Behaviour-Based Control Law for Spacecraft Swarm Operation

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Abstract: *This paper presents a behaviour-based control method to reposition a swarm of spacecraft in order to balance the fuel consumption among the agents. Under the influence of the J_2 perturbation, the agents with larger orbital elements differences with respect to the reference orbit consume more energy to maintain their position within the configuration. The proposed control law can guide the spacecraft in the high-fuel-consumption positions to switch with those in the low-fuel-consumption positions. This approach does not require any centralised command and control. The coordination is achieved through agent-level interactions. From the simulation data, the extension of mission lifetime is demonstrated.*

1. Introduction

The flying of autonomous formations of spacecraft (or spacecraft clusters) has been identified as a potential enabling technology for future space missions. This concept enables the transformation of a large monolithic spacecraft into a network of smaller elements for the purpose of offering improved scientific return through longer baseline observations and a high degree of redundancy in mission-critical systems. Examples include the System F6 program at the Defence Advanced Research Projects Agency (DARPA), the Solar Imaging Radio Array (SIRA), the Magnetospheric Multiscale Mission (MMS), and the Exoplanet Exploration Program (EEP) missions at NASA [1-4].

The guidance and control of formation-flying spacecraft has been a significant area of research over the last decade. A new challenging concept of formation flying spacecraft: spacecraft swarm, which consists of a large number of low-cost mass-producible satellite nodes, has been investigated in more recent studies. The coordination algorithms proposed in previous research mostly employ centralised optimisation methods which do not scale well due to intensive computation [5-10]. Moreover, in these studies, the swarm operates within a limited information network and a record of the full states of the swarm may not be recorded on the network. Therefore, a decentralised control law becomes advantageous if not essential in this new type of scenario. A decentralised formation controller based on the adaptive Graph Laplacian matrix has been proposed to synchronize the relative motions of a large number of spacecraft moving in elliptical formations [11]. In [12], the collision-free initial conditions for the spacecraft swarm composed of hundreds of agents were presented. Gauss' Variational Equations (GVEs) were used to compute the initial conditions which eliminate the secular drift due to J_2 perturbation. The method using differences in mean orbit elements to establish J_2 invariant relative orbits has also been investigated [13]. However, those initial conditions that create a truly invariant relative orbit, in which the formation returns to an identical relative state each orbit, are highly restrictive in terms of the geometry of the formation and as such are not practicable under most envisioned mission requirements. Therefore, it is necessary to reduce the constraints on J_2 invariant conditions to satisfy the mission requirements [14]. Such partial J_2 invariant conditions will cause the formation to deform over the long term unless corrections are performed to reposition a spacecraft in its relative position within the operational orbit. Several formation keeping methods for single spacecraft have been proposed in [15-17]. The results showed that fuel consumption of individual spacecraft will not be uniform across the formation as it depends on initial conditions and the location of the spacecraft within the formation. As the fuel capacity is limited, some spacecraft within the swarm will deplete their fuel reserves earlier than others. This will cause the premature degradation of the mission if the unbalanced fuel consumption is not mitigated. Significant research effort has been invested in recent years into the design and simulation of intelligent swarm systems or Self-Organised (SO) systems[18]. SO systems can generally be defined as decentralised systems, comprised of relatively simple agents which are equipped with the limited communicational, computational and sensing abilities required to accomplish a given task [19]. The individuals within the swarm system are not able to assess a global situation and control the tasks to be carried out by the other agents, i.e. there is no supervisor in a SO system. For example, each time an agent performs an action, the local environment is modified by this action. The new environmental configuration will then influence the future actions of other agents. This process leads to the emergent behaviours at the system level. The concept of SO system has been applied to the formation flying spacecraft [20, 21], in which the spacecraft, modelled as a swarm of agents, follow three biological rules, namely 'avoidance' of both each other and the threat, 'gather' to maintain the formation and 'attraction' towards target locations according to pre-defined artificial potential functions. In this study, the scenario is more complicated than converging to target locations. Therefore the agents will be required to switch between multiple modes and their behaviours are governed by different rule sets under each mode. The objective of this paper is to investigate the feasibility of using the behaviour-based control law based on agent-level interaction to achieve the desired coordination in order to balance the fuel consumption while maintaining desired formations.

The remainder of this paper is structured as follows. Following the problem statement in Section 2, Section 3 describes the behaviour-based control framework. Simulation results and analysis are presented in Section 4 and a summary of the study is given in Section 5.

2. Problem Statement

In this study, the initial configuration of the spacecraft swarm is considered to follow a random distribution centred at the reference orbit. Each individual spacecraft on the periodic relative orbits (PROs) will be rotating with respect to the centre of the relative frame.

Different types of PROs of the spacecraft in the formation have been investigated [15]. The shape of the projection of the PROs perpendicular to the radial direction is of interest for the purpose of ground-observation missions. The projected circular PRO is used in this study as its primary advantage is that the spacecraft are separated by a fixed distance when the formation is projected onto the along-track/cross-track ($y - z$) plane. Figure 1 shows the configuration of the swarm comprising 200 spacecraft. By definition, x, y, and z are the relative displacements in the radial, in-track, and cross-track directions respectively in the local vertical/local horizontal (LVLH) frame.

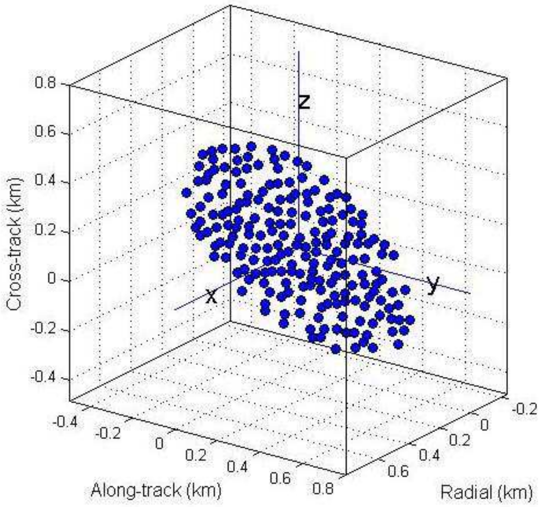

Figure 1(a): The initial position of the spacecraft swarm.

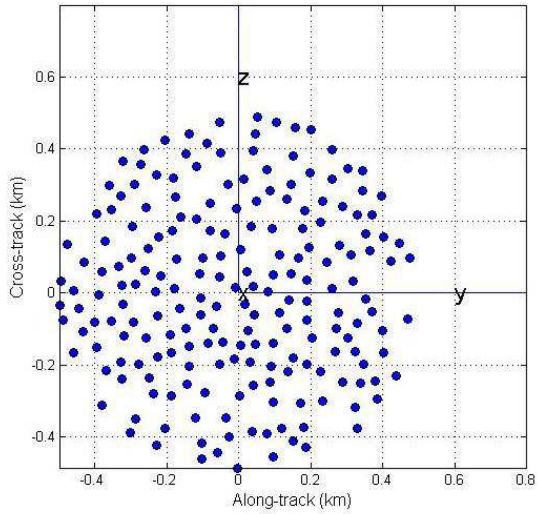

Figure 1 (b): The initial position of the spacecraft swarm on $y-z$ plane.

2.1. Initial Conditions

The secular drift among the spacecraft in the formation which are caused by the earth oblateness (J_2) effects has been studied [13]. The initial conditions must be carefully selected to generate relative orbits that are not only bounded, but also remain close to the desired trajectory. In this study, the numerical approach genetic algorithm (GA) is used to determine the initial conditions. Firstly, the approximate initial conditions that satisfy the relative motions are obtained from Hill's equations [22]. Then, these initial conditions are used to generate an initial population in GA. The fitness function which is used to rank the individuals in GA is given by:

$$J = w_1 \cdot |y_f - y_0| + w_2 \cdot \sum_{i=1}^{n} \sqrt{\left(x_i^{true} - x_i^{desired}\right)^2 + \left(y_i^{true} - y_i^{desired}\right)^2 + \left(z_i^{true} - z_i^{desired}\right)^2}. \quad (1)$$

The first term is drift in the along-track direction (see Figure 2). It is measured as the distance between the spacecraft relative distance at the initial time and after a number of periods. In the presence of J_2 perturbation, the period matching conditions obtained from Hill's equations would not be valid due to the differences in the precession rates of the spacecraft [23]. Thus the secular drift in the along-track direction has to be accounted for to minimize the propellant used to correct the orbits. The second term of the fitness function represents the deviation of the PRO from the desired projected circular formation. It is the sum of the Euclidean distance between the control points on the desired path and the corresponding points on the PRO. The nonlinear dynamics model of the relative motion is used to propagate the dynamics [24]. Therefore the individuals with lower fitness scores represent better solutions. Following the initial phase, the main cycle of the GA refines the solutions iteratively by applying the natural selection process.

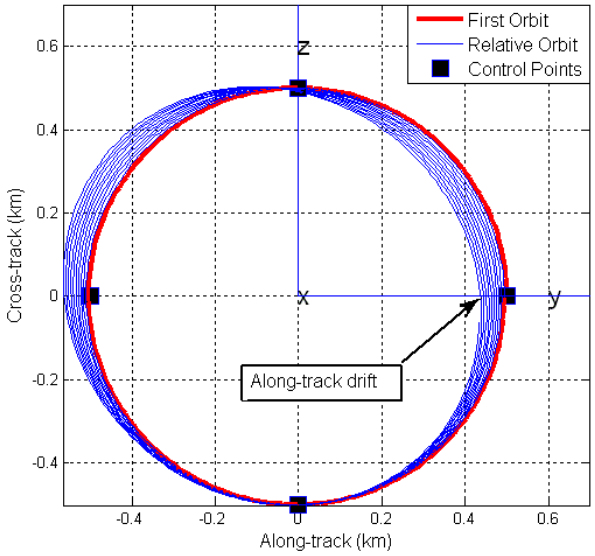

Figure 2: PRO with drift.

The solution obtained from the GA is presented in the following example. The reference orbit with the following initial mean orbital elements is considered: $e_{ref} \triangleq [\bar{a}\ \bar{\theta}\ \bar{\imath}\ \bar{q}_1\ \bar{q}_2\ \bar{\Omega}]^T = \left[7100km\ 0^{\circ}\ 70^{\circ}\ 0\ 0\ 45^{\circ}\right]^T$.

The resulting relative orbit with initial relative position $\delta r_0 \triangleq [x\ y\ z]^T = [0\ 0.5km\ 0]^T$ is shown in Figure 3. As can be seen from Figure 3(1, 2), the initial conditions obtained from Hill's equations result in drift in both the along-track and the cross-track directions over 50 orbits. Figure 3(3, 4) shows the relative orbit resulting from initial conditions generated by the GA after 100 generations. It is clear that the relative motion in the along-track direction is bounded. The growth in the cross-track oscillation is less, but cannot be eliminated. Without control inputs to maintain the spacecraft within the tolerance of the desired states, it will cause the distortion of the swarm configuration in the long term.

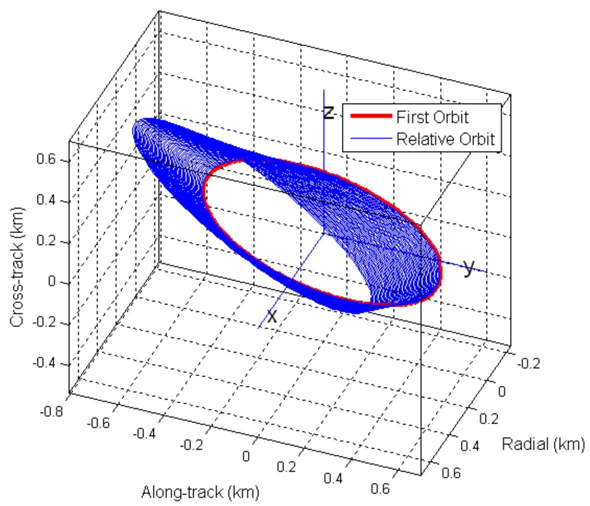

Figure 3(1): Relative orbits obtained using Hill's equations (50 orbits).

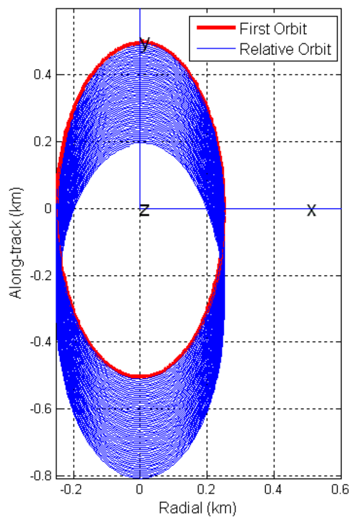

Figure 3(2): Relative orbits obtained using Hill's equations ($x - y$ plane).

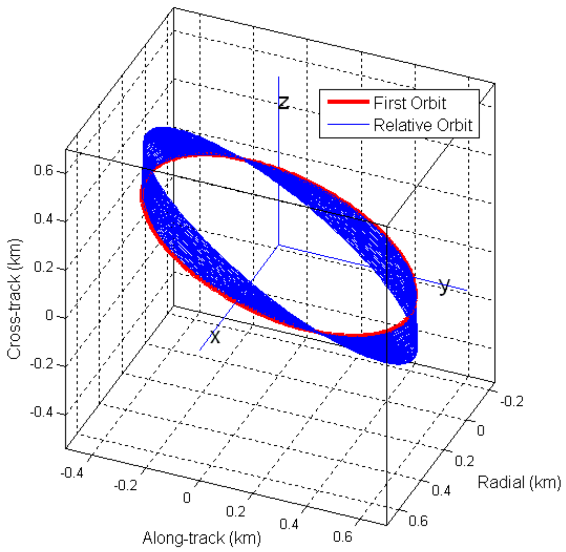

Figure 3(3): Relative orbits obtained using GA (50 orbits).

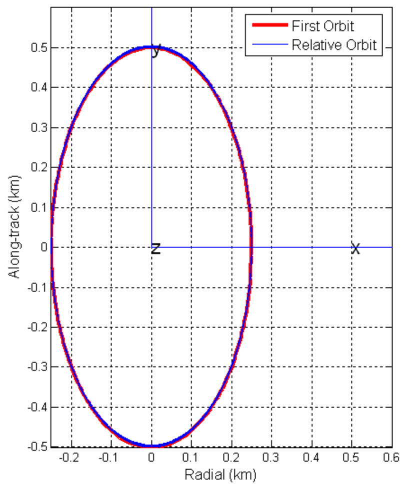

Figure 3(4): Relative orbits obtained using GA ($x - y$ plane).

2.2. Unbalanced Fuel Consumption

To prevent the distortion of the swarm configuration, a control effort is required to counter the effect of the perturbation. The linearised dynamics model for J_2 perturbed relative motion with a mean circular reference orbit is used in this study:

$$\begin{bmatrix} \delta\dot{\boldsymbol{r}} \\ \delta\ddot{\boldsymbol{r}} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ a_{41} & a_{42} & a_{43} & 0 & 2\omega_z & 0 \\ a_{51} & a_{52} & a_{53} & -2\omega_z & 0 & 2\omega_x \\ a_{61} & a_{62} & a_{63} & 0 & -2\omega_x & 0 \end{bmatrix} \begin{bmatrix} \delta\boldsymbol{r} \\ \delta\dot{\boldsymbol{r}} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \boldsymbol{u}. \tag{2}$$

The entries of the transition matrix can be found in [25]. Equation (2) can be compactly represented as a linear time varying (LTV) state-space equation:

$$\dot{\boldsymbol{x}} = A(t)\boldsymbol{x}(t) + B(t)\boldsymbol{u}(t). \tag{3}$$

The discrete equivalent state-space equation with a sampling period T is given by:

$$\dot{\boldsymbol{x}}(k+1) = \bar{A}(k)\boldsymbol{x}(k) + \bar{B}\boldsymbol{u}(k), \tag{4}$$

where

$$\bar{A}(k) = e^{A(k)T},$$

And

$$\bar{B} = \int_0^T e^{A(k)t} dt\, B.$$

With the initial state $\boldsymbol{x}(0)$ and impulsive control inputs $\Delta\boldsymbol{v}(k)$ $(k = 0,1,2, \dots, N)$, the final states can be written recursively as:

$$\dot{\boldsymbol{x}}(N) = \bar{A}(N, N)\boldsymbol{x}(0) + \sum_{k=0}^{N-1} \bar{A}(N-k-1, N)\begin{bmatrix}0\\ I\end{bmatrix}\Delta\boldsymbol{v}(k), \tag{5}$$

where

$$\bar{A}(j, N) = \begin{cases} I, \quad j = 0 \\ \bar{A}(N-1), \quad j = 1 \\ \bar{A}(N-1)\cdots\bar{A}(N-j), \quad j \geq 2 \end{cases}.$$

Based on the linearised system model, the formation-keeping problem can be formulated as a linear programming (LP) problem to minimise the overall $\Delta\boldsymbol{v}$ which is used to maintain the spacecraft flight within the position tolerance [17]. In the simulation, the LP planning horizon is set to be one orbit time. The relative dynamics are discretised on a 5.964 seconds time step so that one orbit contains 1000 time steps. Figure 4 shows the fuel cost (measured in $\Delta\boldsymbol{v}$) per orbit for each initial position within the swarm configuration. As can be seen, the fuel consumption for each spacecraft in the swarm is not uniform. It is related to its orbital elements differences with respect to the reference orbit. If the coordination strategy is not applied to balance the fuel consumption, the mission lifetime will be affected as the spacecraft on the outer perimeter of the configuration will run out of fuel before those nearer to the centre.

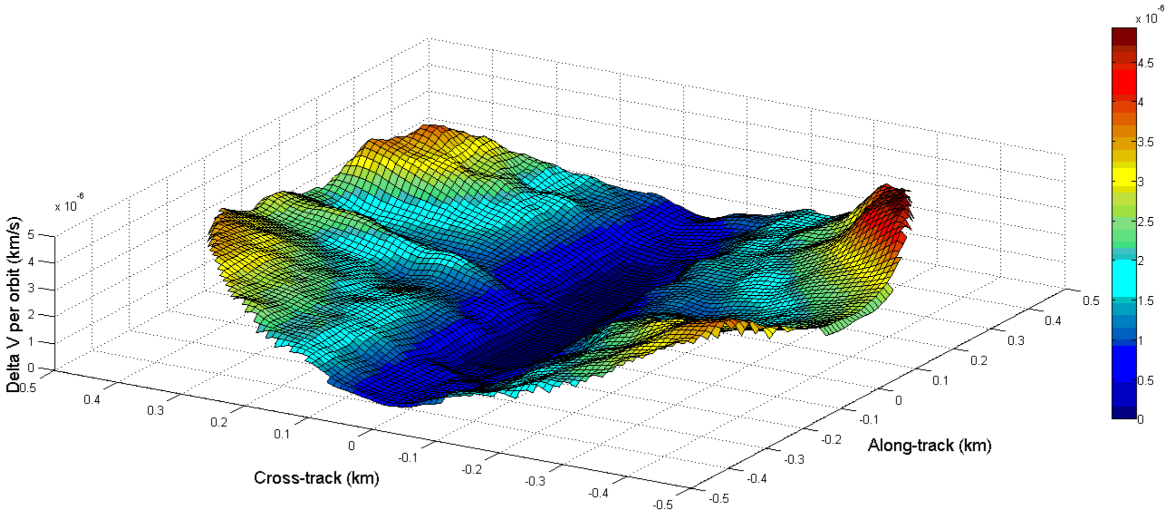

Figure 4: Fuel cost map.

3. Behaviour-Based Control Law

In this paper we investigate the possibility of using the limited local sensing capabilities of each individual spacecraft to coordinate the swarm and achieve a common objective. In particular it is assumed that each spacecraft can sense the presence of its neighbours and measure the inter-spacecraft distances. The common objective is to extend the mission lifetime by allowing the spacecraft in the high-fuel-consumption positions to switch with those in the low-fuel-consumption positions. A behaviour-based control law was developed to achieve this. Each agent carries out reactive behaviours driven by the local environment. At the beginning of each planning cycle (set to be one orbit time in the simulation) an individual spacecraft selects one of four behaviour modes to determine its next move. These behaviours are *position hold*, *descend*, *ascend*, and *position*.

3.1. Position Hold

Position Hold is the default behaviour mode of the agents at the beginning of the mission. In this mode, the spacecraft will maintain their current position within the swarm. The spacecraft will eventually switch back to the *position hold* mode when the remaining propellant is lower than a certain value $P_{inactive}$.

3.2. Descend

As analysed in section 2, those spacecraft on the outer perimeter of the swarm consume more propellant in order to maintain the position. To prevent them from running out of propellant much earlier than the rest, they will change to the *descend* mode and move to a position where the fuel consumption is low. A switch to the *descend* mode is triggered when the amount of propellant becomes less than a pre-set value $P_{descend}$.

As shown in the Figure 5, the spacecraft in the *descend* mode (represented by the black circle) will firstly construct a fuel consumption map for its surrounding area. The size and the resolution of the fuel consumption map are determined by the local sensory information and on-board computational resources. It will subsequently move to the cell with lowest fuel consumption rate without violating the safety distance of its neighbours (represented by white circles). If the agent cannot find any other cell on the map that has lower value than its current cell, it will change to the *position* mode. Furthermore, the *descend* mode will be temporarily disabled if the agent sensing the surrounding space becomes too crowded. If this situation lasts for more than the time of 10 orbits, the agent will change to *position* mode automatically. The purpose of this logic is to: firstly leave enough space for the agents in the *ascend* mode moving outward; secondly prevent the agents from squeezing to the minima of the fuel consumption map.

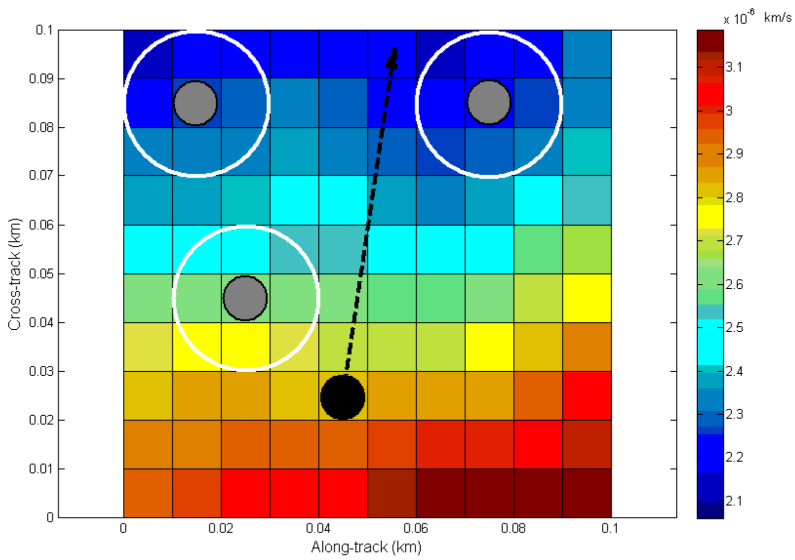

Figure 5: Movement in *descent* mode.

3.3. Ascend

As the agents with high fuel consumption rate relocate, the empty spaces they leave must be filled by other agents in order to maintain the original swarm configuration. Therefore, the *ascend* mode, which is an inverse process of the *descend* mode, is necessary. This behaviour mode is triggered when the agents detect an increased number of neighbours. In the simulation, the sensor range of 50 metres is assumed. The ascend behaviour is activated when the agents detect that the number of neighbours has increased by two. It is worth noting that only the agents who have enough fuel (more than P_{ascend}) are able to change to the *ascend* mode.
In *ascend* mode, the control law is similar to the one used in the *descend* mode. The agents seek for the cell with a high value of fuel consumption instead. The movement will stop when the agents enter into less occupied space where number of neighbours is less than 2. After 10 orbits without motion, the agents will change to *position* mode.

3.4. Position

In the *position* mode, the agents will adjust the inter-spacecraft distance after the reconfiguration. We adopt the artificial potential function method to model the attraction and repulsion between the spacecraft [26]. With this method the movements of all the spacecraft follow the local gradient of the potential field and converge to the desired states. Since the mission scenario does not require accurate position of each agent other than even distribution on the circular plane, the agents in the *position* mode are restricted to take only 10 movements. The agents will change to the *position hold* mode either after 10 movements or when the remaining propellant becomes less than $P_{inactive}$.

4. Simulation Results

The simulation results of applying the behaviour-based control law to a spacecraft swarm are presented in this section. For simulations, the parameters used to trigger the corresponding behaviours are chosen as follows: $P_{inactive}$ = 1 m/s, $P_{descend}$ = 2 m/s, and P_{ascend} = 70 percent of initial $\Delta\boldsymbol{v}$. Figure 6 shows the movements of the spacecraft swarm with 200 agents at four stages. The agents whose fuel consumption is more than 2.5 m/s per orbit in the initial configuration are indicated in red colour. As can be seen, the movements of the agents started around 600 orbits after the initiation of the mission. The red agents gradually moved toward the location with low fuel consumption and pushed the blue agents move outward to fill the empty space. The whole process is finished after 1000 orbits with all the red agents occupying the low-fuel-consumption positions. Moreover, the final configuration of the swarm maintained all of the mission-essential features such as the size of the formation and agent spacing.

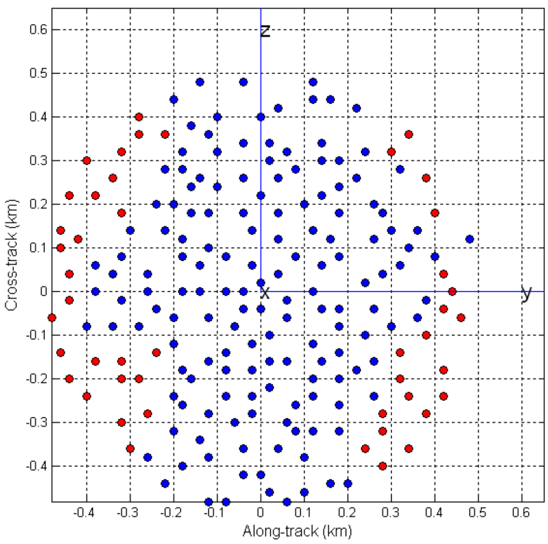

Figure 6(1): Initial swarm.

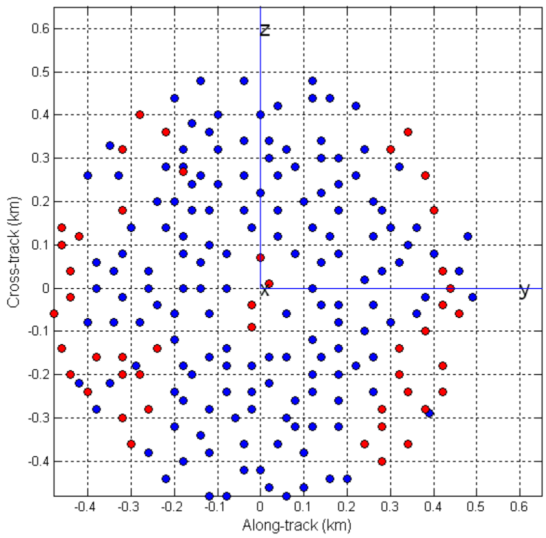

Figure 6(2): Swarm after 600 orbits

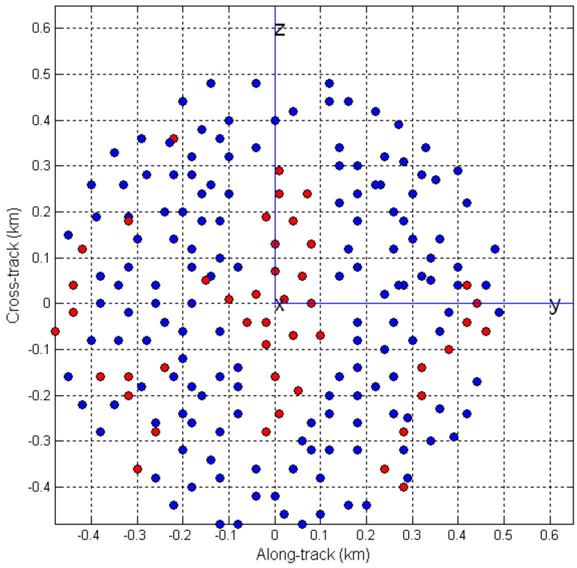

Figure 6(3): Swarm after 800 orbits

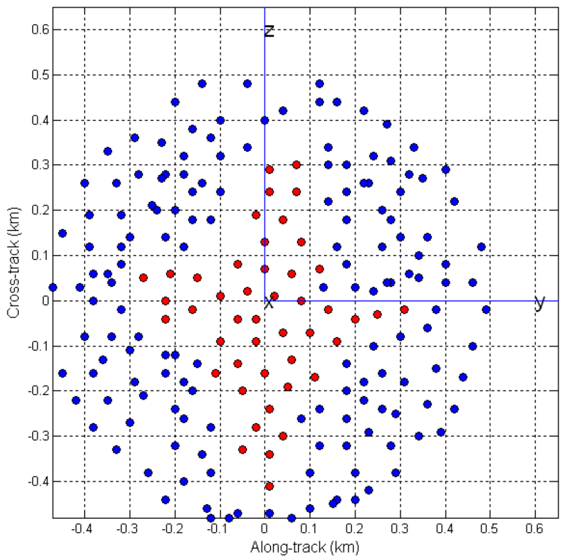

Figure 6(4): Swarm after 1000 orbits

The objective of this study is to balance the fuel consumption among the agents and thus extend the mission lifetime. Table 1 summarises the increase in mission lifetime by using the proposed control law. The useful life of the swarm was regarded to have ended when 10 percent of the swarm ran out of fuel, as we assume this would cause the degradation of mission performance. It is shown that the mission lifetime increases 22.9 percent when the initial $\Delta\boldsymbol{v}$ is 5 m/s and increases more with higher initial $\Delta\boldsymbol{v}$ as the amount of $\Delta\boldsymbol{v}$ spent on the manoeuvres becomes smaller portion of the total $\Delta\boldsymbol{v}$. However, the last two cases did not demonstrate such a trend. This is mainly because of the inefficient manoeuvres that occurred when the agents were in the position behaviour mode.

Mission Lifetime \ Initial DeltaV	5 m/s	6 m/s	7 m/s	8 m/s	9 m/s	10 m/s
Static Swarm	1496	1795	2094	2393	2692	2991
Dynamic Swarm	1839	2329	2820	3301	3735	4153
Lifetime Increase	22.9%	29.7%	34.7%	37.9%	38.7%	38.8%

Table 1: Mission lifetime (measured in number of orbits)

5. Summary

This study investigates the feasibility of applying a behaviour-based control law to coordinate a spacecraft swarm. It is shown that the coordination in the system level could emerge as each agent enacts simple reactive behaviours. The objective which is to balance the fuel consumption while maintaining the swarm configuration is achieved by using proposed method. In future studies, the agent behaviour under *position* mode will be further investigated as they are currently inefficient. The prediction or negotiation algorithm will be considered to reduce the number of the moves that the agents take to achieve the desired spacing.

References:

[1] DARPA. (2012, 3 April). *System F6*. Available: http://www.darpa.mil/Our_Work/TTO/Programs/System_F6.aspx

[2] NASA. (2012, 3 April). *Solar Imaging Radio Array*. Available: http://sira.gsfc.nasa.gov/

[3] NASA. (2012, 3 April). *The Magnetospheric Multiscale (MMS) mission*. Available: http://mms.gsfc.nasa.gov/index.html

[4] NASA. (2012, 3 April). *Exoplanet Exploration Program (ExEP)*. Available: http://exep.jpl.nasa.gov/

[5] I. Gokhan*, et al.*, "Precise formation flying control of multiple spacecraft using carrier-phase differential GPS," in *Guidance, Control and Navigation Conference*, 2000.

[6] M. Tillerson*, et al.*, "Co-ordination and control of distributed spacecraft systems using convex optimization techniques," *International Journal of Robust and Nonlinear Control,* vol. 12, pp. 207-242, 2002.

[7] A. Richards*, et al.*, "Spacecraft Trajectory Planning with Avoidance Constraints Using Mixed-Integer Linear Programming," *AIAA Journal on Guidance, Control, and Dynamics,* vol. 25, p. 9, 2002.

[8] C. Sultan*, et al.*, "Energy Suboptimal Collision-Free Path Reconfiguration for Spacecraft Formation Flying " *Journal of Guidance, Control, and Dynamics,* vol. 29, 2006.

[9] B. Ackmese*, et al.*, "A convex guidance algorithm for formation reconfiguration," in *AIAA Guidance, Navigation, and Control Conference and Exhibit*, Keystone, Colorado, 2006.

[10] L. Breger and J. P. How, "Gauss's Variational Equation-Based Dynamics and Control for Formation Flying Spacecraft," *Journal of Guidance, Control, and Dynamics,* vol. 30, March–April 2007.

[11] I. Chang*, et al.*, "Novel Coordinate Transformation and Robust Cooperative Formation Control for Swarms of Spacecraft," in *Fourth International Conference on Spacecraft Formation Flying Missions and Technologies*, St-Hubert, Canada, 2011.

[12] D. Morgan*, et al.*, "Swarm-Keeping Strategies for Spacecraft Under J2 and Atmospheric Drag Perturbations," *Journal of Guidance, Control, and Dynamics,* vol. 35, September–October 2012.

[13] H. Schaub and J. L. Junkins, *Analytical mechanics of space systems*: American Institute of Aeronautics and Astronautics, 2003.

[14] L. Breger and J. P. How, "Partial J2-Invariance for Spacecraft Formations," in *AIAA Guidance, Navigation, and Control Conference and Exhibit*, Keystone, Colorado, 2006.

[15] C. Sabol*, et al.*, "Satellite Formation Flying Design and Evolution," *Journal of Spacecraft and Rockets,* vol. 38, March–April 2001.

[16] G. Inalhan*, et al.*, "Relative Dynamics and Control of Spacecraft Formations in Eccentric Orbits," *Journal of Guidance, Control, and Dynamics,* vol. 25, February 2002.

[17] M. Tillerson and J. P. How, "Advanced Guidance Algorithms for Spacecraft Formation-keeping," in *the American Control Conference*, Anchorage, AK, 2002.

[18] E. Bonabeau*, et al.*, *Swarm Intelligence- From Natural to Artificial Systems*: Oxford University Press, 1999.

[19] Y. Altshuler*, et al.*, "Swarm Intelligence — Searchers, Cleaners and Hunters," in *Swarm Intelligent Systems*, ed, 2006, pp. 93-132.
[20] D. Izzo and L. Pettazzi, "Autonomous and Distributed Motion Planning for Satellite Swarm," *Journal of Guidance, Control, and Dynamics,* vol. 30, April 2007.
[21] S. Nag and L. Summerer, "Behaviour based, autonomous and distributed scatter manoeuvres for satellite swarms," *Acta Astronautica,* 2012.
[22] H. Curtis, *Orbital Mechanics: For Engineering Students*, 1 ed.: Butterworth-Heinemann, 2005.
[23] S. R. Vadali*, et al.*, "An intelligent control concept for formation flying satellites," *International Journal of Robust and Nonlinear Control,* vol. 12, 2002.
[24] G. Xu and D. Wang, "Nonlinear Dynamic Equations of Satellite Relative Motion Around an Oblate Earth," *Journal of Guidance, Control, and Dynamics,* vol. 31, September–October 2008.
[25] S. R. Vadali, "Model for Linearized Satellite Relative Motion About a J2-Perturbed Mean Circular Orbit," *Journal of Guidance, Control, and Dynamics,* vol. 32, September–October 2009.
[26] C. M. Saaj*, et al.*, "Spacecraft Swarm Navigation and Control Using Artificial Potential Field and Sliding Mode Control," in *Industrial Technology, 2006. ICIT 2006. IEEE International Conference on*, 2006, pp. 2646-2651.