A Robust and Optimal Multidisciplinary Approach For Space Systems Conceptual Design

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Abstract

The problem

Modern approaches to space project management and execution aim at assuring the harmonic balance of interests, since space projects are always more and more value oriented and cost constrained. The management of stakeholders' needs, project schedule and requirements constitute the pillars for the success of a programme.

The current trend of space industry to the Space 4.0 era, pushes the space mission design process towards a multi-stakeholder environment. The increased number of stakeholders and interconnections among them, together with their different and complex needs, increase the complexity of the design process, especially in early phases of the mission lifecycle. The multiple stakeholders' involvement, like public space agencies and private enterprises, is a positive fact, giving the opportunity to shape together the next space exploration targets, but at the same time turns the decision-making process much more complicated. It is indeed during the early design phases that not only the knowledge about the system but also the effects of decisions are affected by the highest degree of uncertainty. The early decisional scenario is also exacerbated by the fact that decisions taken at this stage have huge delayed costs associated with them.

The goal and the method

It is thus necessary to have a clear definition of the problem under analysis, especially when dealing with the initial problem definition. State of the art shows that more detailed definition can be robustly obtained thanks to the generation and exploration of design alternatives with respect to social accepted figure of merits. Nonetheless, it is necessary that this process considers that the design involves various individuals, who take decisions affecting one another. Throughout history, several design approaches have been developed and applied within the space industry and agencies in order to increase the design effectiveness. The most promising approach for dealing with multi-stakeholder scenarios is offered by Concurrent Engineering. This design approach provides a better design process performance, taking full advantage of modern information technology and team management techniques. In this approach, the complete design team, composed of technical domain specialists and external stakeholders, starts working in a quasi-parallel execution on different aspects of the project, already at the beginning of the design process.

Taking full advantage of concurrent engineering approach and with the goal of enhancing the benefits provided by the approach itself, this doctoral research developed a concurrent design methodology which aims to speed up and enhance the effectiveness of space missions conceptual

design. Exploiting NASA JPL concept maturity level, the methodology is built to rapidly evolve the maturity of the design from concept maturity level 1 (born of the idea) to level 7 (integrated preliminary baseline) while guaranteeing the project technical feasibility and the stakeholders' needs satisfaction.

The developed methodology, named *Multi stakehOlder NEgoTiation space exploration (MONET)* encompasses two principal phases: a preliminary concurrent engineering study and a follow up concurrent engineering session.

In the concurrent engineering study, the methodology assists systems engineers and, more in general, stakeholders with the generation and exploration of several design alternatives through a so-called negotiation space. The proposed methodology emulates a collaborative game, in which the negotiation among stakeholders can be optimized in order to balance all the needs and reducing the design iterations needed to satisfy all the different and complex needs involved in the project. The exploration and generation of the negotiation space is carried out by exploiting advanced tradespace exploration techniques, utility theory, and evolutionary algorithms (e.g. genetic algorithms and pattern search optimization) within multidisciplinary optimization, aiming to the maximization of both team social welfare and single stakeholders perceived utility.

Once a reduced set of optimal negotiated designs is selected, each design is than analysed in more details during the concurrent design session. In order to assist the engineers during the concurrent design process, the methodology includes a harmonic integration of artificial intelligence in the form of knowledge based expert systems. This artificial intelligence algorithm, combined with local domain tradespace exploration and autonomous generation of virtual reality, results able to assist the team of engineers during the early decision-making process.

The results

The complete methodology has been implemented into a Concurrent Engineering System (CES) at Politecnico di Torino. The CES is one of the first academic concurrent engineering systems in Europe and it is a smart and flexible facility used for both research and educational purposes. Researchers and students of PoliTO can access the CES with their own credentials and participate in the design sessions using their laptops as clients of the integrated ESA's Open Concurrent Design Tool. In addition, system and mission design tools have been developed, updated and validated throughout their applications on different CES mission studies.

To highlight the benefits of the proposed methodology, the thesis presents, as test case, the design of a CubeSat mission for the observation of Lunar radiation environment. To validate the goodness of the negotiated design solution, a robustness analysis, via epoch-era methods, has been also carried out assessing the value changeability of design solutions. Results show that the methodology ensures inter-compatibility and satisfaction among stakeholders while guaranteeing the technical feasibility of the negotiated design.

Conclusions

The methodology results suitable to handle multi-stakeholder problems at system level and, at the state of the art, provides support to the engineering team in the decision-making process, with inclusion of:

1) novel technologies (such as AI-based techniques) and methods (MDO for tradespace exploration) integrated into a single environment. The integration of these technologies and methods

within a collaborative game framework enables the modelling and optimization of negotiation processes into design alternative exploration

2) approaches tailored for small satellites design, including CubeSats (e.g. simplified spiral model, dedicated calculation sheets)

3) standardisation of session objectives and execution (application of concept maturity level).

4) While a first attempt of integration of Virtual Reality is already present in the current version of the CEF, further development in this direction is seen as a possible improvement of any concurrent design environment.

Another import achievement of the research is represented by the application of the Concurrent Engineering approach and methods in the academia, with involvement of the students as active participants in the design sessions. To this respect, the CEF has been successfully used in the first European Concurrent Engineering Challenge organised by ESA in 2017.