Paper

Control and reconfiguration of satellite formations by electromagnetic forces

Roman Wawrzaszek and Marek Banaszkiewicz

Abstract— Current concept of interferometric missions assume that they employ formations of spacecraft. The cooperation between members of a multisatellite formation is a challenging problem. One of the main difficulties is to implement a reliable system for position control and actuation. A precise control of the position and orientation of each satellite in the array is a key factor in obtaining high quality images of distant objects. The controlling system should frequently collect data about geometry and kinematics of all array elements and use actuators to keep them as close as possible to their nominal positions. Forces that are required for actuation or array reconfiguration in space can be produced by engines of various types. In most cases chemical propulsion is used, with a drawback of limited fuel resources and a danger of polluting optical elements. In our work, we analyze dynamics of satellite formation flight, in which interaction forces result from electromagnetic fields generated by coils with current. We use simple controller equation proposed by members of MIT team to control a formation of two or three aligned satellites rotating around the array's mass center.

Keywords— electromagnetic formation flight (EMFF), satellite formations.

1. Introduction

Current concept of interferometric missions assumes that they employ formations of spacecraft. Optical (Darwin, Terrestial Planet Finder – TPF [1]) as well as microwave missions (TechSat21 [2]) are considered. The cooperation between members of a multisatellite formation is a challenging problem. One of the main difficulties is to implement a reliable system for position control and actualisation. In an interferometric mission, relative distances between array members have to be known with accuracy comparable with the length of detected waves. It means that for optical astrometry with micro-arcsecond resolution intramember distances have to be determined with an accuracy of at least 5 nm [3]. Measurements of relative positions with such accuracy are very difficult. Whatever sophisticated measurement (e.g., laser interferometry) and actuation systems are used, they have to operate permanently, to keep the required spacecraft configuration against perturbing forces (gravitation, solar radiation, etc.).
Apart from the problem of keeping the satellite formation in a stable but fixed state there is another one: how to reconfigure the formation by change the intersatellite distances or the plane of their motion. On the other hand, the stability of the formation should be continuously control against external perturbing forces, such as gravity of the Earth, magnetic field, etc. Both problems pose severe requirements on the control system that should be efficient, flexible and robust.
Following Miller and Sedwick [4], we consider the electromagnetic system of control and actualisation for a multisatellite interferometric mission. The system consists of a few (1–3) orthogonal magnetic dipoles located on each satellite and realized as coils (3 coils get possibility to obtain any resultant direction of magnetic field moment). In addition, flywheels acting as angular momentum storage are used. Kong *et al.* [1] describe such concept in detail.

2. Electromagnetic interactions and system controller

The elementary interaction of two coils is shown in Figs. 1 and 2. It results in producing both radial and transversal forces as well as twisting torques (equations on this figures).

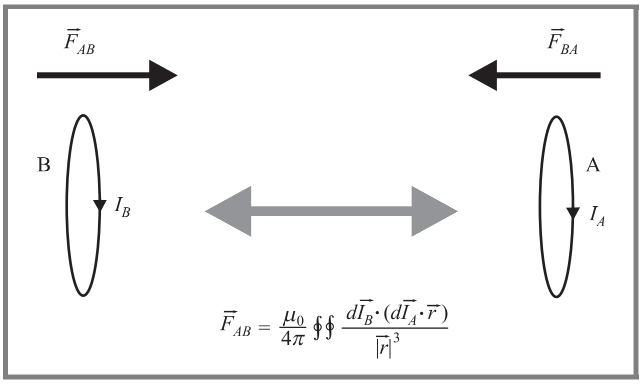

Fig. 1. Radial forces generated by electromagnetic coils.

It is not possible to get stable, static system based on electromagnetic forces only. The stabilising force has to be introduced. For a two-member formation, the stabilising factor can be centripetal force resulting from rotation of spacecraft around the common centre of mass [4, 5]. Such rotation, with an angular velocity Ω, corresponds to an equilibrium but still unstable state of the system, therefore a specially constructed controller is needed.

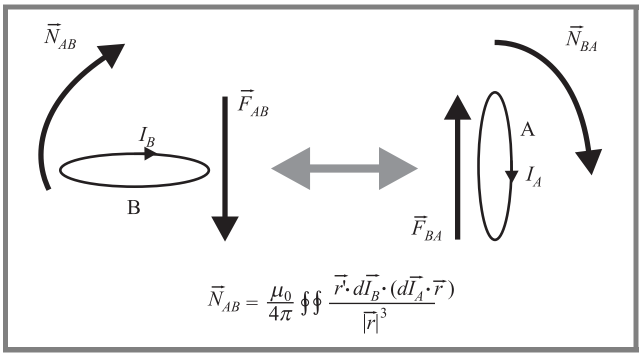

Fig. 2. Transversal forces and torques generated by electromagnetic coils.

After linearising the equations of motion about the equilibrium state and employing the minimum cost-function approach, the resulting equations for control parameter $\underline{u}$ read:

$$\dot{\underline{x}} = A\underline{x} + B\underline{u}, \tag{1}$$

$$\underline{u} = -K\underline{x}, \tag{2}$$

$$K = -\left[\frac{1}{2}\left(1+\sqrt{1+4\frac{\lambda}{\rho}}\right),\ \frac{1}{\sqrt{2\Omega}}\sqrt{1+\sqrt{1+4\frac{\lambda}{\rho}}}\right], \tag{3}$$

where the state vector $\underline{x}$ consists of differences from nominal values in radial distance and radial velocity components.

The only free parameter is λ/ρ. Stability analysis shows that one eigenvalue of linear system Eq. (1) has positive real part what means that nominal system is unstable.

3. Results

All simulations are made in MATLAB. The equations of motion are solved for a multi body system with objects interacting via electromagnetic forces. All calculations are performed in 3-dimensional space. Each object is represented by a 1 kg heavy coil of 1 m radius supplied with tuneable current.

3.1. Free space simulations

Figures 3 and 4 show simulation results for unstable system without controller. Each trajectory corresponds to a different initial separation error in the range from –20 to 20 nm. Actually, there is no possibility of obtaining a stable trajectory without using the controller. Even when the formation starts with the exact nominal values of parameters, the formation collapses or its members escape after about 2000 s. In the figures trajectories only one object are presented for clarity, the second one can be obtain by mirror transformation.

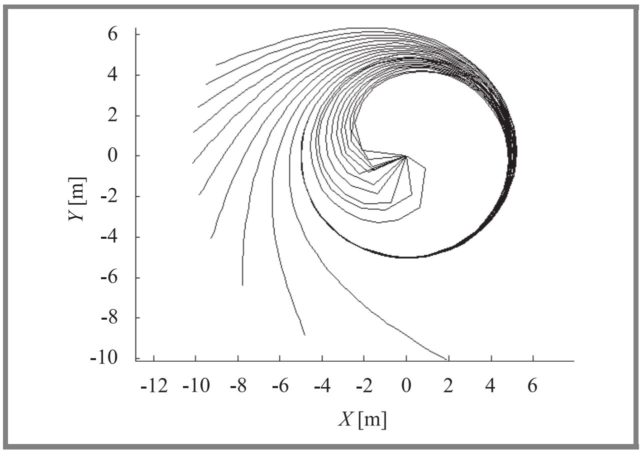

Fig. 3. Trajectories of two object formation member in the motion plane with different initial parameters.

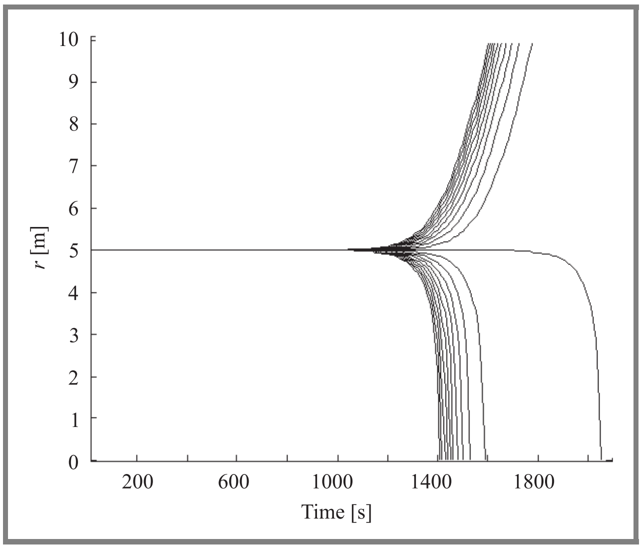

Fig. 4. Distance changes from common mass center for two object formation member with different initial parameters.

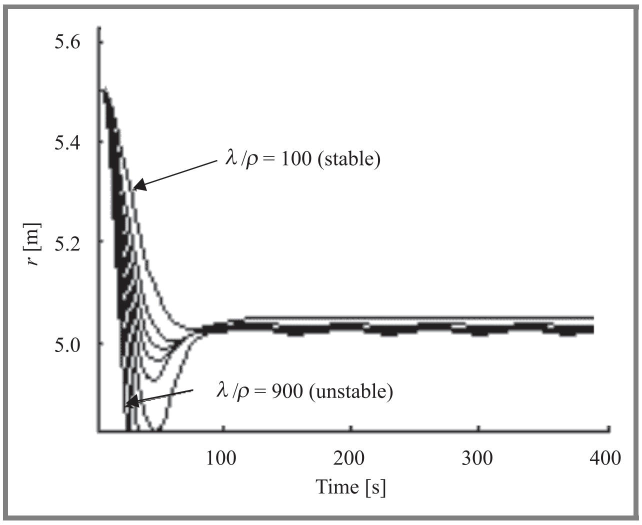

Fig. 5. Radial distance changes in time for different λ/ρ values (2 objects formation).

The control algorithm was tested for several values of control parameters. Controller efficiency as a function of time and a control parameter value is shown in Figs. 5 and 6.

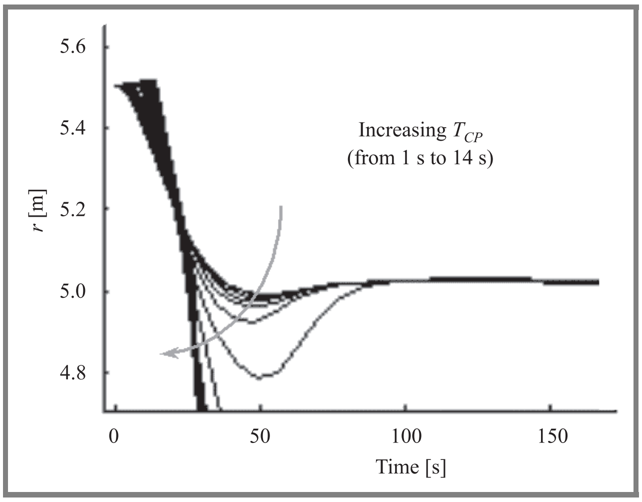

Fig. 6. Radial distance changes in time for different T_{CP} values (2 objects formation).

This example illustrates how the system returns to the nominal state when it starts from a configuration that is 10% larger than a nominal one (5 m distance of each satellite from the common centre of mass).
Figure 3 shows the change of the radial distance for different values of λ/ρ. This parameter represents a weighted combination of "penalty" parameters for displacement (λ) and control (ρ) errors; $\lambda/\rho = 0$ corresponds to the limit of infinitely expensive control. The instability at higher values of λ/ρ can be removed by decreasing the control step T_{CP}. Here, we use a discrete (realistic) control system, in which position measurements are taken and control variables actualised every T_{CP} seconds. As it is shown in Fig. 6, higher values of T_{CP} result in stability loss.

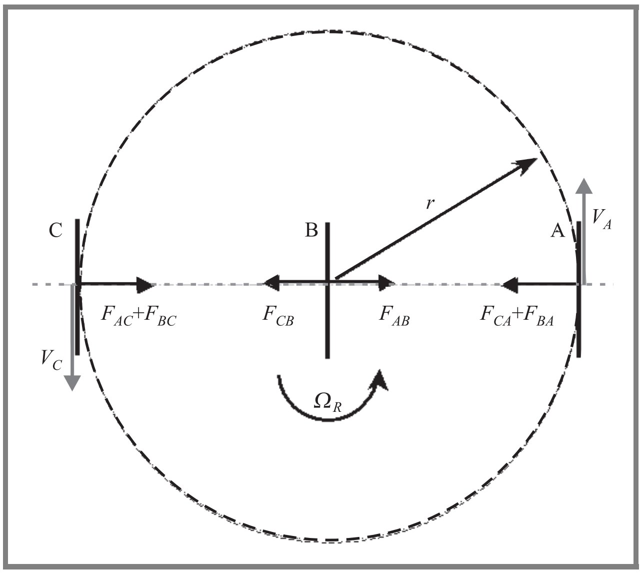

Fig. 7. Three rings on line – configuration view.

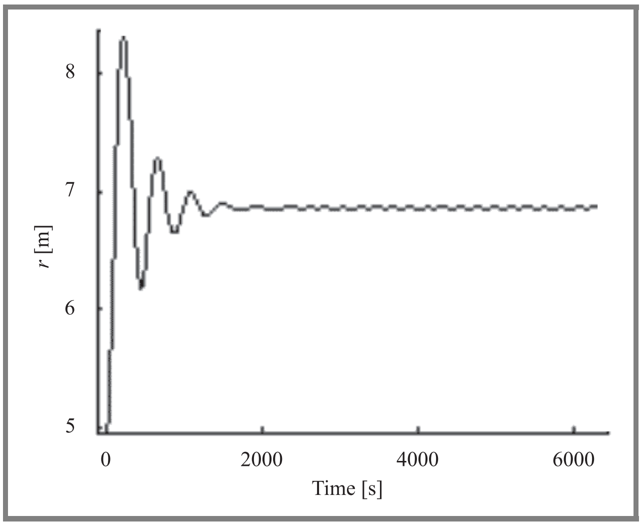

Fig. 8. Example of radial distance changes (r) in time for object A ($\lambda/\rho = 400$, 3 body system with controller).

A 3-body formation is a natural extension of the concept presented before. An example of the control performed for the 3-body linear configuration shown in Fig. 7 is presented (Fig. 8). All tests have been performed assuming that the formation is initially not so far from the nominal, equilibrium configuration.

3.2. Simple reconfiguration

Using the stability margin of a system with controller, we performed tests when intersatellite distance was gradually increased. In that case, we forced the controller to try to get

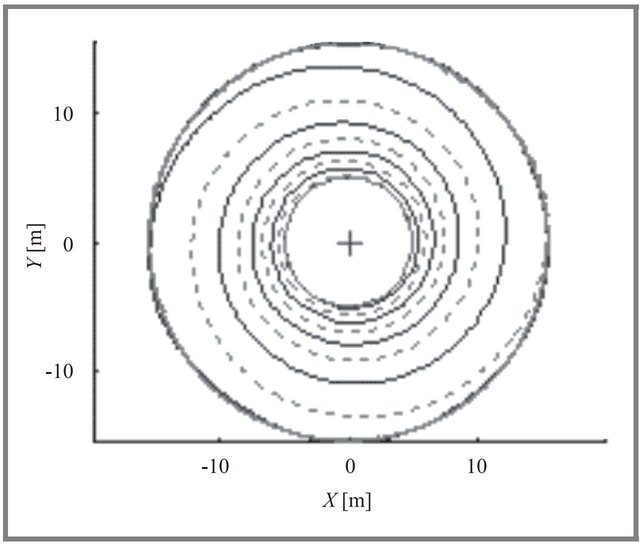

Fig. 9. Simulations with distance changing from 5 to 15 m – trajectories of 3 objects formation members in the plane of motion.

in each step a slightly increased target value by providing it with an artificial error signal. Using this method we made some successful simulations in both two- and three-body

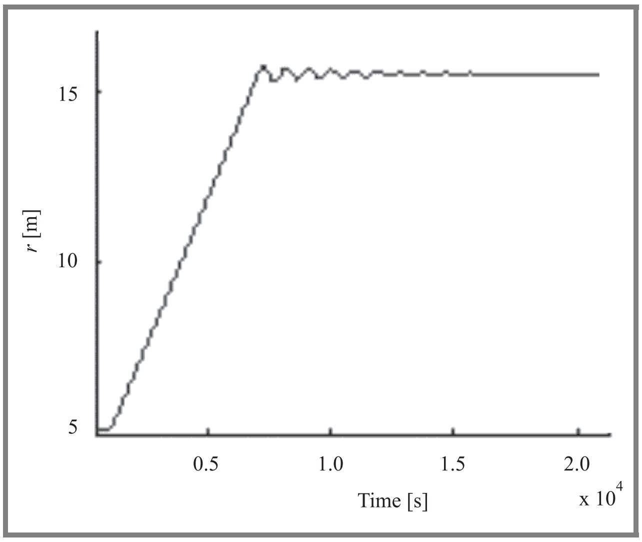

Fig. 10. Simulations with distance changing from 5 to 15 m – object A.

cases. Results of simulations with 3 coils are presented in Figs. 9 and 10. The cross in the centre of Fig. 9 represents the position of object B (see Fig. 7).

3.3. On orbit simulations

In analysing an electromagnetic formation on Earth orbit we neglect any forces but the first term of geopotential series (point mass). The comparison of uncontrolled motion, i.e., without magnetic forces – dotted line in Fig. 11, and trajectories with the control system acting (solid line in Fig. 11) shows that in second case the formation mem-

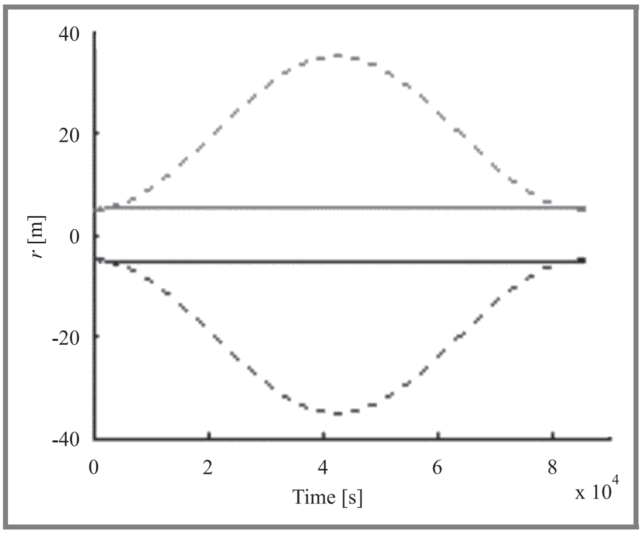

Fig. 11. On orbit simulations without (dotted line) and with (solid line) magnetic control system.

bers can move on non-Keplerian, circular orbits, keeping a 5 m distance to the nominal (Keplerian) orbit. In other words: both objects stays at constant radial distances from the Earth that are 10 m apart. In-between a nominal orbit with 42 000 km radius is located.

3.4. Comparison with interferometer missions requirements

The accuracy of the distance control can be found by calculating differences of resulting position with respect to the steady state value $r = f(t)$. For the analysed configurations the accuracy we found varies from about a few tenths of milimeter for a free flying formation case to a few centimeters in the in the Earth orbiting case. These values strongly depends on λ/ρ and T_{CP} parameters (Figs. 12 and 13). The results were obtained using a very simple model, hence many possible important factors were neglected.

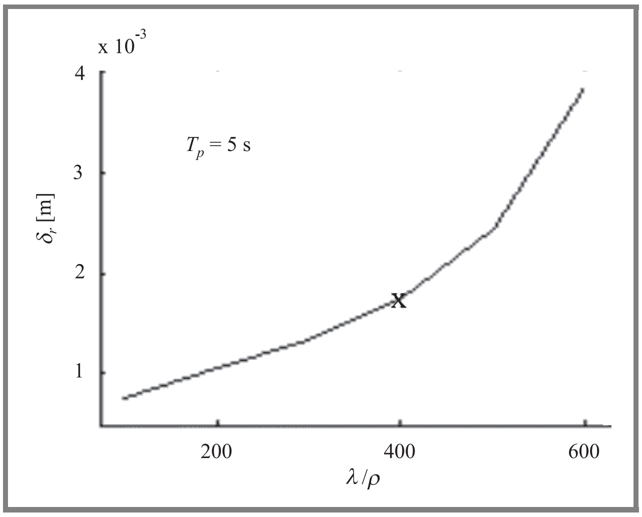

Fig. 12. Mean distance fluctuations in dependence on T_p parameter.

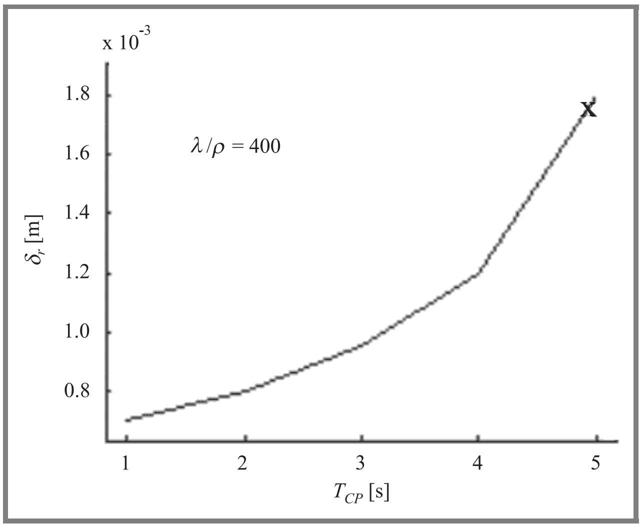

Fig. 13. Mean distance fluctuations in dependence on λ/ρ parameter.

The analysis of λ/ρ parameter impact on position accuracy shows that for small values the system is better stabilised (i.e., distance variations from the nominal position are smaller).
The accuracy obtained in simulations is still too small to fulfil requirements of the optical interferometry missions, but it could be good enough for longer wavelength missions.

4. Summary

In the paper, we presented results of simulations with controllers employing a single parameter (scalar control). Even such simple controller allows to obtain interesting results and works fine in 3-dimensional simulations. The comparison with interferometer missions requirements is not satisfying and shows that there is a need to investigate more advanced controlling and modeling concepts.

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