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Basis for a methodology for roadmaps generation for hypersonic and re-entry space transportation systems

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A R T I C L E I N F O

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A B S T R A C T

This paper presents the very first steps of a methodology aimed at supporting the generation and update of technology roadmaps developed in close cooperation between Politecnico di Torino and the European Space Agency, here focusing on the map elements derivation and characterization in order to simplify the activities that will follow. Roadmapping activities are becoming crucial in several domains dealing with complex systems as well as an urgent demand of a rational process starting from the identification of Stakeholders and relative needs and leading the growth of technology readiness levels has been noticed. This research study seems to be suitable for application in the advanced transportation domain, especially in the aeronautical and aerospace sectors.

In detail, this paper proposes a rational generation of a series of elements that can potentially be involved in the definition of technological roadmaps for re-entry space transportation systems. Indeed, today, there is an important momentum, at national and institutional level, on studying/developing demonstrators and/or experimental new vehicles and propulsion systems targeting different kinds of missions, all around the world but especially at European Space Agency level.

After a brief overview of the major activities related to reusable space transportation system carried out in Europe, the paper focuses on the proposed Systems Engineering based methodology for the generation and combination of the main four pillars (i.e. elements) involved in a roadmap: i.e. Operational Capabilities, Technology Areas, Building Blocks and Mission Concepts. These elements will be derived, characterized and stored according to the future planning needs. The second part of the paper presents the application of this logical methodology to the selected case study, to derive, track and manage the previous pillars. The paper concludes anticipating the following steps that will lead to the technology roadmaps preparation based on the methodology described here. Moreover, the exploitation of a well-defined methodology can allow reaching optimal development strategy, minimizing costs and enhancing the public consensus with respect to space initiatives.

1. Introduction

An important effort has been performed by the European Space Agency, ESA, in the last few years to develop comprehensive European Exploration Technology Roadmaps and an associated review tool (Saccoccia et al., 2012) in the field of space exploration. Politecnico di Torino in collaboration with ESA has been working for a few years to the definition of a rational and versatile methodology to generate and update technology roadmaps (Cresto Aleina et al., 2015; Cresto Aleina et al., 2016a; Cresto Aleina et al., 2017a). The methodology is flexible enough to adapt to different domains dealing with complex transportation systems, like automotive, aeronautics or railway. The basic methodology for technology roadmaps generation and update has been furtherly enhanced by its extension to re-entry space transportation systems. The development of the complete process of the methodology, that starts from the roadmap elements definition and characterization and proceeds up to the TRL increase path(s) definition and eventually to results evaluation, has been finalized and the main roadmap elements of interest for ESA have been derived specifically for re-entry space transportation systems. To define a roadmap in this particular field means to define a mission-oriented roadmap in the context of an ongoing large-scale collaborative programme. The paper

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Nomenclature

C_1	Operational Capability derived through (1)
C_2	Operational Capability derived through (2)
mf	Mission Feature
N	number of Mission Features types
pt	Performance Type

gives an overview of the complete methodology and describes the process that has led to the lists of the roadmap's elements, focusing on the definition of an element derivation process able to simplify and support the methodology in the definition of a database able to ease the roadmap derivation process (Cresto Aleina et al., 2016a; Cresto Aleina et al., 2017a). Indeed, neither the content of the basic elements nor technology roadmaps specific for hypersonic and re-entry systems and agreed upon within the scientific and engineering community, have so far been developed in Europe: to start a roadmapping activity in this context preliminary activities have to be carried out, foreseeing common and standardized inputs. In addition to the methodology for technology roadmaps generation and update, the research activity envisages the development of a flexible and easily updatable database for hypersonic transportation and re-entry systems, strictly connected to the methodology with a structure that closely mirrors the same basic elements. Other examples of similar or comparable initiatives at European level do not exist today, for this reason, this roadmapping effort and the related database represent a fundamental step to preserve the European heritage of hypersonic and re-entry space transportation systems.

The hypersonic and reusable re-entry space transportation field is a highly competitive field, especially in Europe. The mastering of technologies associated to hypersonic transportation and re-entry, for future human or robotic, is a mandatory requirement for Europe to stay competitive in a very innovative and dynamic environment worldwide. The design of space vehicles leads to more stringent reliability and safety requirements when humans are involved in the systems and when dealing with vehicles operating in the existing Air Traffic Management (ATM). Such requirements have to be satisfied whenever the vehicle has to cross atmospheres in order to perform an ascent or a safe entry, in particular during Earth return at the end of a super-orbital trajectory. Despite to other nations such as Russia and US, Europe has a limited experience on controlled re-entry with humans on board.

Indeed, contrary to other major space-faring nations, Europe does have access to space, but only limited experience associated with hypersonic, (re-)entry and landing vehicles on Earth and planets and/or on their moons with atmosphere (e.g. the missions of Beagle 2 (Pullan et al., 2003) and Exomars 2016/Schiapparelli on Mars -not successful-, and of Huygens on Titan in 2005 (Clausen et al., 2002)). In 1998, as part of the run-down Manned Space Transportation Program (MSTP) ending the Hermes related work, ESA has flown Atmospheric *Re*-entry Demonstrator (ARD) (Cazaux et al., 1995), an Apollo-like capsule that performed a suborbital re-entry path. More recently with Phoenix (Germany) (Obersteiner, 2001) and Unmanned Space Vehicles (USV) (Italy) (Russo et al., 2002), Europe has performed some flight experiments on Guidance, Navigation and Control (GNC) during the landing phase for winged space vehicles. Furthermore, with Sharp Edge Flight Experiment (SHEFEX) (Germany) (Longo, 2009; Steffes et al., 2012) Europe has been investigating the potential of very high Lift over Drag configurations for space vehicles, based on a sharp edged faceted concept. Recently, following a sub-orbital flight path, ESA performed a highly successful earth-atmosphere re-entry flight experiment based on the Intermediate eXperimental Vehicle (IXV) (Ramos et al., 2015; Tumino et al., 2008). In addition, only some heritage is available from these and other past programs such as Sänger (Kuczera et al., 1991), Hermes (Trella, 1989), X-38 (Dale Reed, 1997), and IXV's follow up Space Rider (Massobrio and Rufolo, 2016).

In the past few years, commercial private initiatives (in particular in the USA) have developed and are commercializing vehicles capable to perform many kinds of missions including Earth re-entry and, in case, partial re-usability of vehicle elements (Commercial Orbital Transportation Services, 2014; FAA, 2016). This is a potential game changer for future space flight and this approach seems to penetrate even the American military launch market. Europe is missing comparable initiatives, although at least some private developments of commercial character are moving significant steps, i.e. Reaction Engine Limited (UK) with Skylon (Varvill et al., 2004), S3 (Switzerland) with Soar (Forczyk, 2015), Airbus D&S (Luxemburg) with its TBN and to certain extend XCOR (USA/NL) with the Lynx Mark I & II vehicles (XCOR Aerospace, 2012). In Europe, costly and risky new technological developments are still mainly left to government-financed projects.

In the specific area of reusable vehicles in Europe, many technology developments have been demonstrated on ground. Examples are like the Hermes programme (Bayer, 1995), the X-38-related cooperation with NASA (Puettmann, 1999), the Future European Space Transportation Investigations Programme (ESA-FESTIP) (Kuczera et al., 1996) in the past, and the Future Launchers Preparatory Programme (ESA-FLPP), in which IXV was initiated (Chavagnac et al., 2006), EXPERT (Massobrio et al., 2011) project and the inflatable re-entry demonstrator program IRDT (Wilde and Walther, 2001) today. In addition, there is an important momentum in Europe, at national (institutional and private) and European level, on developing demonstrators and/or experimental new vehicles and propulsion system targeting different kind of missions. These include vehicles and dedicated propulsion systems for suborbital and trans-atmospheric missions, vehicles and propulsion systems for servicing the Low Earth Orbit (LEO) (spacecraft deployment and retrieval) and the International Space Station (ISS) (supplies, experiments and transport of astronauts) and vehicles for human space exploration on large scale.

In this European complex scenario, it seems clear that the conditions exist for ESA to coordinate in a unique roadmap, a set of activities for technology development and in-flight validation of hypersonic and re-entry space transportation systems.

In particular, the paper presents the preliminary results of a research activity carried out by Politecnico di Torino in support to the work on-going at ESA on the elaboration of hypersonic and re-entry space transportation systems technology roadmap. The goal of the research activity is the development of a logical methodology, based on System Engineering theories, such as Functional Analysis, Concept of Operations (ConOps) and Decision Analysis (Cresto Aleina et al., 2016b; Cresto Aleina et al., 2016c; Stesina et al., 2017; Viola et al., 2012), to generate and update technology roadmaps and speed up the entire process. Surely, being able to propose at least a draft roadmap in early design phases can ease the design itself and to speed up this draft roadmap definition stakeholders' involvements can be at least reduced, proposing to them a rational roadmap to be reviewed.

Considering this context, the methodology for technology roadmapping shall interface with a dedicated database rather than with a group of experts to fully and easily exploit explorative methods (i.e. based on the exploration of all possible scenarios) rather than normative methods (i.e. based on the formulation of preferred scenarios) (Kleine and Braun, 2014). Therefore, even if there are many methods able to support this type of roadmapping activity (Carvalho et al., 2013; Kleine and Braun, 2014; Moehrle et al., 2013), not all of them are applicable to the case study here presented, i.e. hypersonic and re-entry space transportation systems. Considering the specific application field, a method has to be defined able to manage it correctly and this dealing with a mission-oriented roadmap in the context of an ongoing large-scale collaborative programme. In a similar context stakeholders coming from different companies, that are independent between them but involved in the same programme, can have contrasting specific interests that can limit the roadmap efficacy and can slow down the