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The extravehicular mobility unit: A review of environment, requirements, and design changes in the US spacesuit

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Abstract

Requirements are rarely static, and are ever more likely to evolve as the development time of a system stretches out and its service life increases. In this paper, we discuss the evolution of requirements for the US spacesuit, the extravehicular mobility unit (EMU), as a case study to highlight the need for flexibility in system design. We explore one fundamental environmental change, using the Space Shuttle EMU aboard the International Space Station, and the resulting EMU requirement and design changes. The EMU, like other complex systems, faces considerable uncertainty during its service life. Changes in the technical, political, or economic environment cause changes in requirements, which in turn necessitate design modifications or upgrades. We make the case that flexibility is a key attribute that needs to be embedded in the design of long-lived, complex systems to enable them to efficiently meet the inevitability of changing requirements after they have been fielded.

Keywords: Extravehicular mobility unit; Requirements evolution; Design changes; Flexibility

1. Introduction

Traditional systems engineering wisdom, developed and supported by decades of experience in designing and operating complex engineering systems, holds that requirements should be frozen as early as possible during the system's development phase, one rationale being that requirement changes or instabilities have a negative impact on both system life-cycle cost and development schedule. Furthermore, it is believed that the later in the development phase a requirement change is requested, the higher the cost penalty is to implement this change, as shown in Fig. 1 [1].

In practice however, freezing requirements, whether during the development phases or after fielding a complex engineering system, is unrealistic. The IEEE Standard 1233 for example recognizes this fact and states that [2]:

> Although it is desirable to freeze a set of requirements permanently, it is rarely possible. Requirements that are likely to evolve should be identified and communicated to both the customers and the technical community. A core subset of requirements may be frozen early. The impact of proposed new

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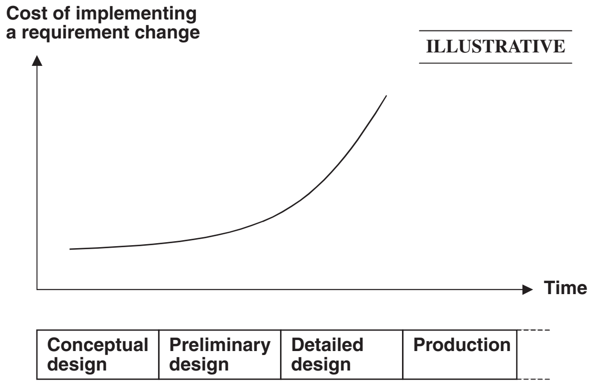

Fig. 1. Rationale for an early freeze of system requirements. Adapted from Ref. [1].

requirements must be evaluated to ensure that the initial intent of the requirements baseline is maintained.

In short, requirement changes in the traditional systems engineering approach are undesirable, but are cautiously tolerated when they are inevitable.

1.1. Complicating factor

The last two decades have witnessed a trend in increasing system design lifetime. Communication satellites for example have seen their design lifetime increase from 7 to 15 years over this time period [3]. This trend—also observed in the design of other aerospace and numerous defense systems—is the result on the one hand of budgetary constraints and financial pressure to maximize the return from such high-value assets, and on the other hand of increased reliability and technical advances that allow complex engineering systems to remain operational for such long periods of time. Why is this observation a complicating factor to the traditional attitude towards requirement changes?

Engineering systems often operate in complex and rapidly evolving environments. As their design lifetime increases, it becomes increasingly probable that the initial environment from which the original system requirements were derived changes during the system's operational life. This environment change, whether political, economic, physical or technological (discussed in detail later), will in turn cause requirement changes as a result of new customer or user needs, or new identified opportunities. However, the same budgetary constraints mentioned previously often mandate that the fielded system be modified or upgraded to satisfy the new requirements and provide enhanced capabilities, instead of developing a new, clean-sheet design. In this context, it is unrealistic to attempt to freeze requirements as early as possible, and the traditional attitude of the systems engineering community towards *change* needs to be revisited: requirement changes will occur, especially in long-lived systems, and instead of resisting them or passively accepting them, it is preferable that system engineers "design for change," or embed flexibility in the design of complex engineering systems. We define flexibility of a design as a property of a system that allows it to respond to changes in its initial objectives and requirements that occur after the system has been fielded, in a timely and cost-effective way [4].

Increasingly, system designers recognize that their systems operate in a dynamic environment, and that the systems are likely to change. Managers are beginning to experiment with how to value uncertainty [5]. Several new tools have been developed, and old tools modified, to attempt to predict how changes in one part of an operating system will affect the whole [6–9]. Rather than passively reacting to change, some system architects are beginning to develop design methodologies that could make their systems resilient to change [10,11]. This paper argues that requirements change is an inevitability in the life of any complex system and that by embedding flexibility in the design of such systems will enable it to react more efficiently to change.

1.2. Paper outline

In this paper, we demonstrate how environment changes, political, economic, physical and technological, triggered requirement changes, which in turn necessitated design changes in the particular case of the US spacesuit, the extravehicular mobility unit (EMU). We further build on this example to make the case for a new attitude towards requirement changes in system design in general, and the need to embed flexibility in the design of complex engineering systems. Herein we discuss the evolution of requirements for the EMU, as a case study in the need for flexibility in systems engineering design. We explore one fundamental environmental change, using the Space Shuttle EMU aboard the international space station (ISS), and the resulting EMU requirement and design changes. The EMU, like most complex engineering systems, faces considerable uncertainty during its service life. Changes in the technical, political, and economic environments may cause changes in requirements, which in turn necessitate design changes.