Reliability analysis of multicellular system architectures for low-cost satellites

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ABSTRACT

Multicellular system architectures are proposed as a solution to the problem of low reliability currently seen amongst small, low cost satellites. In a multicellular architecture, a set of independent k-out-of-n systems mimic the cells of a biological organism. In order to be beneficial, a multicellular architecture must provide more reliability per unit of overhead than traditional forms of redundancy. The overheads include power consumption, volume and mass. This paper describes the derivation of an analytical model for predicting a multicellular system's lifetime. The performance of such architectures is compared against that of several common forms of redundancy and proven to be beneficial under certain circumstances. In addition, the problem of peripheral interfaces and cross-strapping is investigated using a purpose-developed, multicellular simulation environment. Finally, two case studies are presented based on a prototype cell implementation, which demonstrate the feasibility of the proposed architecture.

1. Introduction

A large number of bespoke system architectures, focused on high reliability, have been developed by the space industry [1]. Unfortunately, due to their high implementation overheads, most of the techniques relied upon by these architectures are unsuitable for use on small, low-cost satellites [2,3]. Thus, single-string architectures have become prevalent in this class of satellite, and especially amongst CubeSats, which fall towards the lower end of the small, low-cost satellite spectrum. A survey of 159 CubeSats launched before 2014 reveals that more than 40% had single-string architectures (Fig. 1), undoubtedly contributing to their poor on-orbit reliability seen to date [4,5]. A novel, multicellular system architecture, here referred to as Satellite Stem Cells (SSC) [2,6], aims to improve the reliability of the avionics of these satellites, while minimising overheads.

To prove that systems based on Satellite Stem Cells have advantages over other architectures, the proposed architecture’s reliability is analysed analytically and through simulation. In addition, two case studies, based on the specifications of an implemented prototype cell, are presented.

Several alternative architectures have been proposed for small, low-cost satellites [8–10]. Amongst their aims are increased reliability. However, these proposals lack thorough reliability analyses.

Burlyaev presents an analysis of the fault tolerance of satellite on-board computers (OBCs) based on commercial-off-the-shelf (COTS) components [11], and Engelen et al. present a reliability analysis of low-cost satellite swarms [12]. In both cases the analyses are based on simulations. In this paper, simulations are used in conjunction with derived analytical reliability solutions.

Fayyaz et al. propose a fault tolerant, distributed architecture and predict reliability increases over centralized and triple redundant designs using derived system reliability equations [3]. However, their design does not stray far from traditional k-out-of-n architectures and only applies to the OBC.

In contrast, the SSC Architecture was derived by studying biological life and aims to replace as much of the avionics as possible. In a simplified sense, the SSC architecture imitates the structure of multicellular organisms by splitting a traditional k-out-of-n architecture into a set of smaller, independent k-out-of-n sets. Like the cells of a multicellular organism, these sets operate autonomously, but cooperatively, to isolate failures and adapt the system to changing conditions.

The rest of this paper is structured as follows. Section 2 gives a brief overview of the proposed bio-inspired architecture. Section 3 describes the derivation of analytical equations for predicting the reliability of purely-computational multicellular systems. Peripheral interfaces and cross-strapping, required in systems which are not purely computational, are investigated in Section 5. Finally, two case studies are presented in Section 6, followed by conclusions in Section 7.
2. Satellite Stem Cells

The Satellite Stem Cell Architecture is inspired by multicellular life. It is based on the concept of artificial cells, which mimic the ability of biological cells to adapt their behaviour, live, based on internal and external conditions. In a simplified sense, multicellular organisms start out as a collection of identical cells (stem cells), which later adapt through a process known as differentiation to take on specific roles within the organism. A system based on the proposed stem cell architecture is composed of a set of initially identical hardware blocks. Mimicking their biological counterparts, these artificial cells have the ability to adapt to perform a wide variety of tasks, allowing them to work together autonomously to ensure that system tasks get performed. In such a system, the loss of individual cells can be compensated for by the remaining cells.

The key to a successful multicellular architecture is having adaptable cells. Therefore, it is important to understand how biological cells adapt to perform such a wide variety of tasks. Fig. 2 shows a simplified, schematic representation of this process, together with a proposed artificial implementation. Every biological cell contains a set of DNA, which contains instructions for building proteins. Throughout the life of the cell, large molecules known as macromolecular machinery (MM) respond to internal and external conditions by reading different sections of the DNA and producing the corresponding proteins. Each protein is essentially a piece of custom built machinery which performs a particular task. Most cellular tasks are performed by these proteins. Thus, a cell's role in an organism can change over time as its set of proteins change.

In the proposed artificial cell, the proteins are implemented using discrete microcontrollers (MCUs). Different proteins are represented by having different firmware loaded onto the MCUs. Another MCU takes on the role of the macromolecular machinery. It responds to internal and external conditions by loading different firmware onto the protein MCUs from non-volatile memory (DNA). Since the macromolecular machinery is itself also composed of proteins, the proposed implementation uses the same MCUs for the proteins and macromolecular machinery. This is shown in Fig. 3, where every cell contains a set of MCUs, any one of which can take on the role of the macromolecular machinery (labelled as MM). The generic input/output (I/O) circuitry allows interfacing to a wide variety of external peripherals and communication buses, while protecting the protein from unexpected, damaging transient events.

A system based on the SSC Architecture is composed of one or more artificial cells, connected together with power and communication buses. All system tasks (e.g. attitude estimation, actuator control, health monitoring) are distributed across the proteins of the system's cells. Individual proteins, or whole cells, can fail without causing failure of the system, provided sufficient proteins remain to complete all required tasks. Important system characteristics include:

- Each cell is autonomous and loads tasks onto its own proteins.
- A protein can only perform a single task at a time.
- A protein can either be dormant, actively executing a task, or be in hot or cold redundancy for a particular task.
- The failure of a protein will cause the remaining proteins to re-configure to take up the lost task.
- At all times, one protein per cell must be assigned the role of macromolecular machinery.

In addition to the enhanced reliability discussed in this paper, the proposed architecture offers graceful degeneracy, potential reduced cost through mass production, and simplified user software development (since each protein performs a single task at a time, tasks can be coded and tested without concurrency concerns).

To demonstrate the practical feasibility of the proposed architecture, a set of prototype artificial cells, each measuring 10 × 11 cm and consuming less than 400 mW, have been designed and manufactured (Fig. 4). The prototype cells each contain four proteins based on ARM Cortex M0 MCUs. Each protein has access to six generic input/output (GPIO) lines which can supply up to 1 A of current for driving actuators, or act as digital or analogue inputs for interfacing to sensors or communication buses. Internal and external Controller Area Network buses allow inter-protein and inter-cell communication. Distributed task coordination is handled through peer-to-peer communication enabled by a FreeRTOS-based set of middleware executing on each cell's MM [13]. The specifications of these cells form the basis of the case studies presented in Section 6. More details on the cell design and hardware are available in Refs. [6,7].
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