ESPACENET: A Framework of Evolvable and Reconfigurable Sensor Networks for Aerospace–Based Monitoring and Diagnostics

T.Arslan[1], N.Haridas[1], E.Yang[1], A.T.Erdogan[1], N.Barton[2], A.J.Walton[1], J.S.Thompson[1], A.Stoica[1, 3], T.Vladimirova[4], K.D. McDonald-Maier[5], W.G.J. Howells[6]

[1]School of Engineering and Electronics, University of Edinburgh, Edinburgh EH9 3JL, UK.
[2] School of Biological Sciences, University of Edinburgh, Edinburgh EH9 3JL, UK.
[3] NASA-Jet Propulsion Laboratory, 4800 Oak Grove Drive,Pasadena, CA 91109, USA.
[4] School of Electronics and Physical Sciences, University of Surrey, Guildford GU2 7XH, UK.
[5] Department of Computer Science, University of Essex, Colchester CO4 3SQ, UK.
[6]Department of Electronics, University of Kent, Canterbury, Kent CT2 7NT, UK.
T.Arslan@ed.ac.uk

Abstract

There is an increasing need to develop flexible, reconfigurable, and intelligent multi-spacecraft sensing networks for aerospace-based monitoring and diagnostics. Technical advancements in ad hoc networking, MEMS devices, low-power electronics, adaptive and reconfigurable hardware, micro-spacecraft, and micro-sensors have enabled the design and development of such highly integrated space wireless sensor networks.

This paper proposes the framework for an Evolvable Sensor Network Architecture, investigated as part of the ESPACENET project, collocated at the University of Edinburgh, Essex, Kent and Surrey. The aim is to design a flexible and intelligent embedded network of reconfigurable piconodes optimised by a hierarchical multi-objective algorithm. Although the project is targeted at aerospace applications, the same intelligent network can be used for many earth bound applications such as environmental and medical diagnostics.

1. Introduction

In an ongoing quest to have effective space based earth monitoring and communication links we aim to develop a network architecture, which can be applied to constellations of very small satellites to replace one day existing large multifunctional satellites. The motivation behind the current trend of reducing spacecraft size is that it is cheaper to mass produce and launch smaller satellites, compared to building and launching a large satellite in orbit nowadays. A constellation of picosatellites that weigh less than 1 kg and can carry a few of instruments is the proposed application for this research [14]. These picosatellites will create flexible ad-hoc network clusters and a combination of such clusters would form the constellation, each cluster will have picosatellites that shall perform a specific function depending on the sensors it would carry as payload, a number of such different satellites will contribute to the same functionality as that of today's larger satellites.

Our focus is on the development of effective network and piconode architectures targeting applications where reliability, robustness, flexibility and long network and node life are of prime importance. A unique consortium has been formed to address the issues and is know as the ESPACENET project: *Evolvable Networks of Intelligent and Secure Integrated and Distributed Reconfigurable System-On-Chip Sensor Nodes for Aerospace Based Monitoring and Diagnostics.* This project involves several Universities, the University of Edinburgh, the University of Surrey, the University of Essex, and the University of Kent together with industrial partners such as EPSON, Spiral Gateway, Surrey Satellite Technology (SSTL), and NASA Jet Propulsion Laboratory (JPL).

Previous work done in the field of Piconode networks primarily is focused on the ability of network self organisation and low power pico sensors. At Berkeley Wireless Research Centre [1], researchers have developed small Pico nodes called Pico Beacons and Pico Radio II. These are small wireless transceivers that are capable of forming self organizing networks. They were designed as low power devices that can scavenge

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on incident light or vibrations to power the device, virtually eliminating the need for a battery.

Similarly, Stanford University and California Polytechnic State University joint project CubeSat [2] is a standard platform developed for educational purposes. It consists of a 1kg square satellite, which has its own development board, Real Time Operating Software, and supporting hardware and can be easily integrated with the user's instruments and payload for space missions.

Both models have standard configurations or platforms. The Berkeley group's model is for testing pico radio networks. It has fixed sensors and fixed hardware and no degree of node reconfiguration unless it is taken apart and redesigned. The CubeSat model was designed with no specific application; it has a basic chassis and board which needs to be integrated with the user's modules before launch.

In both cases, once launched there is no capability to change the configuration. We would like to overcome this barrier and enable our picosatellite to reconfigure itself. The overall design can be partitioned into hardware and software, the two main areas where reconfigurability can be targeted.

For a reconfigurable hardware design, FPGA, DSP and other digital modules, and sensors are required. We have already worked on low power FIR filters [3], aadaptive Viterbi decoding algorithms [6], low power architectures for MC-CDMA receivers [9], low power reconfigurable FFT Processor [4], and reconfigurable SoC architectures [11].

From the hardware perspective, it is possible to change how data is gathered from the reconfigurable sensors. However, even the reconfigurable internal architecture determines how this data would be processed and used.

It is important to apply the knowledge gained over the years in the field of sensor development and fabrication. Having reconfigurable sensors will enable the satellite to change its application as directed by network requirements. This enables us to employ a number of generic picosatellites capable of configuring themselves to very specific roles. All the decisions would be taken by a multi-objective algorithm controlling the network. Following on from previous work on genetic algorithms, we are now looking forward to generating more precise algorithms derived from biology that can link with the overall network formation and dynamically configure the network for correct operation in rapidly changing environmental conditions. The resulting system would be competent enough to assign certain tasks to each individual node and reconfigure these nodes to undertake the work.

The initial objectives in this project are:

(i) To specify the Network Architecture and the pico-satellite nodes used in the network,
(ii) To determine the power constraints on the satellites,
(iii) To determine the degree of reconfigurability within the network,
(iv) To develop an algorithm based on biological evolution, which will control the network, and
(v) Explore new propulsion systems for picosatellites.

We will discuss the overall idea in the following sections, (1) Network Architecture for the Constellation, (2) The Hardware Architecture for the satellites, and (3) The Evolvable multi-objective algorithm that would control the network

2. Network Architecture

The Network will be a three level hierarchical, clustered architecture based on a small cluster of Pico Satellites flying sub-orbits to the orbital plane of the larger Micro Satellites. The satellite platform will be derived from the University of Surrey's Micro Satellites building up on the results of the recent Disaster Monitoring Constellation programme [13]. Inter-satellite links will exist between all satellites in orbit [12].

The hierarchy consists of pico satellites which are limited to a small weight of less than 1kg and have limited space for both solar panels and for an on-board battery. Having extendable solar panels would increase the air drag on the satellite, which would mean extensive use of propulsion systems to keep the pico satellite in orbit. Next in the hierarchy are the larger Micro Satellites, having the capability for high performance operations, such as controlling and organizing the picosatellites, for data processing and high powered applications, such as transmitting to the nearest mother satellite or ground based station.

At the top of the hierarchy would be the ground relay satellites, these would be the mother satellites reconfigured for a special purpose, to transmit all information within the network to the ground stations on earth.

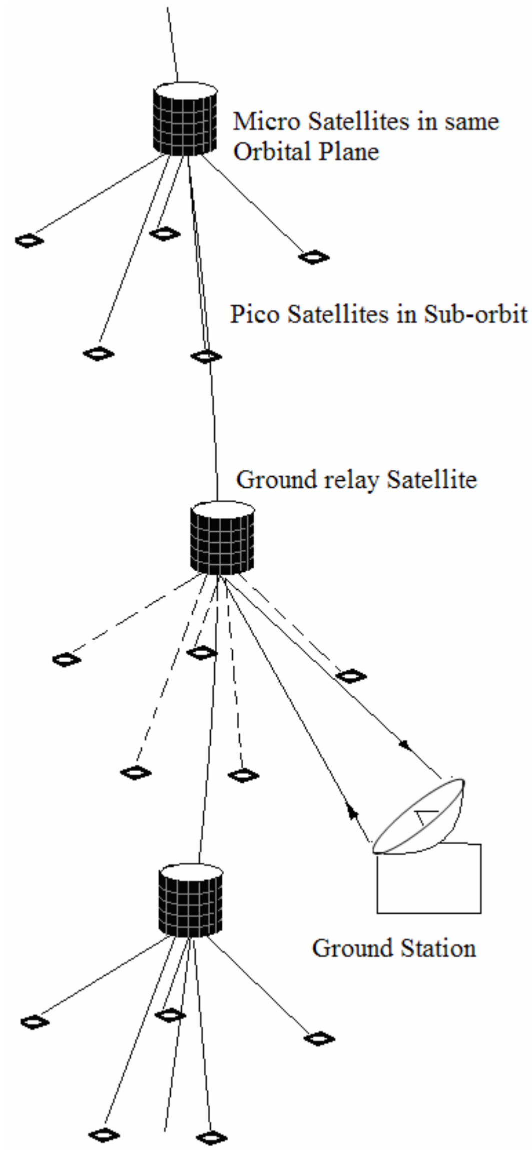

Figure 1 Hierarchical Network of Satellites in Orbit

Since we are following a Low Earth Orbit (LEO), the orbital period is somewhere between 90 to 120 minutes. As each Micro satellite passes over a ground transmitting station, it will relay its data to earth. However, in order to do this, it would need to divert all available power for the use of the high powered antenna. In such circumstances, it will relinquish control of the pico satellites (for a short time) and become a ground relay satellite for all the satellites in orbit. When the pass is complete, it will become a mother satellite controlling the pico satellites in its sub-orbit. Hence the picosatellite will only gather information through its sensors and transmit it to the mother satellite. The mother satellite shall process this data and transmit it to the nearest ground relay satellite.

This heterogeneous network is the first step to developing and testing all the deliverables such as the evolvable algorithm and the individual sensor nodes. As technology improves, we can go in for a more homogenous approach where pico satellites would be employed in all three levels of the hierarchy.

3. Hardware Architecture

The novelty of our project will be the reconfigurable nature of the nodes within the network.

By allowing the individual nodes to reconfigure the network requirements, we can efficiently optimize objectives like power consumption, latency etc. Work can be distributed over the network and nodes can reconfigure in order to efficiently perform those operations.

A low power System on Chip (SoC) based design allows us to configure a number of subsystems, such as the embedded processor, reconfigurable communication module, decoders, encryption and decryption modules, power management, and radio subsystem onto a single substrate eliminating the need for board interconnects reducing the size chip. We can also implement algorithms for network on chip to improve communication between the subsystems and reduces latency.

Satellites require a number of compulsory sensors and subsystems like Attitude Determination and Control System (ADCS), On Board Data Handling (OBDH), and Power system, which form the satellite bus.

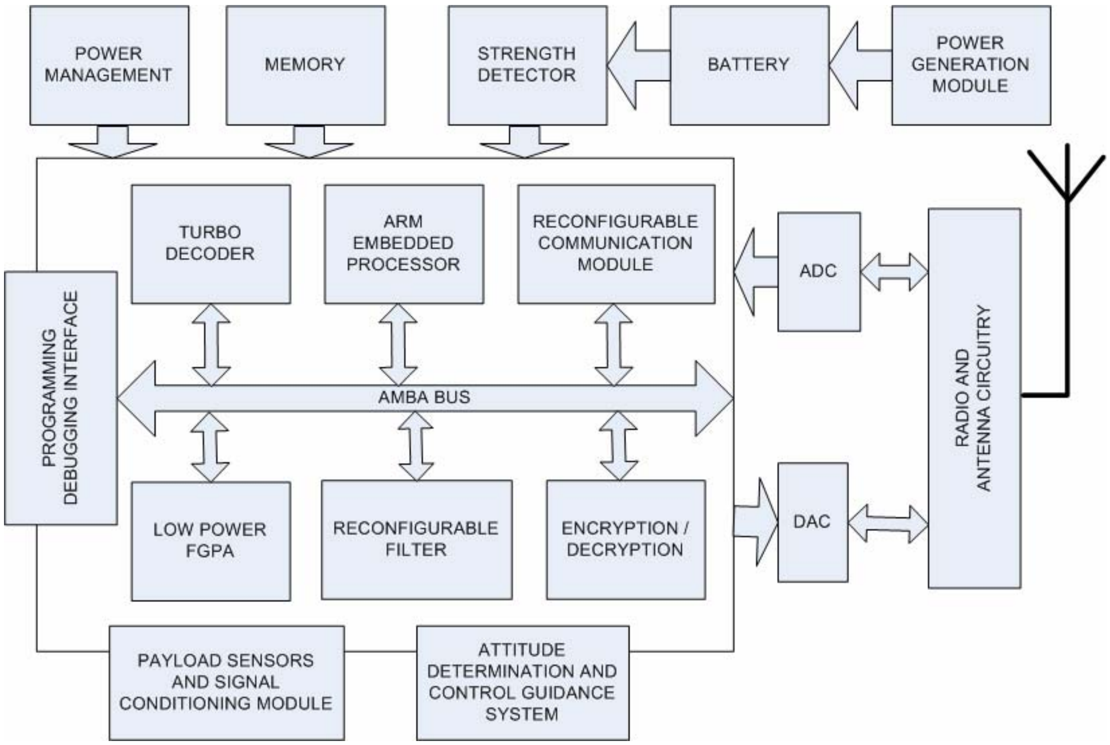

Figure 2 Proposed Hardware Architecture

The ADCS consists of different types of sensors and actuators. For example, the ADCS module of the EyasSat [10] designed by the US Air Force Academy has a solid-state single axis gyroscope, two axis accelerometers, two sun sensors, a yaw attitude sensor and two actuators (reaction wheel and torque rod set) [11]. For picosatellites, the ADCS will be one of the main masses, and the possibility to fabricate digital interfaced micro machined ADCS units, will allow us to have independent flying picosatellites.

The OBDH consists of on-board computers for data processing, RAMs for temporary data, mass memories for storing the data to be transmitted, and the boot loader [11].

The Architecture will be centric to the Advanced Microprocessor Bus Architecture (AMBA) bus, surrounded by programmable SoC devices, sensors, ADC/DAC and on-chip reconfigurable micro-antenna.

The radio is designed for inter-satellite link between all the nodes of the network. There is an example for inter-satellite link. In March 2003, the National Space Development Agency of Japan (NASDA) and the European Space Agency (ESA) successfully tested the inter-satellite communication between the Advanced Earth Observing Satellite II (ADEOS-II), "Midori II", of NASDA and the Advanced Relay and Technology Mission (ARTEMIS) of ESA. This experiment was to use both Ka-band (26 GHz) for data transmission and S-band (2 GHz) for command transmission [11].

At Surrey Satellite Centre, they are evaluating 802.11 as the wireless standard for inter-satellite links, another emerging standard is the 802.16e, which has high capacity in terms of range and data rates, ideal for supporting a large constellation of high performance pico satellites, but has a disadvantage of being power hungry.

Encryption is also an important module since any eavesdropping on data being passed within the network is undesirable. The aim is to develop a secure communication based on unique properties of the communicating satellites.
The architecture relies on effective emulation and debugging architectures to assist the hardware and application development for these dynamically

evolvable systems as a whole entity. It is anticipated that the actual system infrastructure will be used for debugging traffic. New generic algorithms will be developed to debug systems containing reconfigurable and evolvable elements and will form a core part of the evolvable platform. The overall infrastructure within the SoC will be partly based on the debugging infrastructure algorithms currently under development for static SoCs with multiple processor cores at Kent [15].

The architecture relies on optimised mixed hardware / software algorithms to control manage and ensure dependability of on-chip dynamic evolvable systems. To support effective development the debugging support must have access to all aspects of the system and be intrinsically dependable. For sensor nodes distributed in remote locations, this is especially important as the debug support may be the only feasible means of recovery if there is a program error. Hence the debug support must have the capabilities to take full control of the sensor node when abnormal behaviour is detected, for this to happen the debug support must include a dependable interface, this is also required to load a new application program within the node.

The Payload determines the functionality of the satellite, having reconfigurable sensors, which can select specific roles to be performed as directed by the algorithm. Implementing an array of different sensors within a reconfigurable fabric will allow a single satellite to be capable of working within the spectral bands of 400-1650nm table 1, which is divided into 10 spectral bands used by Earth Observation (EO) satellites for remote sensing.

Communication will be driven by a phased array on-chip micro-antenna; this allows highly directional beams, possessing the advantage of being able to transmit in any direction around the satellite without having to change the orientation of the satellite.

Table 1 Scanning range of an EO satellite

Channel	Wavelength (nm)	Primary Use
1	580-680	Daytime cloud, ice and snow vegetation
2	840-890	Daytime cloud, vegetation, water
3	3550-3930	Heat source, night cloud
4	10300-11300	SST, day/night cloud
5	11500-12500	SST, day/night cloud
6	1580-1640	Soil humidity, ice/snow distinguishing
7	430-480	Ocean color
8	480-530	Ocean color
9	530-580	Ocean color
10	900-965	Water vapor

4. Multi-Objective Evolutionary Algorithms

Multi-objective evolutionary algorithms (MOEAs) are crucial in the design and development of evolvable and reconfigurable sensor networks for aerospace-base monitoring and diagnostics. The MOEAs span and evolve the whole sensor network hierarchy including sensor nodes, cluster-based satellite network, and related reconfigurable devices, etc, which can concurrently drive both network and hardware resources to effectively and efficiently solve monitoring and diagnostic problems for aerospace-based applications. The novelty of this research lies in developing a series of evolution-based algorithms which can inherently optimize and evolve the network, node, and sensor architectures concurrently.

Toward this end, we will address the following algorithms relating to the whole research project:

4.1 Hierarchical Heuristic Evolutionary Algorithms.

These hierarchical heuristic evolutionary algorithms will be derived from evolutionary biology and engineering computations, together with specially tailored SoC-based reconfigurable hardware platforms to

a. maximize network efficiency and lifetime in both network and node levels;
b.handle a variety of sensing elements and operational conditions;
c. be of a set of operators for manipulating network efficiency and the heterogeneous reconfigurable nature of individual nodes.

The hierarchical heuristic evolutionary algorithms will drive swarm formation and cluster in sensor networks concurrently with the configuration of architectural components of the sensor nodes.

4.2 Senor Node-Level Evolutionary Algorithms.

It is also very important to study mechanisms for managing energy consumption in low power applications due to the limited availability of power. The sensor node-level evolutionary algorithms will deal with the various nodes with the resultant effect from forming a cluster with the lowest power consumption, and also tackle the issues from communication processes, such as reliability, robustness, and delay. In addition we will investigate how to let sensor nodes rapidly adapt to a continually changing environment.

4.3 Evolutionary-based Overall Network Formation Algorithms.

The development of hierarchical, evolvable, adaptable, and distributed systems capable of dynamically modifying network behaviors is one of main objectives in this research project. The autonomous, adaptable, and distributed nature of the evolvable and reconfigurable sensor network will allow the sensor node to be deployed in a wide range of applications.

Thus, the evolutionary-based overall network formation algorithms must have the capability of dynamically reconfiguring the network to meet different operational requirements under a set of given conditions and constraints. Meanwhile, the adaptability of wireless networks to higher topology changes and higher scalability will also have to be considered. For example, variation in temperature or Ph may result in a change in the dynamic range of values processed by the node's computational unit and hence a number of computational blocks and their associated interconnects could be disabled for the sake of saving energy. Moreover, the variation of node scale and sensing area will also require an efficient algorithm to optimize and evolve the overall sensor networks.

4.4 Other Biologically-Inspired Hierarchical Multi-Objective Evolutionary Algorithms.

In the proposed framework, we will also study other biologically-inspired hierarchical multi-objective evolutionary algorithms. The power constraints, hierarchical topology, and fault-tolerance requirements pertinent to the aerospace domain make the design of MOEAs even more challenging. The aim of investigating other biologically-inspired hierarchical MOEAs is to merge techniques and sciences from the different research domains, such as biological evolution theory, evolutionary-based computations, and true multi-objective algorithms.

Under the proposed framework the objectives will include, but not be limited to, power, cost, size, weight, network efficiency, reliability, robustness, security, and adaptability, etc.

During the optimization, we will simultaneously consider the performance of both the overall network and sub-networks (clusters). In the proposed framework, various populations (swarms) of nodes/agents co-exist in clusters of varying density. These clusters will consist of complete reconfigurable SoC devices with various sensing elements together with various DSP/micro-processors Intellectual Property (IP) cores, and driver capability in order to deal with the information processed by a given node. Considering these aspects of the framework, we will have to investigate theoretical evolutionary and biological processes in order to develop robust and adaptable biologically-inspired algorithms, which will allow configuration and reconfiguration of networked clusters of sensor nodes under different environmental conditions.

5. Summary

We have introduced the ESPACENET Project, providing the framework for an evolvable network of reconfigurable sensor nodes.

The global constellation picosatellites will form an effective network for monitoring earthly activities and early warning system for natural calamities, like floods, tsunami, forest fires and earth quakes. They could also be used providing early warning to incoming meteorites, solar flares and other space based threats.

This project will drive the design and development of new technology, that will find application in many earth based pico node networks.

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