

Electromagnetic Formation Flight

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OVERVIEW

Description of the Effort

The Massachusetts Institute of Technology Space Systems Lab (MIT SSL) and the Lockheed Martin Advanced Technology Center (ATC) are collaborating to explore the potential for an Electro-Magnetic Formation Flight (EMFF) system applicable to Earth-orbiting satellites flying in close formation.

Progress Overview

At MIT, work on EMFF has been pursued on two fronts: the MIT conceive, design, implement and operate (CDIO) class, and the MIT SSL research group.

While all of the progress reports to date have focused on the work completed at MIT, this report summarizes recent progress made at the Lockheed Martin ATC.

INTRODUCTION

The possibility of controlling the relative positions and orientations of a number of satellites flying in close formation by means of applied magnetic fields has been addressed by the Space Systems Product Development Class, Department of Aeronautics and Astronautics, MIT, under the direction of Professor David Miller. We at the Lockheed Martin Advanced Technology center have been working with the MIT group under contract (ATC Project KQ8) to support this effort. In particular, we were tasked with examining control options for satellite formations, studying the feasibility of magnetic control in general, and producing simulations of particular magnetic control scenarios. This report details our efforts in these areas.

The reasons for looking at this type of technology, its possible applications, its advantages and drawbacks, are presented in MIT's Preliminary Design Review of May 7, 2002, entitled Electro Magnetic Formation Flight of Rotating Clustered Entities. This document also discusses generic requirements for a possible Electro Magnetic Formation Flight (EMFF) implementation and presents a plan for further study. Of more immediate interest to us, for the purposes of this report, are the technical results that are presented. These include trade studies between different dipole configurations, the design of a magnetic control system, analytical results obtained on sample two- and three-satellite constellations, and a simple hardware validation demonstration. All this provided an excellent starting point for our own investigations into the subjects.

APPROACH

We decided to use our own tools (AUTOLEV and ANIMAKE) to reproduce MIT's results to date on formation dynamics and then to continue from there. There were two reasons for choosing this approach: the first was frankly didactic; we felt it was the quickest way for us to catch up to MIT's level of expertise in the field and start making our own contributions. The second was a desire, shared by MIT, to independently validate their results to date and to incorporate them in a dynamic simulation that would visually and compellingly demonstrate the efficacy of the technology. From the beginning we also considered ways to expand on MIT's work; therefore, in consultation with them, we defined new simulation scenarios and considered ways to generalize their results. These are presented below.

Our principal analysis tool is a symbolic dynamics program distributed by OnLine Dynamics, Inc., and developed jointly by David Schaechter and David Levinson of Lockheed Martin, Professor Emeritus Thomas R. Kane of Stanford University, and Paul Mitiguy, currently of MSC.Software, Inc. AUTOLEV permits a user to formulate exact, literal equations of motion for any system of interconnected rigid bodies and particles, and creates ready-to-compile-link-and-run Fortran or C simulation programs incorporating the equations. In the words of Professor Kane, "AUTOLEV makes it possible to teach, learn, and practice mechanics in an exceptionally effective way because, in addition to saving the user a great deal of time and effort, it furnishes excellent means for communicating mechanics ideas with clarity and precision."

ANIMAKE, a companion program to AUTOLEV, was developed by Ting Hong Chung and Thomas R. Kane of Kane Dynamics, Inc. It permits one to employ directly the numerical output produced by AUTOLEV-generated Fortran and C motion simulation programs to create animations of the motions under consideration.

The problems we studied are as follows:

1. Steady Planar Rotation of Two Solenoids
2. Steady Planar Rotation of Three Solenoids
3. Three-Dimensional Motions of Two Solenoids
4. Spinup of Two Solenoids from Rest
5. Expansion and Contraction of Formations

A magnetically-controlled satellite is represented herein by a solenoid of given size and number of turns of wire, through which a variable electric current can be impressed. Control is effected by varying the current through the solenoid wire. In some cases, reaction wheels are mounted on the pitch and yaw axes for attitude control. The quantities in which we are interested, as functions of the currents, mass properties, magnet parameters, and initial conditions, are the intersatellite distances and the attitude of the formation as a whole as well as that of the individual satellites. For two satellites it is sufficient to control the current in only one of them to achieve the desired behavior (as can be inferred from symmetry considerations); for three satellites this cannot always be done, as we will show below.

We make the following assumptions in calculating the satellite motions:

1. the satellites are far away from any disturbing body (no gravity, no atmosphere, etc.)
2. all systems are assumed to be “ideal” (ideal current sources, for instance.)
3. system aspects which have no bearing on our analyses are neglected (ohmic heating, if any; solar panel effects, etc.)
4. each satellite is in the far magnetic field of the others, so that a far-field mathematical approximation can be used
5. the satellites are identical as to size and mass properties
6. roundoff error in the simulation algorithm can be used as a surrogate for random system noise.

The expression for the far electromagnetic field \mathbf{B} of a solenoid at a point P in space can be written

$$\mathbf{B} = [\mu_0/(4\pi)] \left(-\mathbf{m}/p^3 + 3\mathbf{m} \cdot \mathbf{pp}/p^5 \right)$$

where \mathbf{p} is the position vector from P to the center of the solenoid, p is the magnitude of \mathbf{p} , μ_0 is the permeability of free space, and \mathbf{m} is the magnetic moment of the solenoid, given by

$$\mathbf{m} = NIA\mathbf{u}$$

with N denoting the number of turns in the solenoid, I the current carried by the solenoid, A the cross-sectional area of the solenoid, and \mathbf{u} a unit vector parallel to the axis of the solenoid and pointing from the solenoid's south pole to its north pole.

When a second solenoid, of magnetic moment $\bar{\mathbf{m}}$ is brought into the magnetic field of the first, the system of magnetic forces exerted by the first solenoid on the second is equivalent to a single force \mathbf{F} passing through the center of the second solenoid, given by

$$\mathbf{F} = \bar{\mathbf{m}} \cdot \nabla \mathbf{B}$$

together with a couple of torque \mathbf{T} , given by

$$\mathbf{T} = \bar{\mathbf{m}} \times \mathbf{B}$$

RESULTS

We present results below for five different scenarios. Because it has a more immediate physical meaning for us, the term “solenoid” is used to signify the simplified spacecraft model. A proper way to think of this is to visualize a satellite within which a solenoid had been rigidly embedded.

1 - Steady Planar Rotation of Two Solenoids

Perhaps the simplest maneuver that can be performed with magnetically controlled bodies is the steady planar rotation of two solenoids acting solely under the influence of their mutual electromagnetic fields. Figure 1 shows two such solenoids. Here, red denotes the north poles of the magnets and blue the south poles. This configuration was already studied by MIT and here we endeavored to reproduce and validate their results.

With the aid of AUTOLEV, we formed exact, explicit, nonlinear equations of motion for this system. By specifying the steady motion of interest, we then used AUTOLEV to solve these equations for the explicit formula relating the electric current, the distance between the two mass centers, the angular speed of the bodies, and the speed of the two mass centers. Our analytic results confirmed the results obtained by MIT, and, on this basis, we proceeded to the production of a simulation of the motion of this system.

With the aforementioned formula in hand, we computed the initial conditions required for bringing about the desired steady motion. By employing these values in connection with the full nonlinear equations of motion, we could, in principle, simulate the steady motion of interest. However, without feedback control, numerical roundoff errors eventually cause the simulated motion to become unstable, as shown in Figure 2. This state of affairs is easily remedied, however, by means of a simple feedback control scheme in

which the electric current of either solenoid is made to depend on the distance between the two mass centers as well as the time rate of change of this distance. Once such a control system is in place, the simulation of the steady motion can proceed without interference from cumulative roundoff errors. Figure 3 shows a snapshot of a controlled motion that takes place at an instant subsequent to the time associated with Figure 2. Both the uncontrolled and controlled motions have been simulated by means of AUTOLEV-generated Fortran programs, and then “movies” of the two motions, based on the Fortran program outputs, have been animated with the aid of ANIMAKE. Figures 1 - 3 are “stills” from these movies.



Figure 1. Two Solenoids in Steady Planar Rotation

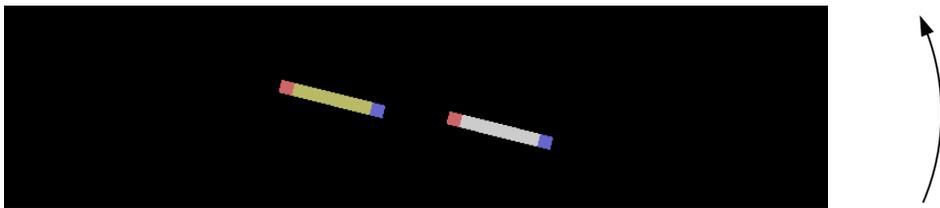


Figure 2. Animation of Spurious Simulation of Unstable Motion Induced by Numerical Roundoff Errors

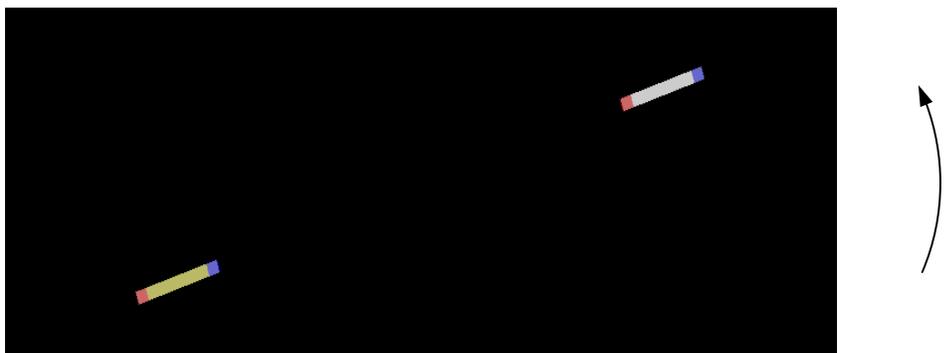


Figure 3. Animation of Stable Motion Enforced by Feedback Control

2 - Steady Planar Rotation of Three Solenoids

Another scenario already analyzed by MIT is the steady planar rotation of three solenoids. The techniques used to analyze the steady planar rotation of two solenoids can be extended directly to larger numbers of solenoids. Three solenoids in steady rotation (see Figure 4) have been analyzed with AUTOLEV and animated with ANIMAKE just as in the case of two solenoids. Here again, there is spurious unstable motion due to roundoff errors when feedback control of electric current is not employed (see Figure 5). By making the electric current in the central solenoid a function of the distance between the mass center of the central solenoid and either peripheral solenoid, together with the time-derivative of this distance, one can stabilize the motion. Figure 6 shows a snapshot of a controlled motion that takes place at an instant subsequent to the time associated with Figure 5. Here, because of symmetry, stability of the system can be enforced entirely from the central solenoid.

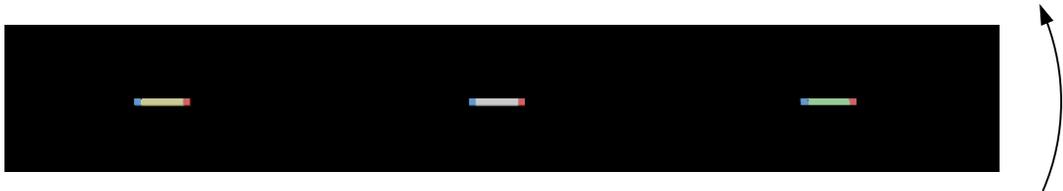


Figure 4. Three Solenoids in Steady Planar Rotation

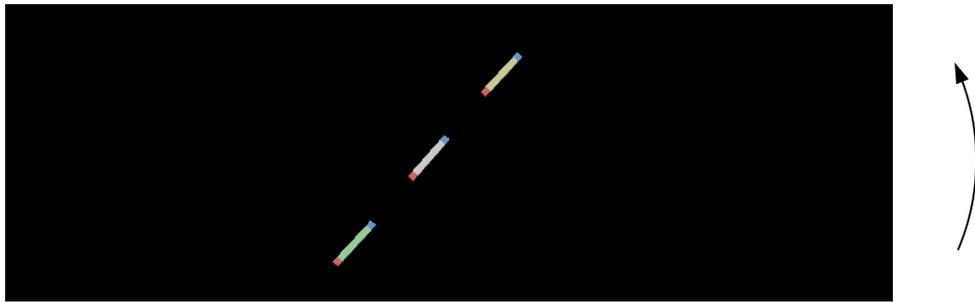


Figure 5. Animation of Spurious Simulation of Unstable Motion Induced by Numerical Roundoff Errors

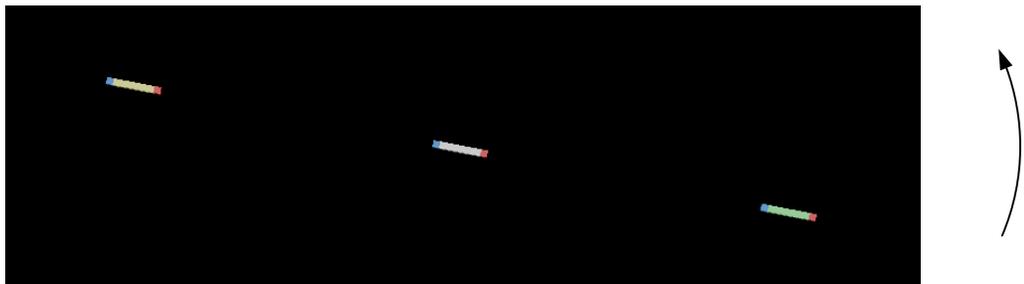


Figure 6. Animation of Stable Motion Enforced by Feedback Control

3 - Three-Dimensional Motions of Two Solenoids

In preparation for studies of three-dimensional motions of two- and three-solenoid systems, AUTOLEV and ANIMAKE were employed to generate equations of motion, Fortran simulation programs, and animations of both systems. These are shown in Figures 7 and 8. In both cases, each solenoid contains pitch and yaw reaction wheels for attitude control. A close-up view of a solenoid equipped in this manner is shown in Figure 9.



Figure 7. Two Solenoids Equipped with Pitch and Yaw Reaction Wheels

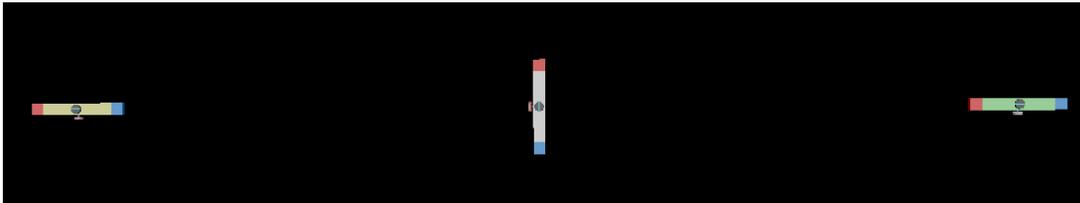


Figure 8. Three Solenoids Equipped with Pitch and Yaw Reaction Wheels

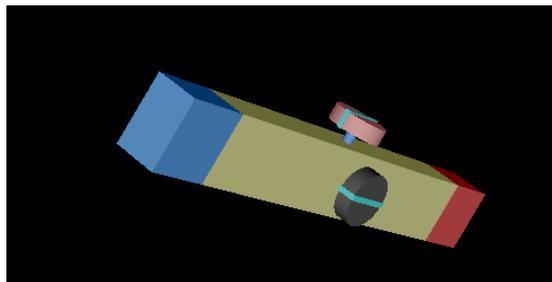


Figure 9. Close-up of Solenoid Equipped with Pitch and Yaw Reaction Wheels

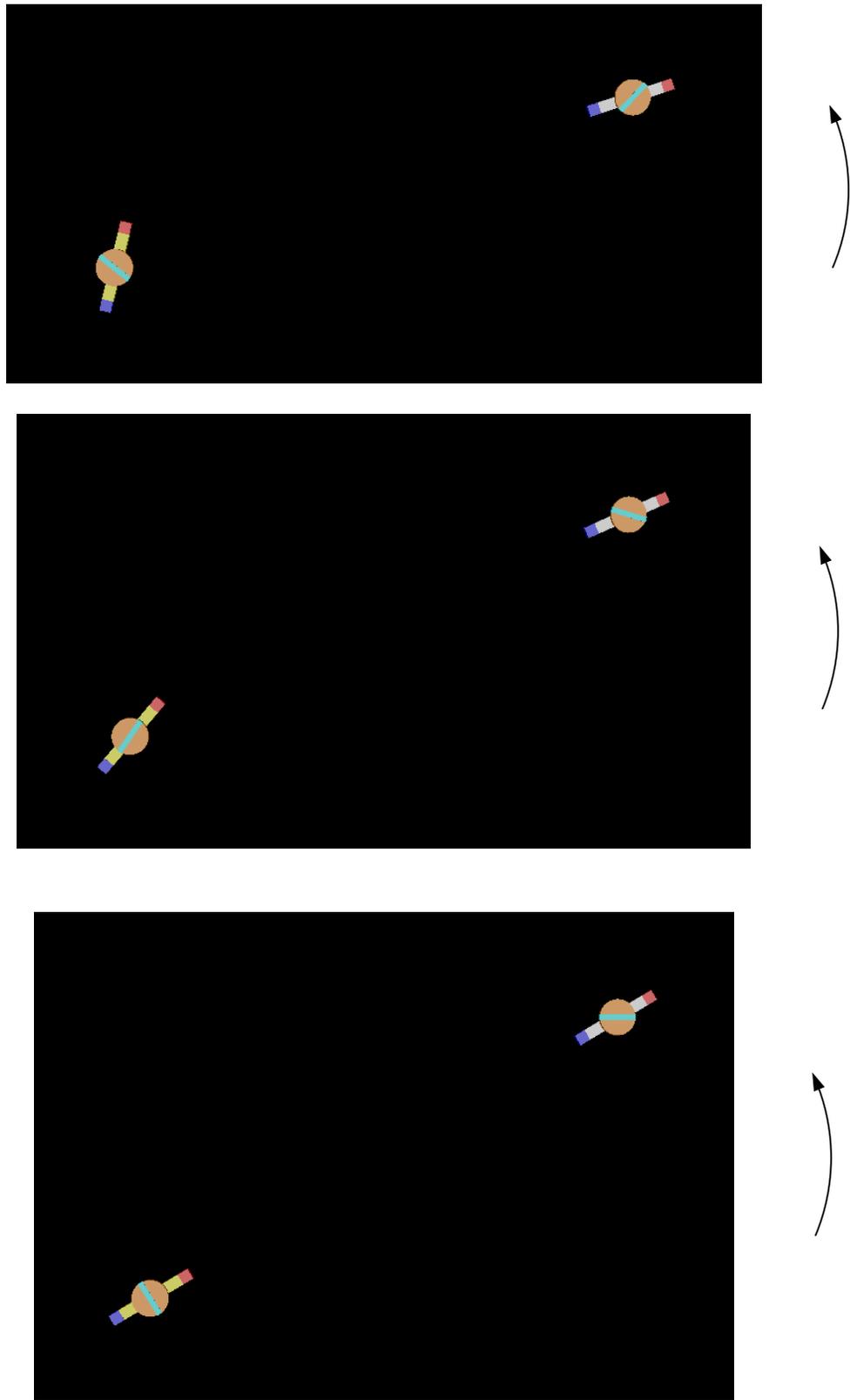
4 - Spinup of Two Solenoids from Rest

An interesting and potentially very useful result obtained by MIT was that two EMFF-controlled satellites at rest in space could be set in motion about their common mass center by employing magnets and reaction wheels alone. We wanted to verify this result and to supplement the analysis with an animation that would show the technique convincingly. Figure 10 shows such a system in its rest state.



Figure 10. Two Solenoids, Equipped with Reaction Wheels, Initially at Rest

Here, AUTOLEV was employed to determine the explicit equations for the two reaction wheel motor torques and the electric current in one of the solenoids that bring the system from rest into an uncontrolled steady motion similar to the one associated with Figure 1. The full nonlinear equations, also formulated with AUTOLEV, then were solved in conjunction with these input functions, and it was found that the system did, indeed, perform as intended. Figures 11-13 show several stills from the ANIMAKE animation of the spinup simulation.



Figures 11-13. Spinup of Two Solenoids from Rest into State of Steady Rotation

In undertaking a spinup from rest, it matters significantly how it is accomplished as to whether or not the target steady motion can be achieved without feedback control to correct overshoot. For example, if the desired time-history of the angular speed of the line connecting the mass centers of the two solenoids is chosen to be a second-degree polynomial function of time, such as the green curve in Figure 14, it leads to an orientation angle time-history for the left solenoid in Figure 10 given by the green curve in Figure 15. This is a time-plot of the angle between the long axis of the left solenoid and the line connecting the mass centers of the two solenoids. It can be seen that the slope of this curve is not zero at $t = 30$ s, the instant of completion of the spinup maneuver. This means that the left solenoid, upon reaching alignment with the right solenoid, has “surplus” angular speed and, thus, overshoots the mark. An animation still of such an overshoot is shown in Figure 16.

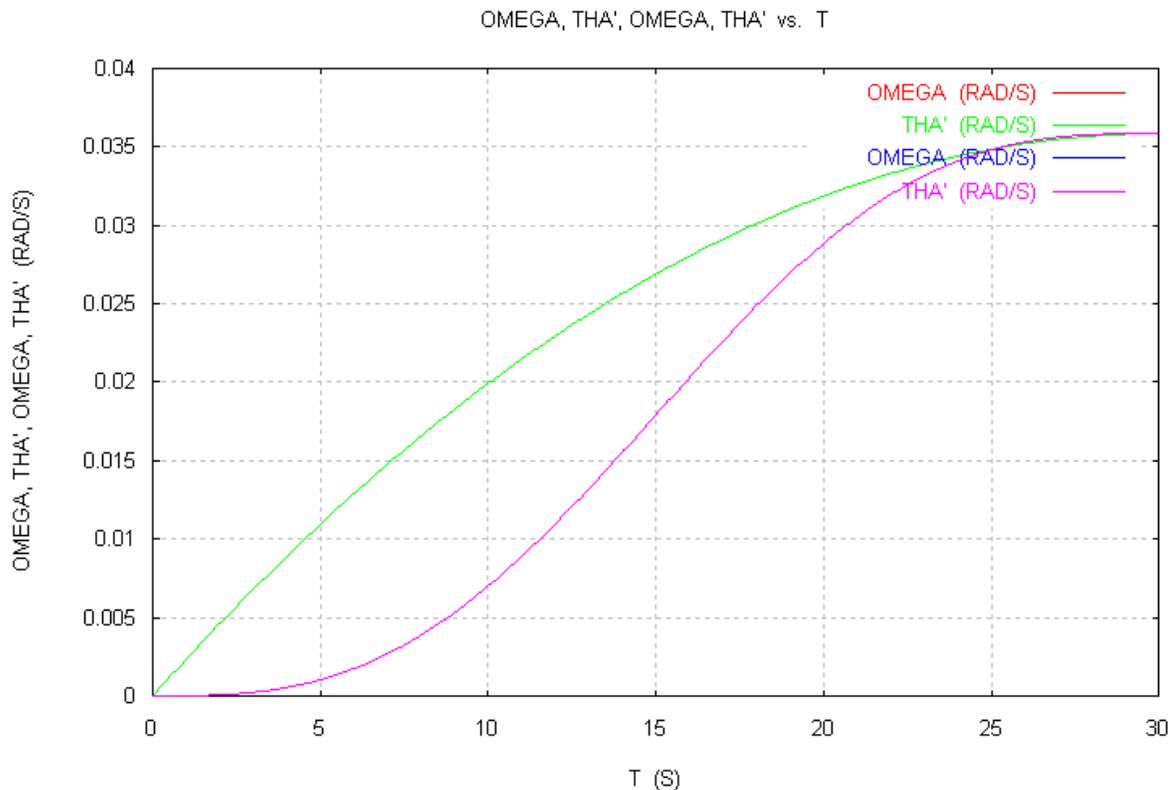


Figure 14. Angular Speed Time-Histories of the Line Connecting the Two Solenoid Mass Centers

In contrast, if one chooses a more suitable function, represented by the purple curve in Figure 14, for the angular speed time-history of the line connecting the two solenoid mass centers, one obtains, correspondingly, the purple curve in Figure 15 for the attitude time-history of the left solenoid. This curve has zero slope at $t = 30$ s, the time at which the spinup maneuver is complete. Thus, there is no surplus angular speed when alignment with the right solenoid is achieved and, therefore, no overshoot. The smooth transition

from rest to steady rotation shown in Figures 11-13 was, in fact, produced with this spinup strategy.

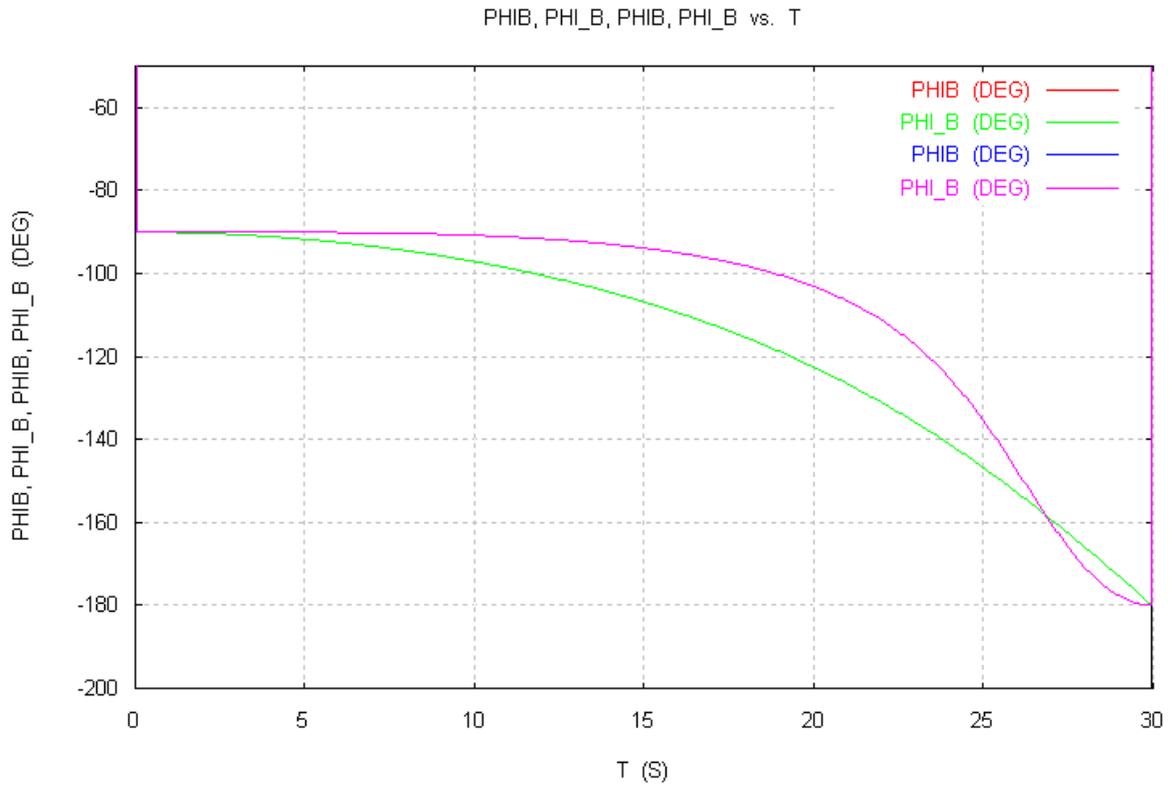


Figure 15. Attitude Time-Histories of the Left Solenoid in Figure 10 Corresponding to Spinup Time-Histories in Figure 14.

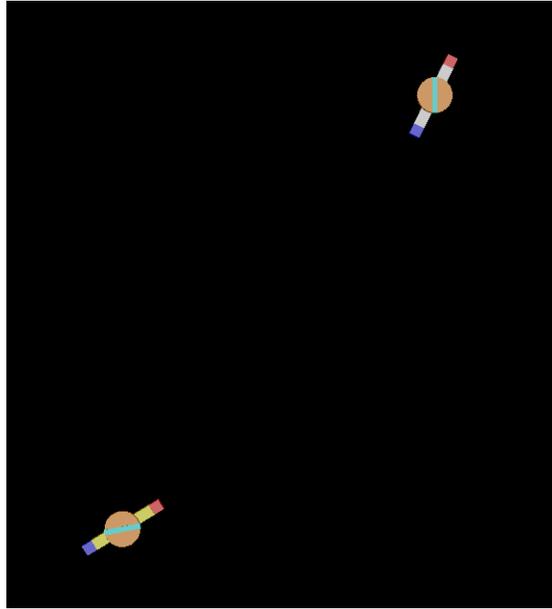


Figure 16. Overshoot of Solenoid Alignment Brought On by Unsuitable Choice of Angular Speed Time-History in System Spinup Maneuver

5 - Expansion and Contraction of Formations

Having developed our tools and having verified the MIT results (and thus the soundness of the EMFF approach), we looked for a different scenario to analyze and simulate. One of the tasks that a realistic EMFF control system in orbit might be called upon to perform is that of controlling the spacing and orientations of the satellites, either to compensate for perturbations that, over time, would destroy the formation's geometrical pattern, or to redefine the spatial pattern in response to evolving mission requirements. We found that it is possible to expand and contract a particular formation of solenoids by decreasing or increasing the current in one or more solenoids while employing reaction wheels to keep the solenoids aligned with each other. Figures 17-21 display the results of an AUTOLEV-generated simulation intended to demonstrate this. In Figure 17, two solenoids are engaged in steady rotation of the kind shown previously in connection with the system of Figure 1. The inner green circle is the path traced out by the mass centers of the two solenoids. Next, by means of formulas obtained from the exact equations of motion generated by AUTOLEV, the current in one solenoid is decreased to cause the mass centers of the two solenoids to separate further, while the reaction wheels on both solenoids are engaged to keep the two solenoids aligned with each other, as shown in Figure 18. When the mass centers of the two solenoids arrive at the outer green circle, control ceases and steady rotation is once again achieved, as shown in Figure 19. To bring the solenoids back to the inner circle, the control system is once again employed, as shown in Figure 20, and, finally, the solenoids arrive back on the inner circle and resume uncontrolled steady motion there, as shown in Figure 21. The time-history of the variable

electric current is plotted in Figure 22. Note the two spikes associated with the arrival of the solenoids at the larger and smaller circles.

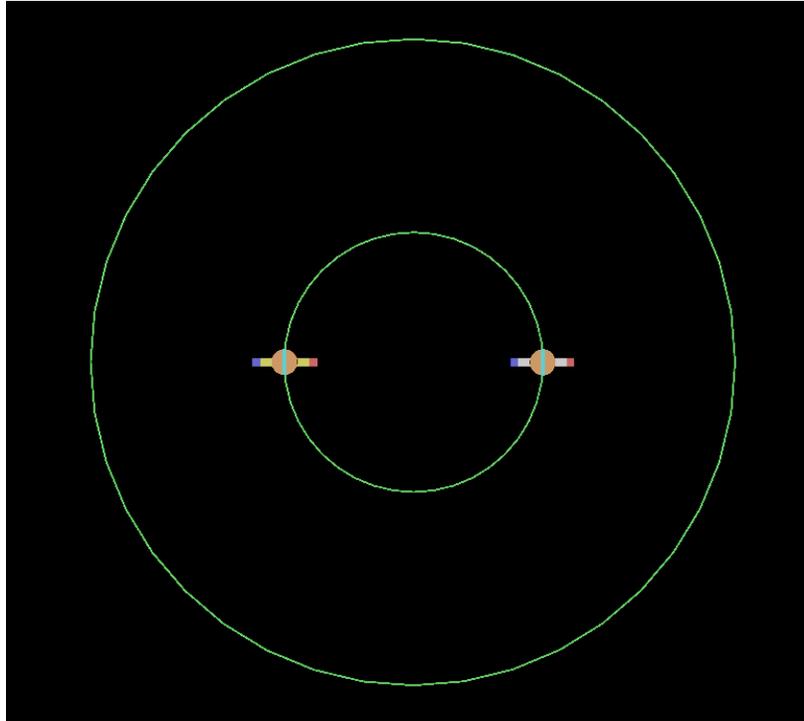


Figure 17. Steady Motion of Solenoids on Inner Circle

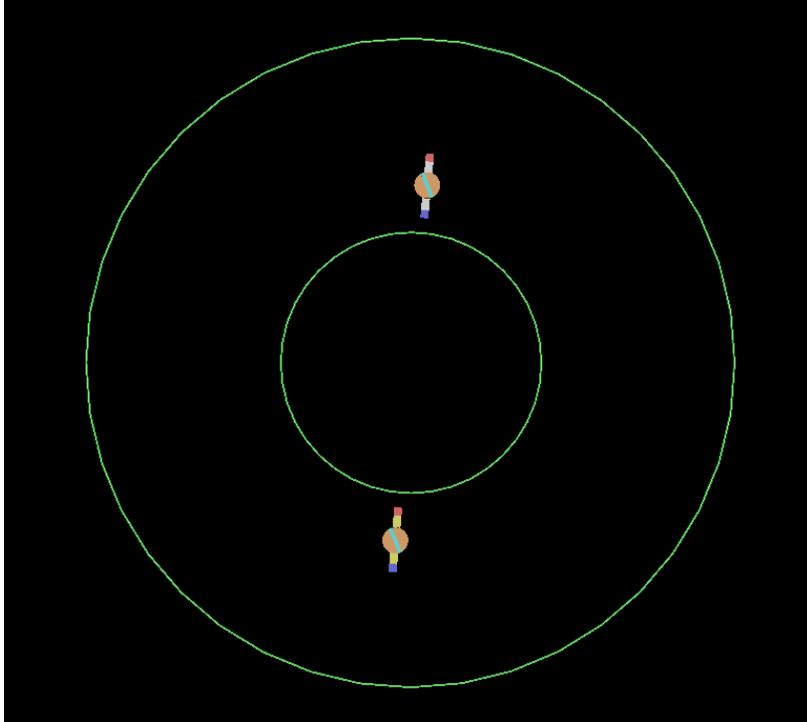


Figure 18. Smooth Transition to Outer Circle

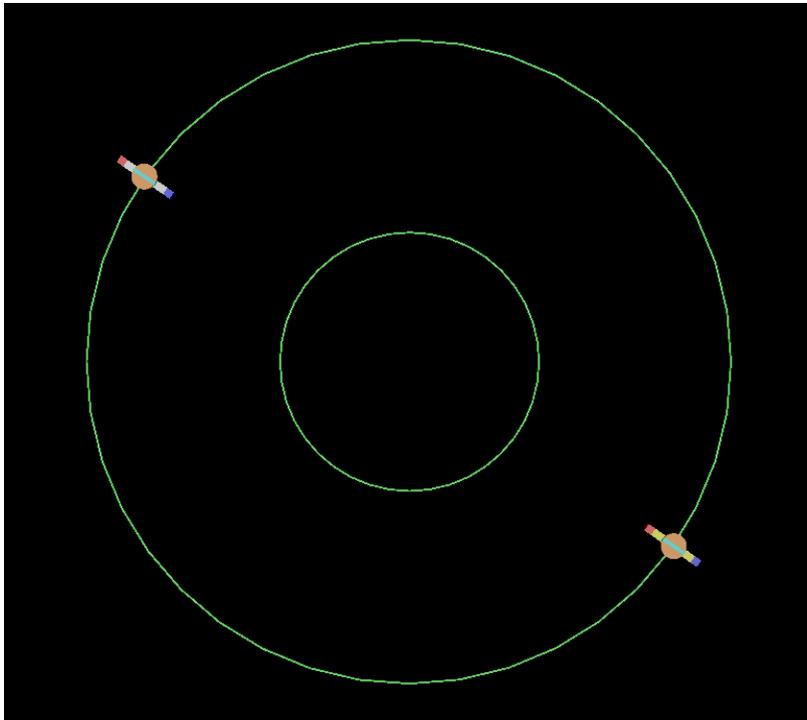


Figure 19. Steady Motion of Solenoids on Outer Circle

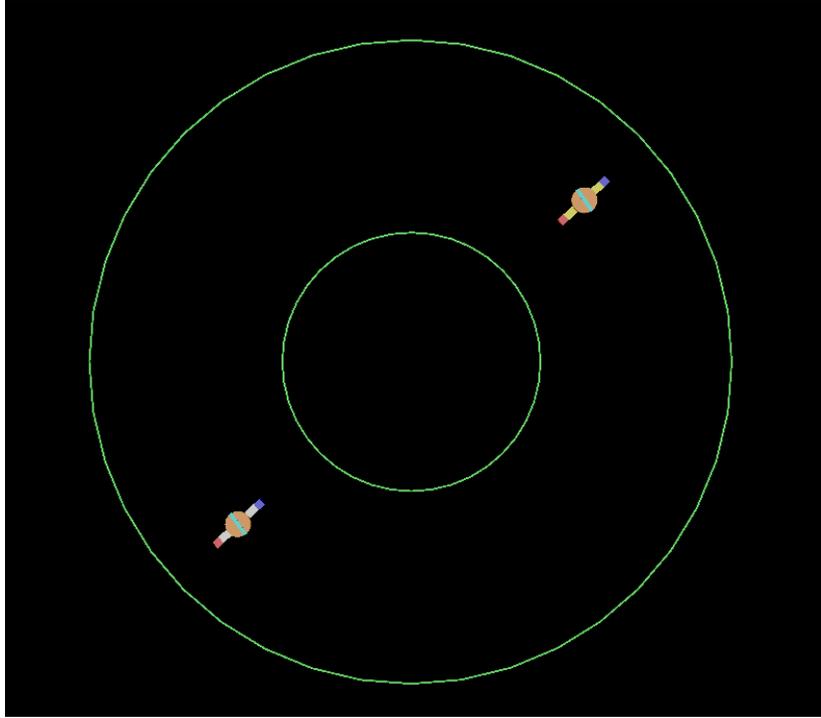


Figure 20. Smooth Transition Back to Inner Circle

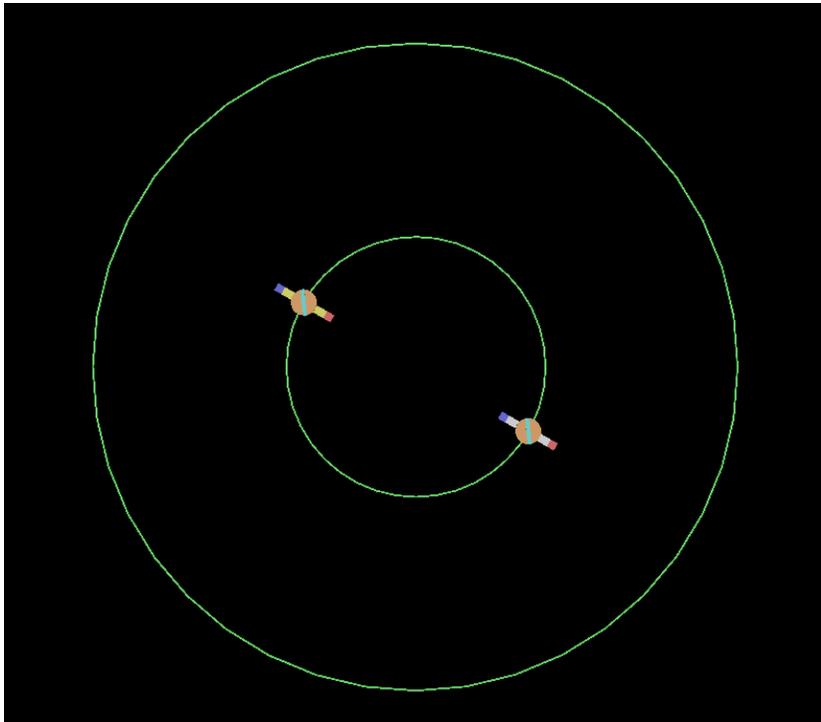
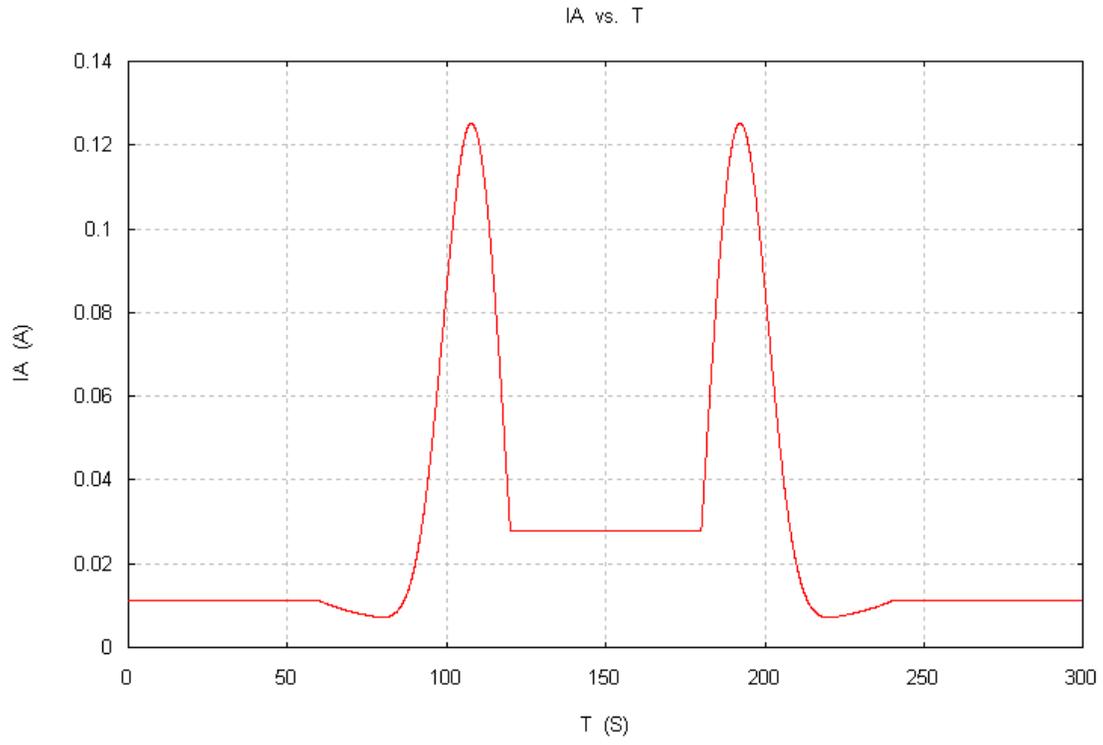


Figure 21. Steady Motion on Inner Circle Once Again



Conclusion

In conclusion, we have verified results already obtained by MIT, but we have extended them in significant ways. First, we have incorporated the motion algorithms in a simulation that allows quick and easy visualization of a particular solution. Analytically, we have suggested a smoother angular time history of the spinning solenoids, reducing the overshoot that was observed with the original MIT-supplied function. We have moved beyond the basic magnetic force problem by incorporating the effects of reaction wheels along all three axes, and have been able to simulate a formation reconfiguration. Most important, we have validated the use of AUTOLEV for magnetic force problem, which will allow us to generalize our simulations in a straightforward way to address more complicated and physically realistic problems.

Future work can move along several directions: more solutions can be sought with the formalism we have developed, giving us insight into the types of formations and missions that can profitably use EMFF technology. More realism needs to be introduced in several important ways. First, the mass properties of candidate satellites need to be modeled more faithfully, ditto for the performance of real coils and control systems. Finally, the effects of the environment must be factored in, particularly the Earth's ambient field, which could be used as a sink for excess reaction wheel angular momentum.