Acta Astronautica 94 (2014) 17–33

Contents lists available at ScienceDirect

Acta Astronautica

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

A Delphi-Based Framework for systems architecting of in-orbit exploration infrastructure for human exploration beyond Low Earth Orbit ☆

Alessandro Aliakbargolkar *, Edward F. Crawley

Massachusetts Institute of Technology, Aero/Astro Department, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

ARTICLE INFO

Article history:
Received 28 February 2013
Received in revised form
17 June 2013
Accepted 11 August 2013
Available online 17 August 2013

Keywords:
Human spaceflight
Systems architecture
Conceptual design
Stakeholders analysis
Delphi method
Space exploration

ABSTRACT

The current debate in the U.S. Human Spaceflight Program focuses on the development of the next generation of man-rated heavy lift launch vehicles. While launch vehicle systems are of critical importance for future exploration, a comprehensive analysis of the entire exploration infrastructure is required to avoid costly pitfalls at early stages of the design process. This paper addresses this need by presenting a Delphi-Based Systems Architecting Framework for integrated architectural analysis of future in-orbit infrastructure for human space exploration beyond Low Earth Orbit. The paper is structured in two parts.

The first part consists of an expert elicitation study to identify objectives for the in-space transportation infrastructure. The study was conducted between November 2011 and January 2012 with 15 senior experts involved in human spaceflight in the United States and Europe. The elicitation study included the formation of three expert panels representing exploration, science, and policy stakeholders engaged in a 3-round Delphi study. The rationale behind the Delphi approach, as imported from social science research, is discussed. Finally, a novel version of the Delphi method is presented and applied to technical decision-making and systems architecting in the context of human space exploration.

The second part of the paper describes a tradespace exploration study of in-orbit infrastructure coupled with a requirements definition exercise informed by expert elicitation. The uncertainties associated with technical requirements and stakeholder goals are explicitly considered in the analysis. The outcome of the expert elicitation process portrays an integrated view of perceived stakeholder needs within the human spaceflight community. Needs are subsequently converted into requirements and coupled to the system architectures of interest to analyze the correlation between exploration, science, and policy goals. Pareto analysis is used to identify architectures of interest for further consideration by decision-makers.

The paper closes with a summary of insights and develops a strategy for evolutionary development of the exploration infrastructure of the incoming decades. The most important result produced by this analysis is the identification of a critical irreducible ambiguity undermining value delivery for the in-space transportation infrastructure of the next three decades: destination choice. Consensus on destination is far from being reached by the community at large, with particular reference to exploration and policy stakeholders. The realization of this ambiguity is a call for NASA to promote an open forum on this topic, and to develop a strong case for policy makers to incentivize investments in the human spaceflight industry in the next decades.

☆ This paper was presented during the 63rd IAC in Naples

* Corresponding author. Tel.: +1 6178525360.
E-mail addresses: golkar@skolkovotech.ru, golkar@mit.edu (A. Aliakbargolkar), crawley@mit.edu (E.F. Crawley).

0094-5765/$ - see front matter © 2013 IAA. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.actaastro.2013.08.004

1. Introduction

While NASA has already selected the Space Launch System as the new man-rated launch vehicle [1,2], one important question that is still open is the definition of the remaining architectural elements of the transportation infrastructure.

This paper supports the architecting process of the future US human spaceflight program by implementing a Delphi-based Systems Architecting Framework (DB-SAF) [3] for comprehensive architecting of the in-orbit transportation infrastructure. DB-SAF supports the objective definition of design goals by identifying and characterizing ambiguities in value objectives through expert elicitation, allowing experts to negotiate with each other through an anonymous and interactive process, and view the impact of their preferences in the architectural tradespace. The analysis is structured in two parts: first, possible objectives for the infrastructure are explored through an expert elicitation approach, with the goal of identifying objectives and characterizing associated technical, scientific, and political uncertainties. The study involved experts from NASA, ESA, academia and industry. The second part of the paper performs a tradespace exploration based on value metrics developed through expert elicitation, developing recommendations on the architecting process. The analysis, therefore, investigates what efficient development strategies could be pursued for future in-space infrastructure, while does not investigate the fundamental rationale of human spaceflight, which has been investigated extensively in recent years by scholars in space policy [4–6].

The paper shows how DB-SAF can be used to characterize and mitigate ambiguity in system-level objectives, therefore being an effective decision-making tool supporting system architects in the design of large engineering infrastructures.

The remainder of the paper is structured as follows: Section 2 provides the motivations and historical context that categorize this study as relevant to the human spaceflight program; Section 3 describes formally the objectives of the study; Section 4 describes the approach used in this paper, namely the Delphi-Based Systems Architecting Framework (DB-SAF), and describes the results that have been obtained following its application to the in-space infrastructure architecting problem; Section 5 summarizes the findings of this paper for consideration by decision-makers involved in the development of the future in-space infrastructure for human exploration.

2. Motivations and context

This section provides the framing context that motivated this research, including relevant historic background on the US human spaceflight program. NASA is presently called to charter a path for its future plans for human exploration. In 2004, President Bush started the Constellation Program with the ambitious goal of returning astronauts to the surface of the Moon [7]. Following 6 years of development and a cumulative investment of $9B billion USD [8], a Presidential panel was chartered with the purpose of assessing the status of the US Human Spaceflight Program and providing recommendations to the White House for future development of the American manned spaceflight program (the "Augustine Committee") [9]. The Committee found the US human spaceflight program to be "*on an unsustainable trajectory* <…> *perpetuating the perilous practice of pursuing goals that do not match allocated resources*" [9]. Following this review, the Obama Administration cancelled Constellation and the programs therein, such as the Ares I and Ares V launch vehicles [10]. Eventually, in July 2011 the Space Shuttle completed its last flight and transitioned to its decommissioning phase, marking the end of an era in human spaceflight [11].

In September 2011, NASA announced the development of the Space Launch System (SLS) as the next generation launch vehicle for future human exploration [12]. While most efforts have been focused on the development of the launch system, less effort seems to have been spent upfront on the remaining elements of the exploration infrastructure. This is partly due to political uncertainty on overall program objectives, which makes it difficult to commit to any hardware development that can constrain destination selection and other program objectives in successive development phases. Stakeholders do not share a unified vision on what constitutes value for the exploration enterprise. They have variegated perspectives on the intrinsic value of space exploration. Debates generate ambiguities that must be identified, characterized, and successively mitigated through careful strategy to define a robust transportation architecture.

3. Objectives

This paper characterizes and identifies ambiguities in system objectives for the in-orbit transportation infrastructure for human space exploration. It provides a characterization of the debate on "what is value" in future human spaceflight programs as perceived by a panel of experts. Based on this analysis, the paper enumerates feasible architectures for the in-space infrastructure and identifies architectures of interest while developing recommendations for further consideration by decision-makers. Architectures are filtered through proxy metrics for cost, schedule, and risk.

4. Approach and results

This section presents the approach that has been used for the analysis of in-orbit infrastructure presented in this paper, and the results that have been obtained by its implementation. The approach is called Delphi-Based Systems Architecting Framework (DB-SAF) [3], and its overview is shown in Fig. 1. DB-SAF is an iterative approach integrating expert elicitation and computational systems architecting. DB-SAF supports the definition of system architectures under ambiguous stakeholder objectives; that is when stakeholders have a plurality of contrasting views on what capabilities should be implemented in the system and what constitutes value for the architecture. DB-SAF is inspired by the Delphi method from social science research [13,14], and integrates an engineering Delphi approach with computational systems architecting techniques developed at MIT in recent years [15,16]. DB-SAF allows experts to be included in the