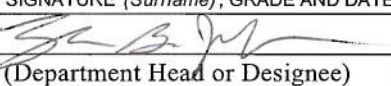
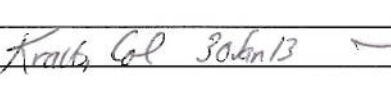


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1 Tab
1. Paper



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DYNAMICS MODELING OF ELECTROMAGNETIC FORMATION FLIGHT

Andrew R. Hilton, Gregory J. Eslinger, David W. Miller

Space Systems Laboratory, Massachusetts Institute of Technology

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DYNAMICS MODELING OF ELECTROMAGNETIC FORMATION FLIGHT

Andrew R. Hilton¹, Gregory J. Eslinger², David W. Miller³

Electromagnetic formation flight (EMFF) is a method of holding satellite arrays in a formation without the use of propellant. A formation of smaller satellites that work together can be more effective and cheaper than one larger satellite performing a similar mission. EMFF will enable the United States Air Force to develop flexible, robust space systems by splitting different systems and payloads into modules that link together on orbit and fly in a formation. Such systems will reduce the complexity of design as well as increase the ability to respond to unforeseen occurrences during mission operations. The concept of EMFF relies on the fact that the spacecraft in the formation are flying relative to each other and uses attraction and repulsion forces to actuate the system. The research presented here analyzes these relative forces while detailing the development and verification of a Simulink dynamics model for an electromagnetic formation flight project at the Space Systems Laboratory. Biot-Savart's law is used to characterize the magnetic fields from each coil and model the resulting forces and torques. The model uses finite element analysis to compute the forces and torques exchanged between different segments on the two coils. The simulation has been accurate in modeling the forces and torques induced by resonant coils as a result of their relative position and orientation thereby allowing future researchers to develop and test formation-flying control algorithms before using the valuable on-orbit time allocated for hardware testing.

INTRODUCTION

Formation flying of satellites is a method for completing a variety of different missions in space in an efficient manner. A formation of small satellites that work together can be more effective and cheaper than one larger satellite performing the same mission. Use of multiple satellites will reduce the cost of launch and maintenance of the system because only the components that break down will need to be replaced as opposed to the entire spacecraft.

Currently formation flying is actuated using traditional thrusters and the mission is limited by the amount of propellant that the vehicle can carry. For missions that require a high degree of precision, thrusters will burn a large amount of fuel constantly making corrections and counter-corrections. The concept of electromagnetic formation flight (EMFF) takes advantage of the fact

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that the spacecraft in the formation are flying relative to each other and uses attraction and repulsion forces instead of thrusters to actuate the system.

The Space Systems Laboratory (SSL) at the Massachusetts Institute of Technology in conjunction with the University of Maryland and Aurora Flight Sciences is working to demonstrate the feasibility of electromagnetic formation flight with the RINGS project. Using SPHERES, an existing formation flight testbed aboard the International Space Station, the SSL plans to demonstrate EMFF capability using RINGS that are each attached to the individual spacecraft.

This report describes the development of a model that was designed to integrate with the existing SPHERES simulation in Simulink. Such a simulation allows the team at the SSL to develop controllers in Simulink for RINGS, and then test those controllers before using the hardware. The simulation outputs the force and torque vectors on each of spacecraft as a result of the magnetic fields generated by the coils. A block diagram depicting the integration of the EMFF Dynamics block with the existing SPHERES simulation is shown in Figure 1. The state vector contains position, velocity, and attitude information in the form of a quaternion and the angular velocity at every time step.

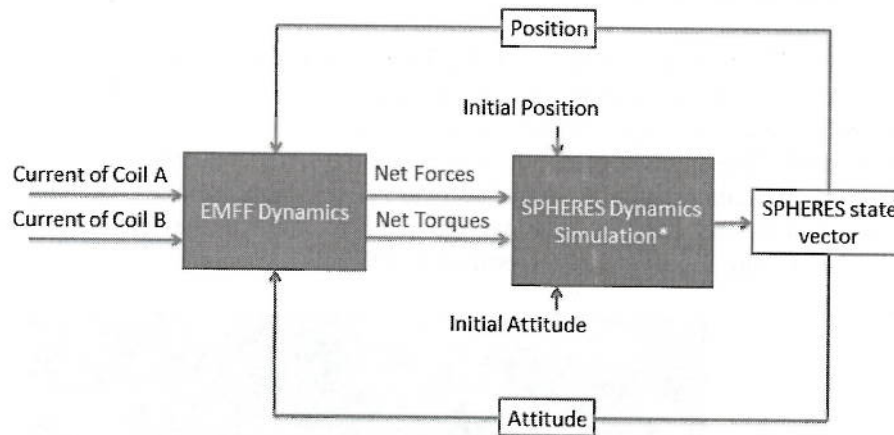


Figure 1. Overview of the Simulation Integration

OVERVIEW OF SPHERES AND RINGS

SPHERES (Synchronized Position Hold Engage and Reorient Experimental Satellites) is an algorithm testbed developed and operated by the MIT Space Systems Laboratory. The testbed is a tool that allows for the development of formation flight algorithms in an environment that is tolerant to risk. This is advantageous for testing algorithms that will be used on high-risk control and autonomy technologies. The developer does not need to risk harming valuable hardware when testing such algorithms because the algorithms can be tested in a six-degree-of-freedom free fall environment using SPHERES aboard the International Space Station.

Three free-flyer vehicles are used, along with five ultrasonic beacons and a laptop control station, to operate the testbed. The satellites are self-sufficient in that they each contain their own power, propulsion, communications, sensor, computer subsystems, as well as operate semi-

autonomously. The astronauts on the ISS are needed to replenish the used power and propellant in addition to initiating each test. Figure 2 displays an example of one of the SPHERES satellites.

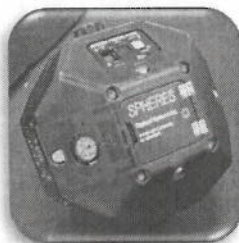


Figure 2. A SPHERES Satellite

Actuation on the vehicle is provided by twelve thrusters positioned so that the satellite can translate along or rotate about all three axes. In order to demonstrate the feasibility of EMFF, thrusters on the SPHERES flight vehicles will only be used to generate torques that model the use of a reaction wheel, or set of reaction wheels, on other space systems. This is purely because the SPHERES testbed does not contain reaction wheels for actuation and therefore must model that capability in another form.

A newer development of the SPHERES program is the capability to attach other hardware for use in control algorithm testing. One addition is the development of RINGS (Resonant Inductive Near-Field Generation System) which will be used to generate magnetic fields using current carrying coils. The hardware was developed by the University of Maryland and delivered to the Space Systems Laboratory for control software development and testing. The coils are actuated to generate forces and torques that can be used to control the spacecraft without the use of propellant. Figure 3 shows a coil mounted to a SPHERES satellite.

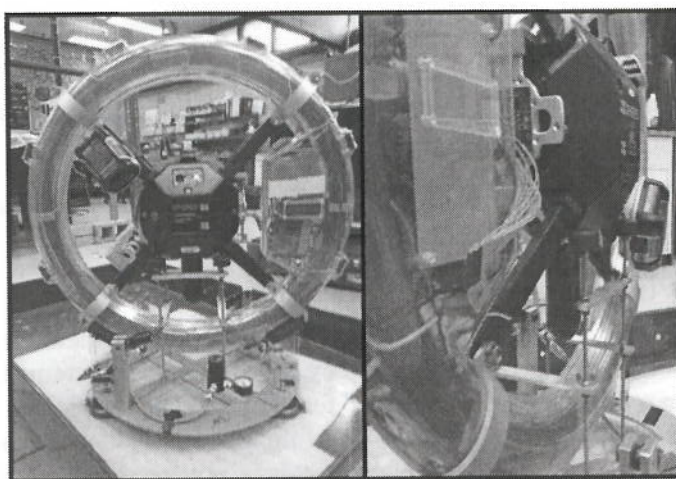


Figure 3. RINGS Coil Mounted to the SPHERES Flight Vehicle

Using thrusters as the actuation source, each SPHERE is capable of moving or rotating in any direction desired by the operator. In order to control the system in the same manner using RINGS, there would need to be three coils—one around each axis. The design of the coil limits the

number of coils per SPHERE to one, thereby making it an under-actuated system and increasing the complexity of the control. A similar example of an under-actuated system is a car because it can only move forward or backwards and not side-to-side. If one wishes to translate the car to the left, he or she would have to pull forward and back-in while rotating the wheels of the car using the steering wheel. This series of motions, known more commonly as parallel-parking, is more complicated than merely translating the entire vehicle sideways. Like a car, the limited actuation capability of RINGS makes it more difficult to control the system. The goal of the RINGS project is to demonstrate that any desired movement can be accomplished solely with the electromagnetic coils and reaction wheels.

MATHEMATICAL DEVELOPMENT OF EMFF DYNAMICS

To assist control algorithm development on SPHERES, the Space Systems Laboratory developed a SPHERES simulation that models the dynamics of the vehicles in inertial space. This allows developers to test their control algorithms on a simulation before testing on the actual hardware, making the overall process more efficient and reducing the risk of damage to the testbed itself. To model the effects of RINGS, an addition to the simulation needed to be developed that modeled the magnetic forces and torques on a satellite from the coils. Such a model would allow the operator to control the relative motion of the two SPHERES by varying the current driven through the coils as well as changing their relative orientation using the reaction wheels. First, a simplified model was developed that was later transitioned into a complete model. Simplified in this case means that the coils are only free to move and rotate in the xy -plane though they still exist in three dimensions. Figure 4 depicts the coordinate frame and parameters of the simplified model.

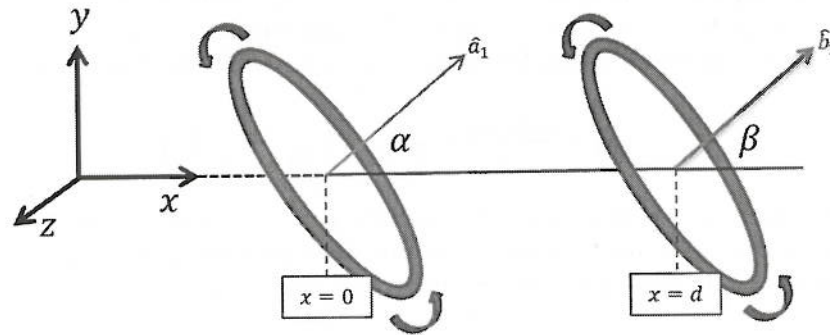


Figure 4. Coordinate Frame of Simplified Model

The model's reference frame is centered at the center of Coil A with x denoting the horizontal axis, y the vertical axis, and z coming out of the page to complete the right-handed coordinate system. Coil B is positioned a distance, d , from Coil A along the x -axis. The coil angles, α and β are measured from the model's horizontal axis to the coil's north dipole. The north dipole is also the first axis in each of the coil's body coordinate frames and is determined by the direction of current in the coil and the right hand rule. The second and third body axes are parallel with the y and z axes when α and β are equal to zero. Due to the fact that the north magnetic dipole is determined by the direction of the current flowing through the coils, coil angles greater than 180° have the same orientation as a coil angle of 180° less with current

flowing in the opposite direction. For example, a coil with $\alpha = 200^\circ$ has the same orientation as a coil with $\alpha = 20^\circ$ and current flowing in the opposite (clockwise) direction.

From Figure 4, equations for the forces and torques on Coil B as a result of the magnetic field generated by Coil A can be developed. The Biot-Savart Law for the magnetic field generated by an electric current for a constant current source is shown in Equation 1.

$$d\vec{B} = \frac{\mu_0 I}{4\pi} \left(\frac{\vec{r} \times d\vec{l}}{r^3} \right) \quad (1)$$

The Biot-Savart Law is rearranged to fit the RINGS model where i_A is the current generated by Coil A, n_a is the number of turns in coil A, $\vec{r}_{AB}$ is a vector pointing from a point on Coil A to a point on Coil B, and $d\vec{l}_A$ are length segments along Coil A. Equation 2 gives the magnetic field generated by Coil A at a point B on Coil B.

$$\vec{B} = \frac{\mu_0 i_A n_a}{4\pi} \int_{Coil A} \frac{\vec{r}_{AB} \times d\vec{l}_A}{r^3} \quad (2)$$

The force on a current carrying wire from a magnetic field is found by crossing the magnetic field vector with the product of the current and the length vector. If Coil B is divided into an infinite number of length segments $d\vec{l}_B$, then the force on each segment from the magnetic field generated by Coil A can be calculated using Equation 3.

$$\vec{F} = i_b n_b d\vec{l}_B \times \vec{B} \quad (3)$$

Combining Equations 2 and 3 yields an expression for the force on a point on Coil B resulting from the magnetic field generated by Coil A. Integrating over Coil B will produce Equation 4 describing the net force on Coil B from the magnetic field generated by Coil A.

$$\vec{F}_B = \frac{\mu_0 i_A n_a i_b n_b}{4\pi} \int_{Coil B} \left(\int_{Coil A} \frac{\vec{r}_{AB} \times d\vec{l}_A}{r^3} \right) \times d\vec{l}_B \quad (4)$$

The torque on Coil B from any point on the coil is given by the cross product of force on that point and the position vector of that point from the center of mass of the coil. Integrating along all of the points on the coil yields the net torque on Coil B. The result is given by Equation 5.

$$\vec{T}_B = \frac{\mu_0 i_A n_a i_b n_b}{4\pi} \int_{Coil B} \vec{r}_B \times \left(\int_{Coil A} \frac{\vec{r}_{AB} \times d\vec{l}_A}{|\vec{r}_{AB}|^3} \right) \times d\vec{l}_B \quad (5)$$

Once the equations for force and torque were developed, a model could be created for use in the SPHERES simulation. The most accurate model would compute the force and torque equations derived above. Due to the close distances of the spheres during docking, far field approximations are not adequate representations of the system because they do not include the radius of the coil in calculations of separation distance. The model cannot solve these equations directly because an explicit solution to the inner integral for both equations does not currently exist.

Due to the fact that the integrals were unsolvable in their current form, they were rewritten as Riemann sums that could be implemented in Simulink using different looping functions. Both coils would be divided into n segments and the forces and torques would be calculated at each

combination of points. The total force and torque on the sphere would then be the sum of all the forces and torques from each combination of points. Dividing the coil into 50 segments was determined to be sufficiently accurate because the difference in results became negligible as n increased beyond 50. The force and torque equations written as Riemann sums are shown as Equations 6 and 7.

$$\bar{F}_B = \frac{\mu_0 i_A n_a i_b n_b}{4\pi} \sum_{i=1}^{50} \left(\sum_{j=1}^{50} \frac{\bar{r}_{ij} \times d\bar{l}_j}{|\bar{r}_{ij}|^3} \right) \times d\bar{l}_i \quad (6)$$

$$\bar{T}_B = \frac{\mu_0 i_A n_a i_b n_b}{4\pi} \sum_{i=1}^{50} \bar{r}_{Bi} \times \left(\sum_{j=1}^{50} \frac{\bar{r}_{ij} \times d\bar{l}_j}{|\bar{r}_{ij}|^3} \right) \times d\bar{l}_i \quad (7)$$

SIMULINK EMFF MODEL

Equations 6 and 7 above were used to model the net forces and torques on each coil using Simulink. This model was developed in two parts in order to simplify the design. First, the simplified version was designed that only enabled rotation about the third body axis and translation in two directions. Figure 4 shows the parameters that govern the simplified model. The main block takes inputs of Coil B's horizontal position on the x -axis, the amount of current through both coils, and each coil's angle relative to the x -axis (α and β) in order to determine the forces and torques on the center of mass of the coil where the spacecraft would be positioned. This section breaks down the process of modeling Equations 6 and 7 using Simulink.

First, a generic coil was developed in polar coordinates and then converted to Cartesian coordinates. Fifty equal segments were designated by dividing 2π by fifty and using a constant radius equal to the radius of each coil (R_c). These polar coordinates were converted into Cartesian coordinates using Equations 8, 9, and 10. Note that the coil is in the yz -plane in accordance with Figure 4.

$$x = 0 \quad (8)$$

$$y = R_c \cos \theta \quad (9)$$

$$z = R_c \sin \theta \quad (10)$$

Once a generic coil is established, it can be translated and rotated to derive Coil A and Coil B. The generic coil is defined as a coil with initial values of zero for both position and rotation. The orientations of Coil A and B are found by rotating the generic coil using a third axis rotation through their respective coil angles. Equation 11 shows the generic form of a third axis rotation matrix through an angle φ .

$$ROT3(\varphi) = \begin{bmatrix} \cos \varphi & \sin \varphi & 0 \\ -\sin \varphi & \cos \varphi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (11)$$

Multiplying this rotation matrix with the 3×1 generic coil coordinates results in the coordinates for Coil A and the non-translated coordinates of Coil B. As Coil B is offset from Coil

A in the x -direction, the separation distance needs to be added to the first element in every coordinate of the generic coil before it can become an accurate representation of Coil B.

To define length segments, dl , at each point along the coil, a 90° rotation was used for each radius vector of the generic coil. The reason the length segment vectors were rotated using the generic coil is so that it would be a simple 90° rotation about the first axis. If the derivation of length segment vectors occurred after the coil rotation, the 90° rotation would be about whatever vector was normal to the coil in its new orientation. The rotation yields a vector that is tangent to the generic coil at each of the 50 segments. Though the direction of each vector is correct, the magnitude needs to be adjusted by multiplying each vector by a factor of $\left(\frac{2\pi R_c}{50} \frac{1}{R_c}\right)$. This factor will divide out the length of the radius and set the magnitude of each $d\vec{L}$ to one fiftieth of the circumference of the coil. The length vectors also need to be rotated using the third-rotation matrix defined in Equation 11 in order to be aligned properly to their respective coils. This completes the coil derivations in Cartesian coordinates and enables the computation of forces and torques on Coil B as a result of the magnetic field generated at Coil A.

The double-summations of the force and torque equations shown in Equations 6 and 7 were executed in Simulink to complete the model. Within the inner loop of the model, the force and torque vectors on one segment of Coil B are calculated from the magnetic field generated at all 50 segments of Coil A. These values were summed and passed to the outer loop. In the outer loop, the summed force and torque on each Coil B segment is computed and summed together to yield the net force and torque on Coil B as a result of Coil A's magnetic field.

Once the simplified model was complete, it was expanded to operate in three dimensions with any set of initial conditions. To more accurately model the orientation of each coil relative to the spacecraft, the reference frame was changed to redefine the generic coil. When the coils are attached to the SPHERES spacecraft, the north dipole of the coil will initially be oriented with the spacecraft's second body axis. Due to the fact that the state vector will come from the spacecraft, the coil orientation needed to be modified in the model to be consistent with the hardware orientation. The coils are also free to rotate about all three axes and translate in any direction for six-degree-of-freedom relative motion.

The attitude of the spacecraft is provided in the state vector using a quaternion and the angular velocity about each axis. Therefore, the complete EMFF model must take inputs of quaternions instead of α and β in order to determine the orientation of the coils relative to the generic coil. The change is simple in Simulink as there is a Quaternion to DCM block that takes a 4×1 quaternion and outputs a 3×3 direction cosine matrix used in place of the axis rotation matrix used in the two-dimensional model. Due to the fact that quaternions are less intuitive to visualize than a rotation about a single axis, the simplified model is useful in understanding the mechanics before moving to the complete model where the rotation computation is more difficult to understand.

The SPHERES state vector designates the quaternion as a 4×1 vector with the first three elements denoting the vector component and the following element denoting the scalar component. The basic idea is that the vector component defines an axis of rotation, while the scalar component defines the angle of rotation about that axis. The quaternion is normalized so that the magnitude of the 4×1 vector is equal to 1. Simulink switches the scalar and vector

components within its definition of a quaternion so a selector block is used to rearrange the elements to maintain consistency with the SPHERES state vector.

The complete EMFF Model uses inputs of coil positions relative to the inertial origin, each coil's time-varying current strength, and the quaternion describing the attitude of each coil in order to output 3×1 net force and torque vectors for each coil. The model is very similar to the simplified model that it was derived from with a few key exceptions. When converting the generic coil from polar to Cartesian coordinates, the coil is now aligned with the xz -axis instead of the yz -axis. This also means that the length segments are derived by rotating the radii of the coil 90° about the second axis instead of the first axis. A new subsystem was designed to translate the coils as they can now both translate along all axes. Also, the rotation of the generic coil is completed using a DCM instead of a third axis rotation.

SPHERES SPACECRAFT DYNAMICS MODEL

With an EMFF model completed, the SPHERES dynamics could be modeled by treating the outputs of the EMFF model as external forces and torques on the body of each satellite. Figure 5 shows the complete Simulink model integrating the EMFF model as the RINGS Dynamics block with two SPHERES dynamics blocks.

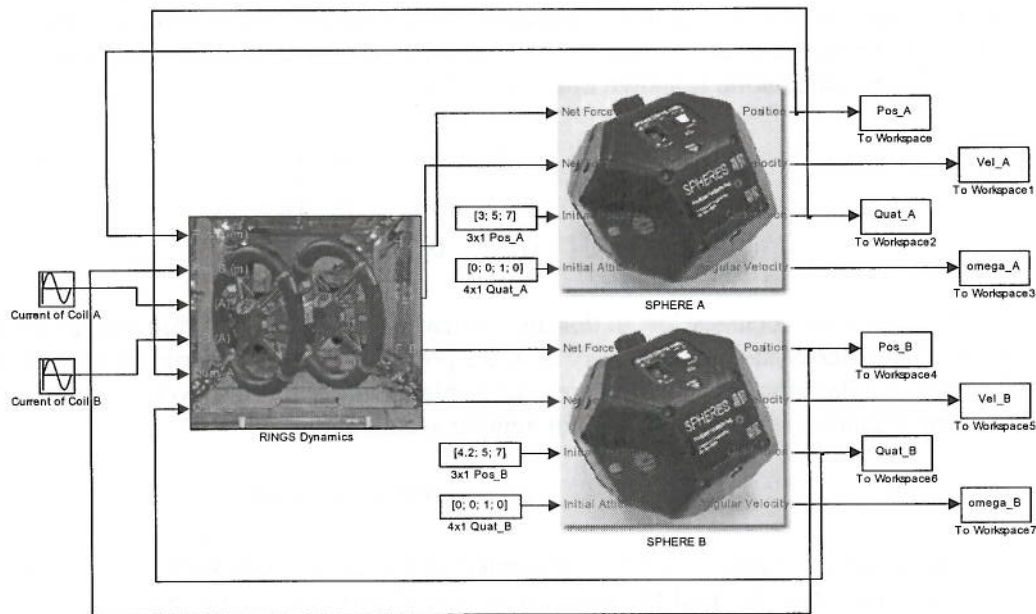


Figure 5. RINGS and SPHERES⁴ Model

⁴ The SPHERES dynamics blocks discussed in this report are an approximation of the dynamics experienced by the spacecraft and are not part of the SPHERES Simulation used by the Space Systems Laboratory.

Notice that the initial attitude and position information for each SPHERE are fed into the SPHERES dynamics blocks as inputs and those position and attitude outputs are then fed into the RINGS Dynamics block. This is important because the forces and torques are dependent on the current position and orientation of the spacecraft. As it is designed, the model will accurately reflect how the forces and torques from the magnetic field will change as the SPHERES move apart or closer together.

The purpose of each dynamics block is to return the spacecraft state vector when subjected to a net force and torque. The state vector includes the position, velocity, attitude quaternion, and angular velocity of the SPHERE at each time step. The force is converted to acceleration by dividing out the mass of the body. The SPHERE mass is already included with a switch that designates whether or not the mass of the coil should be included. For this report, the RINGS mass and inertia matrix are always included. The acceleration is then passed through two integrator blocks to derive the velocity and the position of the spacecraft. The initial velocity on this model is set to zero while the initial position is received as an input from the mask of the dynamics block. This completes the translation portion of the dynamics block.

The rotation portion of the dynamics modeling is less intuitive. First, a subsystem was designed that calculated the angular acceleration ($\dot{\omega}$) using inputs of the inertia tensor, the net torque and the angular velocity. It is important to note that the output needs to be integrated and fed back into this subsystem as the angular velocity input. The torque is an input to the model's mask and the inertia tensor is calculated using the coil mass and the standard inertia of a coil. The inertia matrix calculation is shown in Equation 12.

$$I = \begin{bmatrix} \frac{1}{2}mr^2 & 0 & 0 \\ 0 & mr^2 & 0 \\ 0 & 0 & \frac{1}{2}mr^2 \end{bmatrix} kg \cdot m^2 \quad (12)$$

There is some accuracy lost in this approximation of the coil as a thin wire as the coil is rather thick. The Space Systems Laboratory is in the process of characterizing the true inertia matrix of the coils and therefore these values are used as placeholders for this model. Equation 13 is Euler's Moment Equation rewritten to solve for angular acceleration.

$$\dot{\omega} = I^{-1}(T - (\omega \times I\omega)) \quad (13)$$

The resulting angular velocity is outputted as part of the state vector and is used to calculate the quaternion rate. To find the quaternion rate, it was simpler to split the quaternion into its vector and scalar components and find their derivatives separately. Equation 14 shows the derivative of the scalar component ($\dot{\eta}$) while Equation 15 shows the derivative of the vector component ($\dot{\epsilon}$). I in Equation 15 is a 3x3 identity matrix, not the inertia matrix of the spacecraft.

$$\dot{\eta} = -\frac{1}{2}\epsilon^T \omega \quad (14)$$

$$\dot{\epsilon} = \frac{1}{2}(\epsilon^x + (\eta \times I)) \quad (15)$$

In Equation 15, ε^X is the skew matrix of the 3x1 vector component of the quaternion. A skew matrix of a 3x1 vector becomes a 3x3 matrix as shown in Equation 16.

$$\begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix}^X = \begin{bmatrix} 0 & -e_3 & e_2 \\ e_3 & 0 & -e_1 \\ -e_2 & e_1 & 0 \end{bmatrix} \quad (16)$$

The quaternion rate is then passed through an integrator with the initial condition set to the initial attitude of the spacecraft as defined by the input to the dynamics model. The result is normalized and passed as an output with the rest of the state vector. The quaternion and the angular velocity vector calculated earlier make up the rotational motion portion of the state vector. The SPHERES dynamics block helps one to model the motion as a result of the forces and torques modeled by the RINGS dynamics block.

FORCE CHARACTERIZATION ON RINGS HARDWARE

In order to demonstrate Simulink's capability in modeling the electromagnetic forces and torques, a test needed to be developed to measure forces from the interaction of the coils. The simplest interaction to measure is the two coils set parallel to each other. This case creates a net force in one direction with no net torques. Using the two-dimensional model, with an initial separation distance of 0.195 m and initial coil angles of 0, a simulated output force could be compared to the measured force from one RING on the other. Figure 6 shows a diagram of the test set up.

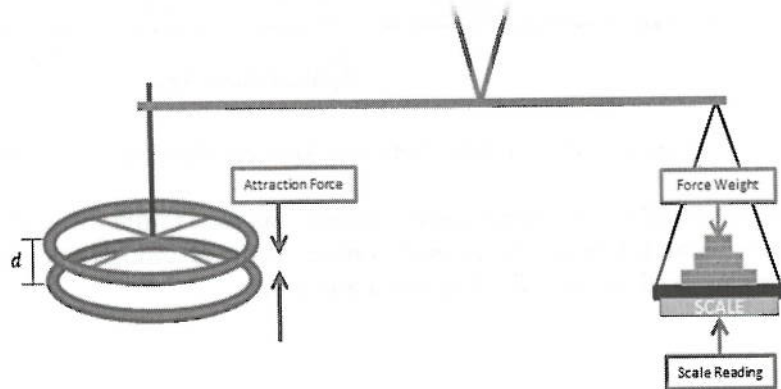


Figure 6. Force Characterization Test Set Up

Built by the Space Systems Laboratory, this harness was designed to characterize the force from the RINGS coils in one direction—normal to the coils. Using weights to counter-balance the Coils, the harness is placed into a level configuration so that the coils are parallel to each other. This ensures that all of the force exerted from the coils will be in the same direction with zero net torque. In this balanced position, the scale is set to zero and the RINGS coils are turned on. The coils are oriented to attract each other so that the force exerted removes weight from the scale on the other end of the harness. The scale will read out a negative number that measures the force exerted on the weights from the coil. This number can be used to determine the attractive force from the coils.

Characterizing the test set up prior to the test is useful in determining the relationship between the scale reading and force exerted on the other end of the harness. With the coils turned off and the counterweights on the tarred scale, small masses are added to a plate on the top ring. These masses are recorded along with the scale reading that resulted from the addition of the mass. The relationship can be approximated using a linear regression and used to calculate the force of the RINGS during the test. It is important that this characterization be completed using the exact same set up that will be used during testing. The RINGS coils should already be wired up with the correct counterweight on the scale. Figure 7 shows a plot of the set up characterization along with the equation describing the relationship. Note that the correlation between the linear regression and the data points used for calibration is extremely high.

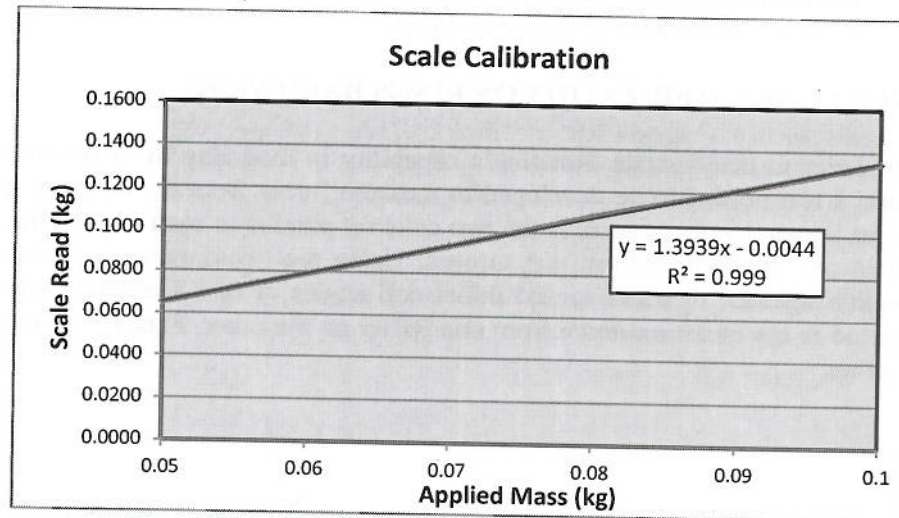


Figure 7. Relationship between Applied Mass and Scale Readout

A GW Instek GPS-2303 direct current source was used to run different currents through each coil while an Escali C136 scale was used to measure the resulting force. Figure 8 shows pictures of the test set up used in the Space Systems Laboratory.

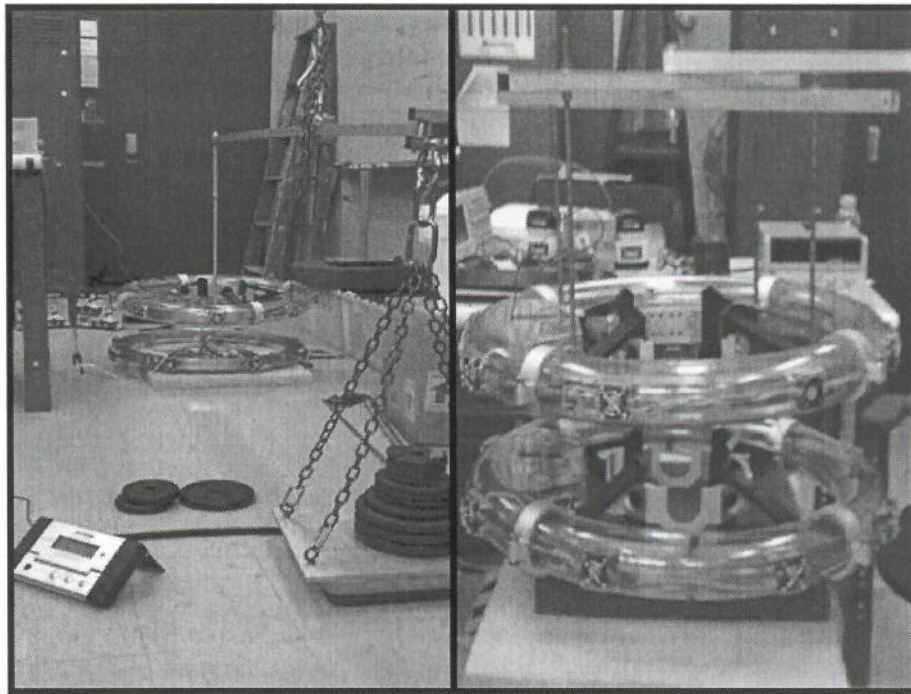


Figure 8. Experimental Test Set Up

During the experiment, it became very difficult to stabilize the structure so that the scale could settle out. Though no movement in the structure could be visually seen, the scale fluctuated back and forth within a 3 gram range. This resulted in an uncertainty of ± 1.5 grams when determining the zero value for the test as well when recording the scale reading after the attractive forces had been applied. Using the slope of the linear equation shown in Figure 7 and adjusting for the acceleration due to gravity, the uncertainty in measured force from this test set up becomes $\pm 0.021114 \text{ N}$. The product of the currents is a good indicator of how much force will be applied as the force calculation contains this product outside of the double integral as part of the constant. Figure 9 shows a plot of force versus current product for both the simulation and the measured force. Error bars are attached to each experimental data point in order to visually show that the simulation falls within the accepted uncertainty throughout the experiment.

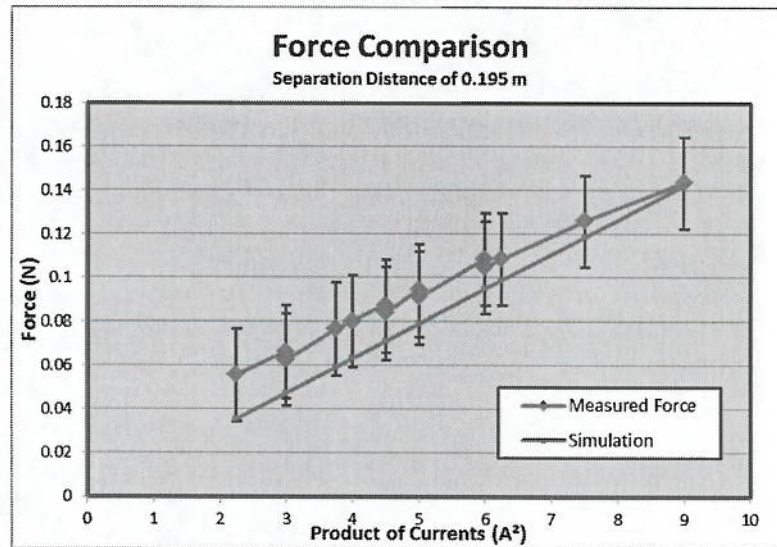


Figure 9. Example of Simulation and Measured Force Comparison

The plot also shows that the measured forces become closer to the simulation as the value of the current product increases. Despite the difficulty in measuring the forces, this experiment provided a good start in demonstrating that the simulation is accurately modeling the forces exerted by the RINGS coils. Tests similar to this one have been completed by other undergraduate researchers in the lab with similar results.

At this stage in the hardware development, the Space Systems Laboratory cannot perform tests with higher values of current or in different orientations—the lab has not currently developed a reliable way to measure torque. The next steps in verification of the model include developing a more accurate way to measure forces, developing a method for measuring net torques, and performing tests with alternating current sources as well as direct current sources up to 18 Amps. This level of verification was sufficient enough to continue developing a higher-fidelity model from the simplified case because it verified the fundamental focus of the model—the force equation. The torque calculation is a cross product with the force value which shouldn't cause error that is not prevalent in the force calculation.

CONCLUSION

Formation flying of satellite arrays has multiple useful applications in space from remote-sensing payloads to remote assembly and maintenance of larger spacecraft. A formation of satellites can improve the efficiency by removing the high launch costs and the large costs associated with quality checking larger spacecraft before launch. Multiple cheaper satellites can be used to accomplish the same mission thereby mitigating risk and reducing overall cost. Electromagnetic formation flight will enable actuation of such a formation using a sustainable energy source, thereby replacing the use of traditional thrusters. Though electromagnetic formation flying theoretically needs three coils per vehicle, the Space Systems Laboratory will use the RINGS project to demonstrate the feasibility of all desired movements with one coil per flight vehicle.

The development of a dynamics model is beneficial in the development of this technology because it allows for preliminary design and testing of control algorithms without the use of the hardware. A dynamics model will allow for the Space Systems Laboratory to find and correct issues with their controller design so that it is more reliable when tested on the RINGS coils. First, a limited model was developed in two dimensions and then that model was improved to create the complete EMFF model. The simplified model enabled the verification of the mathematics using intuitive test cases before moving to the less intuitive complete model. The complete dynamics model for RINGS can be integrated into the current SPHERES Simulation by treating the force and torque outputs as external forces on the SPHERES body. The SPHERES Simulation then needs to be modified to reflect the mass and inertia of the RINGS attachment. Using this dynamics model, the Space Systems Laboratory can more effectively work to demonstrate the capability of electromagnetic formation flight.

The model can still be improved by reducing the time needed to perform the required calculations. Further testing also needs to be performed on the hardware in order to completely verify the simulation's accuracy in predicting the behavior of the flight vehicles in response to the magnetic field created by the coils. Devising an experiment that could accurately characterize torques from the RINGS coils separately from forces from the coils would enable the testing of different orientations with different initial separation distances along all three axes. The Space Systems Laboratory will continue to improve the fidelity of this dynamics model as well as the characterization of the RINGS hardware in order to prepare for the delivery to the International Space Station in July 2013.

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