Acta Astronautica 128 (2016) 21–32

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/aa

Reusable space tug concept and mission

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ARTICLE INFO

Article history:
Received 7 January 2016
Accepted 4 July 2016
Available online 5 July 2016

Keywords:
Conceptual design
Space Tug
Functional Analysis
Concept of Operations

ABSTRACT

The paper deals with the conceptual design of a space tug to be used in support to Earth satellites transfer manoeuvres. Usually Earth satellites are released in a non-definitive low orbit, depending on the adopted launcher, and they need to be equipped with an adequate propulsion system able to perform the transfer to their final operational location. In order to reduce the mass at launch of the satellite system, an element pre-deployed on orbit, i.e. the space tug, can be exploited to perform the transfer manoeuvres; this allows simplifying the propulsion requirements for the satellite, with a consequent decrease of mass and volume, in favour of larger payloads. The space tug here presented is conceived to be used for the transfer of a few satellites from low to high orbits, and vice versa, if needed. To support these manoeuvres, dedicated refuelling operations are envisaged. The paper starts from on overview of the mission scenario, the concept of operations and the related architecture elements. Then it focuses on the detailed definition of the space tug, from the requirements' assessment up to the budgets' development, through an iterative and recursive design process. The overall mission scenario has been derived from a set of trade-off analyses that have been performed to choose the mission architecture and operations that better satisfy stakeholder expectations: the most important features of these analyses and their results are described within the paper. Eventually, in the last part of the work main conclusions are drawn on the selected mission scenario and space tug and further utilizations of this innovative system in the frame of future space exploration are discussed. Specifically, an enhanced version of the space tug that has been described in the paper could be used to support on orbit assembly of large spacecraft for distant and long exploration missions. The Space Tug development is an activity carried on in the frame of the SAPERE project (Space Advanced Project Excellence in Research and Enterprise), supported by Italian Ministry of Research and University (MIUR), and specifically in its STRONG sub-project (Systems Technology and Research National Global Operations) and related to the theme of space exploration and access to space.

Abbreviations: Altec, Advanced Logistics Technology Engineering Center; AOCS, Attitude and Orbit Control Sub-system; ASI, Agenzia Spaziale Italiana (Italian Space Agency); CIRA, Centro Italiano Ricerche Aerospaziali (Italian Center for Aerospace Research); CMFS, Centro Multi-Funzionale Spaziale (Multi-Functional Space Centre); ConOps, Concept of Operations; DMS, Data Management Sub-system; DRM, Design Reference Mission; ELV, European Launch Vehicle; EPS, Electrical Power Sub-system; ESA, European Space Agency; FFBD, Functional Flow Block Diagram; GEO, Geostationary Earth Orbit; GNC, Guidance Navigation and Control; I/F, Interface; I&T, Integration & Test; IXV, Intermediate eXperimental Vehicle; LEO, Low Earth Orbit; MCC, Mission Control Center; MIUR, Ministero dell'Istruzione, dell'Università e della Ricerca (Italian Ministry of Research and University); MLI, Multi-layer insulation; MSC, Mission Support Center; P/L, Payload; PoliTo, Politecnico di Torino; PoliMi, Politecnico di Milano; PRIDE, Programme for Reusable In-orbit Demonstrator for Europe; RCS, Reaction Control System; SAPERE, Space Advanced Project Excellence in Research and Enterprise; STRONG, Sistemi Tecnologie e Ricerche per l'Operatività Nazionale Globale (Systems Technology and Research National Global Operations); SW, Software; TAS-I, Thales Alenia Space - Italia; TCS, Thermal Control Sub-system; TT&C, Telemetry Tracking and Control; UniPa, Università degli Studi di Padova; VEGA, Vettore Europeo di Generazione Avanzata (Advanced Generation European Carrier Rocket)

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http://dx.doi.org/10.1016/j.actaastro.2016.07.003
0094-5765/

1. Introduction

In recent years, international roadmaps show an increasing interest in a new space system concept: the space tug. A space tug is a particular spacecraft that can be used to transfer satellites from Low Earth Orbit (LEO) to higher operational orbits; this would allow reducing the platform mass (mainly due to less performing propulsion subsystem), in favour of larger payload mass. The interest of space agencies and companies in this type of system is not only related to orbital payloads transfer, but it is also due to several other applications.

For example, an important aspect to be considered is that space is becoming more and more crowded, and in this perspective the use of an on-orbit system developed for generic applications and adaptable to a specific critical situation would give the opportunity to face maintenance and refuelling problems without of the need of additional dedicated systems. In addition, a similar system can be exploited also to retrieve or remove space debris. Finally, a Space Tug system is an important building block in missions related to space exploration: issues regarding the assembly of large spacecraft can be solved using this on-orbit system, providing a solution to one of the most challenging aspects related to space exploration in the future [1,2]. An additional application can be related not only to large space systems but also to smaller ones: indeed, it is possible to consider the use of small launcher combined to a Space Tug to deliver in higher orbits also CubeSats or other Small Satellites for interplanetary missions, so designed to operate in orbit not easily reachable by small launchers [3]. In this framework, the development of a new element like a Space Tug is desirable [4].

Usually, Earth satellites are released in a non-definitive low orbit, depending on the adopted launcher: in this case, the payload has to be designed with a propulsion system able to perform the final transfer. The use of a reusable tug system with an adequate propulsion system would be a way to increase the payload mass, giving the opportunity to exploit the Italian VEGA launcher at a larger extent. Indeed, relying on the support of a pre-deployed system such as a reusable space tug in charge of performing the transfer of the satellite platform from a lower orbit to the target orbit, allows minimising the propulsion on the satellite and, therefore, maximising the payload mass capability.

A space tug design is one of the outputs of SAPERE project and specifically of its STRONG sub-project. STRONG is related to the theme of space exploration and access to space and is the frame in which this activity is performed. This project has the objectives both to improve the national space operability in terms of access to space and to increase the Italian industrial capability to realise a Space Tug. In particular, the space tug discussed in this paper is an unmanned system with the main purpose to support satellites deployment on orbit. In addition, another mission scenario to face with is the possibility to retrieve on Earth significant payload samples by means of an operative reusable vehicle, such as for example an evolution of IXV (Intermediate eXperimental Vehicle), PRIDE. In order to better describe the design activity performed on this kind of system, the paper starts with the description of the methodology applied in the design of the space tug and the STRONG system (Section 2), before applying it to the case study. In Section 3 the space tug conceptual design is described. The main outputs of this section are the tug configuration, in terms of subsystems composing it, the mission scenario and mass budget. Eventually, main conclusions are drawn (Section 4).

2. Design methodology

The objective of the space tug presented in this paper is to improve the national space operability in terms of access to space by providing a transportation system capable to transfer satellites platforms from low orbits, where they are released by launcher, to higher operational orbits and back, if needed. This objective may need a particular un-manned pre-deployed system, the Space Tug. This system has to be correctly designed in order to fulfil all the needs and the objectives of STRONG project. In particular, the design process here presented is the typical conceptual design process in Systems Engineering. In this process the main output to be obtained is the definition of the main requirements definition, taking into account all main activities that such a system has to perform to be compliant with stakeholders' needs, regulations and other imposed constraints as, for example, the environment. The core element of the design process here proposed is the Functional Analysis, used to define activities and products able to perform them, according to a System Design Methodology [5–8] (Fig. 1). In particular, at the end of the Functional Analysis the system architecture and the main requirements that drive the system design itself are fully described and listed [9]. To this purpose, the basic tools of the Functional Analysis can be used to derive the requirements that will drive the systems design. The requirements that can be derived are many and can be grouped in specific categories, as shown in Fig. 2. For example, the main category of top-level requirements, i.e. mission requirements, directly stem out from the mission statement and mission objectives and constraints, which are a description of the crucial issue of this paper study and of the major limitations in the systems design. In addition, other top-level requirements, for example programmatic requirements, or constraints are imposed from the analysis of all the actors involved in this project (defined as Stakeholder [10]). However, these two first analyses are able only to define data in a high level of detail, identifying the main purpose to be performed, constraints of the design and impositions. To increase the detail of the design and define a list of all the activities and the products that are required, the Functional Analysis should be introduced.

The requirements definition process is important, considering that requirements represent the basis of the whole system design. For this reason, their derivation has to be part of a rational and logical process, in order not to forget drivers or constraints in the design that could eventually lead to unsuccessful choices. Also for this reason a requirements categorisation is necessary: having all the requirements divided into categories can reduce possible repetitions and helping their verification. For this reason and as already explained, requirements have been subdivided into many categories as shown in Fig. 2 [6,10,11].

In more detail, the first activity to perform, before writing down the requirements, is the definition of the main objectives of the project. As already explained and as suggested in [10], they can derive directly from the Mission Statement and the stakeholders' analysis. In particular, primary Mission Objectives are directly derived from the Mission Statement. This is an important phase in the design of a system, considering that Mission Statement and Primary Mission Objectives represent mission foundation and, for this reason, they cannot be modified during the definition process. Another analysis that can create important constraints and objectives is the Stakeholders' Analysis. The main purpose of Stakeholders' Analysis is to define needs and expectations of the main stakeholders. Certainty, the first activity to be performed before the stakeholders needs determination is the identification of the stakeholders, i.e. of all the actors involved. Consequently, secondary objectives can be derived. A categorisation of stakeholders that can drive their identification process is proposed in [11]. Indeed, the stakeholders can be categorized as sponsors (i.e. those associations or private who establish mission statement and fix bounds on schedule and funds availability), operators (i.e. those