

# The BNSC Space Foresight

## Improved Mission Autonomy and Robustness Programme

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### Abstract

This paper describes work carried out under the British National Space Centre's (BNSC) Space Foresight programme to investigate new approaches to the control of autonomous systems, and especially to those with distributed system architectures. The objective of this work is to achieve improved system level mission design through combining research into intelligent systems, evolutionary robotics and mathematics with traditional space mission design methodologies.

### Introduction

The Improved Mission Autonomy and Robustness (IMAR) project was initiated in 1997, as part of BNSC's Space Foresight programme, in response to a need perceived by the then Matra Marconi Space (MMS) in Bristol (Astrium since 1999) to respond to challenges in autonomy for planetary robotics. These challenges had been exposed by a number of studies for, and proposals to, the European Space Agency (ESA), such as the MOFFIT lunar interferometer programme – Figure 1.

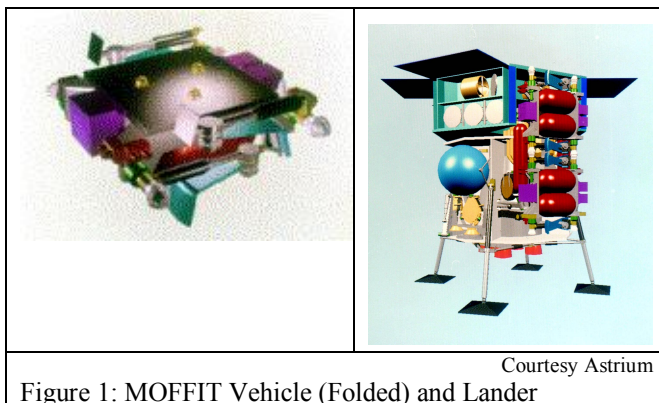


Figure 1: MOFFIT Vehicle (Folded) and Lander

These studies showed that the degree of functionality required for some advanced space missions would not be achievable using available mainstream design methodologies, because the required level of system reliability could not be guaranteed. Furthermore, it was foreseen that the increasing application of

constellations of satellites to communications, and in the future to Earth observation and science, would increase the demands on the design of both onboard and ground control systems.

Novel techniques then being studied in academia were identified as a route to a possible solution to this problem, reducing the costs of future missions whilst increasing robustness. MMS proposed a way forward capitalising on research at the University of Sussex into evolutionary robotics [Harvey et al, 1996 <sup>1</sup>] and a tentative collaboration between Sussex and Matra Marconi Space was established. A first paper on the application of the work within the space arena was presented to ESA at their inaugural ASTRA workshop [Hobbs et al, 1996 <sup>2</sup>], and a Space Foresight proposal submitted to BNSC in 1997 to investigate new approaches to the control of distributed autonomous systems, the robustness of communication satellite constellations, and also planetary robotics [Hobbs, 1997 <sup>3</sup>]. The work aimed to achieve improved system level mission design through combining research into intelligent systems, evolutionary robotics and mathematics with traditional space mission design methodologies. Since 1997, work has been carried out in two phases (1997 – 2000, and 2001) with consortia of Universities and Small / Medium Enterprises – Table 1.

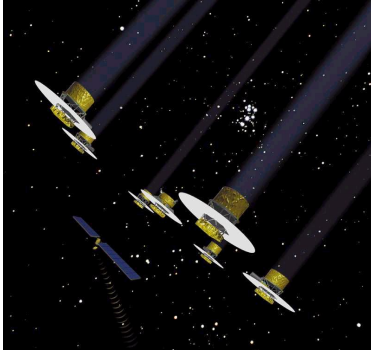
Matra Marconi Space (UK) Ltd. (Astrium)	Astrium
The University of Sussex	The University of Sussex
The Open University	The Open University
Space Innovations Ltd.	Science Systems (Space) Ltd.
Brunel Institute of Bioengineering	The University of Glasgow
<i>Phase One Teaming</i>	<i>Phase Two Teaming</i>

Table 1: IMAR Team Structures

The objective of this work is to investigate emerging, blue skies, techniques for controlling autonomous systems, and in particular, those comprising a number of distributed elements (agents). The intention is to develop new control methodologies applicable to free flying groupings of spacecraft, to systems acting on planetary surfaces, and to the interaction of subsystems within a single spacecraft.

These various distributed system / (remote) agent / artificial intelligence scenarios are applicable to many future mission profiles, such as ESA's Darwin (Figure 2) and BepiColombo (Mercury) missions. The latter is still under definition, but is a (potentially) more autonomous version of the Beagle 2 mission to Mars – Figure 3.

With the advent of advanced structural control methodologies and 'smart' structures, this work can also be regarded as potentially applicable in the structural design domain, as well as to autonomous systems.



Courtesy ESA

Figure 2: Darwin



Courtesy Astrium

Figure 3: Beagle 2

## Multi-Robot Teams

In order to investigate the behaviour of both free flying spacecraft and surface robotic systems, it was considered that the construction and initial programming of a 'constellation' of five 'carpet rover' autonomous vehicles (robots), supplemented by software simulation, would provide the appropriate research capability. The initial build of the robots was carried out by Brunel Institute of Bioengineering. These were commercial robots, modified to produce the required processor functionality, sensor integration, etc. (Figure 4). The Centre for Computational Neuroscience and Robotics (CCNR) at Sussex University completed development of the constellation, and installed a preliminary version of the high level control software. At the end of the first phase, successful operation using behavioural primitives appropriate to foreseeable space mission tasks was demonstrated.

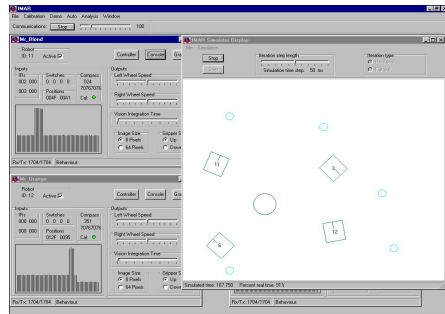
The control software was generated using evolutionary robotic techniques based on the application of genetic algorithms employed as 'adaptive improvers'. This technique involves the evolution over a large number of generations of genotypes representing alternative control strategies. Interbreeding is arranged on a Darwinian basis in which the fittest solutions, judged against specified performance criteria, are those most likely to interbreed. Arrangements are also made for random mutation to be introduced into the genotypes. The resulting evolution tends to avoid the pitfall of concentrating on false local optimisation minima, and searches outward to locate any higher peaks that may exist [Harvey et al, 1992<sup>2</sup>].

Demonstration was carried out by CCNR using a tabletop arena in which a scenario representing the servicing of a number of separate locations by co-operating robots was set up. CCNR were also able to apply the software tools developed under a separate EU Vintage project, and produce a useful PC-based simulation capability for this work – Figure 5.



Courtesy Astrium

Figure 4: Phase One Carpet Rover Constellation



Courtesy University of Sussex

Figure 5: User Interface for Sussex Simulation

During Phase One, some long standing, fundamental questions relevant to the formation of multi-robot teams were identified for attention, including:

- Is some form of mapping of local surroundings required for the agents to navigate successfully, and
- Should the agents all be the same, or should they have specific capabilities? [Turner, 1999<sup>4</sup>].

The physical demonstrations carried out at the end of Phase One clearly showed that mapping was unnecessary for evolved systems. In Phase Two, CCNR [Quinn, 2001<sup>5</sup>] concluded that a clonal rather than clonal programming (ie where individual robots are pre-programmed with individually evolved coding, probably from a common ancestor genotype, rather than all being the same) may be more likely to produce the functionality required of distributed autonomous systems. Further development of this and allied work scheduled for IMAR-2 should produce further useful insights and practical demonstrations in the areas of co-ordination, communication, role allocation and collective decision-making in multi-robot systems [Husbands and Quinn, 2001<sup>6</sup>].

## Spatial and Temporal Mathematics of Robot Behaviour

One of the difficulties inherent in the introduction of autonomy methodologies based on non-deterministic behaviours is that the stochastic nature of the methods pursued could well result in a technique that would have difficulty gaining acceptance within mainstream spacecraft design because of its inherent lack of definition. A major element of this lack of definition is considered to be the absence of any rigorous mathematical treatment of the subject matter involved.

In Phase Two, the OU are establishing such a mathematical approach to the representation of the organisational relationship between agents within a complex system architecture, with the specific intention of providing a formal groundwork for dealing with distributed autonomous systems [Rooney, 2001<sup>7</sup>].

The aim is to establish a common reference mathematical framework within which various behaviours can be compared and contrasted using Euclidean and non-Euclidean, Klein, geometries. The latter include Affine, Projective, and Differential geometries. (For brevity, formal definitions of these are not included in this paper). The OU approach also includes the application of Topology and Set Theory, which are taken as natural, but less structured, extensions of the more formal geometries.

Together, these methodologies offer great potential for the description of the spatial and temporal aspects of robot behaviour. As an example, set theory, when applied in combination with techniques for the construction of hierarchical lattices, provides a powerful method for describing permutations of robot configurations, either in nominal or in fault conditions. Projective geometry may be applied to the description of minimal vision systems. A further promising avenue to be explored is the subject of robot 'pose' and 'posture' – in brief, this considers that whilst a robot (or any form of autonomous or robotic system) may be required to achieve one specific objective – 'pose' – this may be achieved with the elements of the robot system occupying a number of positions and orientations – 'posture'. Furthermore, the time history of these 'postures' may provide valuable insights into the means by which advanced control systems achieve their objectives.

Such a common framework should provide a means whereby not only the evolutionary and cue deficit approaches can be compared, but also the many other techniques that exist. This is particularly relevant to the problem of embedding the techniques within established design organisations (further comment later), since it offers a means whereby both 'traditional' and 'blue skies' techniques can be compared using a common approach.

## **Action Selection**

An alternative strategy is under investigation by the Department of Aerospace Engineering (DAE) at Glasgow University who are continuing to develop their 'cue-deficit action selection algorithm' approach under the IMAR umbrella. This work is aimed at the autonomous control of both individual spacecraft, and groups of co-operating spacecraft, that have to manage the conflicting demands of a number of sub-systems, for example, power generation, data collection and data download. Glasgow's work aims to achieve this by modelling a spacecraft as a non-linear dynamic system with a state space reflecting the status of the key internal variables. A set of behaviours is used to control the status of the systems within the spacecraft, and a 'cost function' is established which is used to measure the deviation of the spacecraft state space from its nominal operating point. The deficits of the state variables can be evaluated at any time, and appropriate actions selected. Action selection rules attempt to optimise the state space of the spacecraft such that deviations from the nominal operating point are minimised, and such that the 'Lethal Regions' surrounding the state space, which represent unacceptable system states, are not entered. The spacecraft is found to demonstrate a degree of

opportunism not always present when conventional artificial intelligence methods are used [Radice and McInnes, 2001<sup>8</sup>][Gillies et al, 1999<sup>9</sup>].

This approach is extended to the mutual cooperation between several spacecraft, and IMAR work aims to develop and evaluate the algorithms to represent a typical Earth Observation mission. This activity [McInnes, 2001<sup>10</sup>] is primarily simulation based, and has synergies with the work by SSSL who are looking at autonomous telemetry management as a means of coping with telemetry bandwidth limitations, as described in the following section.

## **Autonomous Telemetry Management**

Activities associated with on-board intelligent data reduction for telemetry bandwidth management parallel and complement the distributed system aspects described so far. These activities are being pursued within the overall project framework by Science Systems (Space) Ltd, (SSSL), [Woods, 2001<sup>11</sup>]. This work by SSSL builds on previous investigations, and investigates autonomous on-board health monitoring and telemetry management strategies. These are considered in the light of their suitability for treatment using soft computing technologies, in particular fuzzy and neuro-fuzzy systems.

Woods identifies that 'health assessment is a progressive, dynamic activity that only begins to crystallise some time after launch when operators have gained experience and a feel for the spacecraft'. For the introduction of highly autonomous systems, a suitable technique for modelling operator knowledge and experience is necessary. It is proposed that a 'ground first' strategy for the training of soft computing based systems be adopted, where assessment models of the proposed control architecture are developed and fine-tuned by operators on the ground first, thus enhancing the ability to interact with the spacecraft during the mission. It is identified that the adoption of fuzzy methodologies allows this interaction to be based largely on the use of natural language terms, thus speeding up ground – spacecraft interactions, and greatly reducing the need for large telemetry downloads.

## **Embedding the Technique**

Within the industrial partners of the consortium, one of the primary activities is to address the problem of how to embed the output of IMAR-1 and IMAR-2 in the mainstream space mission engineering activity, so that synergies between IMAR and mainstream design can be capitalised upon. This will involve the engaging of mission design, Attitude and Orbital Control Sub-System (AOCS) / Guidance Navigation and Control (GNC) and Software specialists in an ongoing conversation with the partners in this consortium. In this way, a return to all participants, and to the industry generally, in the form of new techniques and building blocks for the future can be achieved.

Within Astrium, AOCS and GNC engineering staff are already involved in considering the practicality of embedding this work in mainstream design tasks, and how it relates to autonomy projects already in work. These include both free flying missions and the ongoing programme of planetary lander missions.

## Concluding Remarks

The IMAR activity draws together complementary activities relating to spacecraft control and operation, in the areas of evolutionary robotics, cue deficit action selection, telemetry management and mathematics. The synergies existing between these various topics and the organisations working on them have proved to be fertile ground for the development of future autonomous systems.

The IMAR programme has some little way to go before fully viable system solutions emerge, but confidence is high that the investment will prove to be worthwhile.

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