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Cooperative Agricultural Operations of Aerial and Ground Unmanned Vehicles

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***Abstract*—Precision agriculture comprises a set of technologies that combines sensors, information systems, enhanced machinery, and informed management to optimize production by accounting for variability and uncertainties within agricultural systems. Autonomous ground and aerial vehicle can lead to favorable improvements in management by performing in-field tasks in a time-effective way. Greater benefits can be achieved by allowing cooperation and collaborative action among Unmanned Aerial Vehicles (UAVs) and Unmanned Ground Vehicles (UGVs). A multi-phase approach is here proposed, where each unmanned vehicle involved has been conceived and will be designed to implement innovative solutions for automated navigation and in-field operations within a complex irregular and unstructured scenario as vineyards in sloped terrains.**

***Index Terms*—Precision Farming, Unmanned Vehicles Coordination, Unmanned Aerial Vehicles, Unmanned Ground Vehicles**

I. Introduction

In recent years, Unmanned Vehicles (UVs) have been growing rapidly in popularity. Tactical unmanned systems are now used extensively by the military and various security services, while professional unmanned systems are becoming increasingly common in a variety of civilian fields. This expanding use of unmanned systems is due to advances in technology as well as the versatility and reductions in size, risks and costs that remotely operated systems offer as a result of not having a pilot or operator on board. One of the civilian field more interested in exploiting different types of drones is *farming*, which is finally undergoing the so-called fourth agricultural revolution exploiting emerging technologies such as robotics [1] and artificial intelligence [2].

The concept of Agriculture 4.0 consists in the harmonious and interconnected use in agriculture of two different digital technologies: (i) *precision agriculture* for carrying out targeted agronomic interventions, which take into account the farming requirements [3] and the physical and biochemical features of the land [4]; and (ii) *Smart Farming*, i.e. the digital connection between field activities and all the other related processes [5]. The Food and Agriculture Organization of the United Nations (FAO) and the International Telecommunication Union (ITU) have identified the use of unmanned autonomous systems as a crucial technology to support and address some of the most pressing challenges in farming in terms of access to actionable real-time quality data and crop monitoring, as highlighted in the second series of *E-Agriculture in Action* published by FAO [6]. Indeed, both Unmanned Aerial Vehicles (UAVs) and Unmanned Ground Vehicles (UGVs) could represent a favorable alternative to conventional farming machines, whenever clear advantages with respect to traditional methods are provided, in terms of higher efficiency in operations, reduced environmental impact or enhanced human health and safety.

Despite the current situation highlights that in a near future the market for drone-powered solutions in agriculture will reach \$32.4 billion [7], nowadays the adoption of drones is mainly confined to remote sensing applications, such as crop monitoring [8], soil/field analysis [9], and irrigation planning [10]. When more complex tasks are envisioned to be performed by UVs, they typically involve specific and limited scenarios, such as flat terrains covered by crop with homogeneous canopies (e.g. wheat or paddy fields), where operations are mainly performed from the top of the crops [11]. These represent ideal situations, in which the advantage of drones with respect to conventional machine is debatable and far from being completely representative of the real potential of such tools.

Aim of this paper is to devise innovative solutions, in the spirit of Farming 4.0 principles, for extending the use of drones in agriculture to scenarios in which they could represent a reliable and valid alternative to conventional machines or where the latter are not employable. This is the case of sloped areas, soils with low traction, multi-strata crops, and whenever clear advantages with respect to traditional methods, in terms of higher efficiency in operations, reduced environmental impact or enhanced human health and safety, may be envisaged. The adoption of drones for spraying or pruning in these situations may indeed represent the sole alternative to human-made operations.

Autonomous ground and aerial vehicle can lead to favourable improvements in management by performing in-field tasks in a time-effective way. Further benefits may be achieved by allowing cooperation and collaborative action among drones [12], even UAVs and UGVs. Indeed, the adoption of drones, both UAV and UGV, in agricultural scenarios can aspire to become a reality if the validation of their effectiveness is sustained by the contemporary and shared improvement of all those technological gaps identified

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Fig. 1. Collaborative fleet composed by a FW-UAV for remote sensing task and UGVs and RW-UAVs for spraying and shredding operations in sloped vineyards.

by current research projects. Within this framework, it is possible to notice that a crucial point is still missing: the interconnection among the distribution systems/implements and the Guidance, Navigation and Control (GNC) capabilities provided to the drones [13]. Typically, the different research approaches focus only on one of the two topics. For what concern crop protection, an innovative approach should provide equal relevance to both the distribution efficiency and the effectiveness of the GNC scheme, by optimizing the spraying spread (to ensure effective pesticide release with low-risk for human health and the environment, and reducing the amount of pesticide) in relation to the precise definition of the optimal path to follow and robust control of the vehicle (to face external disturbances and avoid collisions). For this aim, the accurate knowledge of the environment layout where drones are operating is crucial. Three-dimensional model of field and crops are a valuable tool to spatially describe the agricultural scenario, with detail at parcel [14], crop row [15], [16] and even plant scale [17], [18]. In particular, the interaction among the distribution system and the GNC setup is twofold: i) on one side, the path-planning scheme takes into account the dispersion sequence and the estimated drift [19]; and ii) on the other side, during the aerial/ground operation, the on-board GNC controls the distribution system in order to optimize the product application, minimize the dispersion and the drift, ensuring robustness to external disturbance. Moreover, the robust control algorithm should, in any case, provide collision avoidance capabilities, thanks to proximity sensors equipped on the drones.

In this paper, a multi-phase approach is proposed, where each UV involved has been conceived and designed to implement innovative solutions for automated navigation and in-field operations within a complex irregular and unstructured scenario as vineyards in sloped terrains. The proposed scenario, represented in Fig. 1 foresees a Fixed-Wing Unmanned Aerial Vehicle (FW-UAV) for collecting aerial images later used to generate low-complexity 3D mesh models of vine rows by processing raw 3D point clouds of vineyards. The proposed methodology is based on a combination of convex-hull filtration and minimal area C-gon design, which allow to reduce the computational burden without compromising the efficacy of such simplified maps (see [15] for more details). Then, the same maps will be elaborated to obtain a simplified version to be uploaded on board of the drones for real-time navigation within the vineyard rows, without losing canopy geometry. These maps will be used to identify online the optimal path that a UGV and a Rotary-Wing UAV (RW-UAV) shall follow within vineyard rows to properly accomplish in-field operations as spraying and shredding while minimizing drift and maximize some given performance indices. For the optimal path planning, a combination of a local path planner and a global path planner is here proposed. The optimal path is then passed to robust controllers which in real time will allow to track the given path avoiding collision with unexpected obstacles. In details, the robust control proposed for the 4 Wheel Steering (4WS) UGV will allow to track the given path while optimizing the velocity of each wheel to minimize the slippage produced by the Ackermann Steering Mechanism (ASM) installed on each axes. On the other hand, for the RW-UAV a fundamental aspect has been identified and will be investigated.

A high-level overview of the work flow of the proposed architecture is provided in Fig. 2. The starting point is the remote sensing mission performed by the FW-UAV to collect aerial images required to obtain the 3D point clouds for map generation. Next, exploiting the algorithm proposed in [15], these data will be properly selected and elaborated *offline* to obtain simplified and low-cost maps to be uploaded on board of the drones and exploited in real-time during operations. These maps will be later sent to the on-board GNC system of both UGV and UAV to properly generate the optimal path drones shall follows to properly fulfill tasks while avoiding collisions. Last, ad-hoc robust controllers provide in real-time the control actions required to properly follow the optimal path despite the presence of external and internal disturbance and uncertainty sources. Each block is described in details in the following Sections.

II. The Selected Scenario

As aforementioned, the proposed scenario envisions the cooperation among a FW-UAV, dedicated to remote sensing tasks, and a fleet of UGVs and RW-UAVs, for UVs-assisted operations such as spraying or shredding, as already proposed in [20] for pest control in agriculture. UGVs and multi-rotors would benefit from the former essential and valuable information related to crop and working environment, such as simplified maps properly derived from big-data analysis (see Section II-B for more details). In particular, a vineyard in Serralunga d'Alba, Piedmont, Italy of about 2.5 ha with latitude and longitude positions ranging between [44.62334 44.62539] and [7.99855 8.00250] (see Fig. 3) has been se-

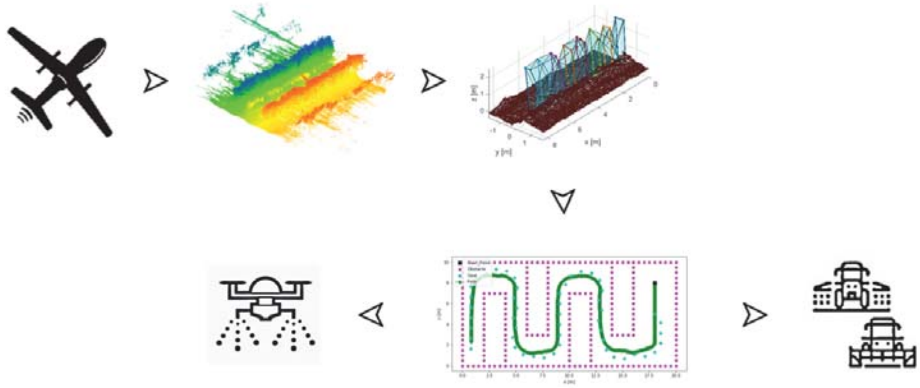

Fig. 2. Collaborative fleet composed by a FW-UAV for remote sensing and UGVs and RW-UAVs for spraying and shredding operations in sloped vineyards.

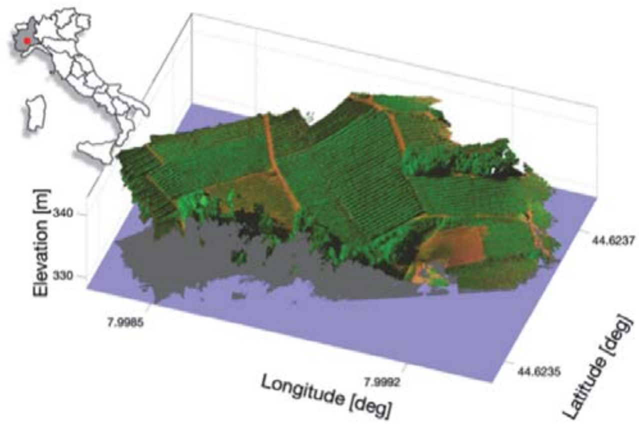

Fig. 3. 3D point clouds map of the considered vineyard region [14].

lected as operating scenario. The vineyard is located on a sloped land with an elevation ranging from 330 m to 420 m above sea level and a predominantly southwest orientation. The vineyard is characterized by wine spacing of 0.9 m and inter row space of about 2.5 m. For the remote sensing mission, the relative height of the UAV flight with respect to the terrain will be set to 35 m in compliance with previous monitoring mission performed on the same area (e.g. see [14]). Analogously, the trajectory to follow will be identified by a set of waypoints, fixed with respect to the vineyard Geographic Information System (GIS) map accordingly to the picture resolution required and the terrain geometry.

A. *FW-UAV for Remote Sensing Task*

To acquire the aerial imagery necessary to generate high density 3D point clouds of selected crops, the MH900 Remotely Piloted Aircraft System, designed by MAVTech S.r.l. mainly for reconnaissance and surveillance territorial monitoring will be exploited. The MH900, represented in Fig. 4, is a fixed wing, tailless integrated wing-body configuration UAV, which guarantees an adequate aerodynamic efficiency providing satisfactory payload capability and good flight performances, such as mission range and endurance, with respect to other existing concepts. Moreover, being a scaled UAV platform with a wingspan of 900 mm and a weight of about 1.2 kg, it provides flexibility with reduced cost and risk. A flight control system, providing automatic stability, GNC capabilities, will be installed on the vehicle autopilot and will allow to evaluate flight parameters either in real time or in post-flight mode. The MH900 cruise airspeed ranges from 12 m/s up to 15 m/s, has an endurance of about 30 min, and is able to tolerate winds up to 40 km/h. With a payload capability up to 250 g, the MH900 will be equipped with a Parrot SEQUOIA+ multi-spectral camera (72 g of weight) to acquire aerial images with a resolution up to 4608 x 3456 pixels, thanks to its innovative brightness sensor.

Fig. 4. The MH900 FW-UAV over a vineyard (credit:MAVTech).

Combining the need of tackling mission, system and mechanical constraints with the need of guaranteeing robustness to external, bounded disturbances, which could compromise the controller performance, several robust MPC techniques have been proposed for remote sensing applications, e.g. [21]–[24]. Hence, the main objective is to rely on a low-cost and high-throughput crop monitoring system, which uses a FW-UAV as an operating platform. The use of a fixed-wing UAV is justified by the need to cover a huge terrain extension and, in combination with the payload (i.e. sensor), the information can be post-processed or processed in real time to obtain an operative map. Thus, the UAV can incorporate in its system the designed map and optimally distribute, through "capsule dropping" techniques, seeds, fertilizer and so on. The key feature of the proposed approach, which relies on the approaches already experimentally validated in a space framework, i.e. [25] and [26], is the design of ad-hoc guidance and control algorithms, e.g. see [27] and [28], able to perform the desired mapping, guaranteeing robustness of the system to external disturbances, optimizing the path, for crop monitoring.

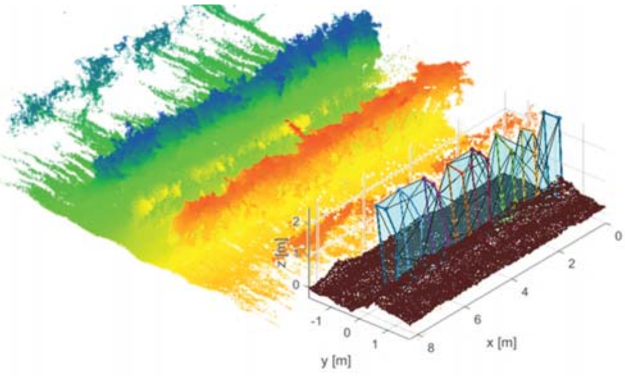

Fig. 5. From 3D point clouds to simplified maps (source: DISAFA [14]).

B. Simplified Maps

Fully autonomous navigation and operations within complex, irregular and unstructured scenario require the development of ad-hoc, effective path planning and navigation algorithms. Moreover, accurate spatial description of the environment in which the drones are going to operate, e.g. inter-row width and crop canopy position and shape to avoid damage, are mandatory to properly accomplish given tasks. Lately, enhanced performance have been achieved exploiting 3D path planning thanks to the exploitation of 3D models as point clouds, i.e. a set of points in an arbitrary reference frame which represents the surface of given objects (see e.g. Fig. 5). These maps can be generated using 3D sensors of by photogrammetry (as in the specific case proposed in this paper) and combining 3D point clouds with proper algorithms for detecting and mapping crops and identifying soil and obstacles. For example, the 3D point cloud was exploited in [9] to derive crop canopy descriptors for estimating the Leaf Area Index (LAI) by a multivariate linear regression model.

The drawback of these approaches rely on their complexity and computational demand for the real-time exploitation of point clouds information in the field. Indeed, when considering cooperating machines and scenarios including drones, data reduction is relevant for enabling rapid communication and data exchange between in-field actors. For this reason, an innovative modeling framework to semantically interpret 3D point clouds of vineyards and to generate low complexity 3D mesh models of vine rows is proposed. This innovative methodology reduces the amount of instances required to properly describe the spatial layout and shape of vine allowing a drastic reduction of the amount of data required without losing relevant crop shape information. An example of how the 3D maps, derived from point clouds, can be simplified is represented in Fig. 5 and more details can be found in [15].

C. 4WS UGV for Spraying and Shredding Operations

Over the last century, agricultural machines have become wider, heavier and more powerful to increase the productivity. However, their impact on soil has been increased and weight is the major limitation to a further increment of machines sizes. For these reasons, agricultural mechanization is moving toward smaller but more flexible machines, which can perform selective operations in accordance to crop status.

To contribute to the technological progress in field application, the Department of Agricultural, Forest and Food Sciences of Università di Torino, is developing a model of a four wheel steering UGV (see Fig. 6) to provide a reliable automatic machine that could completely substitute a vineyard tractor. The UGV has an intelligent traction system, with an Ackermann Steering Mechanism (ASM) on both front and rear axes plus an independent motor on each wheel, able to enhance the traction performances (efficiency and mobility) on wet soils, conjugated with a battery-life (that will be tested in real applications) to guarantee long work sessions.

Fig. 6. The 4WS UGV designed and realized by Università di Torino (credit:DISAFA).

1) Optimal Path Planning for UGV and Multi-Rotor: To ensure autonomy to UVs, it is fundamental to guarantee the ability to generate optimal paths according to the current drone location, mission tasks to comply, environmental, safety and kinematic/dynamical/mechanical constraints to fulfill and the available maps uploaded on board the drone. The criteria of optimal path for drone is often based on one or more features such as shortest distance, low risk, smoothness, maximum area coverage, and fewer energy requirements considering different application constraints. For this specific case, the selected path planning architecture, which will aim at generating a feasible and optimal path for both the UGV and RW-UAV, will be split into a local and a global path planner.

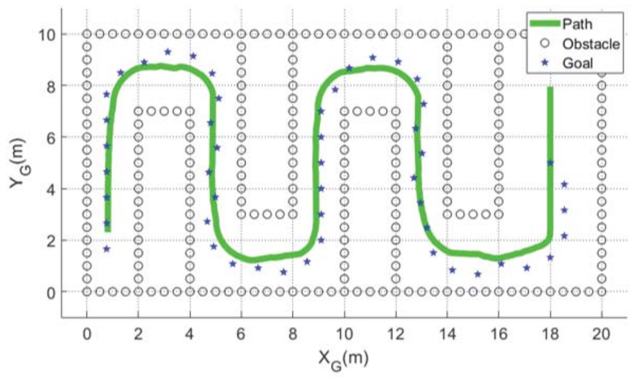

Fig. 7. Preliminary results of local and global path planner for UGV and UAV.

The Dynamic-Window Approach (DWA), based on a receding-horizon scheme and described in [29], has been exploited as local path planner because of its capability to generate a smooth and optimized path for the robot . The typical issue of DWA techniques related to local minima has been overcome combining the local path planner with a Rapid Random Exploring Tree (RRT*) algorithm as global path planner. Moreover, in both planner the typical kinematic constraints have been enforced to guarantee the generation of feasible paths. The preliminary results are represented in Fig. 7.

2) Tracking Controllers for UGV and Multi-Rotor: In the last decades, four wheel steering (4WS) vehicles have been designed for a variety of applications. Indeed, a vehicle that has the possibility of steering with all wheels has two great advantages: i) at low speed, front and rear wheels turn opposite side, thus reducing turning radius and improving steering flexibility; and ii) at increasing velocity, front and rear wheels turn on the same side, thus reducing vehicle side-slip angle, yaw rate and heeling angle while improving the handling stability.

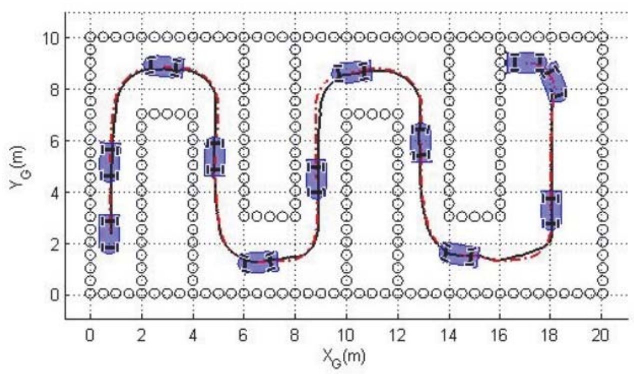

Fig. 8. Example of UGV following optimal path thanks to a cascade of controllers.

When moving into a complex field, the UGV is constrained to move into narrow spaces following an optimal trajectory to guarantee the fulfillment of some performance indices (defined according to the mission tasks) and to avoid obstacles along the path. At this end, an ad-hoc control strategy has been designed and applied, as shown in Fig. 8, to pursue the automatic tracking of the optimal path and to optimize the velocity of each wheel to minimize the slippage produced by the ASM.

D. RW-UAV for Aerial Spraying Operations

To ensure a proper bio-pesticide distribution as well as spraying compliance related to the application requirements [30], it is mandatory to provide optimal and efficient GNC capabilities to the RW-UAV. To this end, flyable GNC schemes shall be implemented on board of the UAV autopilot to guarantee high efficiency and manoeuvrability in precision farming, making UAVs a thrilling and very promising alternative to common aerial vehicles, typically adopted for agricultural applications (see Fig. 9).

Fig. 9. Prototype multi-rotor flying within vineyard rows.

It is crucial at this end to combine the analysis of interactions between spray nozzle configuration (technology, geometry, operating pressure, droplet size distribution) and rotor/multi rotor induced flow with the optimal definition of the path-to-follow within vineyard rows as well as the design of the control strategy, to guarantee the fulfillment of mission, system and safety requirements despite the presence of external and internal disturbance and unmodelled uncertainty sources. This will require the exploitation of advanced control techniques, which will combine robust optimization and predictive control strategies while targeting reduced control effort and computational load without compromising drone endurance and performance. The main class of control algorithms that will be investigated involves model predictive controllers, because of their ability of explicitly handling constraints. The philosophy of MPC can be described simply as follows. Predict future behavior using a system model, given measurements or estimates of the current state of the system and a hypothetical future input trajectory or feedback control policy. Further details on MPC design can be found in [31].

III. Main Conclusions and Future Works

Autonomous agricultural vehicles represent the next logical step in the automation of crop production, if safety and liability can be guaranteed. In that case, the exploitation of both aerial and ground vehicles for complex in-field operations such as spraying and shredding could become a reality in the near future. In this work, a promising scenario is proposed in which several unmanned vehicles are called to cooperate in a complex environment, i.e. a sloped vineyard, to provide a reliable and valid alternative where conventional agricultural machines are not employable.

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