutter the symbology on the map and to measure linear distances on map (very useful tool during the mission creation). Some page examples are reported below in Fig. 129.

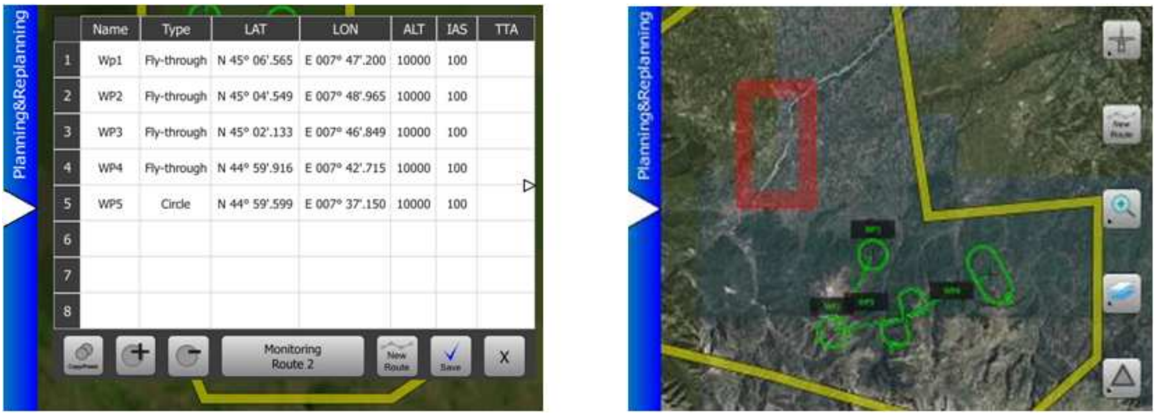


Figure 129. Examples of Mission Planner Page

The interface has been designed taking into account the conclusions of the RAFIV model (see section 4.5 for more details) in order to realize a good interface. In particular the following solutions have been adopted to guide the operator in the mission creation:

- Several fields in alphanumeric keyboard (e.g. coordinates or time) are formatted to remember at the operator the correct format.
- If an out of range value has been entered in the keyboard, the error is immediately shown to the operator.
- Mandatory fields to be filled are properly colored in order to help the operator recognizing.
- Icons in the pop-ups help the operator to recognize the several options.
- Feedback pop-ups provide details to the user about his/her command status and failure conditions (e.g. details about the causes of a not passed validation check).

An example of these solutions is reported below:

Figure 130. Example of Graphical Aids for the Operator in the Mission Planner

9.6 Navigation Format on Digital Map

Having developed a digital map for the planning, it has been exploited to create another Navigation Format on the NSC TSD providing a more detailed spatial situational awareness to the operator

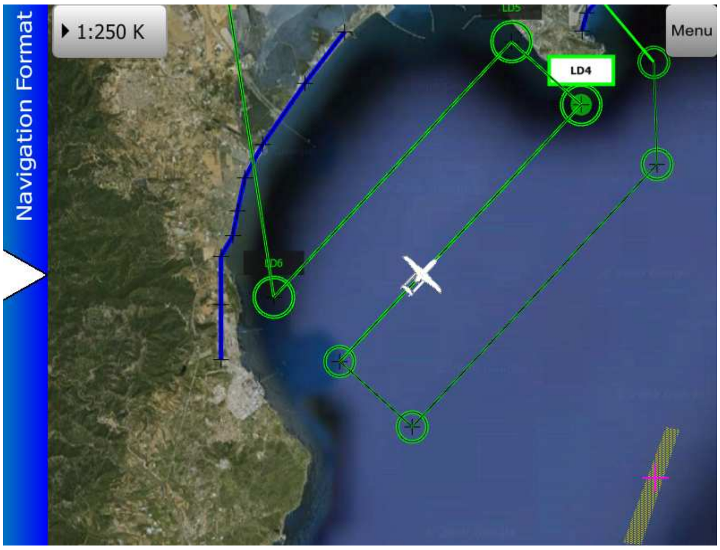


Figure 131. Example of Navigation Format on NSC TSD

From the functional and graphic standpoints, it is analogous to the Main Display Navigation Format, but it provides a greater flexibility about the usable type of maps (not forced to be certifiable) and the easiness of interaction for the user being on TSD. In particular, it can be used as interface to make a quick replan during the mission, without passing from Mission Planner. Without it, in fact, a mission change should be performed on the mission planner page, that requires more interactions and does not show the aircraft position. Navigation Format on digital map, therefore, acts as the classical MCDU page that manages the current flight plan. This solution has been preferred to a more rigid modification in the guidance page, considering the greater flexibility and situational awareness provided by the navigation format on touch map.

10 ADVANCED PLANNING ALGORITHMS

10.1 Algorithm Work Scope

As first step to increase the Level Of Automation to an ACL of 3, a set of advanced algorithms have been studied about mission creation and validation. These functions form a software library from which it is possible to realize automatic options for manual planning or autonomous replanner modules. Besides they have been designed with a parametric and modular structure in order to be as much as possible independent by the considered UAS. This modularity permits in fact to host these functions both on external, GCS embedded and on-board planners. In particular, referring to ground (see Fig. 123) and on-board (see Fig. 124) replanners, these algorithms represent part of the "decision" module. More in detail, the following paradigms have been considered for the route creation/validation:

- Datalink Coverage
    - Line Of Sight
    - Link Budget
- Standard Search Patterns
- Electro Optical / Infra Red Cameras performance
    - target line observation
    - target area observation
- Fuel Consumption and Performances,
- Mission Zone
- Emergency Route in case of vehicle failure.

Practically, these algorithms have been studied from the functional point of view, covering the aspects closer to the operative and HMI standpoints. Design at software level and in particular the definition of the optimization methods have been demanded to software team that has coded the functions.

10.2 Datalink Coverage

10.2.1 Line Of Sight

This function provides a map of the available Line Of Sight (LOS) given the Ground Datalink Terminal (GDT) position. Practically it is realized intersecting the terrain model (obtained by DTED) with a plane at fixed altitude, and then checking the LOS for each DTED point with respect to the GDT position. In other words, the map shows at a given altitude which zones are terrain obstacle free and within the horizon line for LOS datalink communications. A complete representation is obtained merging a set of map created for some discrete altitudes. These maps can be used as an aid for route manual creation, an input for another creation algorithm or for a validation check. An example of the LOS check is reported below in Fig. 132.

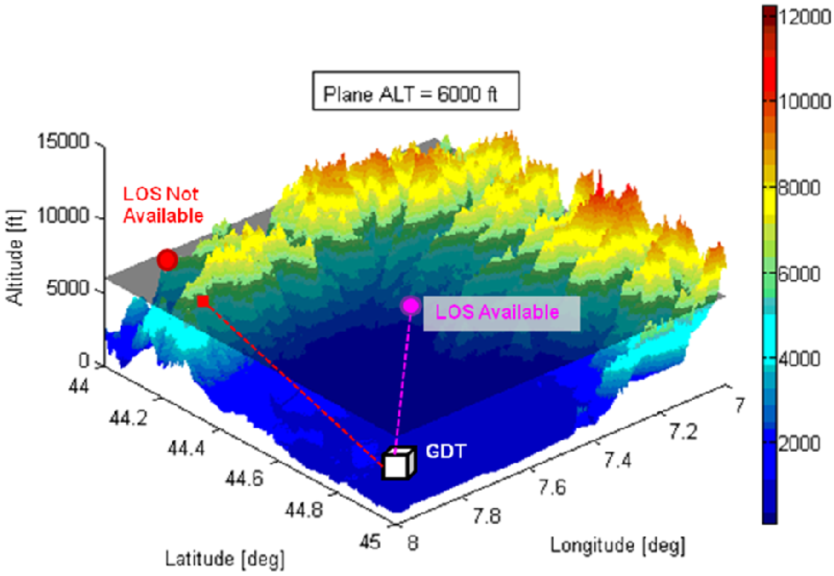


Figure 132. Example of LOS check

This function has been integrated in an external mission planner (hosted on a commercial PC) with a test interface in order to validate it. An example is reported below in Fig. 133, with the free zone in red superimposed to the cartography (South Piedmont):

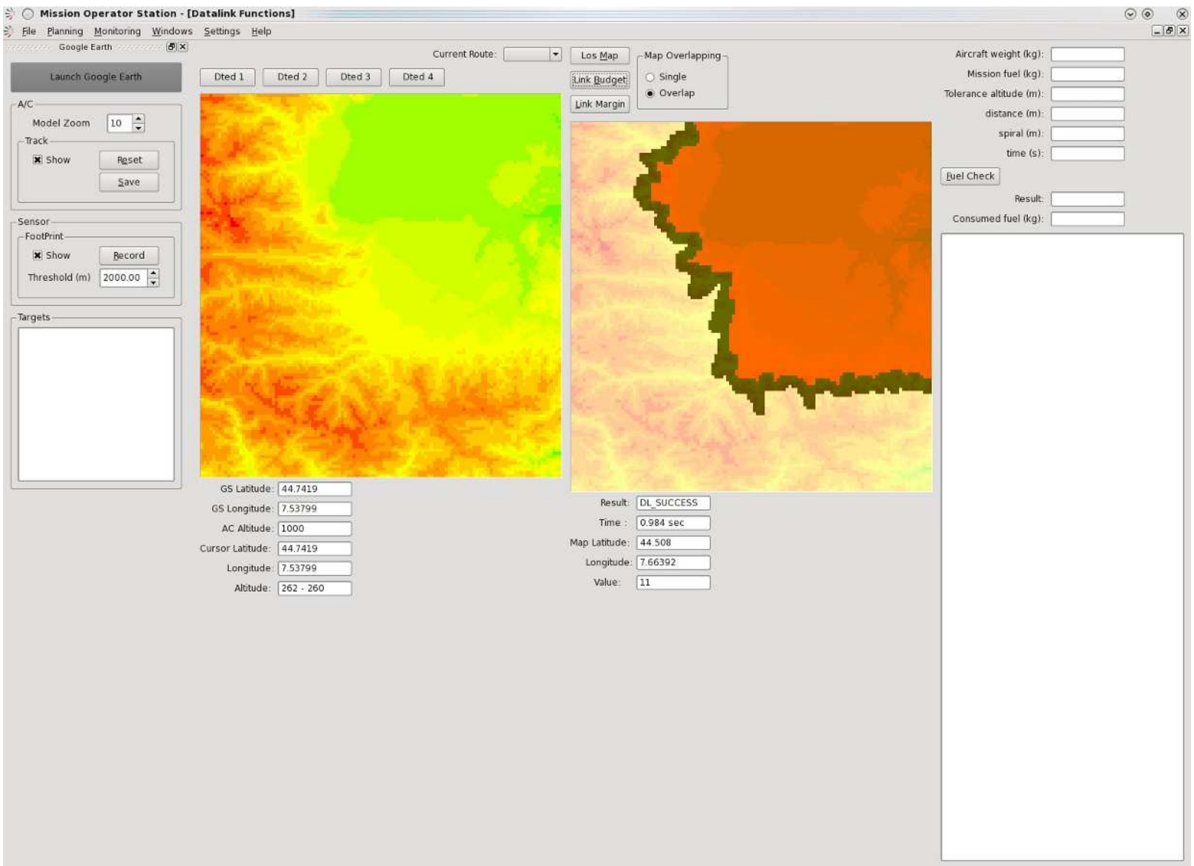


Figure 133. Los Map

In particular, the computation is performed at 360° around the GDT. This function is thought to create a DB relative to the mission zone, at which accessing for several purposes (e.g. during manual route creation or as input for another algorithms). Finally computation time can be long for high precision DTED (i.e. Level 2) and large considered zones, while with lowest precision DTED (i.e. Level 0) the computation is near real-time. Results have been checked by the comparison of the map provided by the free software "Radio Mobile Deluxe" that make the same computation, but does not permit to export the data in a usable form. An example is reported below in Fig. 134, again with the LOS map in red.

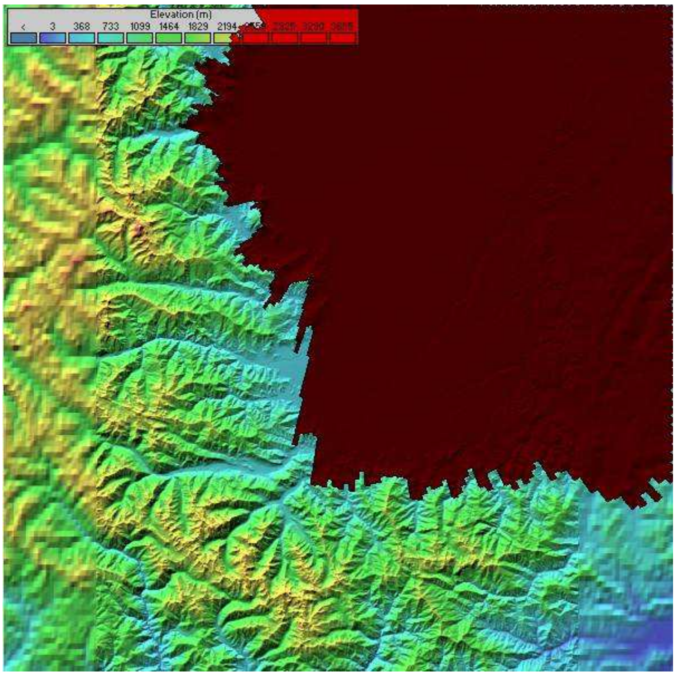


Figure 134. Example of Radio Deluxe LOS Map

10.2.2 Link Budget

Starting from the LOS map, a more detailed information about the link quality is provided calculating the link budget for the points having the LOS with respect to the GDT. Link budget is the power actually received by an antenna – the Air Datalink Terminal (ADT) in our case – taking into account the transmitted power (by the GDT), the antenna gains and several present losses. In particular, it has been evaluated with the Friis's Equation [74], [75]:

$$P_R = P_T + G_T + G_R - L_{FPL} - L_T - L_R - L_M$$

P_R = power received by the ADT [dBW or dBm]

P_T = power transmitted by the GDT [dBW or dBm]

G_T = GDT antenna gain [dBi]

G_R = ADT antenna gain [dBi]

L_{FPL} = Free Path Losses [dB]

L_T = GDT (i.e. transmitter) losses due to coax, connectors, etc. [dB]

L_R = ADT (i.e. receiver) losses due to coax, connectors, etc. [dB]

L_M = losses due to transmission media [dB]

Equation 2. Friis's Equation

$$L_{FPL} = 20\ log_{10}\left(\frac{4\ \pi\ d}{\lambda}\right)$$

d = distance (i.e. slant range) from the GDT [m]

λ = wavelength [m] – λ =light speed in the vacuum [m/s] / frequency [Hz]

Equation 3. Free Path Losses

Friis's equation parameters are given in input to the function. For details about some units of measure very specific of telecommunication engineering see the Appendix B.
Practically, knowing the minimum admissible received power for the ADT (usually evaluated with a safety margin), with this function it is possible to determine the operative datalink range in LOS for a given altitude, that depends mainly by the free path losses. In fact, as the distance between GDT and ADT increases – being constant the other terms – the received power decreases.
As for the previous function therefore, a completer representation is provided by the merging of several maps stored in a DB relative to the mission zone.
Using the Friis's equation involves some assumptions [74], [75]:

1. transmitter/receiver antenna and transmission line are conjugate matched,
2. antennas are correctly aligned and polarized,
3. the bandwidth is narrow enough that a single value for the wavelength can be assumed,
4. antennas are not isotropic,
5. wavelength term is included in the free path losses (acceptable for LOS terrestrial communication),
6. all carrier wave propagation is assumed to be wavelength independent,
7. antennas are not omnidirectional,
8. near obstacles (i.e. terrain in our case) there are further effects due to reflection, absorption and refraction.

9. no electromagnetic interferences are considered.

First six points are usually satisfied by datalinks used for UAS. For the seventh, the antenna has been considered omnidirectional in order to have a single map valid in first approximation for all the possible antenna orientation. Besides GDT antennas are usually mounted on movable pedestals, and hence they can be approximated as omnidirectional. A critic point is the eighth, that makes the result not very precise near the transition between LOS / No LOS zones. However an UAV flies usually over the terrain with a significant separation, and besides the link budget is evaluated with a safety margin. Finally, the ninth is a forced assumption, since the evaluation of possible interferences requires a more complex electromagnetic compatibility analysis. In any case, the use of the Friis's equation for first evaluation of datalink performance has been proven in real operations. Also this function has been integrated in the external mission planner, for which an example is reported in Fig. 135, with the link budget displayed in a grey scale. As reported in the example, the received power decreases from the GDT position as the distance increases. The results have been again compared with the "Radio Mobile Delux" outputs to validate the function.

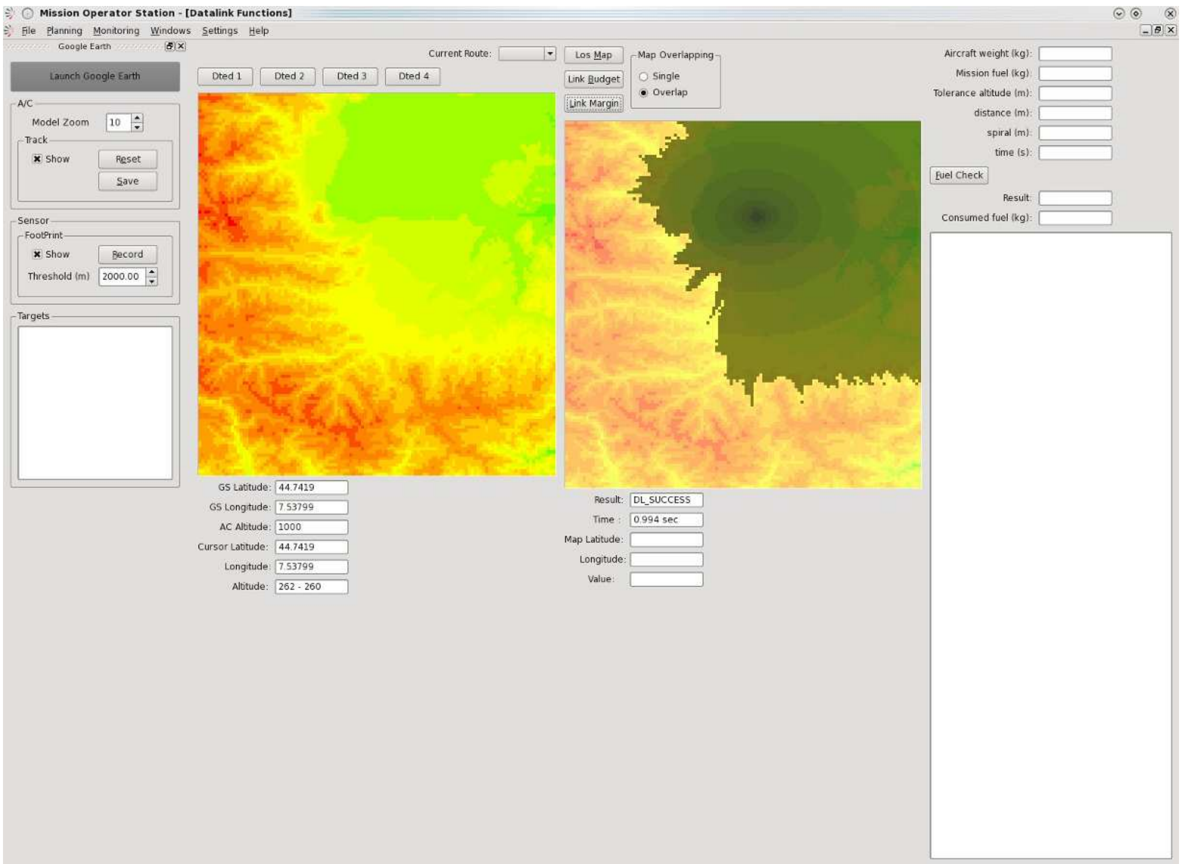


Figure 135. Link Budget

10.2.3 Link Budget Real Time Monitoring

In order to guarantee safe operations, Link Budget shall be always above a threshold. At this purpose it has been designed an on-board monitoring function that can evaluate in real time the ADT link budget for the estimated future vehicle position, updating the theoretical calculation

provided by the Friis's equation with the current signal strength actually received by the ADT. In practice, the output of this function is used to raise an alert about a future lost uplink.
More in detail, the future position is estimated after a time span (given in input to the function) from the function running. This estimation is performed in two different ways according to the engaged guidance mode:

- navigation route mode: projection of the aircraft position along the engaged route.
- other modes: projection of the current NED speeds for the time span.

Possible ADT antenna masking due to aircraft maneuvers is not taken into account. This function has been successfully tested, with a testing devoted integration in the external planner.

10.3 Standard Search Patterns

Typical UAS missions are monitoring or target searching (e.g. a castaway) on an area. To perform these tasks, there are several standard patterns commonly used also by boats or manned aviation:

- Step ladder: optimized path for a complete and progressive scan of an area
- Expanding Square: optimized searching path from the last known target position.
- Sector Scan: path that maximize the probability to quickly find a target in an area, with a not progressive pattern.

Each pattern is characterized by the following geometrical characteristics:

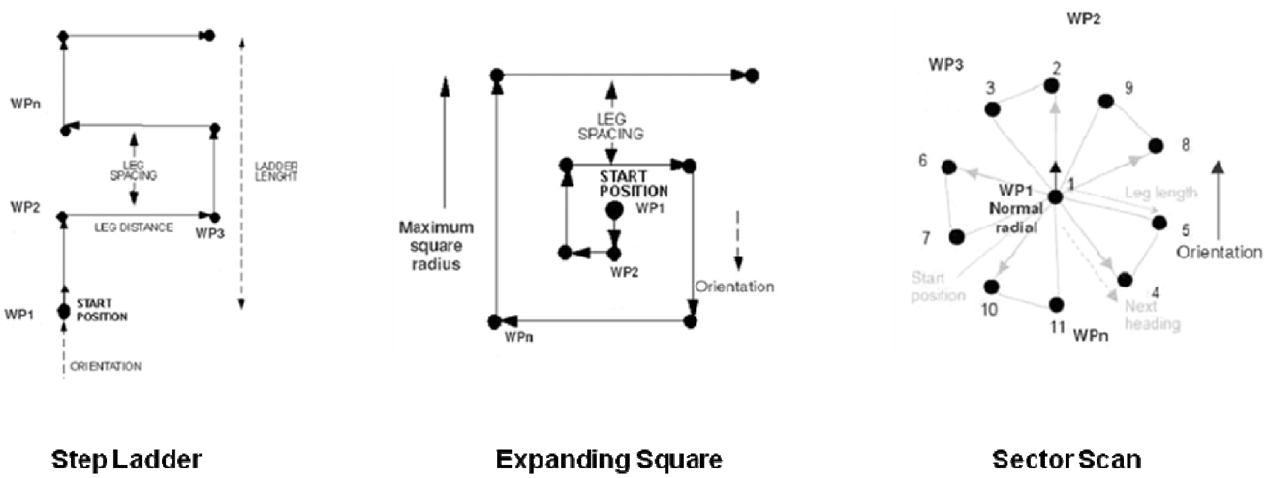


Figure 136. Standard Search Patterns

In particular, the algorithm creates the pattern in terms of WP list, according to the received parameters in input. Altitude and speed are assigned equal for all WP according to the received inputs, while for WP type the Fly-By has been chosen (most suitable to fly path with perpendicular legs). From the practice standpoint, this function can be an aid during manual route creation or a sub-module of a more complex autonomous function.

10.4 EO/IR Sensor Coverage

10.4.1 EO/IR Sensors & NIIRS scale

Electro Optical / Infra Red cameras are the basic UAS payload for monitoring and searching missions, due to their flexibility, high resolution and ease of interpretation with respect to o radars or multispectral sensors. Considering a MALE UAS, these cameras are usually mounted in a gimbaled turrets in order to decouple vehicle and sensor movements (an example is reported in Fig. 137). Looking a target with the proper camera, however, is not sufficient if a good image is not provided to the operator. Evaluating an image quality is not a trivial task, since it depends by many factors like the specific payload considered, the external environment, the looked target and the assigned task (i.e. what the operator wants to retrieve from the image considering the mission goals and the operative context). At this purpose, the "National Imagery Interpretability Rating Scale" (NIIRS) has been created by the aerial imaging community, in order to rate an aerial image with a simple graduated numerical scale (from "0" to "9") and distinguishing between several payload types. NIIRS has become a standard in the aerial imagery evaluation.

Figure 137. Examples of EO/IR Cameras Installation and EO Image

NIIRS level, in particular, can be associated to the Ground Resolvable Distance (GRD), that is the minimum object length that can be distinguished in the image (i.e. a sort of sensor resolution). More in detail, the NIIRS scale is reported in Tab. 40 [78]. Third and Fourth columns of Tab.40 provide only a subset of the available examples for each level. In particular the following terms occur many times relatively to the type of information obtainable by the imagery [79]:

- <u>Detect</u>: the capability to find or discover the presence or existence of an item of interest, based on its general shape and other contextual information (e.g. a ship).
- <u>Distinguish between</u>: the capability to determine that two detected objects are of different types or classes based on one or more distinguishing features (e.g. distinguished that the previously detected ship is a merchant ship).
- <u>Identify</u>: the capability to name an object by type or class, based primarily on its configuration and detailed components, thanks to the image details (e.g. identify the merchant ship as belonging to the "Nemo III" class).

As emerging from the previous considerations, the imagery evaluation with the NIIRS scale is a subjective process that could lead to different results according to the user expectations.

NIIRS	GRD [m]	Example of EO Capability	Example of IR Capability
0	/	Interpretability of the imagery is precluded by very poor resolution	Interpretability of the imagery is precluded by very poor resolution
1	> 9	Detect a medium-sized port facility and/or distinguish between taxi-ways and runways at a large airfield.	Distinguish between runways and taxiways on the basis of size, configuration or pattern at a large airfield.
2	4.5 ÷ 9	Detect large buildings (e.g., hospitals, factories).	Detect individual large buildings (e.g., hospitals, factories) in an urban area.
3	2.5 ÷ 4.5	Detect trains or strings of standard rolling stock on railroad tracks (not individual cars)	Identify individual thermally active flues running between the boiler hall and smoke stacks at a thermal power plant.
4	1.2 ÷ 2.5	Identify, by general type, tracked or wheeled vehicles when in groups.	Identify individual closed cargo hold hatches on large merchant ships.
5	0.75 ÷ 1.2	Identify radar as vehicle-mounted or trailer-mounted.	Identify outdoor tennis courts.
6	0.4 ÷ 0.75	Identify the spare tire on a medium-sized truck.	Identify individual thermally active engine vents atop diesel locomotives.
7	0.2 ÷ 0.4	Identify ports, ladders, vents on electronics vans.	Identify automobiles as sedans or station wagons.
8	0.1 ÷ 0.2	Identify windshield wipers on a vehicle.	Identify limbs (e.g., arms, legs) on an individual.
9	< 0.1	Identify vehicle registration numbers on trucks.	Identify cargo (e.g., shovels, rakes, ladders) in an open-bed, light-duty truck.

Table 40. NIIRS Scale

10.4.2 Sensor Footprint & Pixel Density

In order to use in practice the NIIRS scale for autonomous planning, the starting point is the determination of the sensor footprint, that is the ground/sea area covered by the sensor when it is pointed toward the Earth.

Sensor Footprint is given by the intersection of the sensor Field Of View (FOV) corner versors with the ground (see Fig. 138 for an example). Sensor aiming point (also named Sensor Line Of Sight) is contained inside the footprint. More in detail, the footprint dimension depends by the following parameters:

- sensor field of views:
    - horizontal (FOV_H),
    - vertical (FOV_V).

- sensor orientation with respect to the vehicle body axes (usually gimbaled sensors has not the “roll” degree of freedom):
    - azimuth,
    - elevation.
- vehicle attitude (partially balanced by gimbaled turrets, especially for some sensor modes that keep constant the observed point):
    - roll,
    - pitch,
    - heading.
- sensor distance from the ground (evaluated in term of slant range between the sensor and the relative aiming point),
- terrain orography (FOV versors projection is actually interrupted by the terrain).

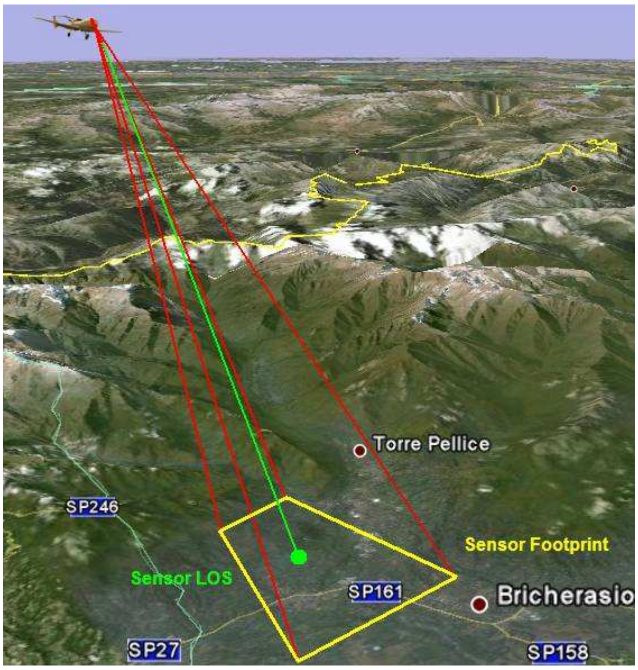


Figure 138. Example of Sensor Footprint

Sensor footprint alone, however, does not provide any information about the image quality, since no data about the camera resolution have been included in the computation. The adoption of a proper figure of merit is therefore needed. At this purpose the pixel density along the footprint has been chosen (expressed in px/m^2), since it takes into account both camera characteristics (i.e. resolution in pixels) and captured image (i.e. footprint area dimensions and shape). Pixel density is in fact not uniformly distributed on the footprint: it is greater in the part closer to the vehicle and increasingly lower toward the farer side. Considering one footprint direction (e.g. the longitudinal) and a flat terrain (i.e. the terrain is considered a flat plane at fixed altitude with respect to the sea level without considering the real orography), the pixel density in a point “Q” is calculated with the following formulas

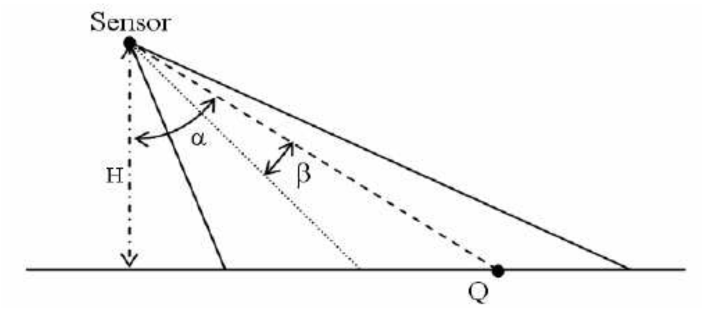


Figure 139. Pixel Density Calculation in a Point “Q” for a Single Footprint Direction [80]

$$\sigma = \frac{cos^2(\alpha)}{H \cdot \gamma}$$

H = sensor height [m]

α = angle between the unit vector from sensor to Q and the normal to the ground plane

γ = pixels angular size [px^{-1}]

$$\gamma = \frac{cos^2(\beta)}{\delta}$$

δ = sensor focal length [px]

β = angular offset of Q with respect to the footprint LOS

Equation 4. Pixel Density in a Point “Q” for a Single Footprint Direction [80]

To calculated the pixel density on the footprint area, the previous equations are used to calculate both horizontal and vertical linear pixel densities on footprint grid points, which are then multiplied to obtain the areal density [80]. In particular, intermediate points for which calculating the pixel density are obtained dividing the footprint into grid of equal pixel size and considering their center. As the grid is larger, therefore, the smaller the px density and hence the image quality will be. An example of pixel density distribution is reported in Fig. 140, in which starting from a default configuration, the effects of FOV, sensor position, vehicle attitude and slant range are shown, changing one parameter at time keeping constant the others. Focal length has been considered constant in all cases. Basic configuration has been calculated with the following data:

- FOV_H = 20°,
- FOV_V = 15°.
- sensor azimuth = 45°,
- sensor elevation = -45°.
- vehicle roll = 0°,

- vehicle pitch = 4°,
- vehicle heading = 0°.
- vehicle altitude = 10000 ft (3048 m).

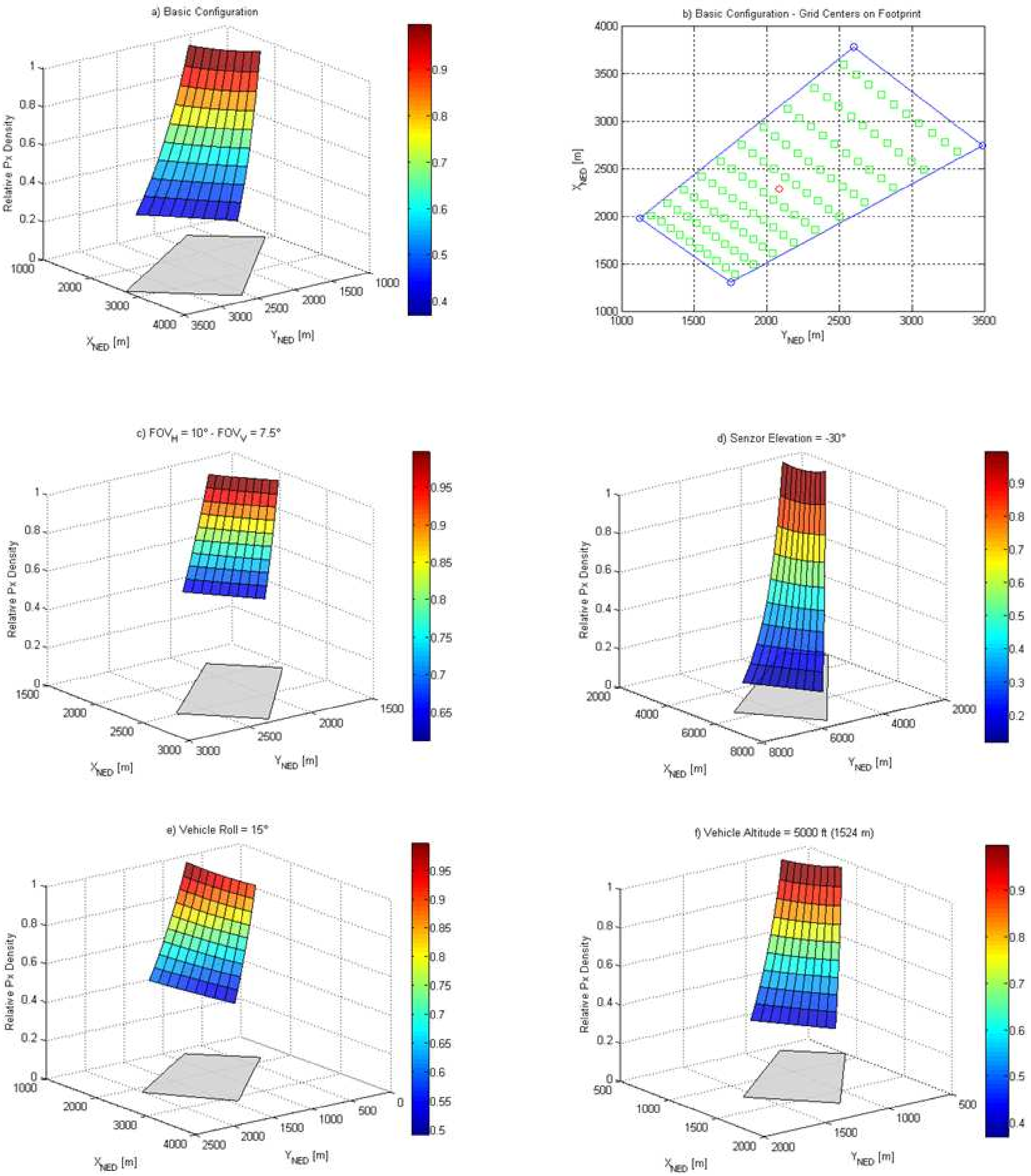


Figure 140. Pixel Density Examples

The pixel density is reported in relatively terms with respect to the maximum value on footprint. In particular, in subfigure a) the basic configuration is presented. Subfigure b) is always relative to the

basic configuration and it shows the grid centers on footprint, giving an idea of the stretching. In subfigure c) horizontal and vertical FOV are halved, and as consequence the footprint is smaller with a greater pixel density. In subfigure d) the sensor elevation is reduced to -30° keeping constant the azimuth. The footprint is stretched, and hence the px density is lower. In subfigure e) the vehicle rolls of 15°, with a consequent footprint distortion and px density variation Finally, in subfigure e), the altitude is halved to 5000 ft keeping constant the sensor orientation at the default value (slant range is therefore reduced). Pixel density distribution is very similar to the basic configuration, but in absolute value it is increased due to the smaller footprint size. In particular the maximum value is the 480% with respect to the basic case.
In order to practically use the pixel density, it is needed to correlate it with the NIIRS scale, i.e. determining the minimum number of pixels covering an area around an object having the relative GRD as characteristic dimension. This is not a trivial task, due to the great variability (e.g. detect a people in a desert is very different than in a wood) and subjectivity of the matter. A possible way is to create a database of px densities relatively to NIIRS scale, comparing the human NIIRS rating of sample images with the relative computed density. This operation could be performed both with real aerial images, or at the simulator. Accuracy of px density and NIIRS correlation is direct function of the database detail. A simulator example is reported below relatively to an airport tower, and considering the imagery displayed to the sensor operator in the relative HMI to evaluate the NIIRS level.

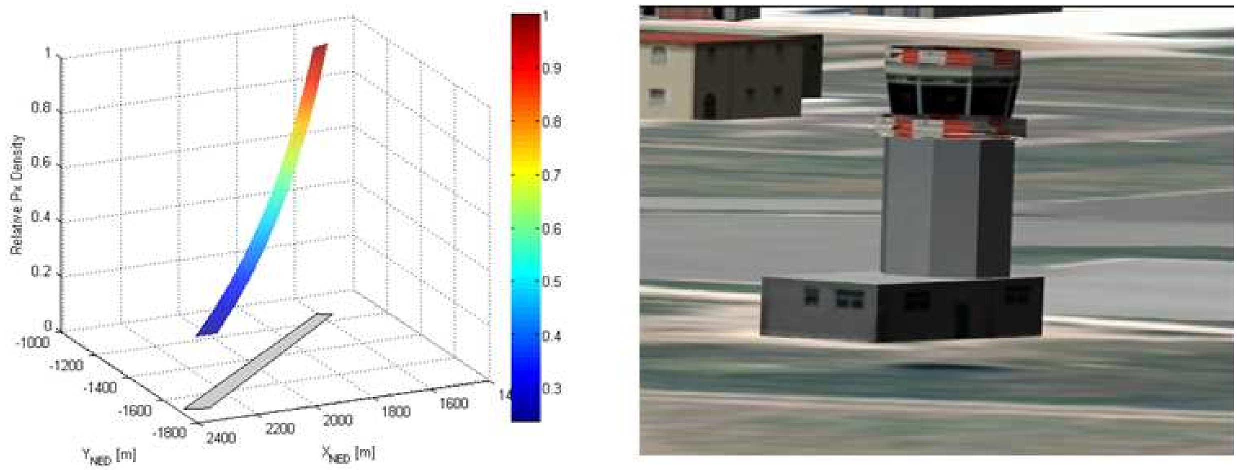


Figure 141. Example for Pixel Density Evaluation

The following values have been obtained:

- FOVH = 1.2°
- FOVV = 0.9°
- sensor azimuth = -23°
- sensor elevation = -6°
- vehicle roll = 0°
- vehicle pitch = 4°

- vehicle heading = 347°
- vehicle altitude = 380 ft (116 m)
- NIIRS level = 5 (GRD = 0.75 ÷ 1.2 m)
- Minimum Px Density = 0.88 px/m^2
- Maximum Px Density = 3.92 px/m^2
- Px Density at the footprint LOS = 1.94 px/m^2
- Medium Px Density = 2.08 px/m2

Noting that the px density is evaluated assuming a flat terrain and not the intersection with 3D objects. Hence the differences between the footprint size and the visualized image on display. The tower, in fact, is located in the closer part of the footprint having a high px density (see Fig. 142 below), and as consequence it is visualized with a good resolution. Differences between actual and ideal flat footprints are annulled when the target is overflown, that is when the sensor aims perpendicular to the terrain. Px density remains however a good measure of the image quality, since the measure can be correlated to a certain imagery quality and hence to a NIIRS level.

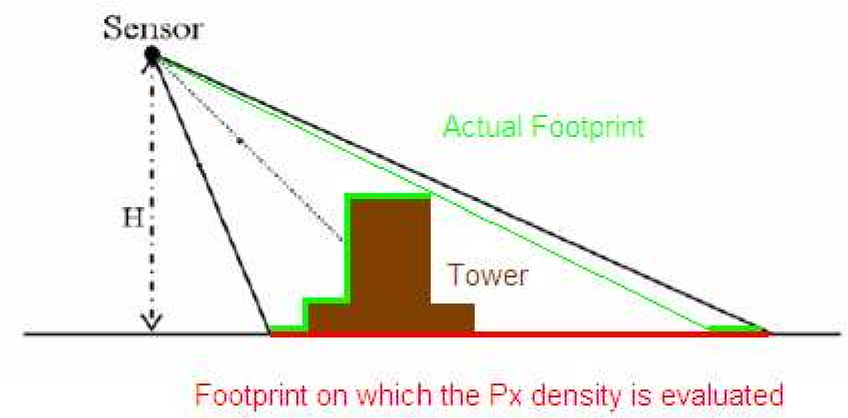


Figure 142. 3D Object Influence on Footprint

10.5 Target Line Algorithms

First sensor planning algorithm family is relative to the observation of a target line, for which a route creation algorithm and the corresponding check function have been designed. In both cases the pixel density has been assumed as figure of merit to rate the imagery, while an automatic sensor pointing mode has been considered as law for determining the sensor LOS from each route point. Being sensor movement decoupled from the vehicle maneuvers thanks to the gimbaled turret, in fact, a relationship between them shall be assumed for algorithm development. The considered automatic mode, in particular, aims to the optimum target line point according only to the vehicle position. The mode "philosophy" is to move as long as possible the sensor and not the vehicle, considering that frequent route changes are not needed with a gimbaled movable sensor and that they are not good for an integration in the civil airspace. In particular, a route created considering the automatic mode is also suitable for the use of a semiautomatic mode, in which the operator is free to vary the line scan speed decoupling it from the vehicle position. These automatic and

semiautomatic modes permit a reduction in the operator workload, especially considering the provisions of BLOS latency (that make difficult a manual sensor control) and the possibility of controlling vehicle and payload from a single station. An example of the aiming logic for the automatic mode is reported in Fig. 143.
More in detail, the route is created having as primary objective the maximization of the pixel density in the assigned range in input (function of the required NIIRS level), and as secondary objective the minimization of aircraft route changes. Initial and final WPs are provided in input. Besides the following constraints have been taken into account:

- no obstacles along the sensor LOS,
- altitude constraints,
- terrain avoidance with safety margins,
- vehicle performances,
- observation side with respect to the target line,
- minimum distance from the line.

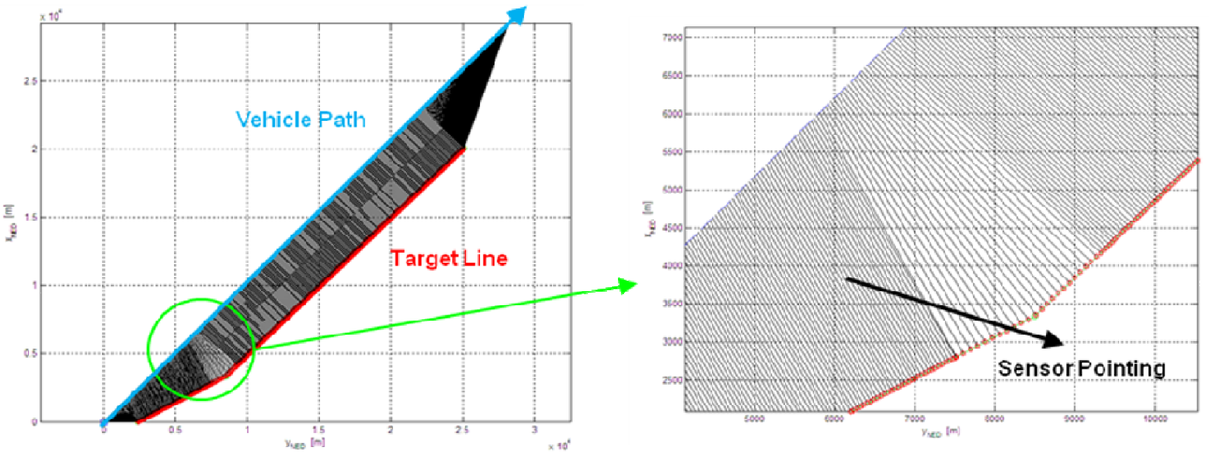


Figure 143. Sensor Automatic Mode

Validation function works in specular way: given a route and a target line, the good observation of the second respecting the assigned constraints is verified.

10.6 Target Area Algorithm

Second item treated relatively to the sensor performance is a route creation algorithm in order to cover an area with a given NIIRS level. Only rectangular areas has been considered, and hence an irregular target shall be included into a proper rectangle to be processed. In particular, the function has been conceived to monitor big areas for which it is not sufficient moving the sensor but also the vehicle shall change its path. Step ladder has been chosen as UAV output route, while the sensor is considered aimed with fixed azimuth at zero (i.e. toward the vehicle) or scanning with a given angle centered on azimuth zero (the mode is a function input). According to the footprint size (determined

in function of the required px density), the geometrical parameters of the ladder are set (see Fig. 144), considering the footprint size for the ladder strip width determination. Ingress and egress WPs are provided in input by the operator.
Besides, the following constraints have been taken into account:

- altitude constraints,
- terrain avoidance with safety margins,
- vehicle performances.

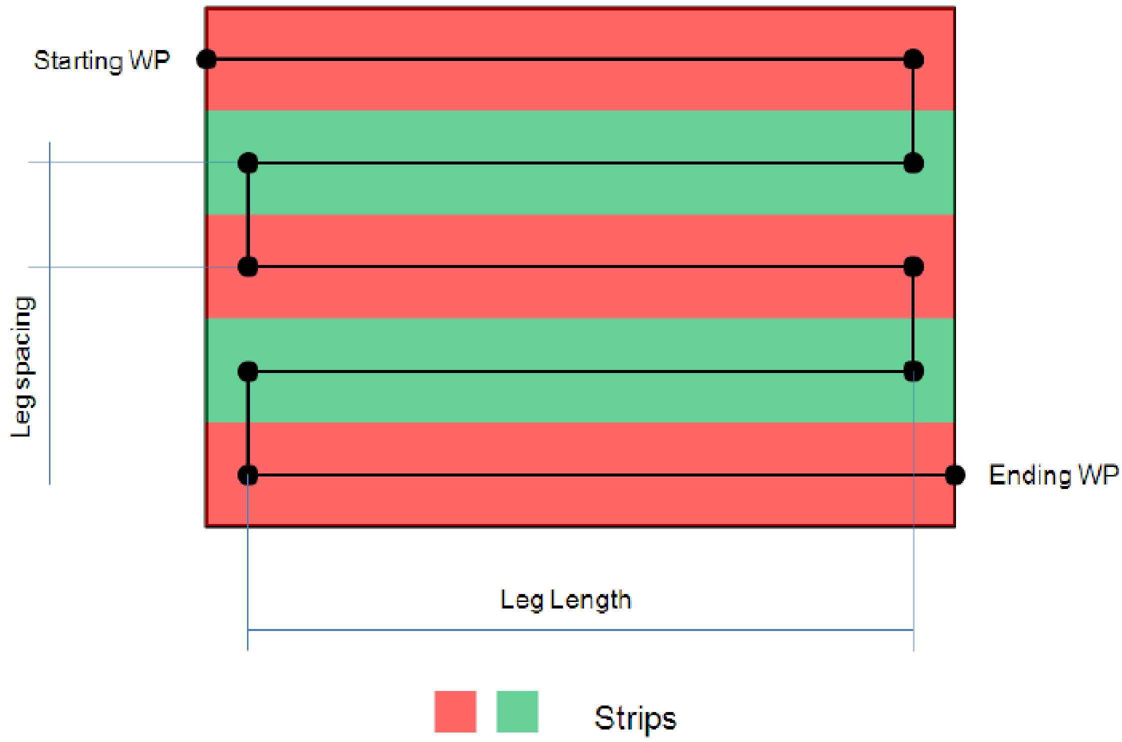


Figure 144. Step Ladder on a Target Area

10.7 Fuel Consumption and Performances

10.7.1 Route Validation

A function verifying the fuel consumption to fly a route has been designed relatively both to the mission planning and performance FMS functions. In case of replan check, in particular, first route WP coincides with the current vehicle position. Together with the fuel verification, secondary checks about vehicle performance respect are done (e.g. assigned IAS and ALT to the WP, or ramp angles for climbs and descents). Climb and descent performances are provided in terms of curves relative to time, horizontal distance and fuel consumption to change altitude, while in cruise fuel flow [kg/min] and specific range [NM/kg] are reported in tables according to different parameters (e.g. weight, speed, etc.). This form of database is very generic and hence it can be extended to other vehicles simply changing the values and not the structure of the DB. Wind and air temperature in altitude are considered. Due to the wind effect, in particular, the fuel consumption in flight is

evaluated through the fuel flow (i.e. from the time to fly each leg) and not from the specific range (i.e. from the leg length). Finally also terrain avoidance and mission altitude limits are checked. More in detail, the fuel check is done leg per leg starting from the determination of the arrival time at each WP. An alert about a missing assigned time is also raised.
This function has been successfully tested and integrated in the external planner, comparing the function results with the values obtained flying the mission at the simulator. A test example is reported below, with a computed fuel consumption relative error of -0.24 % with respect to the values obtained at the simulator. In any case, a further safety margin is provided assigning in input to the function an available fuel lower than the current value.

Latitude [deg]	Longitude [deg]	Altitude [ft]	IAS [kts]	Assigned Time	Type	Loiter Time
N 44.5	E 7.5	3000	90	/	Fly Through	/
N 44.85	E 7.5	5000	/	09:16:00	Circular Loiter	5‘
N 44.85	E 7.85	5000	90	/	Fly Through	/
N 44.5	E 7.85	3000	105	/	Fly Through	/

Initial Time (i.e. time at WP1) = 09:05:32

Table 41. Data for Fuel Consumption Function Validation

10.7.2 Route Creation for Fuel Consumption

Parallel to the route validation function, also a route creation algorithm has been produced to create a route between two entered WPs that optimizes the fuel consumption, according to one of two alternative paradigms chosen by the user:

- best range,
- minimum cost (see Eq. 1 for more details).

This function is especially used to determine transit route toward/outward Areas of Operation, for which the fuel is the key parameter. As secondary optimization objective there is again the minimization of flight path changes, while the following constraints have been considered:

- terrain avoidance with safety margins,
- altitude limitation (mission constraints),
- vehicle performance.

In particular, the algorithm works on the VNAV profile, considering the following aspects:

- balancing between increased True Air Speed (TAS) in cruise at a new altitude (and hence reduced time of flight and fuel consumption considering the fuel flow) with the climb consumption,
- cruise fuel flow variation according to altitude and assigned speed at the leg,
- wind and air temperature at the different altitudes,
- determination of the top of descent point in order to exploit as most as possible the low fuel consumption and high speed of the descent.

Horizontal path is instead determined considering a direct geodetic line between initial and final WPs (i.e. minimum distance), at least of obstacles to avoid.

10.8 Mission Zone Respecting

According to the mission zone types initially assumed (see section 6.4.1), a relative validation function has been designed. In particular, the following checks have been considered:

- No Fly Zones avoidance with a safety margin,
- Areas Of Operations respecting,
- Corridors respecting.

10.9 Autonomous Emergency Ground Replanner

In a successive phase, an autonomous emergency ground replanner has been designed, with a first integration in GCS. Replanner analyzes a series of inputs coming from the UAS health monitoring system, and when an alert is raised it produces a route to land as soon as possible to the nearest admissible airport, that in UAS typical operations coincides with the departure airport where the GCS is located. In particular, this function represents a practical case of human – autonomy integration and plays a relevant role to increase the ACL to 3. According to the previous explanation (see section 9.2.2), the integration has been realized with a “management by consent” logic, in which the system proposes an emergency route to the operator that decides if engaged it or not. As graphical format, the TSD Navigation Format has been chosen in order to exploit the advantages provided by the touchscreen flexibility for the replan and the digital map (see section 9.6 for more details). In particular a proper alert and a pop-up notify to the operator that a new route has been proposed. Then on a Navigation Format the user can approve the route or reject it. Test pilot have been rate positively this implementation. An example of the developed interfaces is reported in Fig. 145. More in detail, the route is created considering the following parameters:

- vehicle performance,
- No Fly Zones avoidance,
- Areas of Operations and Corridors respect,
- terrain avoidance,

- link LOS budget coverage.

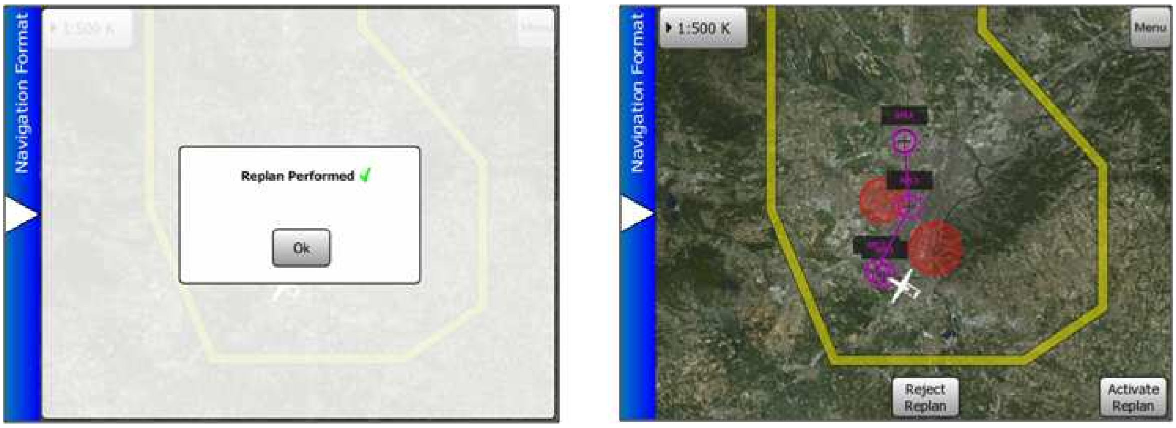


Figure 145. Autonomous Emergency Ground Replanner HMI

11 FMS TESTING & INTEGRATION

11.1 Testing & Integration Overview

As reported in section 6.1, testing and integration activity has been performed in different environments at increasing level of system integration and realism (see Fig. 146). Operating on multiple environments is required to integrate software inside a complex system, since there are many aspects to verify, with each of them that is better evaluated in a certain environment and with particular tools. Besides, before the final flight tests it is mandatory to evaluate as much as possible the software on ground in order to avoid problems affecting the safety – especially considering that there is not a pilot on-board – and taking into account the economic factor that limits the flight activity. Testing and Integration has been an iterative activity, with successive tests in order to verify the bug fixing effectiveness and that no new problems have been added. This aspect has been further stressed considering that the FMS software has been realized in many releases with an incremental level of functions. When a new release is delivered, as first step free tests are performed on it, just to evaluate that it does not have macro bugs prejudicing further tests with other system components. If they are passes, the successive integration and validation activity is done following a fix procedure in order to execute established and repeatable tests. At this purpose many test requirements (successively converged in test procedures) have been defined for each FMS elements in the different environments. In the following sections, test environments peculiarities are analyzed.

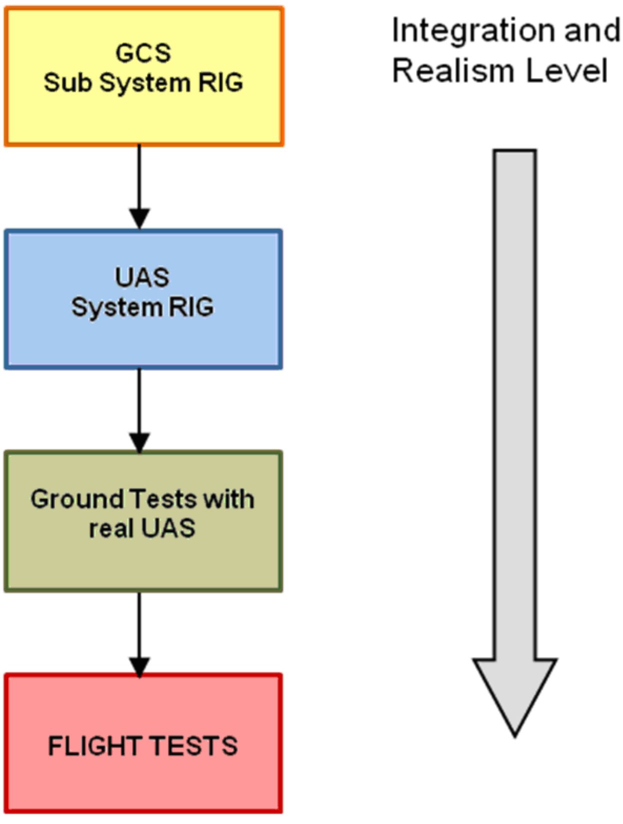


Figure 146. Testing & Integration Process

11.2 GCS Sub System Rig

GCS Sub System Rig (SSR) is made up by a real GCS connected to a simulated on-board segment, and it is used as preliminary GCS testing environment and system simulator for operator training and system demonstration/validation. In particular, since the first steps the real guidance control libraries has been hosted in the simulator, while the avionics (i.e. VSM and navigation laws) software was simulated. Only in a second phase it has been re-hosted at simulator with incremental steps. Datalink is simulated through a latency entered in the simulation model. In Fig. 147 a simulator view is reported (keyboards are present for testing and simulator configuration purposes).

Figure 147. GCS SSR

GCS SSR is the first environment in which a new GCS software has been tested before passing to the system rig where it is integrated with other elements. More in detail, the following aspects have been tested/performed:

- GCS graphics,
- GCS internal moding:
    - NSC function moding,
    - interaction between GCS NSC and SC nodes,
    - SC internal functions,
    - SC function related only to downlink data and not to uplink commands,
- GCS-UAV moding preliminary testing,
- operator evaluation.

Graphics test refers to the evaluation of each symbol requirements (see section 7.2.2 for more details), and more general to the issue reported in the HMI style guide (see chapter 7). Symbol position, color, dimensions, state change moding and interaction quality are an example of considered test points.

GCS internal moding evaluation, instead, involves more issues. Starting from NSC moding, mission planner and navigation format on digital map have been entirely tested at the GCS SSR. This has been possible since the NSC node communicates only with the SC one or an external computer (that simulates an external mission planner or a C4I), while the on-board segment is not directly involved. Therefore, testing these functions at the system rig does not provide any advantages, but only drawbacks due to the absence of the SSR tools. With moding evaluation, it is intended the checks about the functional requirements of each item and the communication protocols if involved. Just to provide an example: considering the mission export from the NSC planner to the SC node, it is checked that pushing the relative controls on the GUI the requested function of export procedure starting is performed, while for the communication standpoint the correct message sequence and content are verified. In particular, the communication protocols have been tested with the aid of specific tools to monitoring the Ethernet traffic (GCS and simulator are connected through Ethernet cables in place of real datalink):

- decoded monitoring tool,
- Wireshark.

Decoded monitoring tool enable a real time monitoring of the Ethernet traffic, with the messages already decoded and displayed on a dedicated GUI. Being a real time device, however, the interface displays only the last sniffed message, and hence it is impossible monitoring a protocol sequence, especially considering that the time between two messages is of the order of milliseconds. A recording with a successive post analysis is however possible. In order to quickly execute the tests of protocols messages, Wireshark is preferable. It is in fact a free "packet-sniffer" tool, that enables the real time messages visualization and analysis on a GUI.

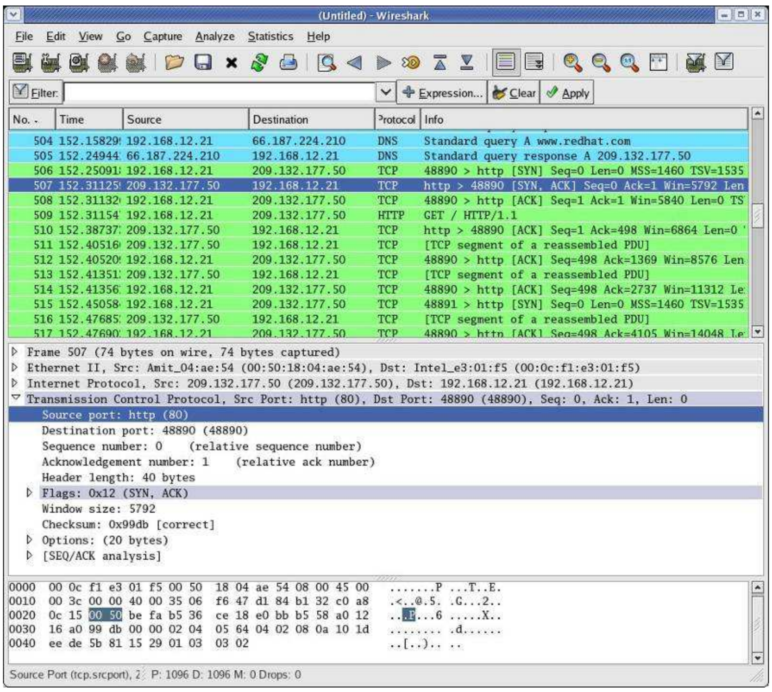


Figure 148. Generic Example of Wireshark GUI

At difference of Decoded Monitoring tool, Wireshark displays each messages byte per byte in hexadecimal form, as visible in the low part of Fig. 148. To retrieve a particular values, therefore, the user shall isolate the relative sequence of bytes in the captured packet referring to the message structure (an example is reported in Fig. 59), and then converting it in a usable form (e.g. decimal for numbers of string for texts). Nevertheless this effort, Wireshark has been fundamental in the integration process, in particular to discover protocol bugs relative to the message content, sequence and scheduling

Finally, internal GCS moding comprises also the internal SC functionalities and the functions relative to downlink vehicle data visualization. The seconds, in particular, have been considered as “GCS internal”, since they are relative to data visualization without message exchange between CUCS/VSM, and with the graphic moding and computations performed on ground. Examples of internal functions are the mission validation checks and the numeric keyboards moding, while for the data visualization there are the Navigation Format and the Vertical Profile. These formats in particular have been mainly tested at the SSR, in order to not engage the very busy system rig with a test not involving bilateral communications with other elements and to use the potentialities of the SSR. Having the full simulator at disposal provides in fact a greater flexibility in the test execution, making possible to quickly change the aircraft state (in terms of position, attitude, etc.), freezing the simulation in order to do a specific test point or to disconnect the GCS by the VSM making a manual setting of the downlink messages. These functionalities have been used for example in the Vertical Profile evaluation, for which some sample terrain profiles have been created (using the software “Global Mapper”) to check the format comparing the expected profile with which actually displayed on the Main Display, placing the vehicle in the foreseen positions and then freezing the simulation. An example of the sample terrain profile is reported below in Fig. 149:

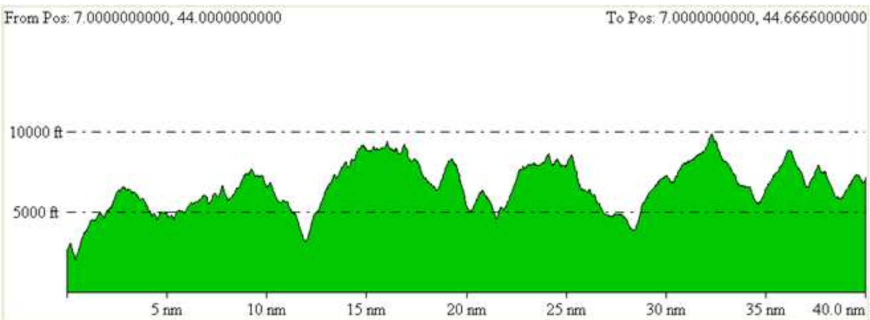


Figure 149. Sample Terrain Profile

Also a preliminary evaluation of the functions involving uplink commands and relative downlink feedbacks (like the guidance control) has been performed at the SSR, especially in order to verify that the correct STANAG message sequences are scheduled in uplink when a command is given through the TSD or HOTAS, and the correct graphic feedback on TSD and Main Display when the VSM feedback are received. These tests represent a sort of threshold to discriminate if the software is able to be tested at system rig, where a more complete and dedicated integration is done.

Last but not least, at the simulator the test pilots have evaluated many times the new FMS when it reached a good level of maturity during the development. More in detail, the evaluation has been provided in qualitative way about generic interface feeling, touchscreen interaction quality, provided functionalities, GUI moding, preliminary situational awareness and workload assessment. Pilot advises and requirements have been translated in software modifications that have improved the system, making the interface closer to the final user expectations according to the User Centered Design principles (see section 7.1 for more details).

11.3 System Rig

System Rig is made up by a real GCS and real on-board avionics (both in terms of hardware components and software), connected to a basic flight simulator for the vehicle dynamics and relative data. This basic simulator has not the flexibility of the full GCS SSR simulator, and in particular the presence of real avionics make not possible adopting some features like the simulation freeze. CUCS and VSM, in particular, are connected with Ethernet cables in place of real datalink.

System rig has been used for the final testing and integration of the FMS with the other system components, before the software installation in the real GCS.

In this environment, in particular, the FMS guidance and configuration functions have been tested. Great care is put in the verification of the STANAG 4586 protocols relative to the guidance commands and the mission upload to the VSM, with dedicated test requirements at this purpose. These tests have been performed in definitive way at the system rig, since in the first integration steps the avionics was simulated at the SSR and therefore there could be divergence between simulated and real software. These software in fact have been developed side by side starting from the requirements, and hence the two final implementations may diverge. In any case, also when the real avionics software has been re-hosted at the simulator, the correct test environment for a full validation remains the system rig where there is also the real on-board hardware, that makes possible discovering problems about scheduling and synchronization between ground and on-board segments. The same Ethernet traffic monitoring tool of the SSR have been used. Ride along the integration tests, also the functions validated at the SSR have been re-tested in a more representative environment.

11.4 Ground Tests

Once the software has been cleared at the system rig, it is installed in the real system and tested with the vehicle on ground and the real datalink. The flight is simulated by a basic portable simulator connected to the vehicle. These tests are the last step before flight and aim to verify the software compatibility in the real system, in particular with the datalink. At this purpose test requirements have involved the check that any possible operator commands are actually performed by the system, verifying their availability by vehicle reactions at the simulator and feedbacks displayed in the HMI. No communication analysis is performed, since the protocols have already been validated at the system rig. Ground tests are usually shorter than that of system rig, since they are only a final check. If a problem is discovered, it is analyzed at the system rig.

Finally, during the design phase, on the real GCS an ergonomics assessment has been performed with the operators about touchscreen position, in order to validate the installation in the real environment, especially taking into account the lighting conditions for the TSD visibility.

11.5 Flight Tests

Definitive system validation has been done with flight tests, in order to verify the system effectiveness in the real operative environment. Activity for flight test has been relative to the definition of the test requirements for the HMI. They are not relative to the system function availability (since this aspect has been already validated before flight), but to a HMI assessment in terms of general operator feeling, global provided workload and situational awareness.

Apart a global interface evaluation, a more detailed judgment for each format has been required to the operators in terms of:

- visibility,
- symbol movement fluidity (when applicable),
- interaction quality (for TSD format),
- interaction feedbacks (for TSD format),
- specific situational awareness,
- specific workload.

CONCLUSIONS

An innovative Human Machine Interface for a MALE UAS Flight Management System has been studied in order to overcome the human factor issues of current interfaces, one of the main causes of UAS mishaps. At this purpose a preliminary analysis has been performed in the first four chapters. Main identified issues are listed below:

- current interfaces do not directly support the execution of mission tasks,
- operator is not guided in the execution of mission tasks,
- interface interaction can be complex,
- related information are split in several formats with consequent visual search workload,
- interface interaction requires an excessive mnemonic load to the operator,
- poor situational awareness about the VNAV profile,
- current automation moding is very complex and therefore the interface suffers of poor transparency (mode awareness issue),
- greater LOA typical of UAS is not well supported by the current interfaces,
- automation mode changes are frequently not perceived by the operators,
- current UAS interfaces are few standardized, with very little application of aeronautical know-how about HMI.

Starting from the above considerations, the interfaces relevant to a large subset of FMS functions have been designed, following the STANAG 4586 as reference standard for the interoperability achievement (see Chapter 5) and the STANAG 4671 for the civil certification. The interoperability is a more and more required feature for new systems, since this capability permits potentially to reduce operational/logistic costs with a single GCS able to control more UAVs, and to enhance the mission effectiveness in terms of exploitation, dissemination and analysis of gathered data. More in detail, the STANAG 4586 provides system architecture, standard communication protocol messages and the structure to define private messages to implement the desired Level Of Interoperability. Although its benefits, the STANAG 4586 is still an early mature standard, and during the work several limitations have been found (see section 5.8). A new issue of the STANAG that takes into account these problems is therefore desirable.
Considering the interoperability requirement and the possibility to easily add new formats/functions (i.e. upgradability characteristic), the interface shall have a structure as modular and parametric as possible. Put together this issue with the complexity of functions to control, the adoption of a Graphical User Interface (GUI) is resulted a natural choice thanks to the flexibility provided by software controls. In this way, concentrating more interfaces typically separated in a manned aircraft (e.g. MCDU, autopilot and radio panels) into a single device is also possible.
In particular, the proposed innovative interface is characterized by the adoption of touchscreens as data entry devices. Touchscreens have been preferred with respect to keyboard plus a cursor control device taking into account the following advantages (see Chapter 6 for the detailed analysis):

- more instinctive interaction,

- greater flexibility with new types of interaction,
- additional displays available (i.e. possibility to visualize further information on demand or emergency backup of fundamental data),
- main display is used only as monitoring device without interaction on it,
- less installation issues.

More in detail, resistive touchscreens have been selected with respect to the other available technologies considering the following issues (see Chapter 6 for the detailed analysis):

- better environmental operative range in terms of temperature, humidity and contaminant resistance,
- MIL-STD-1472 (HMI standard) requires a resistance to the TSD actuation, and therefore the unique compliant type is the resistive,
- the resistance to actuation is a further protection from undesired commands,
- it is cheaper with respect to other types.

Touchscreen use in the aviation is at the beginnings, with few practical applications and many research activities to extend their use. In particular current standards like the MIL-STD-1472 provide poor indication about their use, due to the limited accumulated operative experience.
Realizing a GUI on a touchscreen, in particular, requires the adoption of specific design rules reported in Chapter 7. The main issues to consider are:

- active touch area dimensions,
- type of contact (first or last),
- type of interaction,
- actuation feedback,
- possible overload of the operator visual sensory channel,
- critical commands protection.

In Chapter 8 the formats relative to the vehicle control functions have been presented: guidance, navigation format, vertical profile, communication and system configuration. Starting from the guidance, a complete set for an UAS comprises full automatic modes (default especially in BLOS operation with high latencies), semiautomatic modes (more flexible than automatic and useful especially when the vehicle flies following ATC instructions) and finally advanced sensor slaved modes in which the vehicle position is determined indirectly by the payload (very useful in area of operations for surveillance and monitoring tasks). Manual remote control has still considered, since it is not clear if a future regulation will require it or not for integration in civil airspace, at least as back-up/emergency mode. Studying the human-machine interface for these modes, the issue of mode awareness has been directly taken into account, in order to reduce the problems (and hence the mishaps) due to operator’s poor understanding of automation status and moding. At this purpose the following functional design choices have been taken:

- number of modes at interface level has been reduced as much as possible,

- no automatic mode changes,
- clear and fixed logics for altitude variation control laws (i.e. VNAV profile),
- clear and unambiguous feedback of automation states (especially of automation commands for altitude variation) is provided.

According to the previous considerations the relative GUI has been designed with the real time monitoring on Main Display and the virtual control panel on TSD.
For Navigation Format and Vertical Profile (Main Display formats relative to the navigation and trajectory prediction FMS functions), typical format layouts derived from manned aircraft have been adapted to UASs, taking into account their peculiarities, especially in terms of different route profile and mission situational awareness. In particular, Navigation Format (relative to the LNAV) is configurable by the operator for some aspects like the orientation or the color, in order to be adaptable to different mission contexts or user preferences/expectations. An example is the Compass Rose orientation, preferred by test pilots in Track Up and in North Up by non rated pilot operators. Vertical Profile has been added to increase the situational awareness about VNAV profile like on airliners. Two different terrain profile generation modes have been considered according to the engaged guidance mode and vehicle position. In particular, an automatic switching between them has been foreseen in order to reduce operator workload. The user has however the possibility to force the selection.
Communication and Configuration pages are finally examples of touchscreen flexibility and potentiality in the realization of “smart” interfaces to control complex functions, typically hosted on more physical interfaces/panels in manned aircraft.
In Chapter 9 the issues relative to Mission Planning have been illustrated, beginning from the presentation of a complete mission concept derived from the STANAG 4586 definition. Starting from it, mission planner categories (i.e. external, GCS embedded and on-board) and general planning algorithm issues are analyzed. In particular possible architectures for GCS embedded and on-board replanners have been proposed according to the OODA loop. About the automation management for ground replanners, we have chosen a “by consent” way, considering the support role of the automation, the human will to have the final control authority, the need to share the new route with the ATC in civil airspace operations and the easiness to certificate a system with this strategy. Referring to the proposed architectures, the Management by Consent strategy is more suitable for a GCS embedded replanner rather than an on-board one, since for the latter there are more messages exchanged between GCS and UAV, with consequent latency in new route actuation and bandwidth occupation (especially in case of operator modifications and/or BLOS operations). According to the previous considerations, an on-board replanner becomes convenient only with higher Levels Of Automation, for which it provides to the vehicle the capability to react autonomously at a change in the mission environment/UAV status. Human presence inside the control loop is however considered adopting as consequence a “Management by Exception” strategy, in which the operator has a timeout to put a veto on the automation proposal. In any case there are not adequate rules at this purpose: just to provide an example the STANAG 4671 states only that the autonomous replanner can not take the vehicle in a dangerous condition, but it does not provide any suggestion about the human-automation interaction. Finally Chapter 9 is concluded with the presentation of the GCS embedded TSD planner design, realized in particular taking into account the conclusions drawn from the RAFIV model about the excessive mnemonic load and poor mission task direct support provided by current FMS interfaces. At this purpose proper solutions like prompts in the alphanumeric keyboard, pop-ups and proper color coding have been

adopted. From the mission creation standpoint, each element can be entered on the map with a successive entering of other attributes or directly typing all information in the alphanumeric keyboard (comprised the horizontal position in terms of Latitude and Longitude). First solution in particular has requested the definition of specific interaction laws to distinguish for example between element placing on map, element moving, map panning, pop-up opening, zoom variation, etc. Having studied a planner interface on map, it has been natural to create a real time monitoring format, that is a secondary navigation format on TSD from which a quick replanner function has been considered.

In Chapter 10 the studied advanced planning algorithms are presented in detail, relatively to the following functional areas: datalink coverage, standard search patterns, EO/IR sensor coverage, fuel consumption and performances, mission zones respecting and emergency route in case of vehicle failures. Two macro categories of algorithms can be distinguished: route creation and route validation algorithms. The firsts produce a route optimized for a main objective plus possible secondary objectives, respecting the assigned constraints. The seconds instead validate a route with respect to some parameters. Route validation functions can be used to check both automatic/autonomously created routes for the paradigms not considered during the creation, and manually edited missions. Being these algorithms deterministic, they can be an aid to certificate a planner/replanner in which a route is created by a non-deterministic functions (not certifiable considering the current manned aviation rules). In any case these algorithms have been designed with a structure as modular and parametric as possible, and they form a sort of software library from which several planner modules can be created. In particular the emergency route replanner represents a practical case of human—autonomy interaction, for which also the HMI has been study considering a Management by Consent logic.

First prototypes of the FMS studied interfaces/functions have been realized and integrated in a real GCS, until reaching the flight tests. Integration process has involved many tests in different environments at increasing level of integration and realism: GCS Sub-System Rig (coincident with the full flight simulator), UAS rig, ground test with the real UAS and finally the flight tests. Besides some planning algorithms have been integrated in an external planner for test purposes.

Pilots are the final stakeholders of the developed functions/formats and they have been taken into account during the whole activity in order to create an useful and friendly interface for the users. In particular, they have rated the proposed interface starting from drawings and presentations in the first design stages, passing then to flight simulator evaluations and finally to the flights. Despite touchscreens are not common interfaces in manned cockpit, the pilots get used to them quickly, evaluating positively the proposed interface in terms of provided functions, graphical interface, interaction quality, obtained situational awareness and workload. In particular, the adopted solutions to mitigate the current interface issues have been considered as an significant aid for the user to control an UAV. Also the autonomous replanner – feature really specific of UAS and therefore alien at a first glance for a manned aircraft pilot – has been quickly accepted by them. In particular, pilots have provided many suggestions during the interface study, that have been included into the design. Examples are the guidance demand layout or the indication to balance properly software protection from undesired commands (i.e. confirm pushbutton and or pop-ups) with the interface interaction easiness and quickness.

Although the research has been carried on focusing on UAS, the main outputs can be easily transferred to manned aviation. Touchscreen choice and relative GUI guidelines, in fact, are true also for a manned aircraft, adding specific considerations relative to light conditions (e.g. sun reflection on TSD), aircraft maneuvers (and hence difficult to actuate the TSD) and vibrations. At the same time the proposed formats can be adopted on an aircraft or at least taken as reference to design a specific GUI. Also part of planning algorithms can be adopted, especially the sensor related functions for patrolling aircraft.

More generally, thesis results can be applied with the same logic to the control stations of unmanned ground, sea surface, underwater and space vehicles.

At the end, the results of this work can be the starting point for the following future research activities:

- completion of FMS functions in the interface,
- civil air rules integration in the Mission Planner,
- application of future manned aviation ATM concepts (e.g. SESAR) to UAS FMS,
- develop more complete and advanced autonomous replanner modules (especially on-board),
- working together with the Civil Authorities to define certification rules and standards that cover all aspects relative to the use of touchscreen in aviation,
- extend the use of touchscreen to control other UAS functions not related to the FMS,
- extend the STANAG 4586 considering other UAVs to control (LOI 5) and the relative handover procedure/interface switching mechanisms,
- develop advanced FMS that enable from a single station to control more vehicles or a vehicle plus the relative payload at the same time,
- realize a manned MCDU with touchscreen technology taking into account the relative HMI issues and the future ATM concepts,
- generalize the interoperability concept to different type of unmanned vehicles (e.g. aerial, ground, maritime, etc.) developing the relative Unmanned Vehicles Management interface.

APPENDIX A – DIGITAL TERRAIN ELEVATION DATA

Digital Terrain Elevation Data (DTED) are a standard terrain model initially developed by the US National Imagery and Mapping Agency (NIMA) – now National Geospatial-intelligence Agency (NGA) – for general purposes. Each DTED file is referred to a square of 1° of Longitude for 1° of Latitude, identified by the southwest vertex coordinates. For example the file having as reference coordinates E 007 and N45 refers to the square of Latitude 44° ÷ 45° and Longitude 7° ÷ 8°. Each square is further divided in a grid of different spacing according to the reference Latitude and the precision level. In particular, each hemisphere is divided in five zones, while for the precision three increasing levels have been defined (0, 1 ,2). For each of them, there are the following matrix intervals according to the MIL-PRF-89020B "Performance Specification Digital Terrain Elevation Data (DTED)", 2000 [76].

TABLE I. Matrix intervals for DTED Level 0.

ZONE	LATITUDE	MATRIX latitude		INTERVAL longitude	
I	0° - 50° North-South	30	x	30	seconds
II	50° - 70° North-South	30	x	60	seconds
III	70° - 75° North-South	30	x	90	seconds
IV	75° - 80° North-South	30	x	120	seconds
V	80° - 90° North-South	30	x	180	seconds

TABLE II. Matrix intervals for DTED Level 1.

ZONE	LATITUDE	MATRIX latitude		INTERVAL longitude	
I	0° - 50° North-South	3	x	3	seconds
II	50° - 70° North-South	3	x	6	seconds
III	70° - 75° North-South	3	x	9	seconds
IV	75° - 80° North-South	3	x	12	seconds
V	80° - 90° North-South	3	x	18	seconds

TABLE III. Matrix intervals for DTED Level 2.

ZONE	LATITUDE	MATRIX latitude		INTERVAL longitude	
I	0° - 50° North-South	1	x	1	seconds
II	50° - 70° North-South	1	x	2	seconds
III	70° - 75° North-South	1	x	3	seconds
IV	75° - 80° North-South	1	x	4	seconds
V	80° - 90° North-South	1	x	6	seconds

Figure 150. DTED Matrix Intervals [76]

At our Latitude, for example, there is a post spacing of approximately:

- level 0: 900 m,
- level 1: 90 m,

- level 2: 30.

DTED files are organized in a particular binary format reported in reference [76], and hence a proper decoder function is required to read them. A decoded DTED is a matrix having as value the terrain altitudes (in meters) at grid posts. Location posts, in particular, are determined by the intersection of the matrix rows and columns.
Finally, less precise DTED (i.e. level 0) can be downloaded free from Internet [77].

APPENDIX B – FRIIS'S EQUATION UNITS OF MEASURE

Decibel Watt - dBW

dBW is a unit of power in DB scale referred to 1 Watt (W).

$$P\ [dBW] = 10\ log_{10}\left(\frac{P\ [W]}{1\ W}\right)$$

$$P\ [W] = 1\ W\cdot\sqrt[10]{10^{P\ [dBW]}}$$

Equation 5. dBW – W Conversions

Decibel milliWatt - dBm

dBm is a unit of power in DB scale referred to a 1 mW.

$$P\ [dBm] = 10\ log_{10}\left(\frac{P\ [mW]}{1\ mW}\right) = 10\ log_{10}\left(\frac{P\ [W]}{10^{-3}\ dBm}\right) = 10\ log_{10}\left(P[W]\right) + 30\ dBm = P[dBW] + 30\ dBm$$

$$P[dBW] = P\ [dBm] - 30\ dBm$$

$$P\ [W] = 1\ W\cdot\sqrt[10]{10^{P\ [dBW]}} = 1\ W\cdot\sqrt[10]{10^{(P\ [dBm]-30\ dBm)}}$$

Equation 6.dBm – dBW – W Conversions

Isotropic decibel – dBi

Antenna gains are usually provided with respect to an isotropic antenna, i.e. is an ideal antenna that beams in any direction the same power. According to this, a dBi is "normal" decibel referred to an isotropic antenna.

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