SIMULATING RESOURCE SHARING IN SPACECRAFT CLUSTERS USING MULTI-AGENT-SYSTEMS

Jürgen Leitner (1)

(1) *European Space Agency, Advanced Concepts Team, jurgen.leitner@esa.int, +31 71 56 58518, Keplerlaan 1, 2200AG Noordwijk, The Netherlands*

ABSTRACT

The project presented simulates dynamic resource sharing between multiple small spacecraft similar to the proposed fractionated spacecraft concept. It aims to make a first step from mathematical representation and game theory to the application of resource sharing in orbit, ensuring that each spacecraft module has the needed resources for operation.

Two types of spacecrafts, producers and consumers, are simulated in a *breve* multi-agent system (MAS) environment. The simulation models some basic space environment constraints (e.g. LEO, spacecraft flying in a cluster, etc.), and is aimed to be easily extended and grow in complexity for future use in this and other projects.

Additionally a focus is put onto the modelling of the transfer of the resource (e.g. "cost"), consisting of the loss of resource depending on the transfer method and the distance including the resources needed for transmission.

The simulation is a starting point to evaluate various techniques for sharing resources, taken from non-space areas such as game theory, with respect to sharing optimality and robustness.

1. INTRODUCTION

The concept of *fractionated spacecraft* is currently the topic of a research program within the US Defense Advanced Research Projects Agency (DARPA) aiming to generate a new paradigm for space systems, especially in the responsive space sector. The approach aims to overcome the drawbacks of large, monolithic spacecraft of today, like responsiveness and delay cascading in manufacturing [1]. This approach would also allow for a disruptive change in how satellites are built and used, since the establishing of a space infrastructure lowers the entry barrier for satellite building and allows for resource sharing. The main idea is to further modularize satellites up to the point where the monolithic spacecraft can be decomposed into a network of wirelessly linked modules, all separate smaller spacecraft, flying in a cluster and providing the same or more capabilities than a single spacecraft. For a conceptual assessment, mainly regarding its influences on the aerospace sector, resulting from standardization and mass production market, the reader is referred to [2].

Currently the projects funded by DARPA (under the title of *System F6*) are in their Phase 1 and 2 studies, with the aim of a having a flight ready system in 2012. This prototype mission would last only shortly and just test some of the main capabilities, like proximity flying and wirelessly connecting new nodes. A fully functional system is proposed to be in operation by 2016 [1]. These milestones seem rather optimistic from the current point of view, and 2019 seems to be a more reasonable assumption for a working system, which would also have added functionality by then, for example, multiple orbital configurations. The system aims also to produce plug-and-play satellites, which would reduce the development time and lower the cost due to mass production. These core satellites, with the necessary functionalities to share resources with the other nodes in the system, would then be equipped with the payload and could be launched rather quickly (also from aircrafts or submarines)

Pleiades Proposal

One proposal for the DARPA fractionated space system study was developed by a consortium lead by Orbital Sciences Corp and is called the “Pleiades” system [3]. The technical approach includes four phases: PDR, CDR, integration & test and on-orbit demonstration. The proposed architecture will include five 225-kg (wet mass) and two 75-kg modules flying in loose-formation in Low-Earth-Orbit (LEO). The mission aims to deploy electro-optical imagers with different TRLs and tries to decouple the deployment of the sensors from each other as well as the up/downlink capabilities. The proposed architecture would share resources between the satellites as shown in Fig. 1.

Each module must provide a minimum set of features enabling it to be launched independently, join the cluster and start operation within close proximity of the others. This set will include: attitude control, power management, thermal management, safe mode avionics, propulsion and a telemetry, tracking & control (TT&C) link. The system aims to provide a framework for two independent missions, each with: a mission payload, continuous communication (adds the need for data relay capabilities), high-bandwidth downlink, large volume data storage and on-board data processing. The main research focus is on the distributed computing capabilities, mainly involving the operating of a middleware named Virtual Mission Bus (VMB). The architecture would be launched during three separate launches until fully operational.

Multi Agent Systems

A multi-agent system (MAS) is a system composed of multiple interacting, intelligent agents. Multi-agent systems can be used to solve problems that are difficult or impossible for an individual agent or monolithic system to solve. Examples of problems appropriate for multi-agent systems research include online trading, disaster response, and modelling social structures. Multi-Agent Systems have been used for planning and scheduling tasks also and in space missions [4]. ESA has recently shown a greater interest in using MAS in more areas, from engineering support to spacecraft autonomy. Those systems are though at a very rudimentary level and not yet used in future mission and planning. MAS can be used for a variety of space tasks, but are mainly used for multi-robot systems, e.g. in cooperation/collaboration for exploration, due to the difficulty of testing satellite control algorithms, e.g. using MAS for formation flying, on Earth.

Using multiple, modular and reconfigurable robots has a few possible advantages, even more so in space, where the systems have additional strict requirements. These advantages may include saving weight (used as multiple tools), compressing form (saving space) and increasing robustness (increasing redundancy). Other useful features are adaptability and self-(re-)configurability and even self-repair has been proposed. Because of these advantages a trend towards multiple robots and robot teams can be observed in (space) research and in the plans of the space agencies, of the USA (NASA), Europe (ESA) and Japan (JAXA). In those visions and plans another reason to use multiple cooperating robots is presented, namely to build human outposts (habitats) on planetary surfaces and in space. Chicarro proposed multiple lightweight rovers to explore Mars as a feasible alternative to single robot missions already in 1993 within the MARSNET project [5].

Launch	1		2			3	
Module Name	Alcyone	Electra	Maia	Celaeno	Asterope	Merope	Taygete
Module Wet Mass (Kg)	225	225	225	75	75	225	225
Precision Pointing Payload	●		●			●	
Coarse Pointing Payload				●			
TDRSS	●			●			
Solid State Recorder		●					●
High BW Downlink		●					●
Mission Data Processor					●	●	

Fig. 1: Proposed Resources Shared in the Pleiades Proposal for the DARPA System F6 Study [3]

In publications of multi-robot systems for space applications often humans are included as members of the team, working closely together with the robots to complete the explorative tasks. Areas of interest in research regarding this are human robot interaction [6] and sliding autonomy [7].

2. IMPLEMENTATION OF THE MODELS

This section describes the models used for the *breve* implementation[1] of the multi-agent system. It describes the environment for the satellites, their control, as well as how the resources are modelled.

Environment Modelling

For the spacecraft cluster a circular Low-Earth-Orbit (LEO) was chosen, since in this case the orbital dynamics can be simplified as described by the Hill-Clohessey-Wiltshire (HCW) equations (see Eq. 1). These equations describe the motion of the spacecraft as the relative motion to the centre of the cluster in LEO.

$$\begin{aligned} \ddot{x} &= 2n\dot{y} + 3n^2 x \\ \ddot{y} &= -2n\dot{x} \\ \ddot{z} &= -n^2 z \end{aligned} \tag{1}$$

where n is a gravitational parameter depending on the orbital configuration. Throughout this paper n is 0.08 (LEO). The trajectories (without thrusting) for this environment in 2D are visible in Fig. 2.

Spacecraft Control

A very rudimentary and simple approach to controlling the spacecraft is currently implemented. The spacecraft aim to stay within a box around the midpoint of the spacecraft cluster defined by the *MAXBOX* constant. A limitation is put on the maximum thrust and the orientation for firing. As soon as a spacecraft reaches the boundaries of the box a velocity component is added to the current velocity. The thrust is done along the axes (no orientation of the satellite's thrusters with respect to the axes is assumed) aiming to get the spacecraft back towards the centre of the cluster.

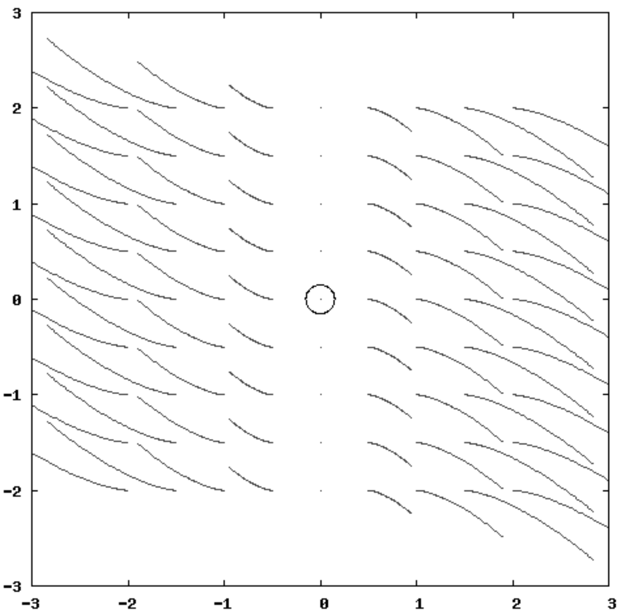

Fig. 2: The gravitational environment in two dimensions, using n = 0:08 (LEO). The equilibrium points can be seen on the Y-axis (Earth pointing).

[1] The breve code for the simulation can be downloaded from the project webpage at http://Juxi.net/projects/FractionatedSpacecraft/

Resource Modelling

The resource sharing modelled here is based on a flexible, extendable simulation, which allows for each satellite to have multiple resources that are reduced per iteration and/or by specific events. For example, the satellite fuel can be modelled to be reduced whenever the satellite needs to fire its thrusters for station keeping. The main focus in this paper is the resource sharing, with the resource assumed to be energy. It is based on a simple power system, a reduced version of a generic satellite power system, as depicted in Fig. 3.

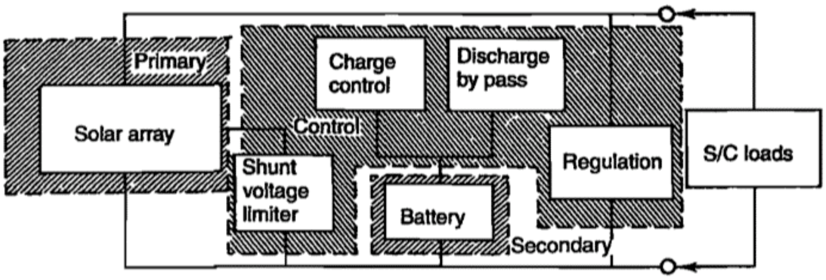

Fig. 3: Schematics of a typical spacecraft power system [8]

The following assumptions for the energy resources were made using the PRISMA satellites as a reference, since no detailed design for the DARPA study is yet available. The two producer satellites use their solar cells to generate more energy than needed and store it in their battery packs (The bigger of the two PRISMA satellites generates 400 W and has 3 Lithium Ion battery packs). These can then transfer the energy stored in their batteries to one of the other satellites, chosen by one of the selection algorithms to be compared, via a LASER (see further down).

Table 1: Resource Properties of the Satellites

	Producer Sat.	**Consumer Sat.**
Unit Production per Iteration	600	100
Unit Consumption per Iteration	400	90
Storage Capacity	3000	500

Each of the consumer satellites will periodically, with a randomly initialized *usageCycle* period, reduce its stored energy, which aims to simulate the use of some instrument or operation without power generation (e.g. due to shade from the Earth or another satellite). This usage operation will reduce the stored resource by the unit consumption per iteration multiplied by a randomly initialized *usageMultiplier*. The usage is *blocked* if there is not enough power available for the operation.

Energy Transfer

The idea to also have power sharing in a fractionated spacecraft architecture was already proposed in one of the first papers for the DARPA F6 study [1]. Transfer of energy from one satellite to another could reduce the need for large and bulky solar arrays. Here a LASER power transfer is modelled. It, similar to the Rayleigh criterion, uses Gaussian optics to analyse the power loss of the LASER. These define the power through an aperture as an exponential decay as a function of the distance and beam width. A loss of 10% is assumed throughout this simulation. And no transfer is done for distances larger than the bounding box of the satellite cluster (*MAXBOX*).

The selection of a consumer satellite by a producer is followed by some attitude control on both satellites leading to the usage of some (other) resource, but this is not modelled so far. Then the spacecraft transfer the energy by reducing the resource level at the producer by a constant (*MAX_TRANSFER*) and at the receiver by a value depending on the distance between the two satellites. The transfer is locked to this satellite for a constant number of steps (*SELECTION_LOCK*).

3. INTEGRATION OF RESOURCE SHARING STRATEGIES

Simple Algorithms

To test the simulation and its feasibility to represent resource sharing some simple algorithms were implemented. These are also used to benchmark the more advanced concepts to be implemented in the future. Three of these algorithms are currently implemented: random selector, closest selector, and lowest selector. All these work on the neighbourhood of the power satellites, which is defined as the satellites that are within a distance of *MAXBOX* from the power satellite, which is also the distance from the centre at which the satellites start firing their thrusters. In this neighbourhood no distinction is made between consumer and producer satellites and instant communication (of resource levels) is assumed. The algorithms select a random, the closest or the lowest resource-storing neighbour from the neighbourhood respectively. In the case of the lowest there is an additional check to not transfer energy to satellites that have more than the producer.

After the selection of the receiving spacecraft for each producer the energy transfer starts as described above.

Game Theory Algorithms

As a comparison to the algorithms above some results from game theory were used to implement resource sharing in the fractionated architecture. The algorithms are based on a notion of social welfare and aim to "solve the resource allocation problem within an agent community" [9]. The three main definitions of social welfare are used and implemented in separate algorithms:

- utilitarian welfare
- egalitarian welfare and
- the Nash product, as a compromise between the other two

For the *utilitarian welfare* (also the algorithm based on the Nash product) an estimate calculated by the agents, spacecraft in this case, is used by the producer satellite to help in the selection of the receiving spacecraft. This estimate is usually based on the resource usage estimated by each agent separately, with the parameters defined above for the resource modelling Eq. 2. can be used to estimate the use. The problem as described in this paper uses standardized (consumer) satellites therefore a simplified calculation (Eq. 3) is sufficient to find the spacecraft with the highest estimate.

In the *egalitarian welfare* the poorest agent is selected as the receiving spacecraft, as long as it would not make the producer the poorest after the transaction.

The algorithm based on the *Nash Product* as a compromise between the other two uses the same estimation function as the utilitarian welfare but checks also if one of the agents in the neighbourhood is reaching the end of its resource. If so this agent is then chosen to be the next receiver. (This is a small modification of the behaviour found in [9]).

$$e_i = \left(t_t + \frac{usageCycle_i - c_i}{t_t} \cdot usageMultiplier_i\right) \cdot u_i \tag{2}$$

$$e_i' = \frac{usageCycle_i - c_i}{t_t} \cdot usageMultiplier_i \tag{3}$$

where e_i is the estimate, t_t the time the selected consumer will be supplied (and therefore not swapped), c_i the time (ticks) since the last use and u_i the usage of the resource per tick for agent *i*.

4. RESULTS AND CONCLUSIONS

The first results obtained for this ongoing project are presented here. The simulations were run with 5 consumer satellites (75kg) and 2 producers (225kg). Each algorithm is run 10 times, with random starting position of all satellites and per run 500 time steps with 20 ticks each (*dt = 0.05* for the integration) are done. A section of a typical run during the simulation is shown in Fig. 4.

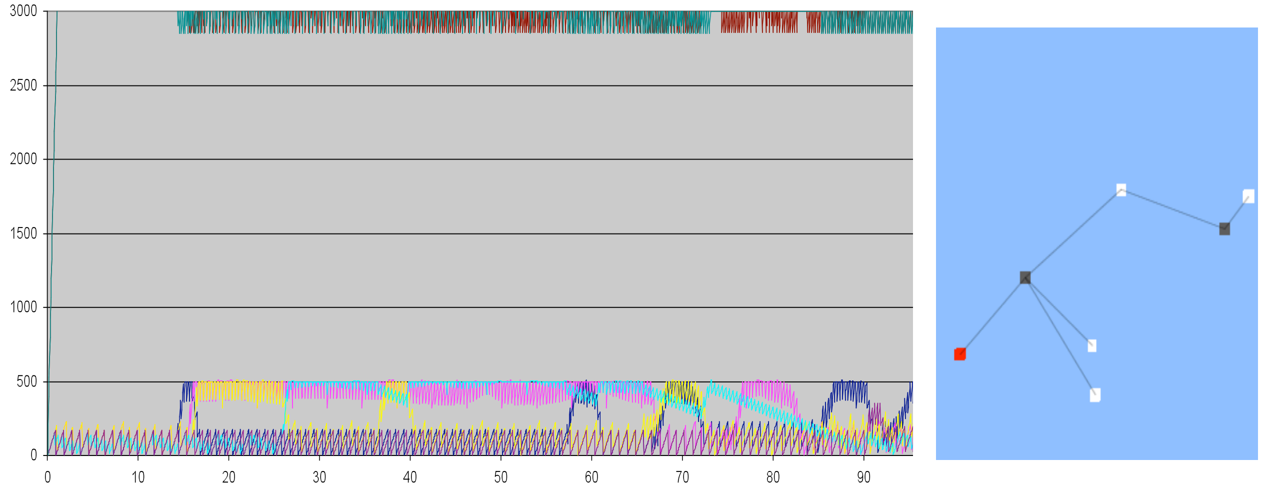

Fig. 4: A typical simulation run, resource level vs. time steps and next to it a snapshot from the *breve* simulation, black cubes are the producers, red cubes are currently firing and satellites, in the vicinity of a power satellite are visualized by a gray connection.

Already these first results show that there is a significant difference in performance and robustness between the chosen algorithms. The resource sharing decision in the dynamic environment can therefore also optimized and the right algorithm is of importance. The comparison of the strategies implemented here is shown in Fig 5, where one algorithm (the one based on the Nash product) allows for fewer blockages (times when the craft wanted but could not use its resource).

Interestingly there was even a large difference between the algorithms selecting simple the lowest and the best algorithm, which would not only chose the lowest but select intelligently which spacecraft to supply in cases where there is no satellite close to “starvation”.

The first step, to show that this simulation can run, has been successful, now more algorithms and details will be added over the course of the next few months to allow the tool to be helpful in the decision making process for fractionated spacecraft architectures.

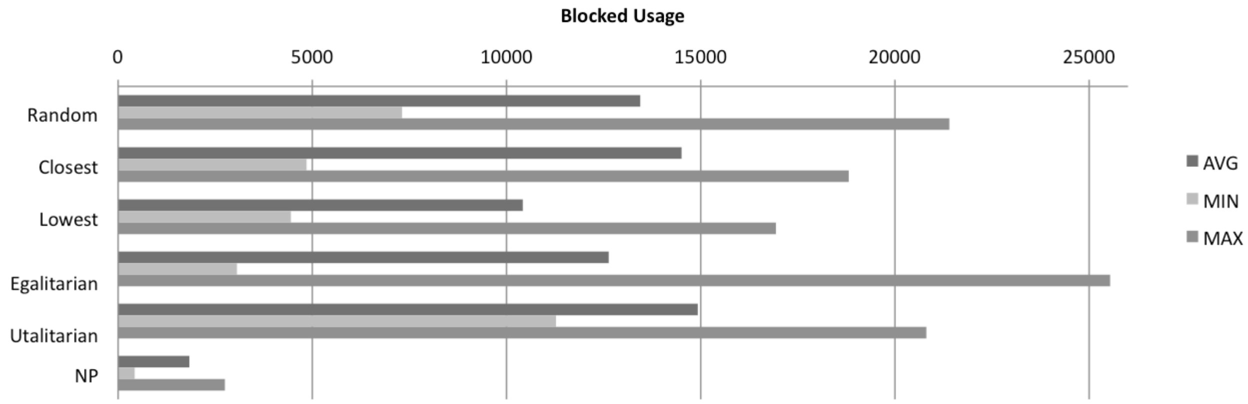

Fig. 5: Comparison of the various algorithms in terms of blocked (due to lack of resources) usage of the satellite payloads

5. FUTURE WORK

This work is part of an on-going project at the Advanced Concepts Team of the European Space Agency. A more detailed simulation is planned, putting emphasis on a more realistic simulation of the space environment, satellite control and the resource sharing (focusing on energy transfer). Also a more detailed incorporation of other studies and architectures proposed (e.g. during the DARPA F6 project) is aimed also in terms of comparability with the value-centric design tools released.

It will be interesting to see how these algorithms perform under different mission scenarios and whether this significant performance increase due to one algorithm will also occur for these. On the other hand a comparison with other algorithms, e.g. from the field of network routing, should also be implemented and compared to these results.

With a more detailed simulation of the spacecrafts also other distribution and resource sharing approaches can be tested, mainly approaches that take the full dynamics of the architecture into consideration. Such a simulation would also allow comparing various types of energy transfer that have been proposed e.g. RF/microwave, concentrated sunlight, induction and how they perform under different mission scenarios.

6. REFERENCES

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