Self Assembly in Space Using Behaviour Based Intelligent Components

Mark Ayre, Dario Izzo, Lorenzo Pettazzi
Advanced Concepts Team
ESTEC, European Space Agency
Keplerlaan 1-2201 AZ
Noordwijk, The Netherlands
mark.ayre@gmail.com

Abstract

This paper describes a novel control scheme termed 'equilibrium shaping' for the control of a swarm of spacecraft in both flat and curved space. This control scheme allows the intelligent and autonomous control of an arbitrary number of elements, suitable for example to self-assembly or formation flying applications.
The control scheme employs three *basis behaviours* that are summed together to provide a dynamical system representing the swarm of intelligent agents. Through suitable selection of parameters, this system has as equilibrium points the desired formation of the agents – thus the global behaviour of the agents is, although *emergent*, entirely predictable. The kinematical field resulting from the solution of this system can then be imposed on the agents using suitable control laws. The scheme is shown to exhibit *emergent* behavioural artifacts typical of a swarm intelligent approach.

1 Introduction

1.1 Self Organisation and Assembly in Nature

Self assembly can be considered a sub-domain of self organisation, where lower-level components actually form structures out of themselves rather than inert elements of the environment. Both self organisation and self assembly are ubiquitous throughout nature: taking a tour through the natural world from the smallest to largest scales, we can observe the self-organisation of subatomic particles into stable atomic configurations, crystal formation, nanoscale self organisation of peptides and polymer chains, organisation of polymers into larger functional structures, DNA replication (Winfree, 1998) and virus shell assembly (Berger & Shor, 1994). At a cellular level, processes such as morphogenesis and mineral deposition lead to a multitude of hiearchical structures such as muscle, bone, cutin, bark etc, whilst morphallaxis (Hotz, 2003) allows the structural reordering of cells without proliferation. At the level of whole individual organisms, we can see the construction of incredibly complex nests by eusocial insects such as Termites (Luscher, 1961) and Tropical Wasps (Jeanne, 1975). Some species of social insects can also self-assemble into structures composed of their own bodies – for example in the chain formation of *Oecophylla longinoda* (Holldobler & Wilson, 1978). Observing these instances of self-organisation and assembly we can marvel at the robustness of the processes and the complexity of the structures that are produced. Completely unsentient artifacts such as biological cells achieve advanced global structure, and their orchestrated actions are superbly tolerant in the face of pertubations such as random cell death or malfunction (Kondacs, 2003). The mechanisms involved in natural self organisation are very attractive to a number of engineering fields.

1.2 Automated Self Assembly for Space

For engineering purposes, a self assembling system can be defined as one where order and structure arise without human intervention. Self assembly can also be characterised as the formation of large structures out of smaller components. These two descriptions of self assembly immediately reveal why engineering the ability to self-assemble into future space structures would be very desirable. Firstly, there are upper mass and volume limits associated with the delivery of structural elements to space. For example, the International Space Station has been delivered to orbit over the course of many launches for the simple and obvious reason that it could not be contained within the fairing of a single launch vehicle. This is coupled with the fact that there will be many construction situations in the future where a human presence is not possible or practical: from a cost perspective, the assembly of large structures by astronauts even in Low Earth Orbit (LEO) is prohibitively expensive (Shen et al., 2003). Remote supervision and control of assembly could be possible from the ground for LEO and near Earth instances, but obviously further afield would also be impractical due to typically long communication delays.

There are a number of mission concepts that will require automated assembly. The development of automated on-orbit assembly has been identified as a key requirement by the AURORA program (ESA's exploration program). Advanced mission concepts being developed also rely upon the use of swarms of satellites - examples are the APIES and ANTS architectures (EADS, 2004; Curtis et al., 2000). Under the *gossamer spacecraft initiative* NASA has identified several new mission concepts, including very large aperture telescopes, large deployable and inflatable antennas, solar sails and large solar power collection and transmission systems. One example of this array of concepts is described in the ULTIMA studies (Zeiders, 1999), which have shown that a very attractive configuration for a very large space telescope is the three-mirror Gregorian design, shown in figure 1.

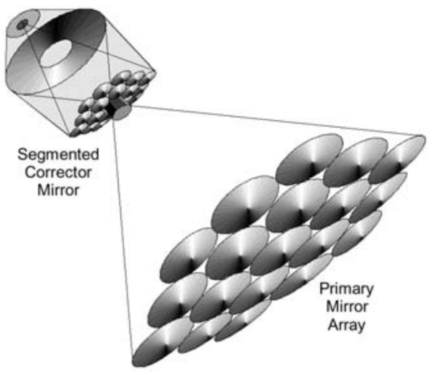

Figure 1 - The ULTIMA telescope configuration, image adapted from (Zeiders, 1999)

The most ambitious group of structures that require in-situ assembly of a number of separate components in space are a number of SPS concepts such as those described in (Carrington, 2002). The concepts can be divided into three primary classes, all of which are conceived of as being not only extremely massive and composed of literally thousands of components, but also placed at geostationary orbit far from the Earth: Figure 2 shows an Integrated Symmetrical Concentrator (ISC) configuration (incoming sunlight is collected in two large clamshells located on the ends of a mast, reflected on photovoltaic arrays located midway along the mast) with a lower reference mass of 18,000 MT.

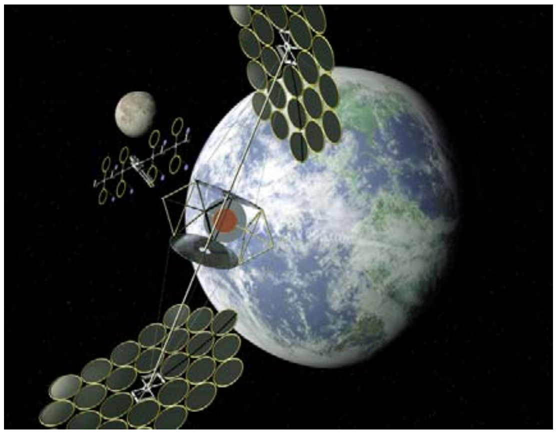

Figure 2 - ISC SPS array concept

1.2.1 Systems Concepts for Automated Assembly

At a systems engineering level, the work done to date in realising automated assembly in space can be best represented by the SOLAR (Self Assembly for Space Structures) project – this is based around the FIMERS concept described in (Shen et al., 2003), a system for self assembly of a space structure using Intelligent Reconfigurable Components (IRCs), and a number of free-flying **FI**bre-rope **M**atchmaker **R**obots (**FIMERs)**. All the IRCs are envisaged to be equipped with GPS/Gallileo receivers and wireless communication, an on-board computer that will control the information gathering processing and communications, canonical connectors to dock with other components and FIMER units, a position and orientation sensory system, an on-board controller for topology discovery, action planning, communication with FIMERS and other IRCs and monitoring the progress of assembly, and auxiliary connections for fluid-gas pipes and electric connections so the structure can operate as a unified whole when fully assembled.

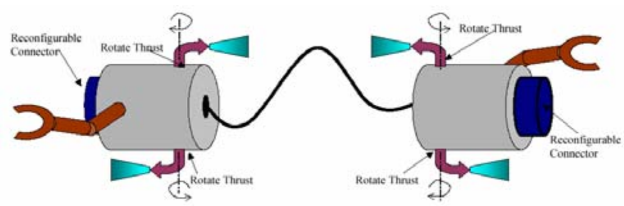

Figure 3 – FIMER robot with two free flying heads, adapted from (Shen et al., 2003)

The assembly of the IRCs is conceived as being mediated by one or more FIMER robots (figure 3). Each FIMER robot consists of a pair of robot *'heads'* attached by a thin fibre that can be reeled in or out by the heads. Each head can fly autonomously and (de)dock with any IRC or other FIMER robots. Each head is equipped with a rotational/translational thruster system, a motor to manage reeling of the fibre, GPS/Gallileo, wireless communications, a robotic manipulator arm, and a reconfigurable connector. The self-assembly process is orchestrated by the Digital Hormone Model (DHM) developed for the CONRO reconfigurable robot system (Castano et al., 2002). Summarised simply, IRCs signal that they wish to dock with each other, and then call a FIMER for help. The FIMER heads attach one to each IRC and provides docking guidance through reeling them together. The canonical connectors will use infra-red to provide guidance signals for alignment in the docking process, as used in the CONRO system (Rubenstein et al., 2004). The mechanics of pulling two IRCs together using the Fibre allow simplified control, naturally avoiding undesirable rotation. At this final stage, the manipulator arms on each head will be used to provide fine-grain control of the docking process. The connectors can detect their state and gathering this information allows the current topology of the structure to be determined. The IRCs then negotiate to decide on the next sequence of actions to take. The sequence of IRC assembly is embedded in the IRCs themselves. For a homogeneous system of IRCs, each IRC and it's connectors do not require unique identification and sequencing is not required. In the case of a heterogeneous set of IRCs, unique identifiers are used for each connector (for a semi-homogeneous set of IRCs, type-identifiers for generic components is sufficient).

2 The Equilibrium Shaping Approach

2.1 Work to Date

We are interested here in spacecraft which have to accomplish proximity operations and have to reach, with a group of other satellites, a very tight formation, or indeed dock with those other spacecraft. A fundamental component of spacecraft swarm operations therefore involves position and velocity control. As such, the lessons learned in terrestrial robotics research would appear to highly relevant, in particular research into terrestrial robot path planning. From path planning approaches, the artificial potential method has to date been considered as the main tool that would allow a group of spacecraft to perform as required. Work using artificial potential fields defined in the space around the agent(s) has been performed through from terrestrial plath planning (Khatib, 1986) to spacecraft proximity and rendezvous (McInnes, 1995) and self-assembly in space (McQuade, 1997).

The artificial potential method is supposed to create in the space around the spacecraft (or the 'agent' in general) a potential field that will drive the agent far from any obstacle and towards any desired target. This method is suitable to be used both for a single spacecraft and for a swarm of satellites and is capable of tackling the problem of the guidance of a vehicle in a time-varying environment. However, when combining multiple behaviours through the superposition of multiple potential fields, it is impossible to guarantee avoidance of undesired local minima.

Examples of other approaches include work by (Ren & Beard, 2004) who introduce the Virtual Structure method in order to design a decentralized formation scheme for spacecraft formation flying, whilst (Campbell, 2003) applies some results from optimal control theory in order to design an off-board computed procedure for the design of a formation reconfiguration method.

In general all these methods have been used to design systems that have only one target configuration as a final objective. Therefore there is a general requirement for a method able to tackle the multi-target problem for a swarm of *homogeneous* agents. In such an algorithm the final position occupied by each agent in the target configuration should be chosen in an autonomous way between all the of possible ones according to the initial conditions imposed. Each satellite belonging to the swarm will be then able to autonomously decide what its final position in the target configuration will be, exchanging a minimum amount of information with the other swarm components. This kind of procedure can drive a self-assembly process of homogeneous agents in space and it clearly scales well with the increasing of the number of satellites belonging to the swarm due to the lack of explicit global coordination.

2.2 The Control Scheme

In this section an algorithm able to lead an arbitrary number of *homogeneous* spacecraft towards a final formation by autonomously deciding which agent will get to each position of the final configuration is presented. Such a method draws inspiration from behavioural robotics, and a model recently developed by (Gazi, 2003; Gazi & Passino, 2002), in which a kinematical field is proposed that can lead a swarm of agents to reach a stable configuration. The resulting procedure is made up of two different steps:

- A desired kinematical field is imposed in the space around the agents belonging to the swarm. This kinematical field is time dependent and it assigns for each configuration, i.e. each position of each spacecraft, the desired velocity vector of each agent as a sum of different weighted contributions.
- An appropriate feedback signal is defined to enforce the real dynamics of each spacecraft towards the desired one.

In this way it is possible to keep the desired kinematical field design separate from the control feedback design, which is arbitrary - this control scheme has been tested using four different steering laws. The velocity field used in (Gazi & Passino, 2002) is given by the sum of two different contributions, both of which are functions of the distance between two agents *i* and *j*. The first contribution introduces a linear global attraction effect whereas the second one introduces a local exponential repulsive effect, defined by:

$$V_{d_i} = -\sum_j x_{ij}\left[c_i - b_i \exp\left(\frac{-x_{ij}.x_{ij}}{k}\right)\right] \tag{1}$$

Where xj is the distance between the agents, and c anb are coefficients determined by the formation geometry. This approach allows a final desired formation to be reached only if the required distance between a generic *i-j* couple of spacecraft at the end of the simulation is pre-assigned. Thus the resulting system doesn't have the general capability of deciding autonomously where each agent should go. In order to increase the fault tolerance and the degree of parallelism of the system, the position of each swarm component in the desired final structure **should not to be pre-assigned**; this constraint becomes a particularly important feature for swarms composed of very large numbers of elements, where exploitation of parallelism between homogeneous elements would be very desirable. In that way the final formation reached would be autonomously decided by the agents according to the information that each of them can obtain by the use of sensors and would not be imposed at the beginning of the manouevre.

The final configuration can be reached in such an autonomous manner according to a particular definition of the desired kinematical field given from the *equilibrium shaping* approach developed here. This technique consists in building a dynamical system that has as equilibrium points all the possible configurations suitable for the final purpose, i.e. all the agents permutations in the final desired configuration.

As example let us consider a situation in which a swarm of two satellites has to reach a final configuration made up of the two geometric positions given by:

$$\vec{x}_1 = [1 \quad 0 \quad 0],\ \vec{x}_2 = [-1 \quad 0 \quad 0] \tag{2}$$

If the agents are identical two final formations will be valid, one in which agent 1 is in $\vec{x}_1$ and agent 2 in $\vec{x}_2$ and one in which the final positions are inverted. We define a desired kinematical field according to the relation:

$$\dot{\vec{x}} = \vec{f}(\vec{x}) \Rightarrow \vec{f}(\vec{x}_e) = \vec{0} \tag{3}$$

in which the $\vec{x}_e$ vector represents all the possible final formations achievable (in the example, both the final configurations in which Agent1$_{\Rightarrow \vec{x}_1}$ and Agent2 $\Rightarrow \vec{x}_2$ and in which Agent1$_{\Rightarrow \vec{x}_2}$ Agent2$_{\Rightarrow \vec{x}_1}$). The desired velocity field used to obtain this effect can be written as a superposition of different contributions.

Taking inspiration from (Brooks, 1991), three behavioural primitives required for the task of assuming a formation in space (including assembly) have been defined to allow the swarm of satellites to function: ***Gather***, ***Avoid*** and ***Dock***. *Note that this model does not take into account control of the attitude of the agents, although this is possible, and work is currently underway to extend the repertoire of behaviours to include attitude control.* The governing expressions of each basis behaviour along with some brief comments are presented below. Each contribution to the *i-th* agent desired velocity field establishes a relation with an agent if it has the *j* subscript, whereas it refers to a desired final position in the formation (hereafter a *sink*) if it has the t_j subscript:

(i) Gather behaviour This basis behaviour introduces *N* different global attractors towards the sinks of the desired formation. Therefore each agent has to know at each time where is the position of each point of the final formation to be achieved. The expression for this kind of behaviour is defined as:

$$\vec{f}_{gather}^{\,it_j} = -c_j \vec{x}_{it_j} \tag{4}$$

where $\vec{x}_{t_j}$ is the distance between the *i-th* agent and the *j-th* sink (t_j). This behaviour can be written for each sink and for each agent and is linear with the distance between them. Summing up for one agent the contribution of each sink it is easy to understand that all these contributions are equivalent to a single global attractor pointing towards the center of the desired formation (figure 4).

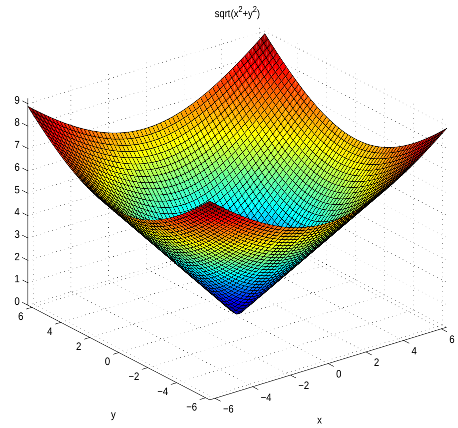

Figure 4 – The gather behaviour global attractor

(ii) Avoid behaviour This basis behaviour establishes a relationship between two different agents that are in proximity with each other. In such a case a repulsive contribution will assign to the desired velocity field a direction that will lead both the two agents away from each other. The expression that describes the assigned velocity for this kind of behaviour is given below:

$$\vec{f}_{avoid}^{\,ij}(\vec{x}_{ij}) = -\vec{x}_{ij}[b\exp(\frac{-\|\vec{x}_{ij}\|}{k_1})] \tag{5}$$

In this relation $\vec{x}_{ij}$ is the distance between the two agents that are proximate and k_1 is a parameter that describe the sphere of influence of this contribution, i.e. at what distance this behaviour would have a non-negligible effect. In order to maintain the symmetry between all the agents the *b* parameters of the avoid behaviour all have the same numerical value (figure 5).

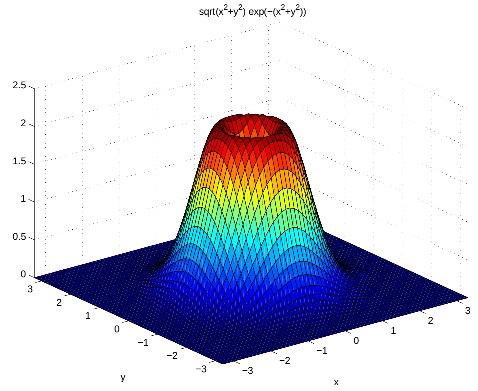

Figure 5 – The avoid behaviour

(iii) Dock behaviour This last basis behaviour expresses the local attraction of each agent towards each sink. The component of the desired velocity field due to this behaviour has a non-negligible value only if the agent is in the vicinity of the sink. The parameter *d* determines the radius of the sphere of influence of the dock behaviour. The expression for this basis behaviour is:

$$\vec{f}^{ij}_{dock}(\vec{x}_{it_j}) = -\vec{x}_{it_j}[d_{it_j}\exp(\frac{-\left\|\vec{x}_{it_j}\right\|}{k_2})] \qquad (6)$$

in which again $\vec{x}_{it_j}$ is the distance between the *i-th* agent and the *j-th* sink t_j and k_2 determines the radius of the sphere of influence of this behaviour. The values of the weighting parameters can be different for any sink (figure 6).

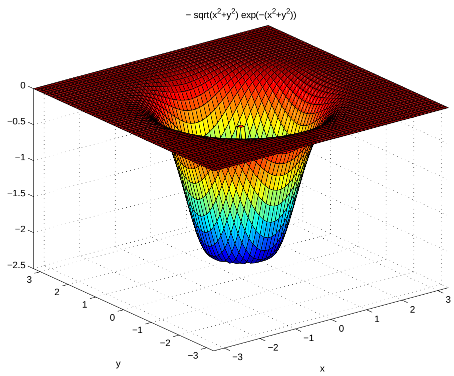

Figure 6 – The dock behaviour

Having defined behavioural primitives for each member of the spacecraft swarm, we define the velocity field for each configuration of spacecraft simply by summing the contribution from each of the basis behaviours:

$$\vec{v}_i = \sum_j \vec{f}^{ij}_{avoid} + \sum_{t_j}(\vec{f}^{it_j}_{gather} + \vec{f}^{it_j}_{dock}), i = 1 \ldots N \qquad (7)$$

This strategy leads to build a dynamical system which can be sketched in the simple form:

$$\dot{\vec{x}} = \vec{f}(\vec{x};\underline{\lambda}) \qquad (8)$$

The resulting dynamical system is obtained as a function of some parameters $\underline{\lambda} = \lfloor c_{it_j}, d_{it_j}, b \rfloor$ that can be evaluated in order to impose that all the final desired configurations are equilibrium points. If $\vec{x}_e$ is the final target configuration to be achieved the relation that has to be fulfilled in order to impose the existence of such equilibria can be written in the compact form:

$$\dot{\vec{x}} = \vec{f}(\vec{x}_e;\underline{\lambda}) = 0 \qquad (9)$$

this is the *equilibrium shaping* formula, written below as a function of the distance between two different sinks each of them occupied by an agent $\vec{x}_{e\,t_i t_j}$:

$$\sum_j \left[b\exp(\frac{-\vec{x}_{t_i t_j}\cdot\vec{x}_{t_i t_j}}{k_1}) - c_{it_j}(-\vec{x}_{t_i t_j}\cdot\vec{x}_{t_i t_j}) - d_{it_j}\exp(\frac{-\vec{x}_{t_i t_j}\cdot\vec{x}_{t_i t_j}}{k_2}) \right]\vec{x}_{t_i t_j} = 0 \qquad (10)$$

$$i = 1.....N.$$

This equation is a linear system made up of *3N* scalar equations in *2N* unknowns where the unknowns are the weighting parameters $\underline{\lambda}$. If a regular formation, or a planar formation are the target configurations, the number of independent scalar relations becomes $\leq 2N$ and the solution of the equilibrium shaping formula can be found. Note that this evaluation theoretically only needs to be evaluated once at the beginning of the maneouvre; thus in principle the agents will not require updating of global knowledge during the maneouvre (although in practice this may not be practical).
This system in theory can be designed for each agent and can be thus considered as the "subjective" view of the *i-th* spacecraft. In this way for a system of *N* satellites it is possible to write *N* equilibrium shaping formulas each of them representing the subjective kinematical field of each agent. In figures 7, 8, 9, and 10 some examples of swarms of *N* agents reaching regular formations are presented. The lines displayed in these figures are the desired trajectories that each agent has to follow in order to reach the final desired configuration and as such represent the solution of the path planning problem given by the velocity field.

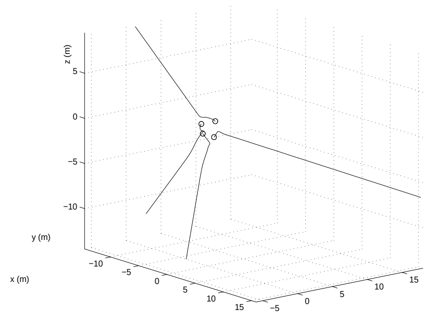

Figure 7 – Trajectory plot of four spacecraft adopting a formation

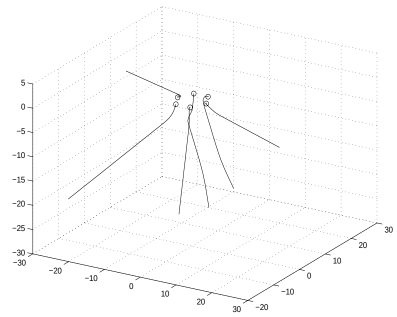

Figure 8 – Trajectory plot of six spacecraft assuming a regular hexagonal formation

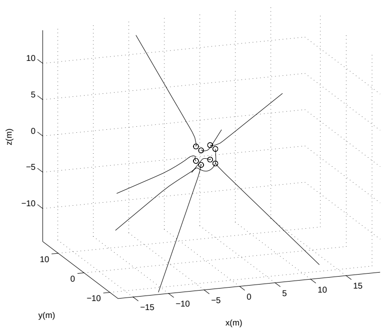

Figure 9 – Trajectory plot of eight spacecraft adopting a regular cube formation

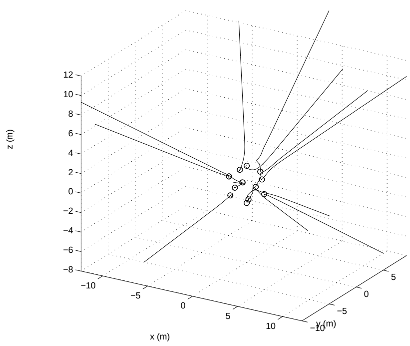

Figure 10 - Trajectory plot of twelve spacecraft adopting a regular formation

During the simulations *emergent* behaviours may be observed due to the interaction between the basis behaviours. These behaviours include waiting for other agents to adopt their position, and coordinated avoidance between agents.

2.2.1 Modification for a Gravitational Field

In the absence of a gravitational field, the velocity field designed in the previous section allows the spacecraft to reach the final formation following trajectories that are straight lines in long parts of the simulation (i.e when only the ***gather*** behaviour has a non-negligible value). In field-free space this is of course appropriate and efficient: however, in field-space, the desired velocity field should be modified to take into account and exploit the natural trajectories that exist between two points on different orbits. The desired velocity that accomplishes this will here be found by substituting the linear ***gather*** behaviour defined by equation 4 with a new one. The starting point for the design of the new ***gather*** behaviour is the well known system of Hill's Equations:

$$\begin{cases} \ddot{x} - 2\omega\dot{y} - 3\omega^2 = 0 \\ \ddot{y} + 2\omega\dot{x} = 0 \\ \ddot{z} + \omega^2 z = 0 \end{cases} \tag{11}$$

These equations allow as their solution the following relation:

$$\begin{bmatrix} \rho \\ \dot{\rho} \end{bmatrix} = \begin{bmatrix} A(\tau) & B(\tau) \\ C(\tau) & D(\tau) \end{bmatrix} \begin{bmatrix} \rho_0 \\ \dot{\rho}_0 \end{bmatrix} \tag{12}$$

With $\begin{bmatrix} \rho \\ \dot{\rho} \end{bmatrix}$ being the non dimensional state space vector, τ the non dimensional time and A, B, C, and D have well known forms (see McQuade, 1997). Equation 12 can now be used in order to define a new gather behaviour that could allow each agent to exploit the gravity field in order to reach the final desired configuration. If one wants to impose that a satellite will reach a certain point ρ_d in the relative space in a certain time τ_d, the following relation has to be valid:

$$\rho_d = \rho(\tau_d) = A(\tau_d)\rho_0 + B(\tau_d)\dot{\rho}_0 \tag{13}$$

This relation assigns for each position in space ρ_0 and each desired time τ_d a desired velocity vector:

$$\vec{v}_d = \dot{\rho} = B^{-1}(\rho_d - A(\hat{\tau}_d - \tau)\rho) \tag{14}$$

in which $\hat{\tau}_d$ is the time at which at the beginning of the simulation the agent is supposed to reach the position ρ_d. In order to track the natural trajectory the resulting desired velocity vector depends explicitly on the time. This contribution can be added to those obtained by equation 5 and equation 6 and in order to build the final desired kinematical field that the swarm has to follow. Since at the end of the assembly procedure each spacecraft will probably operate in a condition in which it is close to the other swarm components it is not possible to allow the spacecraft to have high velocities in that situation. Furthermore equation 16 becomes singular as long as *t* approaches the $\hat{\tau}_d$ value. For both these reasons the agents are not permitted to follow the natural trajectories until the end of the formation acquisition. To implement this we divide the desired kinematical field into two different sections: (i) far from the desired final configuration, in which the gather behaviour takes into account the gravitational force and (ii) close to the desired final formation, in which space can be linearised and considered flat. The geometrical shape of the edge of these two different zones of the space can be easily set as a sphere, with a radius that can be decided by the system designer. Figure 11 shows an example of the ballistic (i.e. outer section) trajectories followed by an assembling group of six spacecraft.

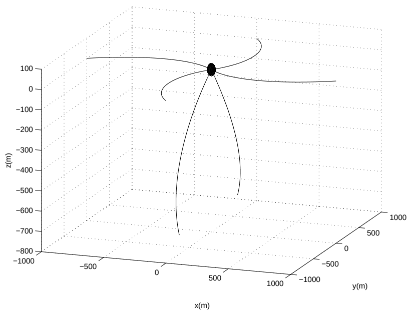

Figure 11 – The ballistic phase trajectories of an assembling group of six spacecraft

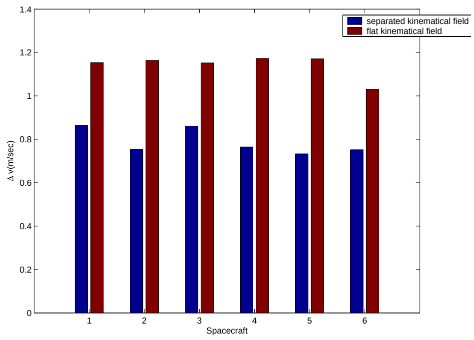

Figure 12 – comparison of the delta V for each of six spacecraft assembling into a regular formation in curved space, using flat and curved space *gather* behaviours

By exploiting the natural trajectories that exist in curved space, substantial delta V savings are made, when compared with the flat space control scheme. Figure 12 shows an example of the delta V saving when using the ballistic gather behaviour in curved space.

2.2.2 Implementation

This control scheme can be easily embedded into algorithms that can allow assembly of large structures in space under more constrained conditions (e.g. heterogeneous agents, sequentiality constraints etc.). Two architectures have been studied within the context of this work: The first uses the TRS scheme developed by (Jones & Mataric, 2003) to control the assembly of an arbitrary structure with sequencing constraints, and the second scheme has been developed to allow assembly of a structure by 'slave' robots, analogous to the FIMER robots introduced in section 1.2.1.

3 Conclusions

A novel scheme for autonomous control of a swarm of spacecraft for self-assembly or formation flying has been presented, both in flat and curved space environments. It has been shown to exhibit intelligent *emergent* coordination at a global level (avoiding fellow agents, waiting for fellow agents to dock before moving) under tests using a variety of steering laws, despite lack of explicit coordination between agents. It should not only allow maximum exploitation of parallelism in systems with large numbers of homogeneous agents, but is also easily embedded within algorithms that can coordinate the assembly process under more constrained conditions. Solution of the dynamic system controlling the agents theoretically only needs to be solved once at the beginning, potentially obviating the requirement for continuous global updating during the course of the maneouvre. Additionally, there are *N* dynamical systems equations for *N* agents, and therefore the technique scales linearly.

The control scheme has been implemented in Matlab/SIMULINK, using the Virtual Reality Modelling Language (VRML) Toolbox to allow visualisation of the assembly process – an example storyboard of the VRML output is shown in figure 13.

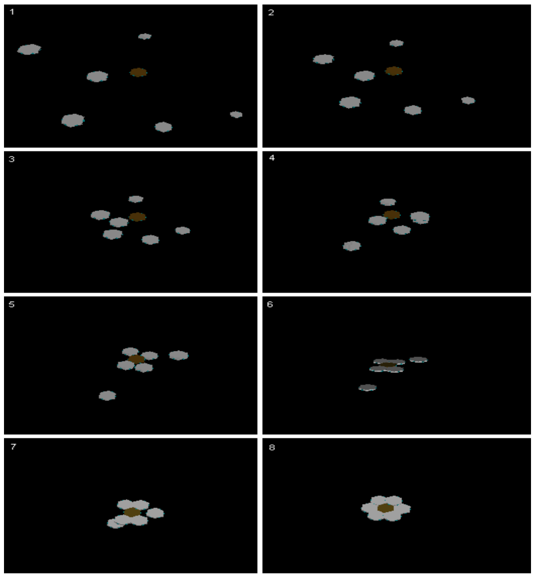

Figure 13 – VRML storyboard of the assembly process of 7 agents around a static 'seed' agent

Further information about the project and resources (including videos of the assembly process) are available at:

http://www.esa.int/gsp/ACT/biomimetics/testcases_research_SAA.htm.

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