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0 Program Overview

0 Program Overview

0.1 Introduction

Formation flight of satellites is the technology by which a cluster of satellites maintains a specified formation in orbit. Although formation flight of satellites has yet to be used in practice, it is being discussed in the aerospace industry as a way to provide new mission capabilities for satellites. The MIT SSL SPHERES project demonstrated the initial feasibility of satellite formation flight. The CDIO3 class aims to expand on the SPHERES research with the electromagnetic formation flight project.

0.1.1 Background & Motivation

Before discussing the design of the EMFFORCE testbed it is important to understand the background and motivation for this project. To accomplish this, a definition for formation flight must be presented. Formation flight is defined as a cluster of satellites maintaining a designated formation in space flight. <GG>

Applications of formation flight include surveillance and high-resolution imaging applications. Formation flight can achieve large sensor apertures that increase resolution without large physical structures that are difficult and costly to launch, deploy, and maintain. It is therefore advantageous to use formation flight in conjunction with interferometry for such purposes. <GG>

Servicing and maintenance can also be done on individual vehicles, thereby allowing the mission to continue during these processes. Formation flight allows the integration of new technologies during the mission as well. Because of its flexible system geometry, the system can also react to evolving mission requirements and/or address multiple missions at once. <GG>

Challenges to formation flight do exist. Because current systems utilize thrusters, the propulsion system actuates each vehicle with absolute degrees of freedom (relative to an inertial point) rather than relative degrees of freedom (relative to the other vehicles). However, in order to remain in the desired geometry, formation flying satellites should be able to control their relative position. Thrusters use propellant, which limits the lifetime of the spacecraft. Propellants also create exhaust, which can cause both contact contamination that damages sensitive imaging equipment, and radiative contamination that creates a blurring cloud through which the telescopes must look. <GG>

Because of these drawbacks to thruster-actuated formation flying satellites, the EMFFORCE Team is investigating the use of electromagnetic control for formation flight. Electromagnetic control uses electromagnetic dipoles along with reaction wheels to provide the "thrusting" forces and torques between vehicles. Varying the amount of current through the electromagnet coil can control the strength of these dipoles. Control of the dipole strength and magnet direction can provide maneuvering forces as well as small disturbance rejection for more precise control. <GG>

The use of electromagnetic control avoids the drawbacks that thrusters and their propellants pose to formation flight. Because electromagnetic forces interact with surrounding electromagnetic forces, this type of control operates with respect to the relative motion and position of each vehicle. However, the control problem for electromagnetic formation flight (EMFF) becomes increasingly complex when the coupled control of relative forces is paired with the already unstable control problem of rotating vehicles. There are also many drawbacks to the electromagnet itself. Not only is ferromagnetic material heavy, but electromagnetic forces are weak, dropping off as the 4^{th} power of the separation distance between vehicles. The EM fields can also cause interference with other electronic subsystems. <GG>

0.2 Mission Statement

The EMFFORCE mission statement reads:

Demonstrate the feasibility of electromagnetic control for formation flying satellites.

This means that Project EMFFORCE aims to operate a formation flying testbed that represents a real-world system. The mission statement also implies that a 2-D operational testbed must be translatable to a 3-D operational testbed. Electromagnetic control suggests the design and implementation of a controller using no thrusters but instead coupled electromagnetic forces with angular momentum storage. <GG>

0.3 Requirements Overview

This section provides a high-level requirements summary. For more detailed requirements please refer to the EMFFORCE Requirements Document.

0.3.1 Customer Requirements

The customer requirements as derived from the Executive Summary EMFF Proposal by MIT SSL and the Technical-Management Proposal by MIT SSL and Lockheed-Martin ATC are:

- The system must consist of multiple vehicles
- The system must be representative of formation flying vehicles used in real world space missions
- The system must use electromagnetic control to replace thrusters
- The system must control three degrees of freedom, traceable to six
- The system controller must reject disturbances as well as reposition vehicles

This project must show representative formation flying maneuvers to demonstrate the feasibility of using electromagnetic control for actual space missions. More specifically, the system must show dynamically changing formation geometries and the ability to replace failed formation elements. Because the purpose of this project is to demonstrate an alternative to thruster control, no thrusters may be used. The vehicles must be controlled in three individual degrees of freedom (X,Y, θ), with the potential for translation to six individual degrees of freedom. Finally, the controller must counteract any disturbance force and be able to reposition satellites within the formation. <GG, LS>

The EMFFORCE team must operate within specific constraints while trying to achieve these requirements:

- Schedule – Deadline: May 2003

- Budget – $50,000
- Human resources limited to CDIO class and staff
- Tests must be conducted in a maximum area of ten by eight meters.
- The system cannot use umbilical resources for power, air supply, or communications.
- The system must record test data to ensure requirement satisfaction.
- The system must keep itself, the testing facility and human involved safe.

0.3.2 Functional Requirements

The system functional requirements can be separated by requirements that *must* be met versus requirements that *should* be met:

The system *must*:

- Demonstrate stability with at least three vehicles
- Control in each relative degree of freedom

The system *should*:

- Complete a five-rotation test maneuver
    - One rotation spin-up, three rotations steady state, and one rotation spin-down
- Operate in the far field
    - Separation distance of at least ten times the length of the electromagnet

The system must demonstrate stable maneuverability using at least three vehicles. This will facilitate translation to more vehicles. The system must also control each *relative* degree of freedom in two dimensions with identifiable transition to three dimensions. The system will not be able to control absolute motion of the entire system center of mass. <GG, LS>

A five-rotation maneuver will include one for spin-up, three steady-state, and one for spin-down. The spin – up maneuver should start from rest and finish at a separation distance of at least two meters. The system should perform three steady-state rotations at a constant angular rate of six degrees of arc per second for a two-meter separation distance. The system should also operate in the far field of electromagnetic control. Far-field currently implies a separation distance of at least ten times the separation distance. However, the Electromagnet Team is currently running tests to develop a more precise definition. <GG, LS>

0.3.3 Operational Requirements

The Requirements Team also derived the following operational requirements from customer requirements:

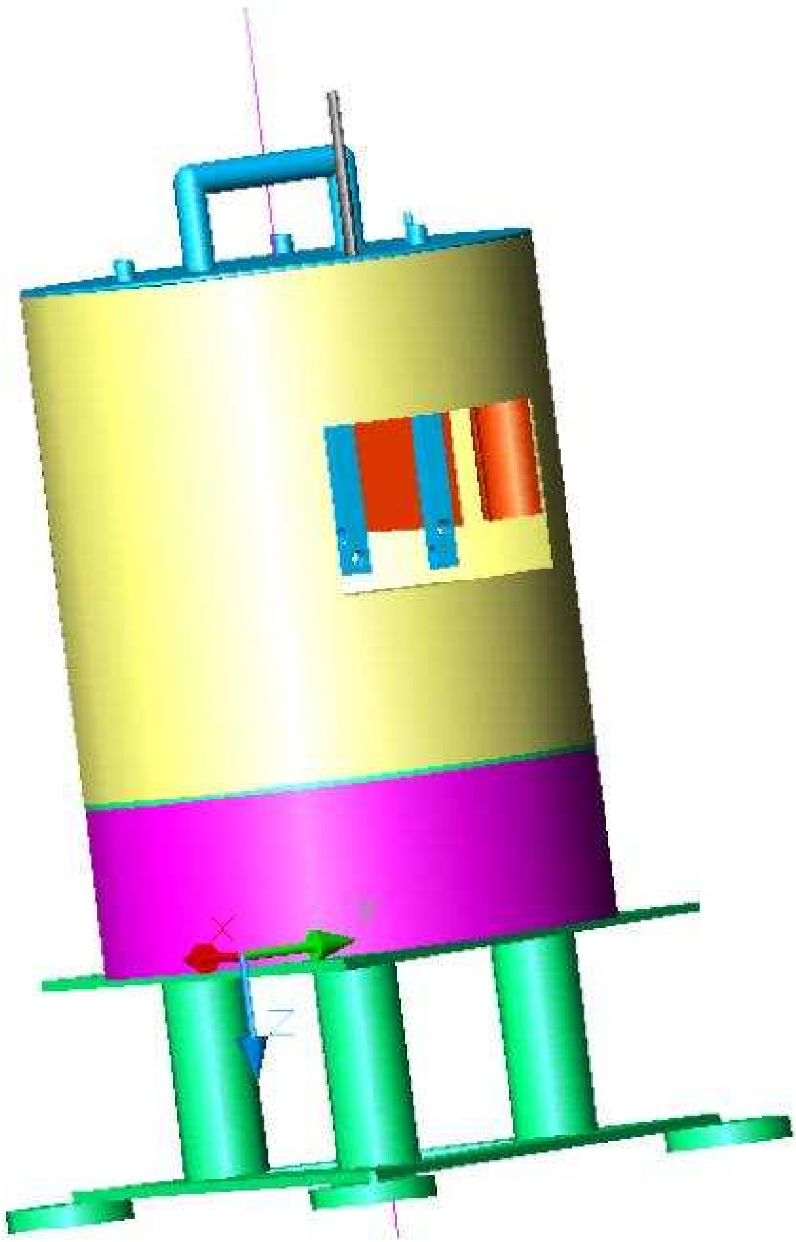
- Test time should equal five minutes
- Vehicles should be identical and interchangeable
- Vehicles must send and record test data
- Vehicles must respond to other satellites
- Vehicles must respond to user input
- Vehicles must demonstrate autonomy
- Vehicles must maintain safety

The system shall operate without needing to recharge batteries for a period of time useful to perform several tests. In order to maintain flexibility among vehicle roles in the overall system, to keep costs low, and to replace parts with ease, each vehicle should be identical to the others in the system. Each vehicle also must record test data including position and health for in-flight analysis and for post-test analysis. The system must respond to other satellites in real-time at a distance of at least two meters. This will demonstrate the far field assumption. The vehicles will not be able to respond to each other at distances greater than eight meters due to the size of the testing facility. The system must respond to user input from a ground station within 0.1 seconds. To demonstrate autonomy, each vehicle must be able to complete without further instruction commands that it receives. Finally, the system must not harm itself, the testing facility or any humans. <GG, LS>

0.4 Purpose

The Project EMFFORCE Design Document is a written report of the preliminary testbed design. Although the design may not be complete, the EMFFORCE Team has identified and designed for high-risk elements in the testbed. <GG>

1 System Overview



1 System Overview

1.1 Visualization

The EMFFORCE mission is to demonstrate the feasibility of EMFF. As discussed in section 0, the system will operate in three degrees of freedom on a flat floor testing facility. The three vehicles in the cluster will be induced to rotate about a common center of mass using solely electromagnetic forces and reaction wheel torques. The following describes the contribution of each subsystem to the complete EMFFORCE testbed. <ESS>

1.1.1 Actuation

The electromagnet drives the entire design. It is by far the heaviest functional component, and its mass is about the same as that of all remaining structural pieces combined. Increasing the mass of the EM core increases the available force, but also increases the force required to make the vehicle move. Because the electromagnetic forces generated are so weak relative to the mass required, all other components must be optimized for minimum mass, and enter the mass equation as constants. The electromagnet is what characterizes the project as EMFF; however, ultimately it is a large mass of metal that converts a current flow into a change in the local magnetic field. There is still much more to accomplishing the mission. <ESS>

The reaction wheel assembly (RWA) serves to counteract the torques generated by the electromagnet. This makes the system feasible to control. As the magnets generate forces from each pole, they also generate unwanted torques in the host vehicle. The RWA converts this torque to angular momentum. <ESS>

1.1.2 Formation Flight

Forces and moments generated by the actuators must be combined into a coherent, stable, automatic control algorithm that keeps the vehicles flying in formation. The control subsystem is the brain of the entire system, planning its movement from operator input and making corrections as the vehicles deviate off-course. The control subsystem must know the state of all three vehicles to make its calculations. The relative positions and orientations of the vehicles are measured by the metrology subsystem through a combination of ultrasonic and infrared transmitters and receivers. This data provides the input for the control subsystem. <ESS>

1.1.3 Electronics

Information gathered by each vehicle needs to be shared with all the other vehicles to promote consistency, and the control calculation must be made by one vehicle to promote stability. In this highly coupled system, it would be impractical for each vehicle to operate independently, trying to guess what the others were going to do next. The communications subsystem serves this function, sharing data between all vehicles and the ground station and providing synchronization among all units. These three information-based subsystems need a solid base to rest upon. None can exist by itself. The avionics subsystem provides the computational power needed by the control subsystem and the link between the metrology and communications subsystems. It is the electronic backbone of the system. <ESS>

1.1.4 Power and Structure

All of the electronic components require power. The electromagnet requires the most, but without constant uninterrupted power to every component, the unstable system would quickly go out of control. The power subsystem provides regulated uninterrupted power to each system from a common battery source. Finally, the system needs something to hold all its parts together. The structure subsystem holds each piece in place. The structure's air carriage component reduces friction with the environment. As the electromagnets react to the changing magnetic field created by their counterparts, the structure moves along the floor, demonstrating electromagnetic formation flight. <ESS>

1.2 Flowdown

1.2.1 Information Flowdown

The interfaces between subsystems and thus the required inputs and outputs from each subsystem are summarized in Figure 1.2.1. <ESS>

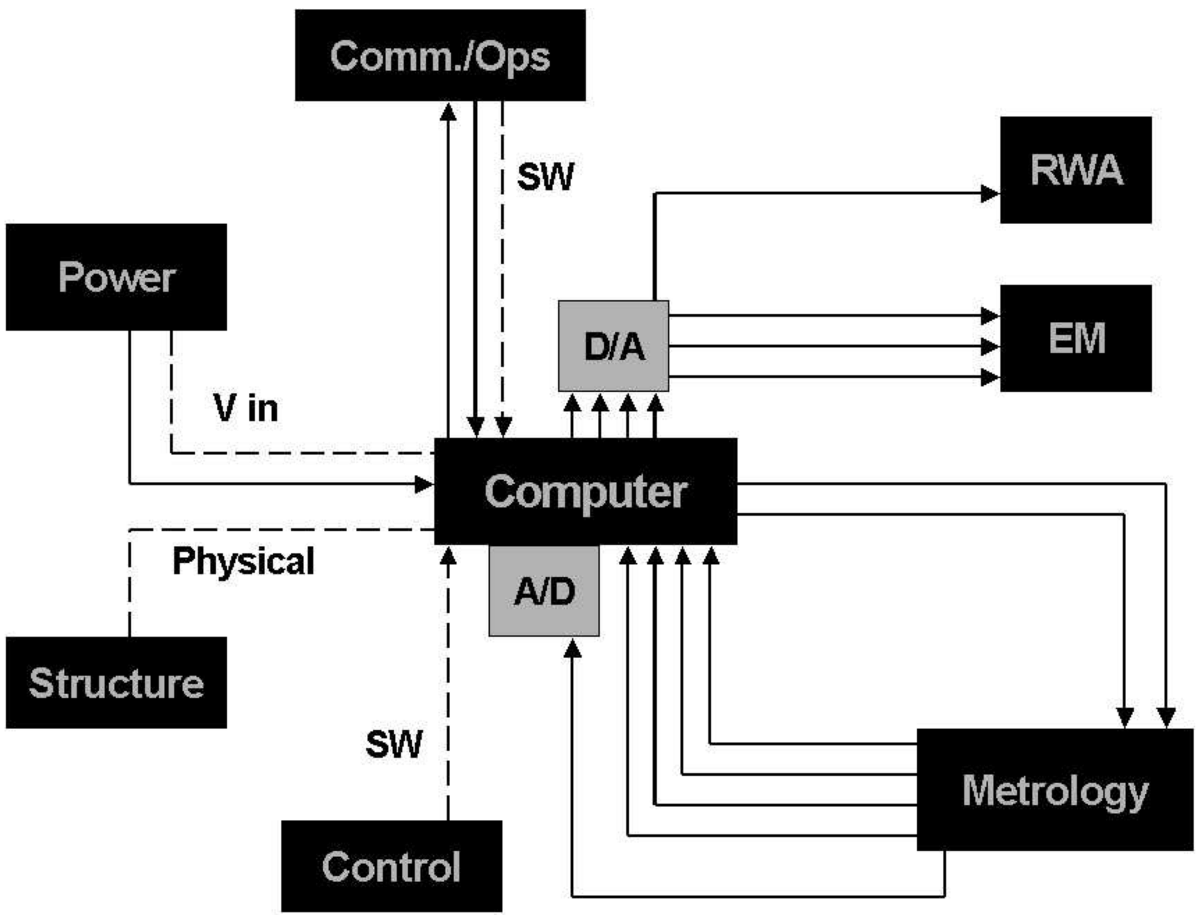


Figure 1.2.1 Flow diagram showing connectivity of various subsystems from information perspective

2 Subsystems

2 Subsystems

2.1 Electromagnets

2.1.1 Subsystem Overview.

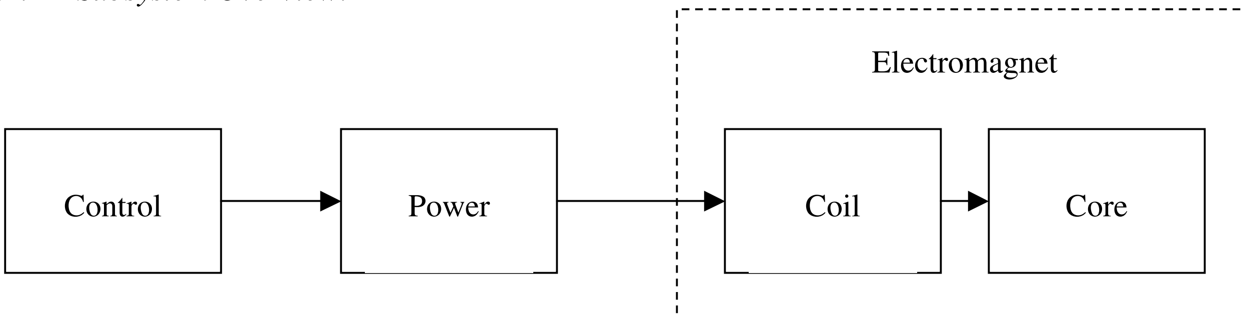


Figure 2.1.1: High Level Diagram of RWA Function in System

The actuation system includes the electromagnet and reaction wheel subsystems. The electromagnet is designed to provide the electromagnetic force used to induce the spin-up of the vehicles in formation. The reaction wheel assembly is designed to provide torque to counteract the torque induced by the electromagnet. Figure 2.1.2 shows two dipoles in a perpendicular orientation at a separation distance s. The arrows represent the direction of the induced forces and torques on the dipoles. Figure 2.1.3 depicts the spin-up of two dipoles from an initially perpendicular orientation. As current is applied to the dipoles, they begin to move in the direction of the induced forces and torques. The reaction wheel is then used to apply torque to counteract the induced torque. This applied torque is then decreased until the dipoles are in steady-state rotation, aligned along the same axis. <MSW>

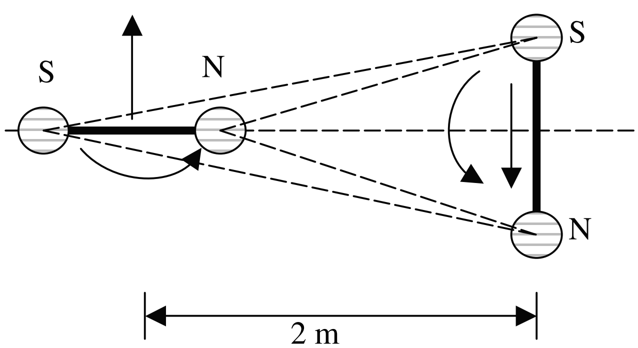


Figure 2.1.2: Perpendicular Dipoles

This figure shows two perpendicular dipoles at a separation distance s. The arrows represent the direction of the induced forces and torques on each dipole. <MSW>

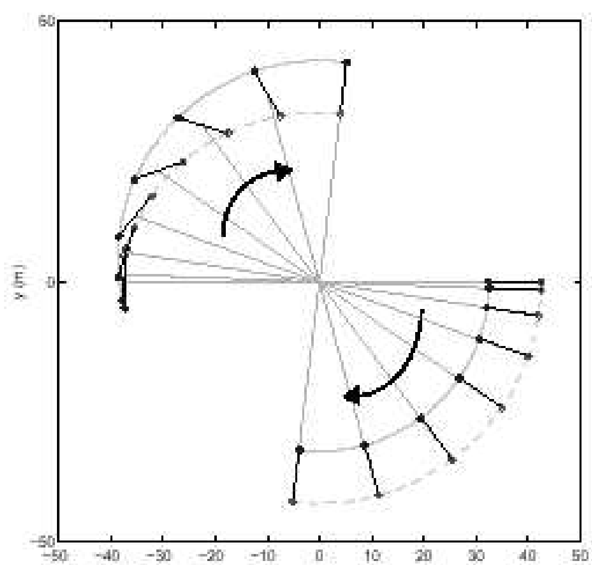


Figure 2.1.3: Spin-up

hThis figure depicts the spin-up of two perpendicular dipoles to steady-state rotation in an

2.1.2 Purpose of Part

The amount of force induced by the electromagnet, made up of a solenoid coil and core material, is dependant upon the strength of its magnetic field. The solenoid coil produces a magnetic field when current is applied to it. When the solenoid is wrapped around a ferromagnetic material, this core has the effect of multiplying the strength of the magnetic field. <MSW>

2.1.3 Interfacing

The solenoid coil will be wrapped *n* times along the length of the ferromagnetic core.

2.1.4 Trade Analysis

For the electromagnet, trade analyses were conducted to determine the core material, core configuration, and mass of the core, coil, and system. <MSW>

2.1.4.1 Core Material

One of the main focuses of the EMFFORCE project is to optimize the amount of force generated by the electromagnet while minimizing its mass. This force depends upon the strength of the induced magnetic field. Therefore, the core material will be selected based on magnetic properties that provide the maximum induced magnetic field at a minimum mass. <MSW>

When current is applied to a solenoid wrapped around a ferromagnetic core, a magnetic field, or B-field, is induced on the core. As the current is increased, the strength of the B-field increases until it reaches a strength that cannot be exceeded with increasing current. This value is known as $B_{saturation}$ for a given material. Table 2.1.1 compares the values for $B_{saturation}$ and density for several magnetic materials. <MSW>

Table 2.1.1: Properties of Magnetic Materials

Material	Composition	$B_{saturation}$ [Tesla]	Density [g/cm^3]
Iron	99.91% Fe	2.15	7.88
Steel	98.5% Fe	2.10	7.88
45 Permalloy	54.7% Fe, 45.0% Ni	1.60	8.17
78 Permalloy	21.2% Fe, 78.5% Ni	1.07	8.60
Supermalloy	15.7% Fe, 79.0% Ni, 5.0% Mo	0.80	8.77

This table lists the $B_{saturation}$ values and density for several ferromagnetic materials. (taken from Dorf) <MSW>

Iron and steel have the highest values for $B_{saturation}$ of 2.15 and 2.10 Tesla respectively. Both iron and steel have the same density, 7.88 g/cm^3, which is the lowest among the magnetic materials considered. High $B_{saturation}$ values combined with lower densities are both desirable properties to increase the strength of the induced magnetic field while keeping the mass as low as possible. <MSW>

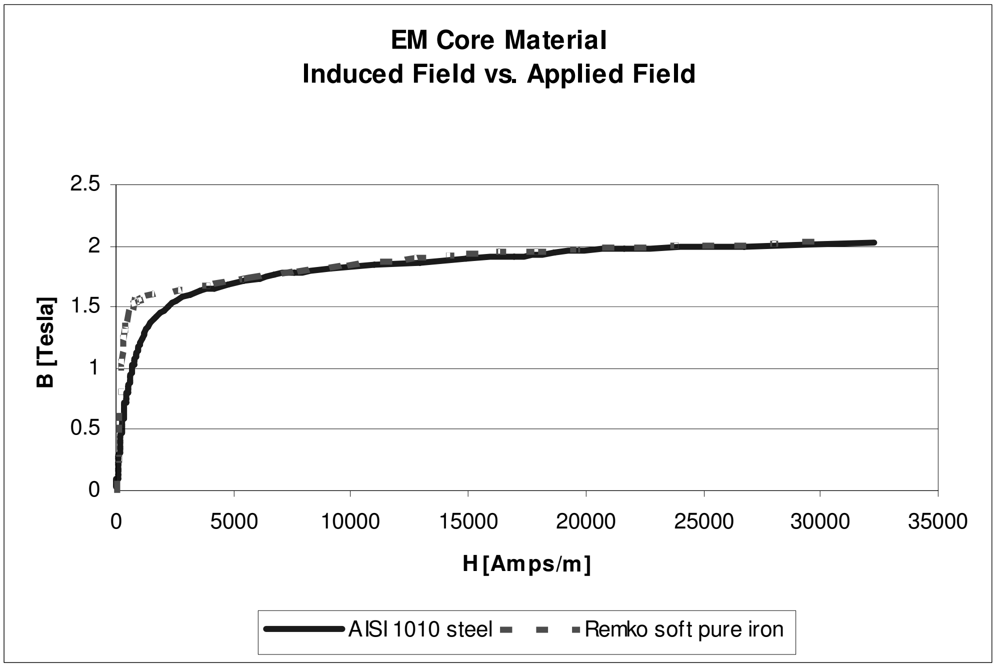


Figure 2.1.4: Iron and Steel - Induced Field vs. Applied Field
This figure shows the relationship between the induced field [Tesla] and the applied field [Amps/m] for iron and steel.

Figure 2.1.4 is a plot of induced field vs. applied field for iron and steel. For higher values of applied field, both iron and steel reach a $B_{saturation}$ point at approximately 2.1 Tesla. However, for lower values of applied field, this plot shows that iron has higher values for induced field than steel. This is important because it indicates that iron will induce a larger magnetic field and therefore higher levels of force than steel at lower current levels. <MSW>

Another magnetic property consideration that must be taken into account is the hysteresis effect. When a magnetic material is magnetized by an applied field, it will not completely demagnetize when the applied field is reduced to zero. In order to bring the induced field back to zero, a field must be applied in the opposite direction. The strength of this applied field is called the coercive force. The coercive force for iron and steel are 79.6 and 143.2 Amps/m respectively. Therefore, hysteresis is less of an issue with iron since it requires less of an applied force in the opposite direction to drive the induced field back to zero. <MSW>

Recently, another possibility for the electromagnet core was discovered. Hiperco 50A, a magnetic alloy made up of 48.9% Fe and 49.0% Co, exhibits better magnetic properties than iron which was previously the best choice for core material. Table 2.1.2 shows that Hiperco 50A has a higher value of maximum induced field and requires the same amount of applied field to counter the hysteresis effect. <MSW>

Table 2.1.2: Hiperco 50A vs. Iron

Material	$B_{saturation}$ [Tesla]	Coercive Force [Amps/m]
Hiperco 50A	2.40	79.6
Iron	2.15	79.6

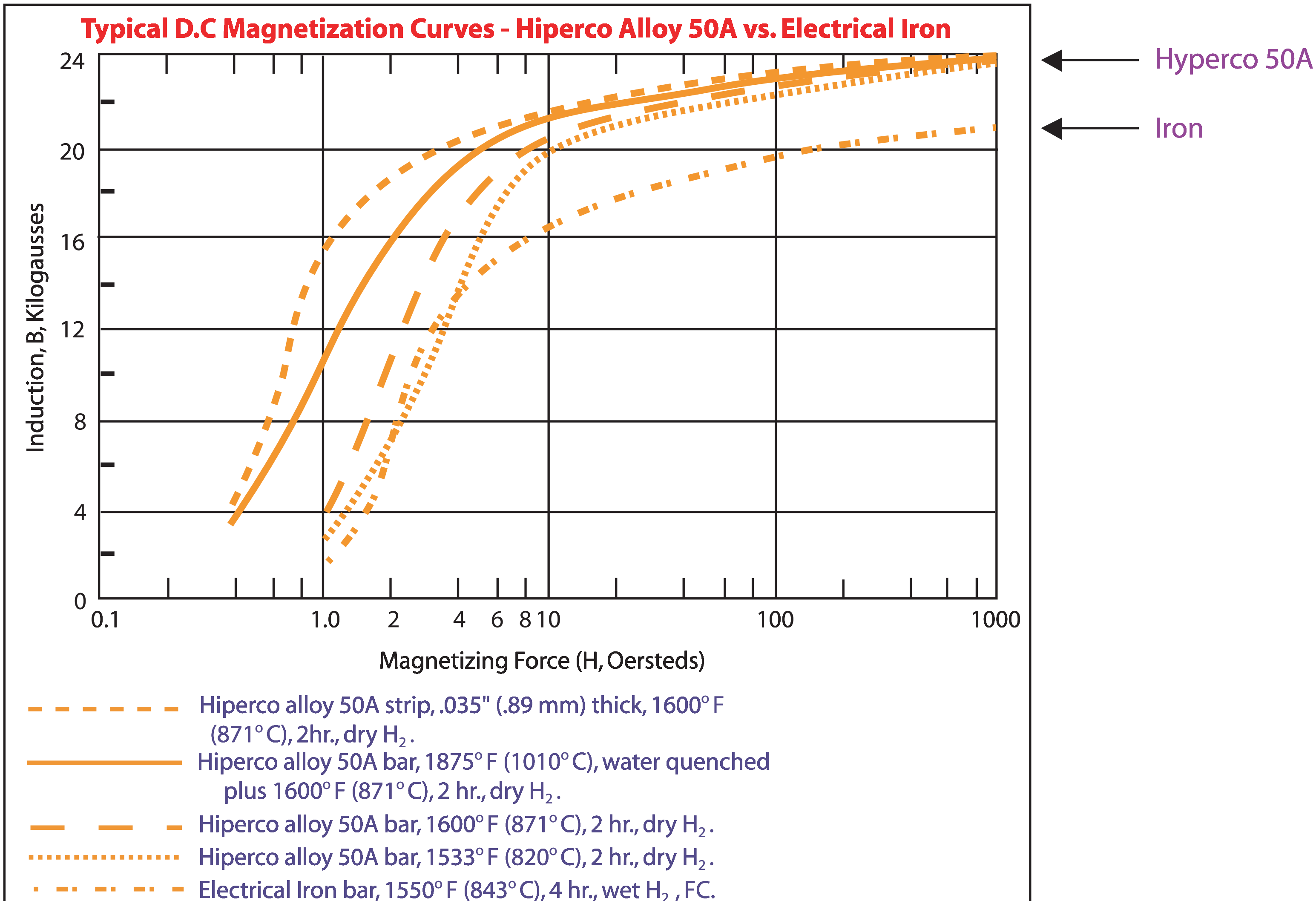


Figure 2.1.5 Hiperco 50A and Iron – Induced Field vs. Applied Field (Adapted from www.cartech.com.)

Figure 2.1.5 shows the relationship between induced field and applied field for Hiperco 50A and iron. Hiperco 50A has significantly higher values for induced field for a given applied current than iron. <MSW>

At the time of this design document publication, more analysis needs to be done to determine whether Hiperco 50A is a better choice than iron for the electromagnet core material. Initial analysis indicates that while Hiperco 50A exhibits better magnetic properties than iron, it will be extremely costly to the project and may exceed the electromagnet budget allocation. There are very few distributors of Hiperco 50A, and it will be considerably more expensive to purchase and machine this material than iron. <MSW>

2.1.4.2 Configuration

Several preliminary options for the electromagnet configurations were considered. Included in those were the basic dipole, Y-pole (3 legs), L-pole (2 legs connected at their ends), and X-pole (4 perpendicular legs). All shown in figure 2.1.6-2.1.9. <JB>

Figure 2.1.6: Dipole

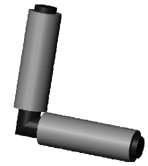


Figure 2.1.7: L-Pole

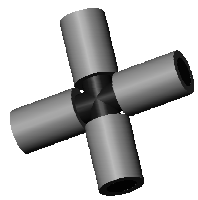


Figure 2.1.8: X-Pole

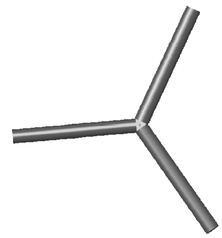


Figure 2.1.9: Y-Pole

Before going into the details about each configuration, it is important to point out the requirements of the system. The reasoning will come in the following sections, but for now it can be assumed that our system is driven by its mass. Thus, for a given configuration, if two magnets are at distance between zero and two meters, the mass should be minimized for a given force. <JB>

Also the selected configuration needs to produce the least amount of torque for a given force, since this excess torque must be transferred to the reaction wheel. The reaction wheel's mass will be proportional to the amount of torque that needs to be stored in it, so any unnecessary torques on the system should be minimized. <JB>

Finally, there is a requirement that the design of the electromagnet should make it easy to transition from a system that works only in two dimensions to a system that works in three dimensions. This means that the direction of the poles in the magnet must be able to change for the selected configuration. <JB>

In order to determine which configuration will satisfy these goals, preliminary calculations were run and a modeling software called "MagNet" was used. From these calculations, the following table was constructed. <JB>

Table 2.1.3: Trades Evaluation

Trades / Conf.	Transition to 3D	Minimum mass for a given force	Minimum torque for a given force	Totals
Y-Pole	**4**	**3**	**2**	**9**
L-Pole	**4**	**2**	**3**	**9**
Dipole	**2**	**5**	**4**	**11**
X-Pole	**4**	**1**	**3**	**8**

For each configuration, assignment goes from 1 to 5, with 5 being the best and 1 the poorest poerformance

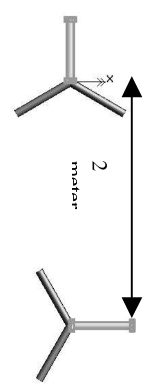
In addition to the most important trades summarized in the table, there are some additional arguments against using the L-pole and the X-pole. <JB>

The L-pole has a center of mass problem and would produce adverse torque that would have to be countered by the reaction wheel; this problem is caused because the forces on the system would not be acting through the system's center of mass. The X-pole was eliminated due to the fact that the mass would have to be distributed to 4 legs. Energizing one of these legs would only be utilizing ¼ of the mass that would be used in the single dipole situation and would not produce a large enough force.

As mentioned before, these are preliminary calculations, and they must be supported with more modeling and more testing. However, the choice is now between the Y-pole and the dipole. <JB>

In order to determine whether to use a dipole or a Y-pole, it will be necessary to compare them closely, with the help of the modeling software and some tests. <JB>

Two simulations were carried out on the modeling software. In both simulations each configuration has the same volume and mass. The first simulation was with two Y-poles separated by a distance of 2 meters; one leg on each Y-pole was energized with a current of 6 amps and 1200 turns of wire. The energized legs were perpendicular to each other. See figure 2.1.10. <JB>



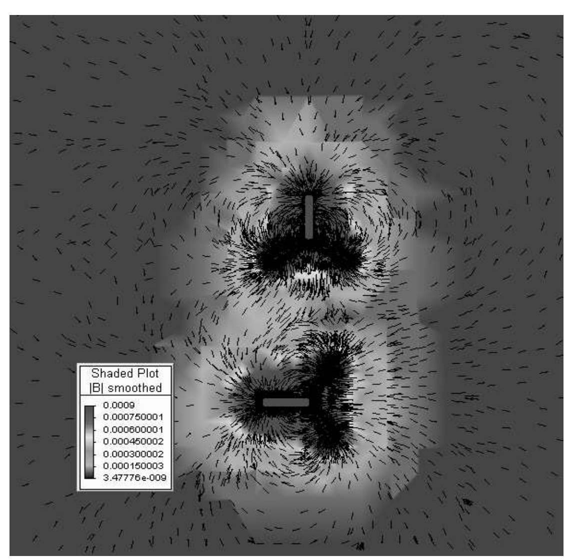


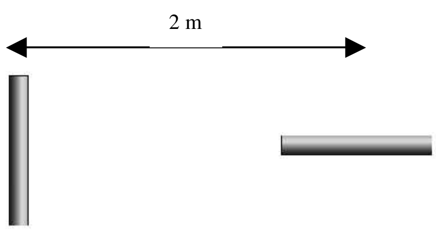
Figure 2.1.10: Y-Pole simulation from MagNet

For the dipole simulation, two dipoles were used, separated by a distance of 2 meters and perpendicular to each other. Both were energized with a current of 6 amps and 1200 turns of wire. See figure 2.1.11. <JB>

From the results, the following conclusions could be made:

It was originally believed that the dipole would generate a greater force for a given mass, because for a set core mass, it utilizes the entire core. Also, the Y-pole would not energize the entire core mass at one time and thus it would “waste” some mass. Since the force is what drives the satellites to spin up this was a key feature that needed to be checked. <JB>

After running the simulation, it turns out that the Y-pole magnetizes the remaining ends that are not energized and the amount of force generated is greater. This can be explained through figures 2.1.10 and 2.1.11, which show that the legs on the first Y-pole (that are not energized) are closer to the second Y-pole legs (that are not energized) than are the two dipoles’ main cores. <JB>



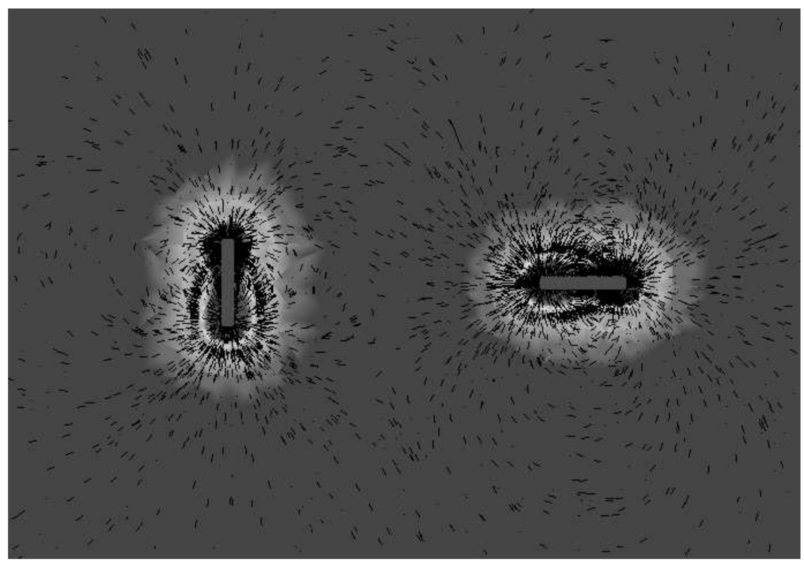


Figure 2.1.11: Dipole simulation from MagNet

For the transition to 3D requirement, it was determined that the dipole cannot change the direction of its poles in any direction. The Y-pole, on the other hand, is more versatile and more translatable into 3D applications. This is due to the fact that the Y-pole magnetic field direction can vary by changing the amount of current energizing each of its legs. This would decrease the time it would take to rotate the electromagnet to a desired alignment using the reaction wheel. The Y-pole configuration, however, also generates a greater adverse torque than the dipole, which would have to be counteracted by the reaction wheel, making it bigger. <JB>

Summarizing, the Y-pole simulation showed a greater force than the dipole configuration, yet it produces more unnecessary torque. The Y-pole performs better in transition to 3D and has a less mass for a given force than the dipole configuration. However, the torque produced by the Y-pole configuration is greater than the torque produced by the dipole configuration; in other words the dipole performs better in terms of minimizing the amount of torque for a given core mass. <JB>

Although it seems that the Y-pole would be the best configuration, this cannot be determined yet. For example, the torque on the electromagnets could be more important than the force on the electromagnets, in which case the performance of the Y-pole and the dipole could change. Since this is unknown, more tests must be run to find out what are the relations between these factors. <JB>

Another consideration that would be worth considering is an improved dipole configuration, consisting of the dipole mounted on a rotating disk, so that the direction of the poles could be changed just as easy as it is done with the Y-pole. The only disadvantage of doing this is that it would make the dynamics of the system more complicated, but this is something that is definitely worth considering, since it could turn out that this configuration is better than the other two.

2.1.4.3 Core and System Mass

The driving parameter for this design problem is mass. Increases in total system mass quickly ripple through the system causing increases in the size of the electromagnet, power system, and structure. Therefore the design of the electromagnet was conducted with the intention of working at the minimum system mass for a given system performance (i.e. separation distance and spin rate).

In order to design the magnet size, a mathematical model of the system was developed. The total mass of the system is given as:

$$m_{tot} = m_{core} + m_{coil} + m_{power} + m_o$$

Equation 2.1.1: Total Mass Equation

where the terms are the total mass of the system, the mass of the magnetic core, the mass of the coil of the magnet, the mass of the power system, and the initial system mass respectively.

For the time being the system has only been analyzed for the steady-state spin mode, as seen in Figure 2.1.10. In this mode, the electromagnets must provide a force that is equal and opposite to the centripetal force of the system.

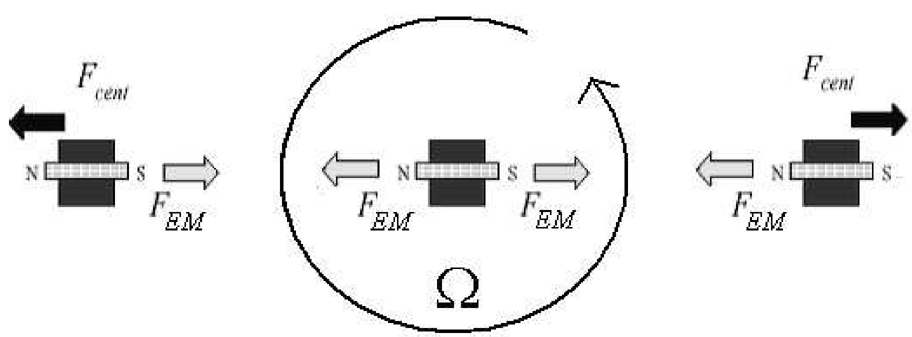


Figure 2.1.12: Steady State Mode
Model of the current system at steady state

The magnetic force on the leftmost vehicle resulting from the other two is given by:

$$F_{mag} = \frac{3\mu_o \mu_A \mu_B}{2\pi(\frac{s}{2})^4} + \frac{3\mu_o \mu_A \mu_C}{2\pi(s)^4}$$

Equation 2.1.2: Magnetic Force for 3 Vehicles

where s is the separation distance between the two outermost vehicles in Figure 2.1.10, μ_a, μ_b, and μ_c are the magnetic moments of each electromagnet and μ_o is the permeability of free space. The magnetic force must be set equal to the centripetal force defined by:

$$F_{cent} = \Omega^2 (\frac{s}{2}) m_{tot}$$

Equation 2.1.3: Centripetal Force

where Ω is the spin rate of the system and m_{tot} is the total mass of a single vehicle.

The magnetic moment of an electromagnet can be approximated as B, the induced magnetic field, times the mass of the core divided by the density of the core. Equating Equation 2.1.2 and 2.1.3 with this substitution for the magnetic moment and solving for the total mass of the system yields:

$$m_{tot} = \frac{51}{\mu_o s^5} (\frac{B m_{core}}{\rho_{core} \Omega})^2$$

Equation 2.1.4: Total mass in terms of m_{core}

Finding the mass of the other components in Equation 2.1.1 in terms of the mass of the core yields:

$$m_{coil} = \frac{\rho_{coil} (\pi r_{coil})^2}{i\alpha} (\frac{4 m_{core} \alpha^2}{\rho_{core} \pi})^{\frac{2}{3}} H$$

Equation 2.1.5: Mass of the coil

where the mass of the coil is expressed in terms of the radius of the coil, the density of the coil, the current, i, the aspect ratio of the core, α, (defined as the length divided by the diameter), and the applied magnetic field, H. The relationship for the mass of the battery is defined based on the available battery parameters and can be found in Appendix B. These equations define the necessary parameters to model the system. The only effect that is left out of the model is the effect of system mass on the mass of the required structure. This is incorporated into m_o, which has been assumed to be a constant for the current analysis.

This model has been incorporated in a Mathematica script, which can be run to find the optimum operating masses for the system. This script is included as Appendix B at the end of the document. Before the results of this design are finalized there are a few more factors which must be incorporated. First, it is important to get detailed material properties for the core and coil. This includes B-H curve data for the core material. Also, the model does not yet include an accurate trade between current and number of wire wraps. This trade essentially is a trade between coil mass and battery mass for a given amount of applied magnetic field. With a little more time it will not be difficult to adapt the script to incorporate this trade.

Preliminary calculations have the mass of the core at approximately 6.5 kg and the total mass of the system at 15 kg. The goal is to reduce the mass as the optimization of the system design continues.
<WDF>

2.1.5 External Interfacing Needs

The electromagnet will need a physical interface with the structure system where it can mount to the vehicle. The system will also need an interface from the power subsystem where the necessary current can be applied to the magnet coil. The power interface will occur on some type of voltage switch, which is controlled by the algorithm of the control group through the required avionics systems and is given power from the vehicles power supply. This switch will then supply the desired current to the electromagnet coil.
<WDF>

2.1.6 Budgets Estimates

These estimates come from the calculations and from the assumptions explained before.

Table 2.1.4: Budget Estimates

	Cost ($US)	Mass (kg)	Power (W)
Iron core	200	6.5	84
Copper wire	50	1.5	
Total	250	9	84

2.1.7 Conclusion

The electromagnet will be composed of a coil and a core. The coil configuration will depend directly on the core and system analysis. The core material has not being set between Hiperco 50A and Iron. For the core configuration there is still more testing and simulations to be completed. Basically, tests for these two parameters need to be carried out in order to make a decision.

The most important conclusion from the electromagnet subsystem design is that the success of the system will depend on reducing mass while still fulfilling the necessary requirements.

2.2 Reaction Wheel Assembly

2.2.1 Subsystem Overview

Both the electromagnet and reaction wheel teams are responsible for the spin-up of the system to the steady state configuration. The reaction wheel assembly (RWA) is an integral part of the spin-up process. Figures 2.2.1 and 2.2.2, below, depict the process of spin-up. <LLW>

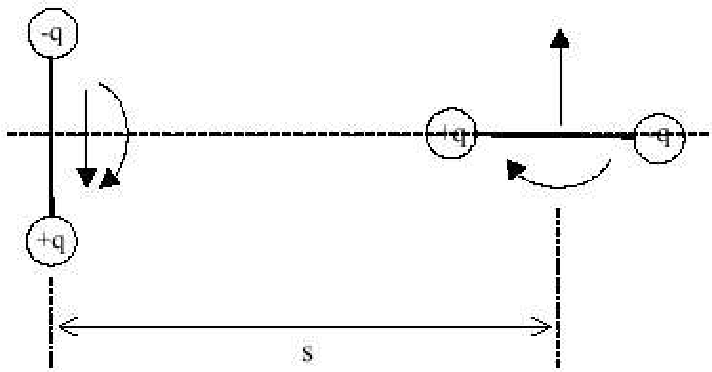


Figure 2.2.1: Initial Dipole Configuration

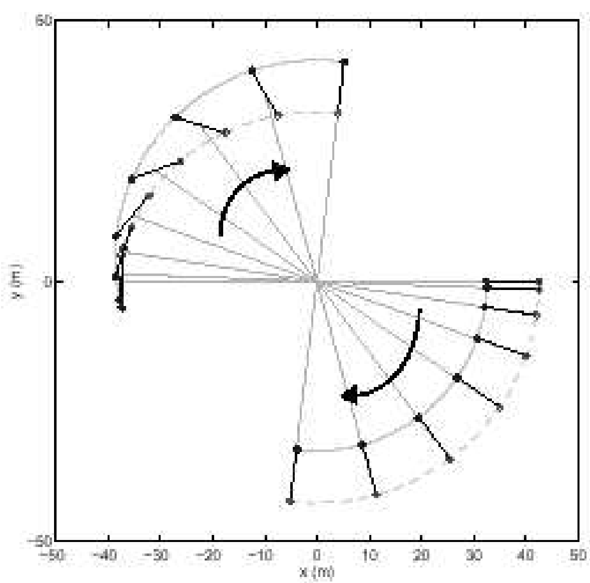


Figure 2.2.2: Spin-up Configuration
Path of dipoles from initial configuration to steady state.

Figure 2.2.1 shows the initial configuration of the dipoles. The dipoles begin perpendicular to each other. Figure 2.2.2 depicts the two dipoles as they begin to spin up. As soon as a current is applied to the electromagnets, forces and moments are induced in the dipoles. The moments are due to the perpendicular geometry of the system at this point. These moments must be counteracted by applied torque from the reaction wheels. The dipoles initially move in the directions of their respective net forces. As they begin to move, the applied torque from the reaction wheel is decreased to induce centripetal motion. As centripetal force increases, the applied torque continuously decreases, allowing the rotating dipoles to slowly align along the same axis. At the point when no more applied torque is necessary, the dipoles are perfectly aligned and the centripetal force is equal to the magnetic force. At this point, the system is in steady state rotation. Figure 2.2.2 shows the process of spin-up. <LLW>

The RWA must provide the necessary torque to balance the forces and moments that are produced by the electromagnets. The assembly is powered by a motor, which drives the reaction wheel. The spinning wheel then stores the system's angular momentum, balancing the system, and guiding the system through spin-up to steady state rotation. <LLW>

2.2.2 Purpose of RWA

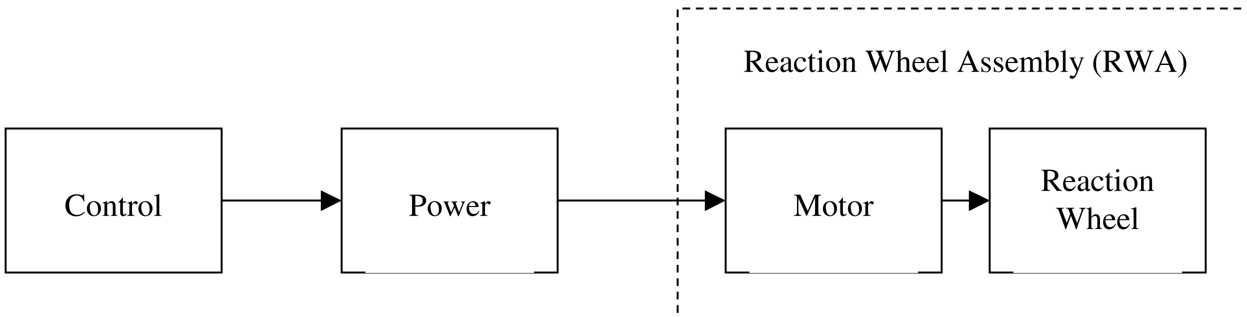


Figure 2.2.3: High Level Diagram of RWA Function in System <LLW>

The purpose of the RWA is to use stored angular momentum to control the system. The application of this purpose is twofold. First, the RWA must guide the system to a steady state configuration during spin-up. Second, it must keep the system in the steady state configuration during the remainder of operation by making needed adjustments to account for frictional forces acting upon the vehicle. <LLW>

2.2.3 RWA Internal Interfacing

As shown in the flow chart above, the RWA is composed of the reaction wheel and a motor that provides power to drive the wheel. The reaction wheel consumes power mainly when it is providing torque to balance the system. This takes place during the spin-up process. For the remainder of operation, the reaction wheel requires only small amounts of power from the motor to correct for friction effects. Therefore, once the system has reached the steady state, the RWA is fairly independent with respect to inputs from the rest of the system. <LLW>

The motor for the RWA is not yet selected, as it depends on the final design of the reaction wheel. The analysis in this document provides estimates for the mass of the reaction wheel and the power required by the reaction wheel. However, the design of the actuation subsystem is not finalized at this time. The motor will be selected concurrently with the other parts comprising the actuation subsystem. <LLW>

2.2.4 RWA Trade Analysis

The trade analysis for the RWA involves four main issues. The first is the selection of the material used to manufacture the reaction wheel. The second is the method of production for the reaction wheel – building a wheel versus buying a pre-manufactured wheel. The remaining analysis is dedicated first to deriving preliminary estimates for the mass and size of the reaction wheel, and second to deriving an estimate for the power consumption of the motor in order to function under operational conditions. <LLW>

2.2.4.1 Reaction Wheel Material Selection

The material selection for the EMFFORCE reaction wheel is more complicated than the typical material selection process for a reaction wheel. Steel is the standard material used for reaction wheels. However, due to the specialized nature of the EMFFORCE project, the RWA team has selected aluminum as the reaction wheel material. The use of a non-magnetic material prevents interaction of the reaction wheel with the magnetic field. Plastics were also considered as a possible reaction wheel material. However, the higher density of aluminum makes it favorable over plastics. A higher density material allows for a reaction wheel with a smaller radius. The size of the EMFFORCE vehicles depends on the size of the electromagnet and the size of the reaction wheel. Since these sizes are codependent, it is favorable to minimize reaction wheel radius, thereby decreasing the minimum size of the vehicles. <LLW>

2.2.4.2 Reaction Wheel Manufacturing

Commercial suppliers of reaction wheels machine wheels for full-scale spaceflight applications. These reaction wheels are machined to the specifications of the buyer on an individual basis, and are therefore very expensive. In addition, these reaction wheels are *sized* for real space applications. EMFFORCE needs reaction wheels on a much smaller scale. The RWA team has chosen to machine reaction wheels to the EMFFORCE project specifications rather than buy a pre-made wheel. <LLW>

2.2.4.3 Reaction Wheel Mass and Size Estimates

The role of the reaction wheel is to balance the system by providing a counter torque during the spin-up of the system. Therefore, the angular momentum stored in the reaction wheels of all the vehicles combined must be equal to the angular momentum of the system, but in the opposite direction.

$$H_{cluster} = -nH_{RW}$$

Equation 2.2.1: Angular Momentum Balance

Equation 2.2.1 gives the angular momentum balance for the system, where $H_{cluster}$ and H_{RW} are the angular momentums of the cluster and reaction wheel, respectively, and n is the number of vehicles present in the cluster. For this analysis, it is assumed that there are only two vehicles in the cluster. This is to simplify the analysis, allowing the derivation of preliminary estimates. Both the cluster and the reaction wheel obey the definition for angular momentum, where omega (Ω) is the rate of rotation of the cluster:

$$H = I\Omega$$

Equation 2.2.2: Definition of Angular Momentum

The moment of inertia due to each vehicle in the cluster is a sum of the vehicle's moment of inertia (I_0) and the moment of inertia the vehicle contributes to the system. The moment of inertia of the cluster (I) is this vehicular moment of inertia multiplied by the number of vehicles, which is here assumed to be two. For this analysis each vehicle is modeled as a cylinder of uniform density.

$$I = 2\left(I_0 + m_{tot}\left(\frac{s}{2}\right)^2 \right)$$

Equation 2.2.3: Cluster Moment of Inertia

For the purposes of modeling, the reaction wheel is assumed to be a combination of a flat disk and a circular ring. It is optimal to have as much of the reaction wheel mass as possible at the radius of the wheel. However, this outside "ring" must be connected with a thin plate so that the reaction wheel can be attached to a shaft. A rough cross section of the reaction wheel is shown in Figure 2.2.4 below.

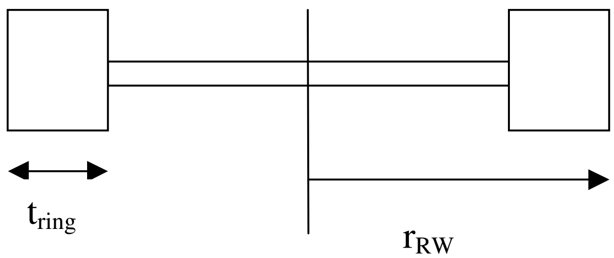


Figure 2.2.4: Cross Section of Reaction Wheel <LLW>

The moment of inertia for the reaction wheel is therefore a sum of the moment of inertia of the flat disk and the moment of inertia of the circular ring.

$$I_{RW} = m_{RW} r_{RW}^2 + \frac{1}{2} m_{RW} \left(r_{RW} - t_{ring}\right)^2$$

Equation 2.2.4: Reaction Wheel Moment of Inertia

The mass of the wheel depends on the geometry of the system, and is the product of the volume and the density of the core, as shown in Equation 2.2.5.

$$m_{RW} = t_{ring}^2 2\pi r_{RW} \rho_{Al}$$

Equation 2.2.5: Reaction Wheel Mass

Using the balance of angular momentum and the geometry of the system, the mass of the reaction wheel can be expressed in terms of the radius of the reaction wheel. The following numerical parameters are used to achieve this expression:

$$m_{tot} = 15kg$$
$$\Omega = 0.105\, rad/s$$
$$\Omega_{RW} = 210\, rad/s$$
$$\rho_{Al} = 2700\, kg/m^3$$
$$s = 2m$$

Equation 2.2.6: Numerical Parameters Used in Reaction Wheel Mass Calculation

Equation 2.2.7 shows the final derivation for the mass of the reaction wheel:

$$m_{RW} = \frac{0.0077}{r_{RW}^{\ 2} + 0.5\left(r_{RW} - 2\sqrt{\frac{m_{RW}}{2700}\frac{1}{\pi 2 r_{RW}}}\right)^2}$$

Equation 2.2.7: Reaction Wheel Mass

Figure 2.2.5 shows the mass of the reaction wheel plotted versus the radius of the reaction wheel:

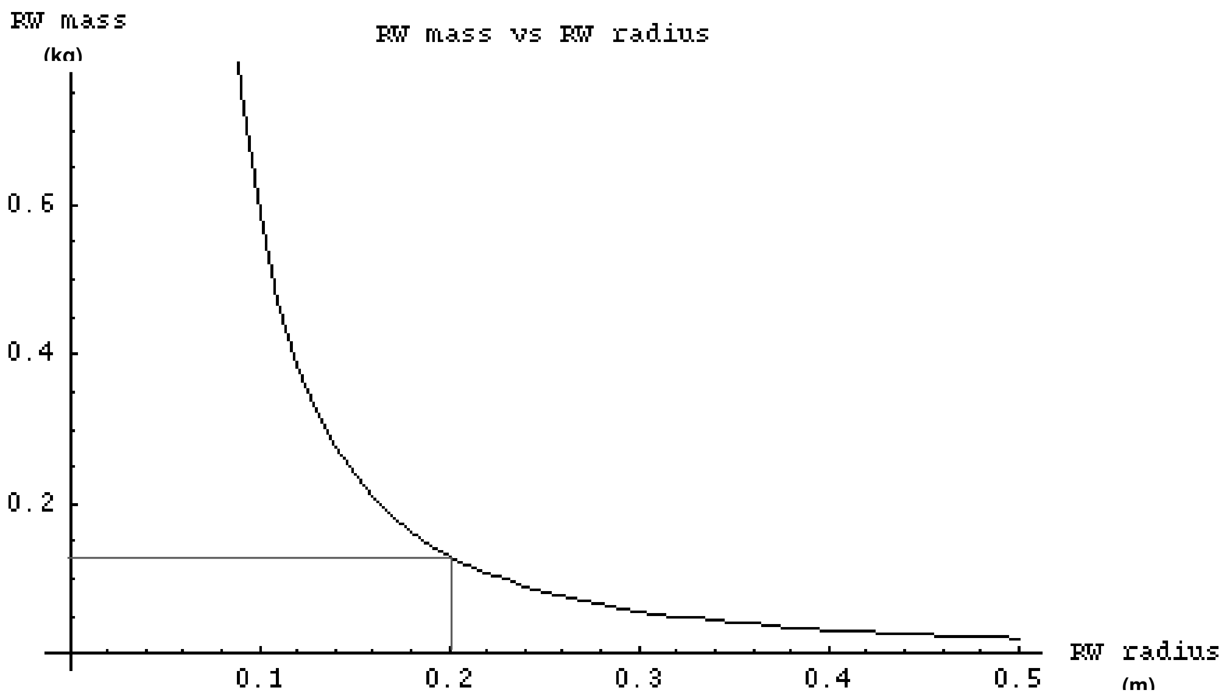


Figure 2.2.5: Reaction Wheel Mass vs. Reaction Wheel Radius <LLW>

The reaction wheel team has selected a radius of 0.2 m for the reaction wheel. This radius comes from the most recent estimates for the electromagnet. The electromagnet has a length of approximately 0.5 m. This yields a vehicle radius of approximately 0.25 m. To allow the RWA to fit within the dimensions of the vehicle, the reaction wheel radius is set at 0.2 m. The above analysis yields a reaction wheel mass of approximately 0.16 kg. This is a reasonable mass estimate for the EMFFORCE system. <LLW>

2.2.4.4 RWA Power Estimate

The reaction wheel requires power mainly while it is in the process of providing torque to balance the system. For the remainder of the operations period, it requires minimal power to overcome the force of friction while spinning. The following power analysis only addresses the power required during spin-up. This is a reasonable approximation for a required power estimate.

The power required by the reaction wheel is proportional to the torque applied by the reaction wheel:

$$P_{RW} = \tau_{mag} \Omega_{RW}$$

Equation 2.2.8: Reaction Wheel Required Power

The torque, τ_{mag}, is the torque induced by the dipole. This torque is given by the expression in Equation 2.2.9, where μ_A is the magnetic moment of a given dipole and B is the magnetic field induced by a dipole.

$$\tau_{mag} = \mu_A \times B$$

Equation 2.2.9: Torque Induced by Dipole

The induced field, B, is a function of the magnetic moment of the dipole that induces the field, represented here as μ_B. The expression for B is given in Equation 2.2.10. *x* is a distance parameter, which is defined as the distance from the center of the dipole to a point in the field, B.

$$B = \frac{\mu_0}{2\pi} \frac{\mu_B}{x^3}$$

Equation 2.2.10: Induced Field

Magnetic moment is a function of the volume of the core, and is defined in Equation 2.2.11. The parameters used to define the volume of the core are the preliminary estimates for the electromagnet size. A core length and radius of 0.5 m and 0.02 m, respectively, are used.

$$\mu_A = \frac{BV_{core}}{\mu_0}$$

Equation 2.2.11: Magnetic Moment of Dipole

A final expression for the power required by the reaction wheel is given in Equation 2.2.12.

$$P_{RW} = \frac{\mu_0}{2\pi}\frac{\mu_A \mu_B}{x^3}\Omega_{RW}$$

Equation 2.2.12: Reaction Wheel Required Power

The following numerical parameters are used to get the final power estimate:

$$x = 1m$$
$$L_{core} = 0.5m$$
$$r_{core} = 0.02m$$
$$V_{core} = 6.3\times10^{-4}m^3$$
$$\Omega_{RW} = 2000rpm = 210\,rad/s$$

Equation 2.2.13: Numerical Parameters Used in Reaction Wheel Power Calculation

Using the parameters given in Equation 2.2.13 yields a power estimate of 13 W. This is a worst-case estimate. This estimate assumes that the reaction wheel is already spinning before it provides the torque to balance spin-up. This case requires more power than only spinning up the reaction wheel when it is needed. <LLW>

2.2.5 Summary of Reaction Wheel Selections

Table 2.2.1: Reaction Wheel Material Selection <LLW>

Material	Density (kg/m^3)	Magnetic Permeability
Aluminum	2700	Non-magnetic
Steel	7850	2000
Plastic	1000	Non-magnetic

The reaction wheel is to be manufactured by project EMFFORCE and not by an outside manufacturer. The current mass estimate for the wheel is 0.16 kg, with an estimated radius of 0.2 m. The RWA will require a power supply of approximately 13 W. <LLW>

2.2.6 External Interfacing Needs

The RWA requires external interfacing with the Power and Structure subsystems. A power supply is required to operate the motor that drives the reaction wheel. Interfacing with the Structure subsystem is necessary to secure the RWA to the vehicle in a manner in which it may spin freely. <LLW>

2.2.7 Budgets

Throughout the process of designing the RWA, budgets for mass, power, and cost are developed. <LLW>

Table 2.2.2: Reaction Wheel Budget <LLW>

	Mass (kg)	Power (W)	Cost ($US)
Reaction Wheel	0.16	13	500

2.2.8 Conclusion

The analysis provided in this document provides a material selection for the reaction wheel as well as mass, size, and power estimates for the reaction wheel. These estimates will be finalized concurrently with the electromagnet design. <LLW>

2.3 Control

Subsystem Overview

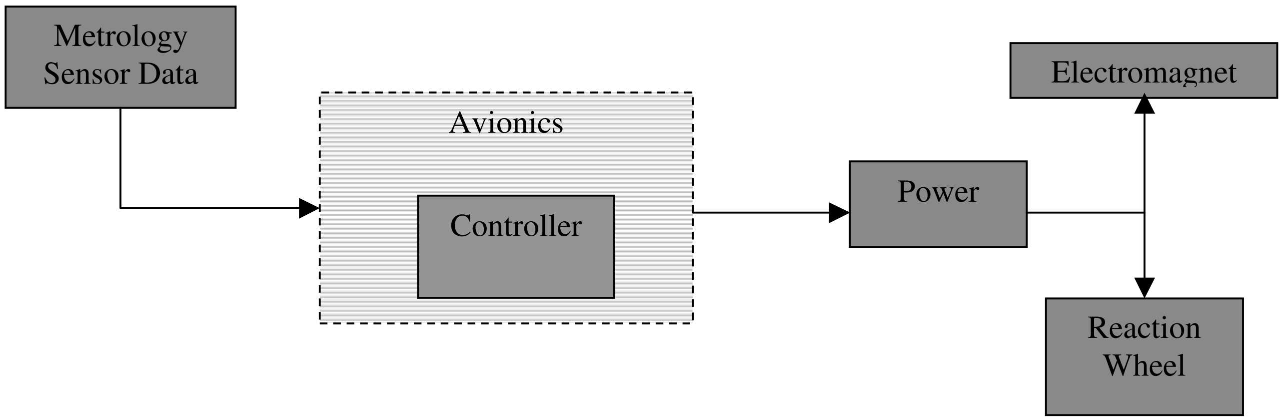


Figure 2.3.1 Control Subsystem Flow Chart

The control subsystem, a computer program located within the avionics processor, takes state inputs from the metrology subsystem and compares the current state with the desired state. It then outputs commands, in the form of an output voltage, to the actuators to adjust the current state to match the desired one. The output voltages are fed through the power system, which powers the actuators. <BAB>

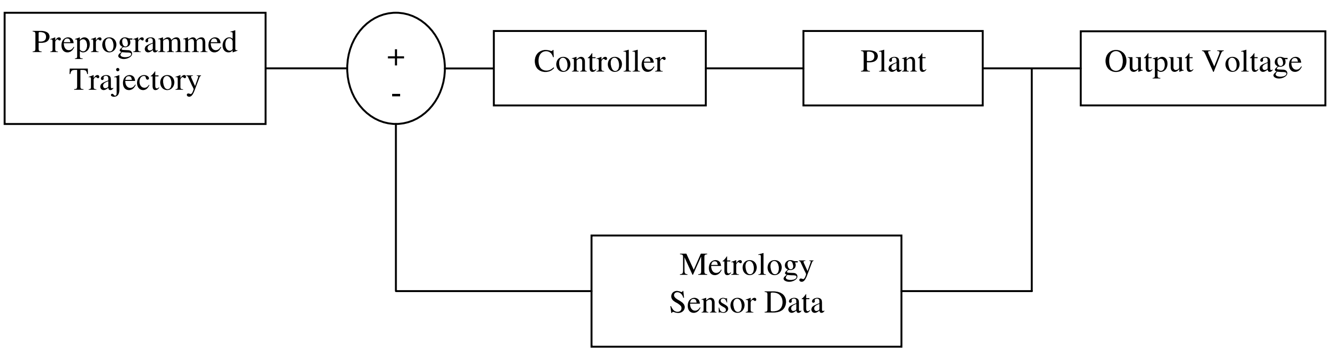


Figure 2.3.2 Feedback System

There are two different actuators to control the system, the electromagnets and the reaction wheels. The electromagnets can provide forces and torques along the three degrees of freedom in which the vehicles operate (x, y, and θ). Unfortunately, since the forces produced by the electromagnet cannot be independently controlled, there is also need for a reaction wheel. The reaction wheel produces a torque about the θ axis and it provides the opportunity to place the electromagnet's magnetic poles. It is with these two actuators that all controlling forces will be produced. <BAB>

The requirements for the controller are derived from the requirements document. The main requirement is to create a robust controller. This implies both rejecting any disturbance force that the formation may encounter and having enough control authority to reposition satellites within the formation. <LS>

To demonstrate a robust controller, the system must execute three maneuvers: spin-up, steady state spin, and spin-down. The spin-up maneuver consists of controlling three vehicles initially at rest in a straight line with perpendicular magnetic fields (See Figure 2.3.3) to follow a specified trajectory to the steady state configuration. In steady state spin the cluster is spinning about the center vehicle with an angular rotation rate of at least 1 RPM. This configuration has all three magnetic fields lined up along a common axis. Spin-down follows the same trajectory as spin-up in reverse. From the steady state the system will gradually cause its magnetic fields to be perpendicular so as to stop the clusters motion. These maneuvers are further developed in Sections 2.3.2 and 2.3.3. <LS>

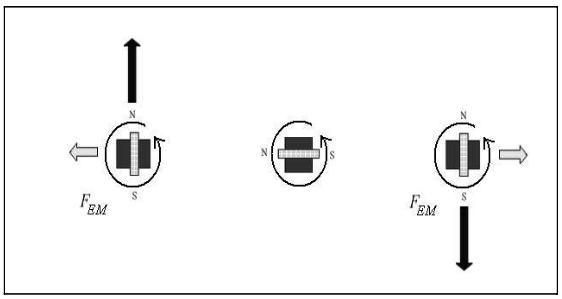


Figure 2.3.3 Three Vehicle Spin-Up

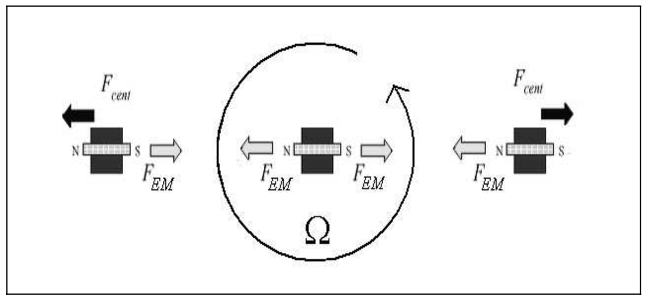


Figure 2.3.4 Three Vehicle Steady State

The last requirement determines the control tolerance. Derived from the accuracy of our analysis, the maximum displacement error allowed is one tenth of the separation distance between two adjacent vehicles. For the specified maneuver, the maximum displacement error should not exceed 20 cm. <LS>

2.3.2 Steady State Mode

2.3.2.1 Definition of Steady State Mode

After the vehicles have completed the spin-up maneuver, they should complete three revolutions in steady state mode. The steady state mode defines the control algorithm for this system maneuver. The steady state mode will seek to decrease the error between the desired separation distance and the actual separation distance. Since the purpose of the steady state mode is to keep the vehicles in configuration, this controller will mostly reject disturbances. To design a controller, the system must first be analyzed. Since the force from the electromagnets is axial then it is necessary to analyze the axial dynamics of the system. <LS>

First, a system model must be developed. Force balance and perturbation analyses are used to find the dominant poles of the system. In this mode, the forces acting on the system are the electromagnetic forces from each electromagnet, and the centripetal force due to rotation. For a configuration with three vehicles where $\square_A = \square_B = \square_C = \square_{avg}$, the forces are:

$$F_{cent.} = \frac{mv^2}{s} = m\Omega^2 s = \frac{mh^2}{s^3}, \quad F_{EM} = \frac{c_0 \mu_{avg}^2}{s^4} + \frac{c_0 \mu_{avg}^2}{(2s)^4}$$

Equation 2.3.1 Centripetal and Electromagnetic Forces Used in Steady-State Force Balance

where Ω is the angular rotation of the system and s is the separation distance from the middle vehicle to the outer vehicles and h is the angular momentum of the cluster per unit mass. <LS>

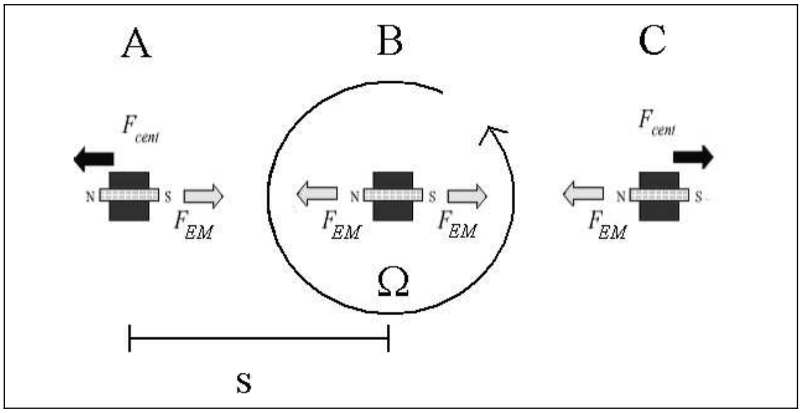


Figure 2.3.5 Three Vehicle Steady State Force Balance

The difference of these forces produces acceleration of the vehicles. A perturbation is then added to the equation.

$$m(\ddot{s}_0 + \delta\ddot{s}) = \frac{17c_0(\mu_{avg} + \delta\mu_{avg})^2}{16(s_0 + \delta s)^4} - \frac{mh^2}{(s_0 + \delta s)^3}$$

Equation 2.3.2 Perturbation Analysis

Using binomial expansion and neglecting the higher order terms, the equation is simplified to

$$m\delta\ddot{s} = \frac{mh^2}{s_0^4} \delta s + 2\frac{mh^2}{\mu_{avg} s_0^4} \delta\mu$$

Equation 2.3.3 Simplified Equation of Motion

Taking the Laplace transform of the equation of motion, the homogeneous solution indicates the poles are at plus and minus Ω on the real axis. With this analysis, carried out in great detail in Appendix C.1, it is determined that steady state spin is unstable with a pole in the right half plane. A controller can, however, be designed to stabilize the system based on this model. <LS>

Discussion of Trades Analysis

Different approaches can be used to design the controller to stabilize the steady state mode. Two different control approaches were explored, phase lead and state space.

2.3.2.2.1 Phase Lead Controller

One approach is a phase lead control. A pair of students, Farmey Joseph and Richard Cross, in MIT's Aeronautical and Astronautical department's junior design project class, 16.62x, explored a system with a similar model as the steady state mode model found above, and implemented a phase lead controller to stabilize the system. <LS>

Their setup consisted of a linear air track and two magnets. Originally, both magnets were to be electromagnets that would glide on the air track and be controlled through current regulation. Due to a miscalculation, the electromagnetic forces produced were not strong enough to demonstrate control. Therefore, the free magnet was replaced with a permanent magnet. <BAB>

With the 16.62x system, there are two different possible setups, one stable and one unstable. The 16.62x students examined the stable setup, in which the air track is raised on one end and the electromagnet is fixed at the other end. The electromagnet must repel the permanent magnet to maintain a fixed separation distance. The arrows indicate the direction of the magnets' north poles.

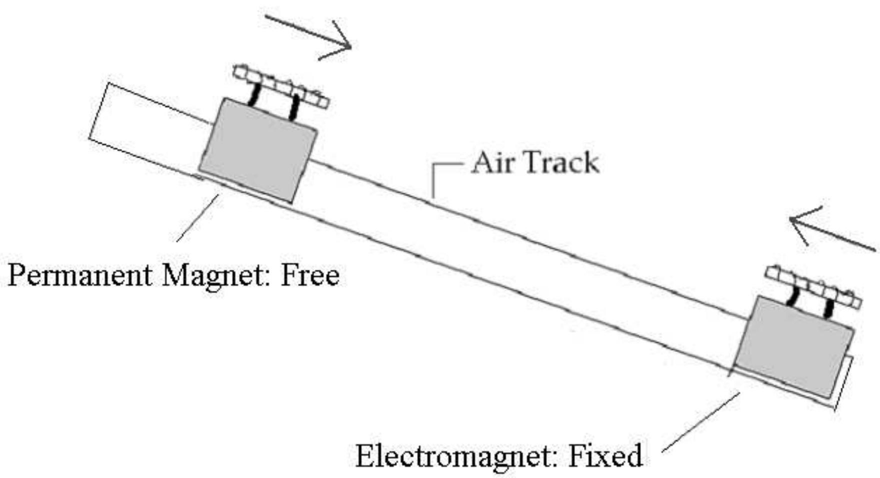
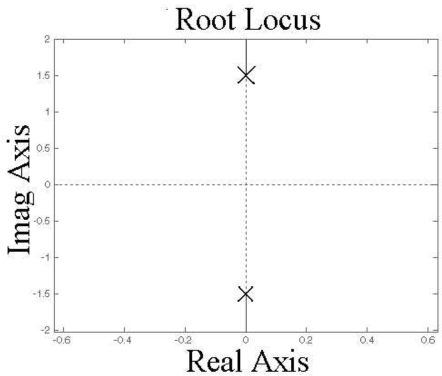


Figure 2.3.6 16.62x Stable Setup

The stable system is modeled in Appendix C.2.1. The dominant system poles are found to be at $\square\sqrt{\frac{6\square_0\square_{avg}^2}{\square s_0^5 m}}i$, with a root locus on the imaginary axis. The 16.62x students located the poles by taking a step response of the system, which depicts the lack of damping in the uncontrolled system. <LS>



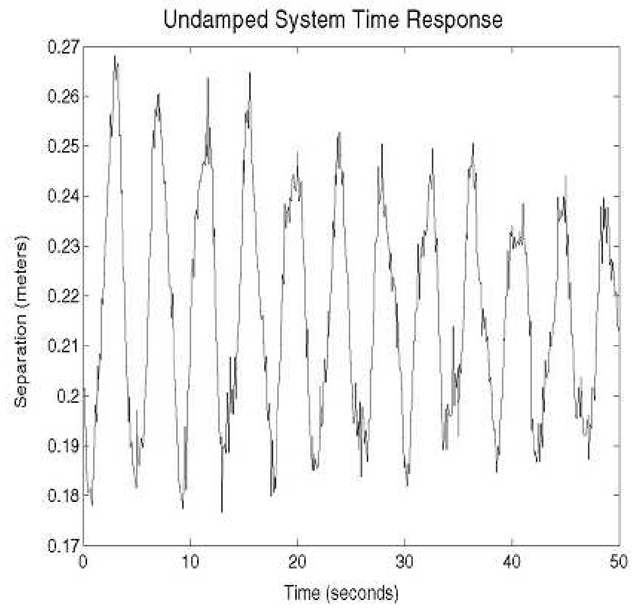


Figure 2.3.7 Root Locus of the Stable System

Figure 2.3.8 Uncontrolled Step Response

The actual poles were found to be at plus and minus 1.5i. A phase lead controller was implemented with a pole at -20, a zero at -2, and a gain of 0.5. This effectively reduced the oscillations of the system when a step was introduced. The controller provided a damping ratio of 0.11. There was some error, however, which was due to sensor noise. <LS>

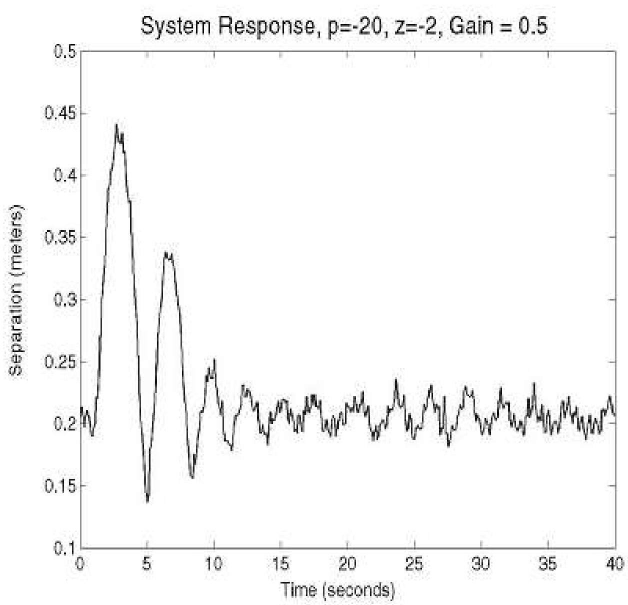


Figure 2.3.9 Controlled Step Response of Stable Setup

Another possible setup with the linear air track demonstrates the unstable case. To create this setup, the air track is raised on the same side as the fixed electromagnet. To maintain a fixed separation distance, the fixed electromagnet must attract the free permanent magnet to maintain a fixed separation distance.

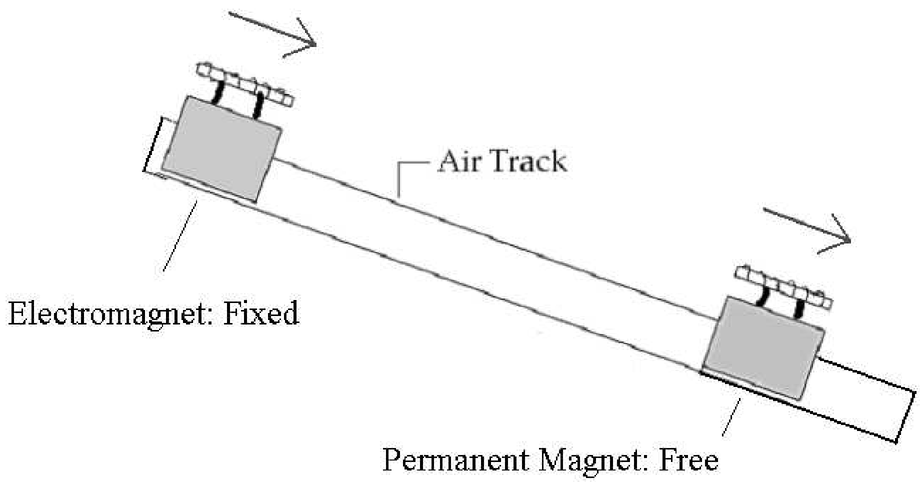


Figure 2.3.10 16.62x Unstable Setup

The unstable setup is modeled in appendix C.2.2. Like the stable setup, the dominant system poles are found to be at $\square\sqrt{\frac{6\square_0\square_{avg}^2}{\square s_0 m}}$, but on the real axis instead of the imaginary axis. This puts a pole in the right half plane, making the system unstable. In this way, the unstable setup is similar to the steady state mode of the project. Controlling the unstable setup should be similar to controlling the steady state mode. <LS>

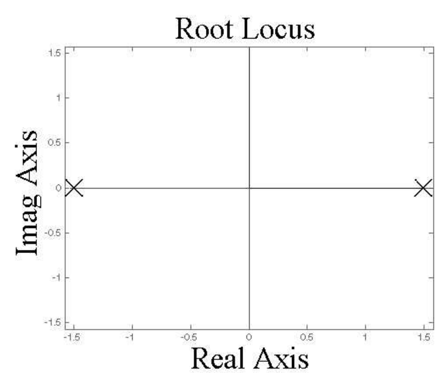


Figure 2.3.11 Root Locus of Unstable System

The 16.62x students did not implement a controller for the unstable system, so the EMMFORCE controls team designed a controller in SISOTOOL in MATLAB. A phase lead controller, similar to the one used in the stable setup, was used, with a pole at –20, a zero at –3, and a gain of 30. This gives a damping ratio of about 0.68. The step response shows a small steady state error, but the system stabilizes quickly, within about 1 second. The overshoot is small, with no oscillations. When this controller is implemented on the unstable setup, it should demonstrate control. <LS>

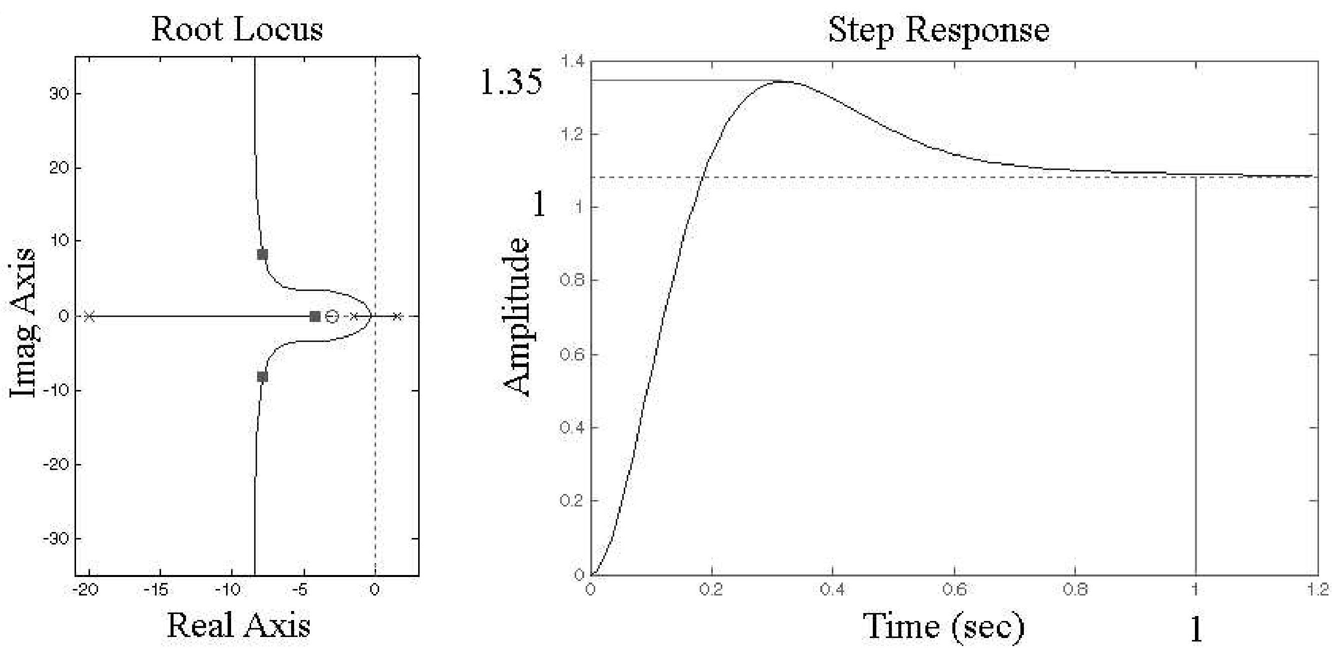


Figure 2.3.12 Root Locus and Step Response of Controlled System

2.3.2.2.2 State Space Analysis

From equation 2.3.3, the equation of motion, a state space equation can be developed.

$$\begin{bmatrix} \frac{\Delta \dot{s}}{s_0} \\ \frac{\Delta \ddot{s}}{s_0} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ \Omega^2 & 0 \end{bmatrix} \begin{bmatrix} \frac{\Delta s}{s_0} \\ \frac{\Delta \dot{s}}{s_0} \end{bmatrix} + \begin{bmatrix} 0 \\ 2\Omega^2 \end{bmatrix} \frac{\Delta\mu}{\mu_{avg}}$$

Equation 2.3.4 State Space Equation of Motion in Form $\dot{x} = Ax + Bu$

Using modern control techniques the closed loop poles for cost efficient controllers can be found. The following derivation is performed in more detail in Appendix C.3. To develop this controller, a cost function is created to weigh the importance of different parameters. R_{xx} is defined as a two by two matrix that allows one to penalize differences in separation or velocity of the vehicles. R_{uu} is a scalar that describes the cost of using control. Because the controller commands power to be supplied to the actuators, controlling the system has a cost of power. The cost function weighs the importance of accuracy in positioning the satellites with the limited resource of power. <LS>

$$J = \int_0^{\infty} [x^T R_{xx} x + u^T R_{uu} u] dt$$

Equation 2.3.5 Cost Function

Cost is minimized when the following two equations hold.

$$R_{xx} + PA + A^T P - PB R_{uu}^{-1} B^T P = 0$$

Equation 2.3.6 Equation 1 for Cost Minimization

$$u = -R_{uu}^{-1} B^T P x = -Fx$$

Equation 2.3.7 Equation 2 for Cost Minimization

Here, the P matrix is an unknown. When P is determined from equation 2.3.6, it can be substituted into equation 2.3.7 and the feedback F can be solved. Because displacement is more important for our control than velocity, R_{xx} is given a variable λ in displacement term. R_{uu} is assigned a variable ρ. <LS>

$$R_{uu} = \rho \qquad R_{xx} = \begin{bmatrix} \lambda & 0 \\ 0 & 0 \end{bmatrix} \qquad P = \begin{bmatrix} P_{11} & P_{12} \\ P_{12} & P_{22} \end{bmatrix}$$

Equation 2.3.8 Variable Definitions

As shown in the derivation in appendix C.3, P can be solved for in terms of λ, ρ, and Ω. With these variables, the most efficient controller can be calculated given a set ration of λ and ρ. If the ratio λ/ρ is evaluated from $0 \to \infty$, a graph of the closed loop poles for the most efficient controller can be created. <LS>

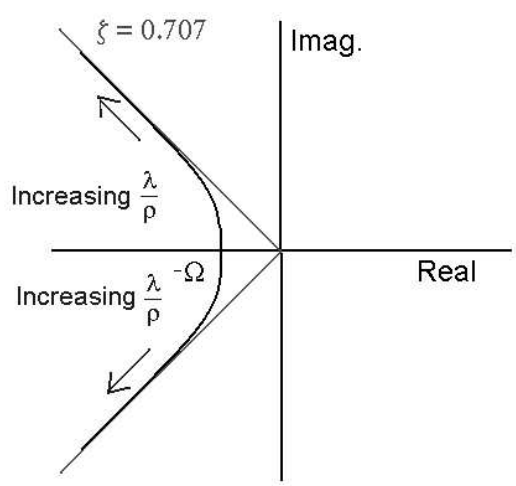


Figure 2.3.13 Closed Loop Pole Locations for Varying Ratios of λ/ρ

When the ratio is zero, use of control is infinitely expensive and the poles are both located at –□. When the ratio is infinity, use of control is infinitely cheap. The location of the closed loop poles move out to infinity along the 45□asymptote, where the damping ratio is 0.707. <LS>

Summary Of Options/Selection Criteria

Both methods of developing a controller provide beneficial information. The phase lead approach will most likely be simpler to calculate and easier to analyze with the current knowledge of the EMFORCE controls team. Though it is more complicated, the state space approach allows greater focus on the important factors of cost and accuracy. For a preliminary control design, the classic control technique of phase lead controllers will be implemented. For a final control design, the state space approach may be used. <LS>

2.3.3 Spin-up/Spin-down Mode

2.3.3.1 Definition of Spin-up/Spin-down

When starting from rest, the vehicles must perform a spin-up maneuver to reach steady state spin. After three steady state revolutions, the vehicles must perform a spin-down maneuver to return to rest. These maneuvers are similar and will be modeled and controlled by similar means. The spin-up/spin-down mode defines the control algorithm for these system maneuvers. This controller will try to move the vehicles, initially at rest, along some pre-defined trajectory to the steady state spin configuration (See Figure 2.3.14). To design a controller, the system must first be analyzed. Since this mode involves mostly electromagnetic torques and translational forces, these system dynamics must be analyzed. <BAB>

Initially the three vehicles will be positioned on the test bed at the appropriate separation distances with the magnetic fields perpendicular to each other. The effects of this configuration are that the magnets experience a shearing force, shown in the following figure by straight arrows, and a torque, shown by the curved arrows. <BAB>

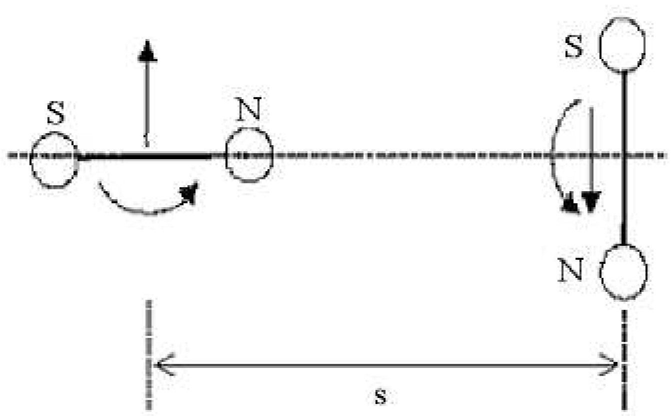


Figure 2.3.14 Spin-up Force Balance

This figure depicts two vehicles, but the same forces apply with three or more vehicles. When these forces and torques are controlled to follow a specified trajectory, the electromagnets can be caused to move from rest to orbiting about a midpoint. This trajectory, for three vehicles, is depicted below:

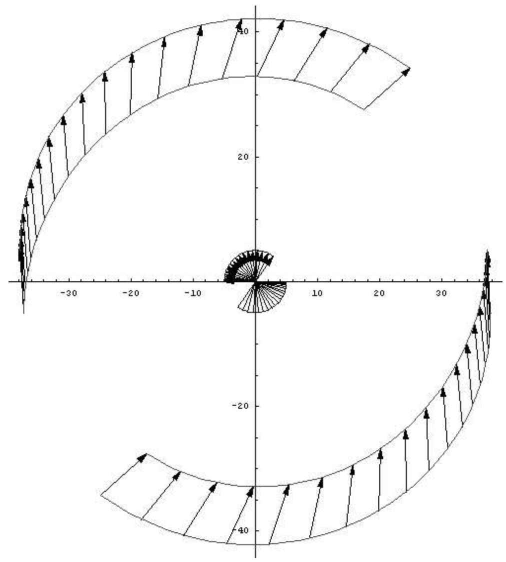


Figure 2.3.15 Three Vehicle Spin-up Trajectory

When spinning up, the vehicles will experience disturbances. Any number of disturbances can cause one or more vehicles to translate. Therefore it is important to take into account the translational forces of two electromagnets with perpendicular magnetic fields. As shown below, the translated vehicles motion will be governed by a translational force that changes depending on the translated distance. This line of motion is broken into three regimes. If a magnet is disturbed past a critical distance in either direction, then the translational force will change direction. <BAB>

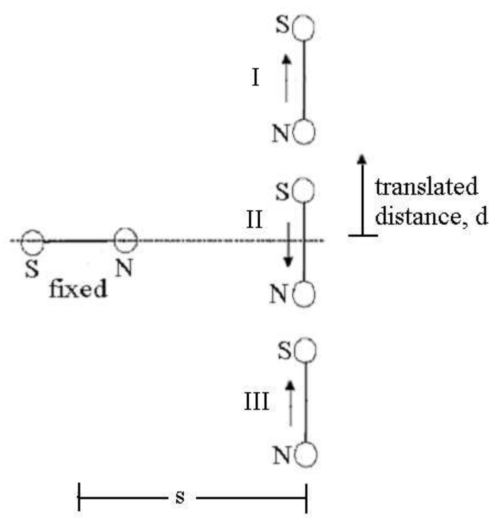


Figure 2.3.16 Three Regimes of Motion for Spin-up

At the critical points, where the translational forces change direction, the magnitude of the force is zero, making them equilibrium points. To locate the points, the translational force must be calculated for a given displaced distance. The translational force is a function of the angles of each electromagnet's magnetic field to the axis that runs between them. As one magnet becomes more and more displaced these angles change. The angles are defined as follows:

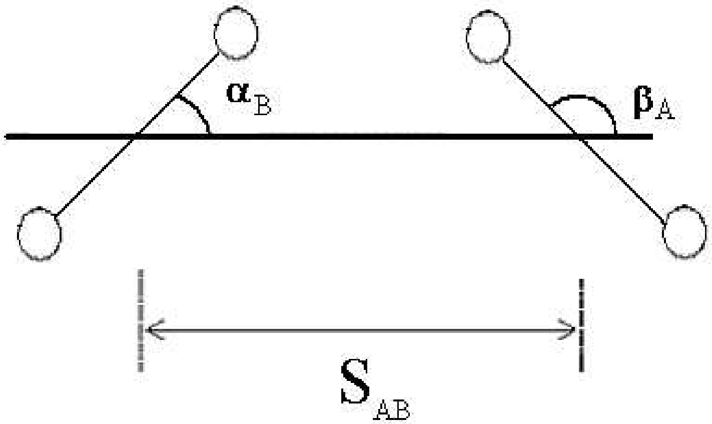


Figure 2.3.17 Angle Definition

Defining force based on angle,

$$F_{trans} = \frac{3\mu_0 \mu_{avg}^2}{4\pi s_{AB}^4} Sin(\alpha_B + \beta_A)$$

Equation 2.3.9 Translation Force Dependent on Angle

At the equilibrium points, $\sin(\alpha_B + \beta_A) = 0$. From the geometry, the equilibrium points occur when the translated distance, d, is equal to the separation distance, s_{AB}. Shown below is a phase plane plot of the movement of the vehicle. This analysis defines the movement of the vehicles in any regime, as shown below. If near the equilibrium point on the left, the vehicle will oscillate forever. In any other location, the vehicle will move towards infinity. <BAB>

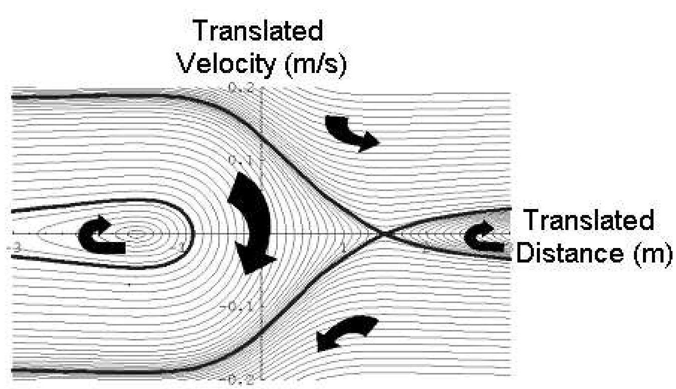


Figure 2.3.18 Travel Paths for Given Translated Distances

A controller must be designed to follow the given trajectories without leaving the stable regimes.

2.3.3.2 Discussion of Trades Analysis

There is a trade between the two possible spin-up configurations.

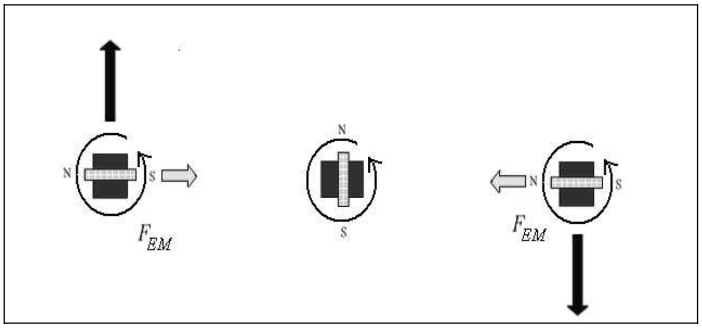


Figure 2.3.19 Spin-up Configuration 1

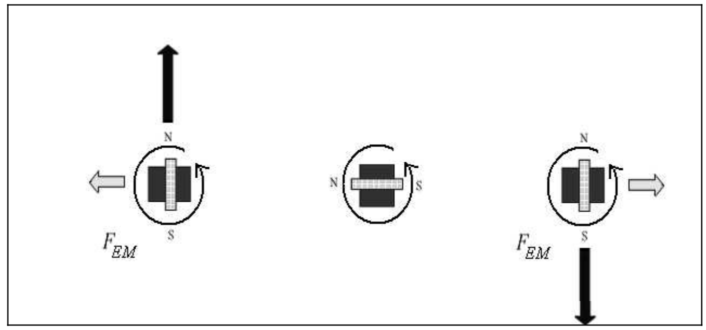


Figure 2.3.20 Spin-up Configuration 2

The basis for this trade lies in the fact that the forces and moments on each magnet are not equal. As shown in the following figure, due to the geometry of the configuration -- mainly that the separation distance, s, significantly larger than the half length of the electromagnetic core -- the torques are different on each vehicle. <BAB>

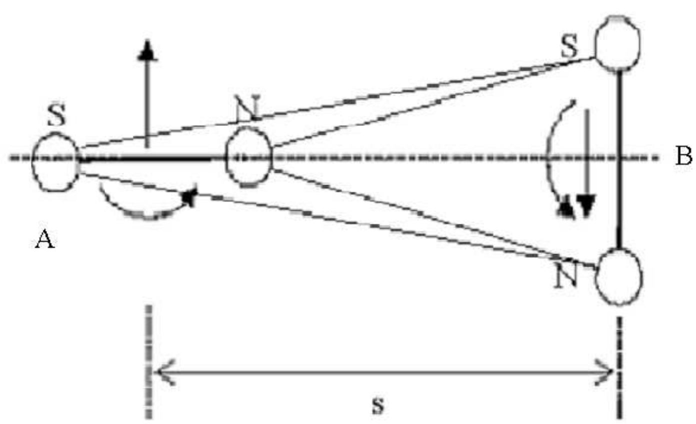


Figure 2.3.21 Unequal Torques on Vehicles

In this configuration, the torque felt by magnet B is greater than the force felt on magnet A. If a straight-line force between the poles is assumed, it is seen that the angle at which the force reaches the poles on magnet B approaches 90 and the angle at which the force reaches the poles on magnet A is closer to zero. Since torque is the product of the force and the sine of the angle, the torque on magnet B is much greater than the torque on magnet A. <BAB>

More analytically, the torques on each magnet can be calculated.

$$\tau_A \square \frac{\mu_0 \mu_{avg}^2}{8\pi}\left[Sin(\theta_B \square \theta_A) \square 3(\theta_B \square \theta_A)\right] \qquad \tau_B \square \frac{\mu_0 \mu_{avg}^2}{8\pi}\left[Sin(\theta_A \square \theta_B) \square 3(\theta_A \square \theta_B)\right]$$

Equation 2.3.10 Torques on Vehicles

When $\theta_A = 0^\circ$, and $\theta_B = 90^\circ$, the torque on magnet A is half the torque on magnet B.

$$\frac{\tau_A}{\tau_B} = \frac{\frac{\mu_0 \mu_{avg}^2}{8\pi}\left[Sin(\theta_B - \theta_A) + 3(\theta_B + \theta_A)\right]}{\frac{\mu_0 \mu_{avg}^2}{8\pi}\left[Sin(\theta_A - \theta_B) + 3(\theta_A + \theta_B)\right]} = \frac{2}{4} = \frac{1}{2}$$

Equation 2.3.11 Torque Ratio

Because the torques are not equal on each vehicle, there is a trade between the two configurations in figures 2.3.19 and 2.3.20.

2.3.3.3 Summary of Options/Selection Criteria

Since the torque on the vertically aligned magnets is greater than the torque on the horizontally aligned magnets, it follows that the initial positions of the magnets is important. In the configuration of figure 2.3.20, the center magnet feels half the torque of the outer one; its torque is then doubled due to the other outer vehicle producing an even distribution of moments among the three vehicles. In figure 2.3.19, the center magnet feels twice the torque of the outer one, which is then doubled due to the existence of the other outer vehicle. Therefore, the center magnet feels four times the amount of torque as compared to the outer ones. <BAB>

The amount of torque on a vehicle determines the amount of counter-torque the reaction wheel will have to exert for control. If the torque is concentrated in one vehicle then this vehicle will have to have a larger reaction for adequate control. On the other hand, a large center vehicle means that more of the system mass is concentrated at the center leading to less cluster angular momentum thus less total reaction wheel angular momentum. Less reaction wheel angular momentum means that the reaction wheels can be smaller, which affects the electromagnet size. A larger center vehicle also allows for a larger central magnet, therefore a stronger central magnetic field. The result of a larger central magnetic field is that the system can operate with lighter outer vehicles, at greater separation distance, and/or at greater angular velocity. A large center vehicle with smaller outer vehicles, unfortunately violates our interchangeability requirement. This requirement stipulates that all three vehicles must be the same. The interchangeability requirement favors the configuration of figure 2.3.20, since this configuration more evenly distributes the angular momentum among the three vehicles, leading to the smallest possible reaction wheels, thus lighter-weight vehicles. <BAB>

Because the requirements must be met, the configuration of figure 2.3.20 is the feasible configuration. However, if the requirements change, the configuration may change to that of figure 2.3.19. <LS>

2.3.4 Control Architecture

2.3.4.1 Definition of Control Architecture

The control subsystem must know what mode to control, steady state or spin-up/spin-down. It then must know how to implement the correct control for the determined mode. There are different methods of processing the sensor data and issuing response commands. The control architecture determines the desired trajectory and implements the appropriate controller. It also determines the manner of communicating the control instructions. <LS>

2.3.4.2 Discussion of Trades Analysis

The main trade for control architecture is the location of the controller within the entire system. Three options were analyzed. These were independent, centralized control, and hybrid control. <LS>

With independent control, the vehicles each collect and process data to derive a control solution for each separate vehicle. Because each vehicle will be processing and responding to its own data, the response time will be very quick. The main disadvantage, however, of independent control is conflict with multiple vehicles controlling the same disturbance. The system is coupled, therefore, when one vehicle moves, it affects the others. It will be very difficult to implement independent control with each vehicle impacting the state of the others. <LS>

In centralized control, all of the information from metrology will be sent to a hub vehicle. The hub would calculate the control solution and send the commands to the other vehicles. This is a good solution to the problem of a coupled system. With only one vehicle making decisions, there is no conflict with vehicles responding to other vehicles. However, there is a significant time delay associated with a centralized controller. Having a hub run calculations and then send commands to other vehicles slows down the response time. <LS>

The last form of control is hybrid control. In this case, all three vehicles will possess the ability to control independently. In times when a quick response is needed, independent control will be implemented. The system will also be capable of controlling through a hub vehicle in cases where timing is not as crucial or the coupled effects of using electromagnetic actuation jeopardize adequate control. <LS>

2.3.4.3 Summary Of Options/Selection Criteria

Neither independent control nor centralized control is very feasible to use separately. The effects of being a coupled system are too large to use only independent control, and response time will most likely not be quick enough if a hub did all of the calculations. Therefore, the best option is to implement a hybrid control system. When timing is crucial, independent control will be implemented. At all other times, a centralized controller will process the data and issue the commands to the other vehicles. <LS>

2.3.5 External Interfacing Needs

The control subsystem is located within the avionics subsystem. It is programmed onto the avionics processor. In this way, it interfaces with avionics.

The controller will need inputs from metrology of the current state. This will include at least the separation distance, the vehicles relative bearing, and the relative angles of the electromagnets' poles.

Other inputs that will not be required, but helpful in implementing control are the velocity and acceleration of the vehicles.

After calculating the control algorithms, the control subsystem will output commands to the power subsystem. These commands will indicate how much power needs to be supplied to the actuators. <LS>

2.3.6 Budgets

The control subsystem has no mass or power budget because it is only software on the avionics processor. A budget of $500 has been allocated to the control subsystem, however, to cover the cost of maintenance of lab equipment that will be used for preliminary testing. <LS>

2.3.7 Conclusions

The control design is central to building a successful system. Indeed, as stated in the mission statement, it is what the system is attempting to show is feasible. Unfortunately the controller design is not straightforward. As has been mentioned, the control problem is unstable and the main actuator, the electromagnet, produces forces and torques that are coupled. Through careful analysis the system's dynamics can become well understood and certain trades can be made leading to possible control designs. <BAB>

2.4 Metrology

2.4.1 Subsystem Overview

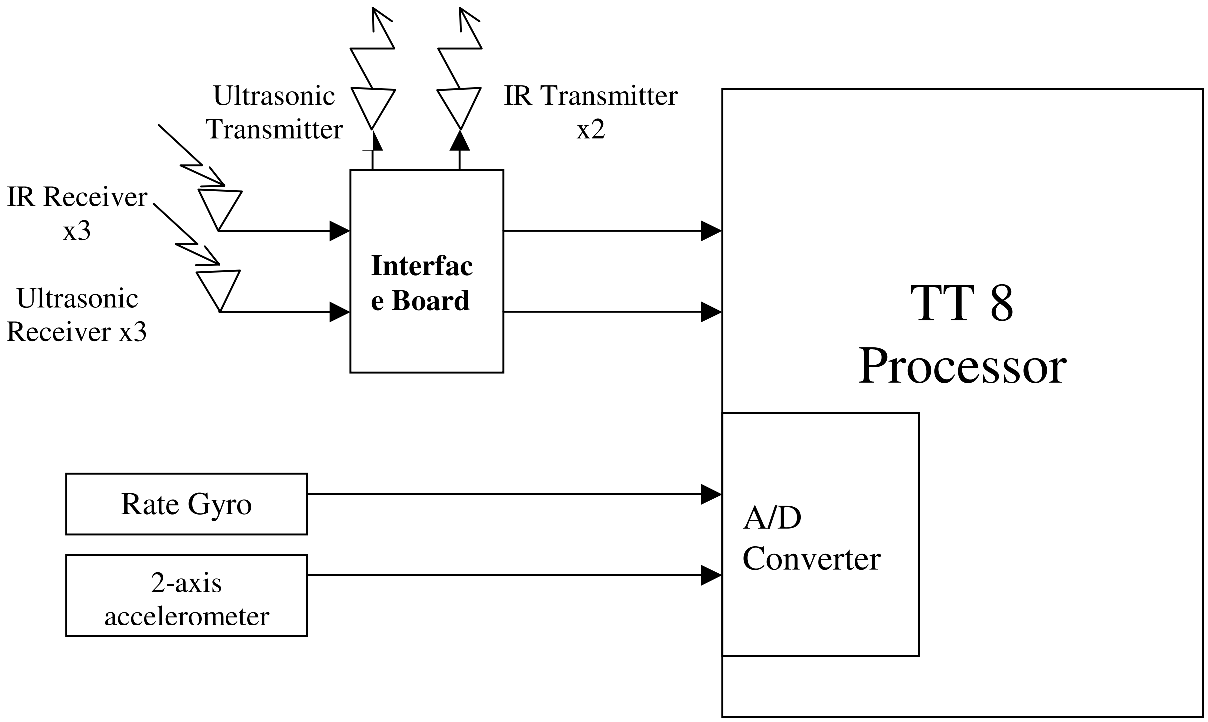


Fig 2.4.1 Metrology Block Diagram

Extracted from the requirements of the overall project, the goal of the metrology system is to accurately calculate relative distance and attitude. Per the requirements document, accurately is defined as 1/10 of the control tolerance for both distance and angular readings. In addition, the metrology system needs to have a field of view of 360º in a 2-D plane. Finally, the system needs a detection range compatible with test facilities. These test facilities include the test facility at MIT and the Lockheed flat floor facility in Denver, CO. <OM>

2.4.2 System Trade Analysis

The initial trade analysis for the metrology subsystem was to compare sonic ranging systems, indoor GPS, and inertial navigation. Sonic ranging may be implemented in many ways. In the current incarnation, the sonic system uses time differences between transmitted sonic signals to triangulate the position of a vehicle (this is explained in much greater detail in the design section below). Inertial navigation uses velocity and acceleration information from rate gyros and accelerometers to calculate the position of a vehicle. The second derivative of acceleration gives linear position and the first derivative of angular rate gives angular orientation. The indoor GPS system is very similar to the current design for the sonic system except that it uses radio frequency. Indoor GPS relies on several radio frequency antennas. The system measures the time difference between incoming RF signals to triangulate position. <APA>

The metrology team could not find substantial technical information on the indoor GPS system. It was also assumed that the system would require more computational cycles than the other systems since it was assumed that the RF interface would be more complicated. Additionally, the RF signals are prone to interference from the electromagnet. For these reasons the indoor GPS system was deemed infeasible. The inertial navigation system seemed well suited to our purposes; however, it also seemed to require excessive computational power. Also, inertial navigation systems may experience unacceptable drift. Each experiment is expected to run for approximately 5 minutes. Accelerometers with sufficiently low drift rate to meet this time requirement are prohibitively expensive. A sonic system is very desirable because there are many people within the department who have experience with sonic ranging. SPHERES has demonstrated and documented one functional system for sonic ranging. Also the Virtual Ink Corporation has developed an electronic whiteboard system (Mimio) based on sonic ranging which seems to demonstrate performance that meets our requirements. These design considerations lead us to choose the third option of sonic ranging. <APA>

The SPHERES metrology system has several mounted ground units that emit ultrasonic pulses, which are received by the vehicles. The Mimio whiteboard system also uses a fixed unit to track a moving unit. The original designs for the EMFFORCE metrology system utilized similar ground units to give position of the vehicles relative to the fixed ground coordinates. This design is desirable since it has already been tested and proven to be effective. However, the system architecture dictates that the actuation system will have only relative control authority. The electromagnets will allow only for control of the vehicles relative to each other and not relative to the ground, therefore ground referenced positioning is unnecessary. The best option is to eliminate the ground units and put both the emitters and receivers on the vehicles. The sensors will determine the position of the other vehicles just as it would have determined the position of the ground units. This is the current design of the metrology system. <APA>

2.4.3 Design Overview

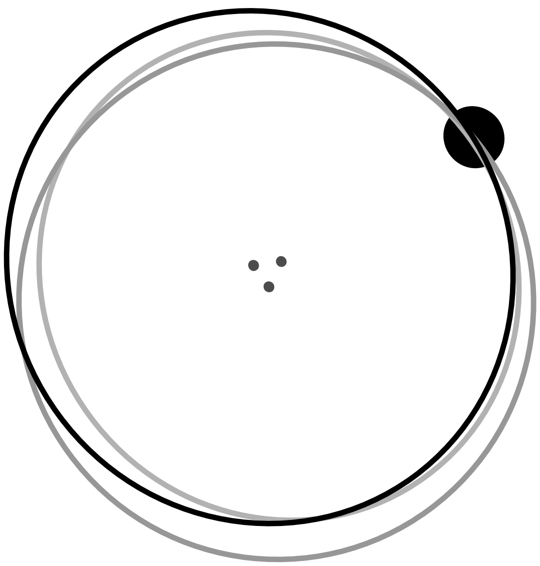
The current design of the system relies only on distance readings. Previous designs used distance readings and the time difference between each ultrasonic receiver on board (in addition to the time difference between the IR and ultrasonic signals) to determine the angle. It was decided that this data might not be precise enough. SPHERES uses a similar system, but cannot get good accuracy on distance using the time difference between the signals. However, the Virtual Ink Corporation has achieved millimeter accuracy with the Mimio system, and has shown interest in helping the EMFFORCE Team. <OM>

The current design uses data from all three sensors, while a few previous designs used only data from two sensors. The third sensor served only to determine a positive of negative reading. This design was flawed since there was a range where the sensor wasn't able to determine if the signal had a positive or negative orientation. <OM>

Finally, the design calculates the angles and distances directly to the center of the vehicle. In all previous designs, the algorithm would calculate the relative position to the sensor and a coordinate transformation was needed to go from an orientation around the sensor to the center of the vehicle. The current design eliminates these calculations and decreases the number of calculations for the processor. <OM>

2.4.3.1 Algorithm

The algorithm of the system uses the distance readings from the sensors. Because it knows the distance, it knows an infinite number of points the signal can be coming from, all lying on a circle. Using the information from the three sensors, one can overlay these three circles to determine the exact location (within a tolerance) of the vehicle. Using the following three equations, one can determine the two unknowns. It is possible to use only two sensor readings, however, there are times when there will be two solutions. The third equation removes this second solution. However, if a sensor fails, previously know information can be used with the two solutions to determine which is the correct solution. <OM>



$$(x_{sat} + x_1)^2 + (y_{sat} + y_1)^2 = d_1^{\ 2}$$
$$(x_{sat} + x_2)^2 + (y_{sat} + y_2)^2 = d_2^{\ 2}$$
$$(x_{sat} + x_3)^2 + (y_{sat} + y_3)^2 = d_3^{\ 2}$$

Fig 2.4.2 Metrology Algorithm Overview

2.4.4 Ultrasonic Transmitter

2.4.4.1 Purpose of Part

The ultrasonic transmitter transmits an ultrasonic signal to aid in the calculation of distance. To keep the number of transmitters on board to a minimum, the system utilizes an omni-directional transmitter. This transmitter has been implemented on an electronic whiteboard system that tracks whiteboard erasers and pens. The Metrology Team has contacted the company (Virtual Ink Corporation, maker of the Mimio electronic whiteboard system) to inquire about the sensor, in addition to the overall technology they implement in their system. <OM>

2.4.4.2 Discussion of Trade Analysis

Drawing from the design of the Mimio whiteboard system, the Metrology Team decided to use omni-directional sonic emitters. One option for omni-directional sonic units is to purchase them off them shelf. The units are inexpensive and readily available. Another alternative is to use directional sonic units, which are currently available, and affix a cone to reflect sound waves in all directions (in a plane). The available off-the-shelf transmitters have very even output profiles and are probably superior to those that could be manufactured by the metrology team. Based on current information the metrology team has decided to use off-the-shelf transmitters. <APA>

2.4.5 Ultrasonic Receiver

2.4.5.1 Purpose of Part

The ultrasonic receivers on board are to receive the signal from the ultrasonic transmitters emitted by the other vehicles. The configuration of the receivers is critical to the calculation of distance and position. To minimize the complexity of the algorithm, omni-directional receivers will be used. <OM>

After doing some searching, it was determined that the best way to obtain these types of receivers is just to build them in lab from directional receivers. The following picture is from a concept design test of our setup. A cone has been added to a directional receiver to direct the sound wave to the microphone of the receiver. Further testing is required to confirm the quality of the design. This testing will be executed over the next stage of the program. <OM>

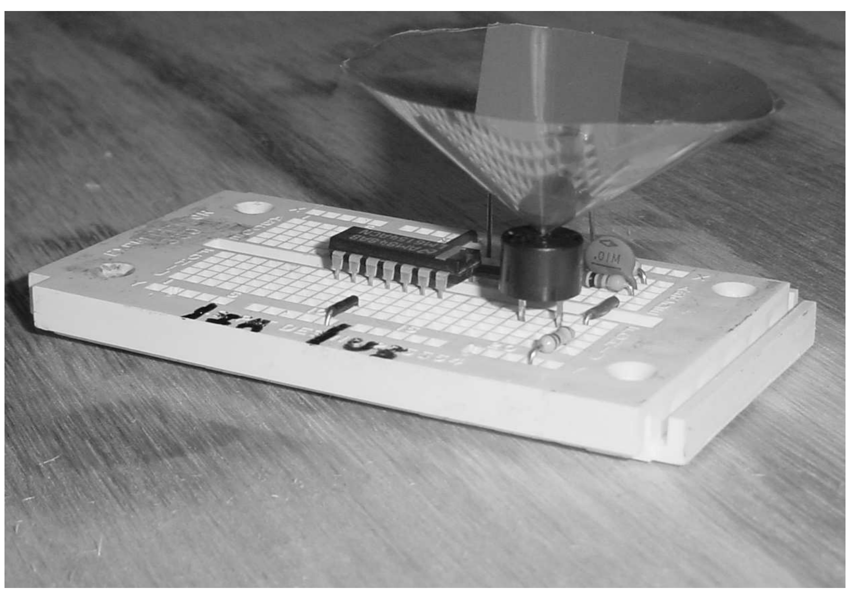


Fig 2.4.3 Omni-directional Receiver Concept

2.4.5.2 Discussion of Trade Analysis

The current options for omni-directional receivers are off-the-shelf receivers and the cone receivers mentioned above. The available off-the-shelf receivers only have effective receiving angle of 150 degrees. It is believed that the proposed cones will provide a receiving angle of 360 degrees, though this will need to be verified through experimentation. If the cones can be manufactured accurately enough to provide even 360-degree reception they will be superior to the available off-the-shelf receivers. Pending further test results the metrology team has decided to use the conic receivers. <APA>

2.4.6 Infrared Transmitter

2.4.6.1 Purpose of Part

The infrared transmitter is needed to determine the time difference between the emissions and the reception of the ultrasonic signal. The ultrasonic and infrared signals are emitted at the same time. Since the signal is traveling at the speed of light, it's assumed that the other vehicles receive the signal instantaneously. This gives a reference start time to determine the time of flight of the sound wave. The time of flight along with the know value for the speed of sound is used calculate the separation distance. Although omni-directional transmitters are being used, two have been implemented in the design to reduce the shadowing effects. <OM> <APA>

2.4.6.2 Discussion of Trade Analysis

The current options for infrared emitters are either to use one omni directional emitter (similar to the ultrasonic system), or to array several directional emitters. The infrared transmitters are very low in both mass and power consumption. As a result there is very little difference between the two options. The choice to use omni directional emitters comes mostly from the fact that the emitters will come as part of the Mimio electronic whiteboard eraser. The metrology team is currently planning on obtaining both the ultrasonic and infrared emitters from the same erasers. The choice of infrared sensors will most likely be determined by what types of emitters are readily available.

2.4.7 Infrared Receiver

2.4.7.1 Purpose of Part

Infrared receivers are used to receive the IR signal emitted by the vehicles. Since the field of view is 180° for the sensor, we use an array of three to cover the required 360° set forth by the requirements document. <OM>

2.4.7.2 Discussion of Trade Analysis

As with the infrared emitters, there are various receivers available. Again there is no fundamentally important difference between the various receivers, thus the metrology team will most likely use whichever receivers are readily available.

2.4.8 Rate Gyro

2.4.8.1 Purpose of Part

The data from the ultrasonic and IR sensors provide enough data to determine relative angle and position, however the data is not obtained fast enough. Integrating the data from the rate gyro will provide the current angle at a higher rate than is available from the sonic/IR system. Since the data from the rate gyro can be polled at 50 Hz, the control system can use accurate data. <OM>

2.4.8.2 Discussion of Trade Analysis

It was initially believed that the ultrasonic positioning system would provide information quickly enough to maintain control of the system. At this point the limiting factor on the metrology system is determined by the speed of sound. Thus in order to increase the refresh rate it was necessary to add additional hardware. The rate gyros are expensive but they have proved successful when used on SPHERES. The rate gyro is also important because the control team requested rate data. <APA>

2.4.9 Accelerometer

2.4.9.1 Purpose of Part

The accelerometer is added for the same reason as the rate gyro. Integrating the data twice can give us a position reading to satisfy the need from the control subsystem of data readings at 50 Hz. <OM>

2.4.9.2 Discussion of Trade Analysis

As with the rate gyro, accelerometers will provide data in order to increase the refresh rate of the position information. The accelerometers are also expensive but they have proved successful when used on SPHERES. The accelerometers are also important because the control team requested rate data. <APA>

2.4.10 Metrology Design Issues

The system still needs testing. The first test Metrology Team needs to conduct is the best design for the cones for the hand made omni-directional sensor. We will have to investigate and research acoustic documents to determine what design (parabolic, angle, etc.) will give us the strongest signal from a transmitter. <OM>

Another test we wish to conduct is the effects of the Electromagnetic on the sensors. Since there will a be significant B field around the sensors, we want to test to see how much effect the magnetic fields have to the readings of our sensors. <OM>

Next, we hope to test our accuracy based on range. We know as we start increasing the separation on the vehicles we start getting less precise on the distance and angle data. We hope to keep this error as minimal as possible. We hope to come up with a graph of Accuracy vs. Range so that we know where our systems starts to “fail.” <OM>

Finally, we need to look at the refresh rate. Because we use Ultrasonic transmitters, we have to wait for the sound to leave the testing area so that we don’t get “bad” data. Based on initial numbers, we need 23 ms between each vehicle saying “I’m here.” Rate gyros and accelerometers will can lower that refresh rate. <OM>

2.4.11 External Interfacing Needs

The metrology subsystem interfaces with the avionics, communications, control, power, and structure subsystems. The following are descriptions of the interface requirements for each vehicle. <APA>

2.4.11.1 Avionics Interfaces

The metrology subsystem will interface physically with the avionics subsystem. The IR emitters will require one digital output from the avionics board (TT8). Regardless of how many emitters are used (to get full 360 degree coverage), all of the emitters will be wired in series and transmit the same signal. Thus they will only require one output. Likewise the IR receivers will require one digital input on the avionics board. It is unknown at this time exactly what form of signal conditioning or support hardware will be required between the IR units and the avionics system. This hardware is the responsibility of the Metrology Team and will be determined after more experimentation. The ultrasonic emitter will also require one digital output. The ultrasonic receivers will require three digital inputs. The rate gyro will require one analog input to the avionics board. The accelerometers will require two analog inputs to the avionics board, one input for each direction of motion (X and Y). <APA>

Table 2.4.1 Avionics Input/Output

Part	Inputs/Outputs Required
IR Emitter(s)	1 digital output
IR Receiver(s)	1 digital input
Ultrasonic Emitter	1 digital output
Ultrasonic Receivers	3 digital inputs
Rate Gyro	1 analog input
Accelerometers	2 analog inputs

2.4.11.2 Communications Interface

The metrology system will interface with the communications system through the avionics system. Using the current design for the metrology system, each vehicle will determine the separation distance to each other vehicle and the angular orientation of the vehicle. The angular orientation of the other vehicles is also necessary to control the formation. This information will be relayed to the control software via the communications system. Exactly what information needs to be transmitted and the required bandwidth will depend greatly upon the design of the control software. <APA>

2.4.11.3 Control Interface

The metrology system will interface with the control subsystem via the avionics system. The metrology software will take all inputs from sensors. The metrology software will then calculate the separation distance between each vehicle as well as the relative angular orientation of each vehicle. This information will be provided in polar coordinates with the origin at the center of each vehicle. Specifically, the metrology software will return values for s_{AB}, s_{BC}, $s_{AC}$$\mu$ $_{\Omega}$,μ $_{C}$, $\rho_{\alpha\mu}\rho_{C}$, $\pi_{\alpha\mu}$ and,,π_{Ω}. (see figure 2.4.4 below) The metrology software will also return linear velocity data (by taking the derivate of the data from the accelerometers) and angular velocity data from the rate gyros. The form of this data and the refresh rate will be determined by the control team and has not yet been determined. <APA>

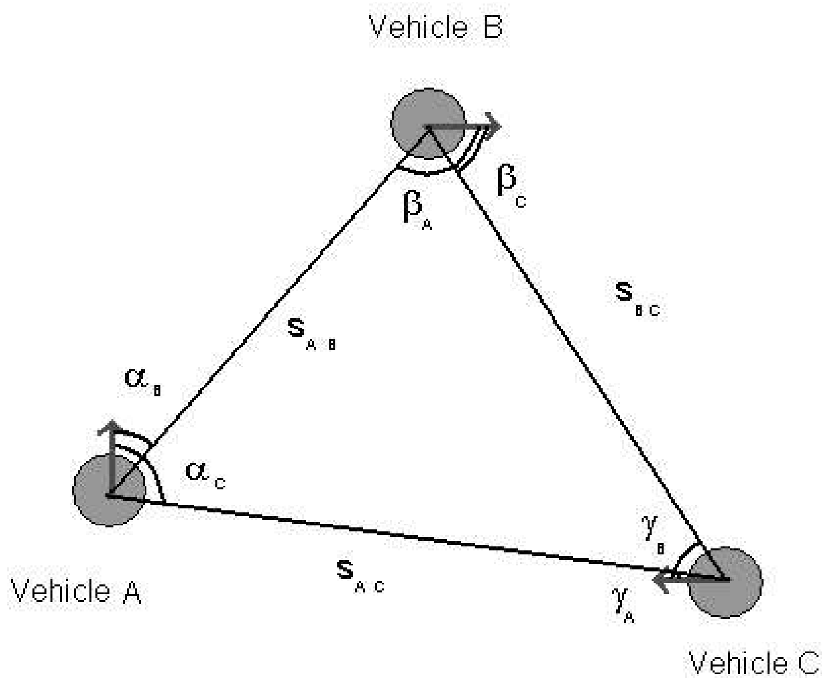


Fig 2.4.4 Distances and Angles Determined

2.4.11.4 Power Interface

The metrology system will interface with the power subsystem physically. The metrology subsystem will most likely require a low voltage power bus (5-12 volts) with low current draw (less than one amp). These are the exact voltage requirements for the metrology system has not yet been determined. The exact nature of the physical interface between the power and metrology subsystems has not yet been determined. <APA>

2.4.11.5 Structural Interface

The metrology system will interface with the structures subsystem physically. The metrology subsystem will be attached to the top surface of the vehicle so that the sensors and emitters will have an unobstructed 360-degree view. Signal conditioning and support hardware will fit on one of the racks allotted for circuit boards. The exact nature of the physical attachment for the metrology subsystem has not yet been determined. <APA>

2.4.12 Estimated Budgets

Table 2.4.2 Budget Estimates

Part	Cost ($)	Mass (kg)	Power (W)
Sonic (1+3)	70	0.05	0.30
IR (2+3)	30	0.04	0.25
Gyros	1200	0.06	0.36
Accelerometers	1200	0.05	0.18
Total (per vehicle)	**2500**	**0.20**	**1.09**
Total (system)	**7500**	**0.60**	**3.27**

The cost estimates are taken from various sources including, but not limited to, documentation from project SPHERES, discussions with SPHERES metrology team, retail prices and specifications sheets from the Mimio website, and estimations from experience with related systems. <APA>

The cost for the sonic and IR components is estimated from the retail price of a Mimio brand whiteboard eraser. The erasers contain two omni directional sonic emitters and four omni directional IR emitters. Two such erasers will provide all of the IR and ultrasonic emitters required for the current design of the metrology system. The Mimio whiteboard erasers retail for $60 from the Mimio online store. Based on information from the SPHERES team, the ultrasonic receivers will cost around $5 each. It is estimated that the IR receivers will be similarly priced. <APA>

All weight and power consumption estimates are estimated from the SPHERES documentation. Similar equipment will be used. It was assumed that any differences between the equipment would be negligible. Requirements for signal conditioning and other interfacing hardware have not been directly addressed at this time due to lack of available information. <APA>

2.4.13 Conclusion

The current design of the metrology system is based on the designs for the SPHERES metrology system and the Mimio electronic whiteboard system. There are still several details that need to be sorted out however the basic design of the system is set. Various components will need to be tested before implementation of the current design of the system. Most significantly, the reflective cones for the receivers will need to be tested extensively. Also, the entire system will be tested for variations due to range, input power, and magnetic field effects. The algorithm will need to be more precisely determined and coded as well. There is a significant amount of work left to do, however it should be possible to complete the project in the allotted time and with the requested budget. <APA>

2.5 Communications

2.5.1 Subsystem Overview

Communications is the technology employed in transmitting messages. The communications subsystem includes the architecture, or protocol by which messages are transmitted and received, the hardware and software necessary to implement the architectural design, and a consideration of the needs of the other subsystems. The end goal is to achieve predictable and robust message transmission and reception. <JEU>

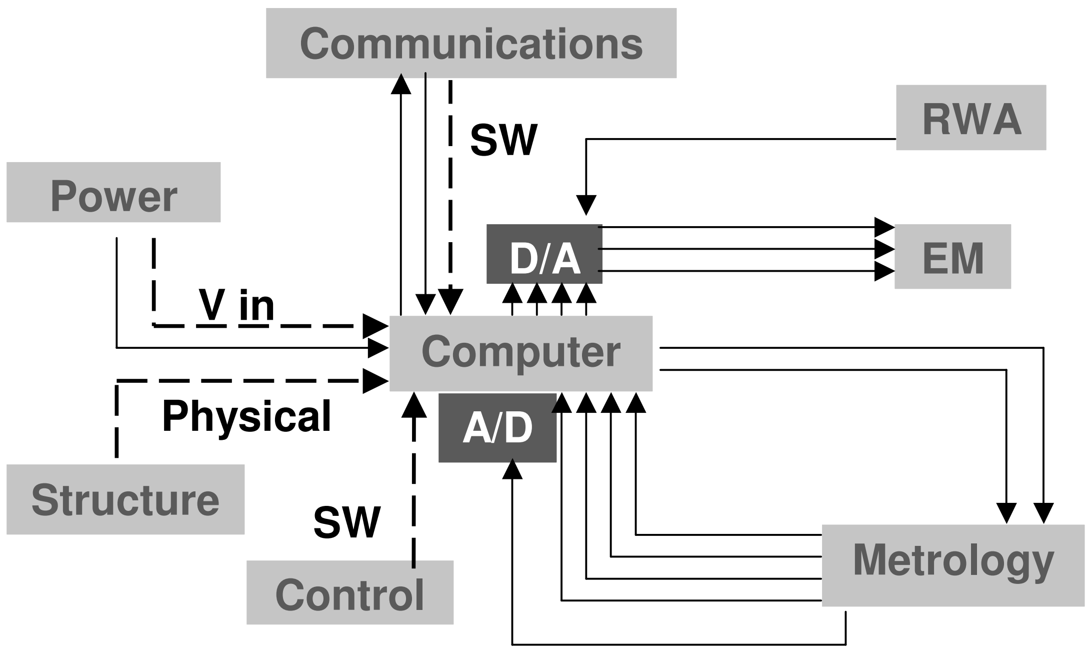


Figure 2.5.1: Information Flow Perspective of the Communications Subsystem
The above diagram demonstrates the information flow interfacing of all the subsystems with the main computer. The communications subsystem is interfaced with the main computer in two ways. First, the communications software is loaded onto the main computer and all necessary computations are handled there. Second, the transceiver module must interface with the main computer using digital input/output channels. <JEU>

The communication subsystem must provide internal and external digital communications between the TT8 processor board, the communication transceiver modules, the other cluster vehicles, and the laptop serving as the ground station. <JEU>

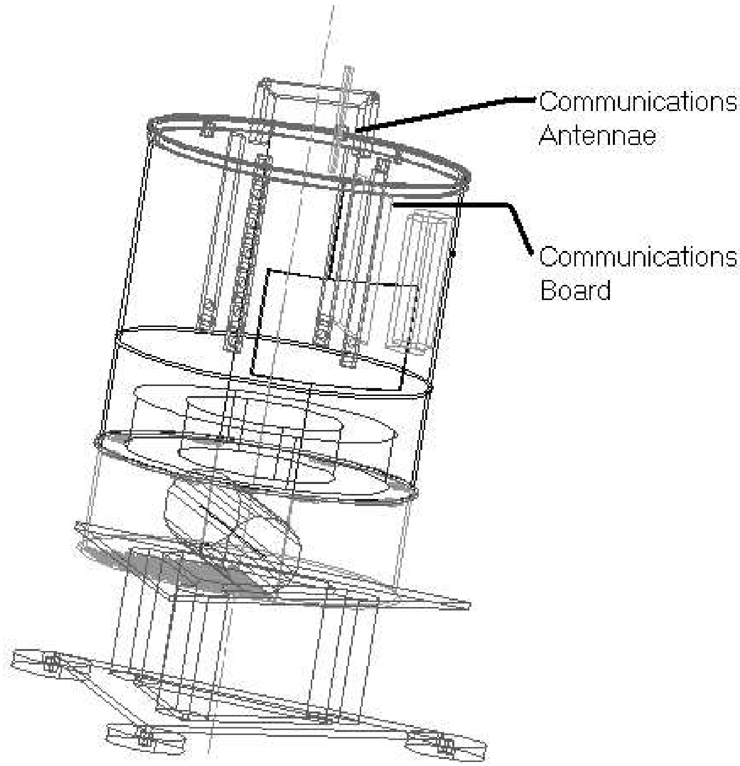


Figure 2.5.2: Systems Perspective of the Communications Subsystem
The communications subsystem hardware is comprised of the transceiver module (communications board) and the transmitting antenna, both of which are shown above in their current locations. <JEU>

2.5.2 Radio-Frequency Transceiver

2.5.2.1 Purpose Of Part

The radio-frequency transceiver is a piece of hardware that operates as a transmitter and receiver in the radio-frequency range. The transceiver is necessary to achieve wireless communications among the cluster of vehicles and between the cluster and the ground station. <JEU>

2.5.2.2 Part Interaction with Subsystem

The transceiver hardware includes an antenna and a circuit board module that interfaces with the main processor via digital Input/Output ports. The transceiver transmits and receives messages sent between vehicles and between the vehicles and the ground station. The digital information that is sent between the processor and the transceiver is interfaced with the software component of the subsystem. The software receives information from other subsystems, other vehicles, and the ground station, interprets and packages data packets, and then forwards the packets through the transceiver and the antenna for transmission. <JEU>

2.5.2.3 Discussion of Trades Analysis

2.5.2.3.1 Radio-Frequency Transceiver Modules Versus Wireless LAN Systems

The high-level hardware options for the radio-frequency transceiver selection are radio-frequency (RF) transceiver modules and Wireless LAN systems. Both systems operate using the radio-frequency spectrum. However, each system utilizes different hardware and protocols. <JEU>

By comparing the two available hardware options, a preliminary selection can be made. Recent internet searches suggest that on average, a LAN card costs more than the average RF transceiver module. The LAN system also requires a base station (the central LAN node, used in conjunction with the Ground Station) that would add a lot to the total hardware cost of the subsystem, as well as to the weight and volume that must be shipped to Denver. On average the size and weight of a LAN card is relatively greater than that of the RF. The LAN system has greater bandwidth and range than an RF transceiver. However, given that only telemetry, control, and health information are being transmitted within a short range, the extra bandwidth and range of the LAN seem redundant and wasteful especially when the extra cost, weight, and size is considered. The RF transceiver drains less power on average than the LAN system. Both systems appear to have the capacity to reject electromagnetic interference since both operate at frequencies around or above 1GHz. Both are easily interfaced; the LAN system consists of cards that can be readily interfaced with most modern systems, and the RF transceiver modules can be connected directly to the onboard processor. <JEU>

Given all of the above considerations, the best selection for the EMFFORCE system is the RF transceiver module. <JEU>

2.5.2.3.2 Radio-Frequency Transceiver Selection

Next, it's necessary to apply the previous metrics with respect to the available RF transceiver options. Two transceivers were chosen for comparison: the AeroComm AC5124C-10 and the RF Monolithics DR3000-1. The AC5124C-10 meets all requirements and comes with a development kit. However, it is rather expensive and the company is based in Europe. Furthermore, the power consumption is quite a bit more than that of the DR3000-1. The range, data rate, and frequency of the AC5124C-10 is far beyond what is required in the class, and doesn't make up for the extra cost, size, and weight. The DR3000-1, on the other hand, is familiar to many members of the staff who worked on the SPHERES project, is small, lightweight, inexpensive, and meets all other requirements. It also comes with a development kit. A model similar to the DR3000-1, the DR1012, is available for immediate prototyping use by the EMFFORCE Team. <JEU>

Upon consideration of the transceiver options, it is determined that the RF Monolithics DR3000-1 more closely matches the needs of our subsystem. <JEU>

2.5.2.4 Summary Of Options/Selection Criteria

Table 2.5.1 Summary of Options/Selection Criteria for Radio Frequency Transceiver

Metrics	AC5421C-10	DR3000-1
Size	2.65″x1.65″x0.20″	1”x1.5”
Power	0.35 W	0.04 W
Frequency	2.402 –2.478GHz	916.5 MHz
Weight	0.02 kg	Hardly any, < AC5124C-10
Data rate	115.2-882 kbps	115.2 kbps
Range	91m indoors	Short-range wireless
Ease of interface	Relatively Easy	Relatively Easy
Cost	~$245	$35
Availability	Company in Europe	DR1012 avail from SPHERES for prototyping
Complexity	OEM kit, not familiar	Development kit ready, familiar to staff, students

Based on the above metrics, it is obvious that the DR3000-1 is the best choice for the EMFFORCE communications subsystem. More detailed trades analysis is discussed in section 2.5.2.3. <JEU>

2.5.3 Communication Subsystem Architecture

2.5.3.1 Purpose Of Part

The communications subsystem architecture sets the message transmission and reception protocols. Determination of the architecture design is essential to the development of communication procedures and coding algorithms, and to the estimation of transmission rates. The protocols also address the needs of the other subsystems, particularly that of control. <JEU>

2.5.3.2 Part Interaction with Subsystem

The subsystem architecture links every vehicle to every other and links the cluster of vehicles to the Ground Station. Additionally, it ascertains the transmission protocols between them. In essence, the architecture is everything but the hardware. The hardware is merely the physical means by which the messages are propagated between the entities comprising the test bed. <JEU>

2.5.3.3 Discussion of Trades Analysis

There are three possibilities for the overall architecture design. Each assumes two communication channels. The first channel allows the Hub and Ground Station to communicate independently while the cluster communicates on the second channel to maintain autonomous formation control. <JEU>

2.5.3.3.1 Sequential transmission

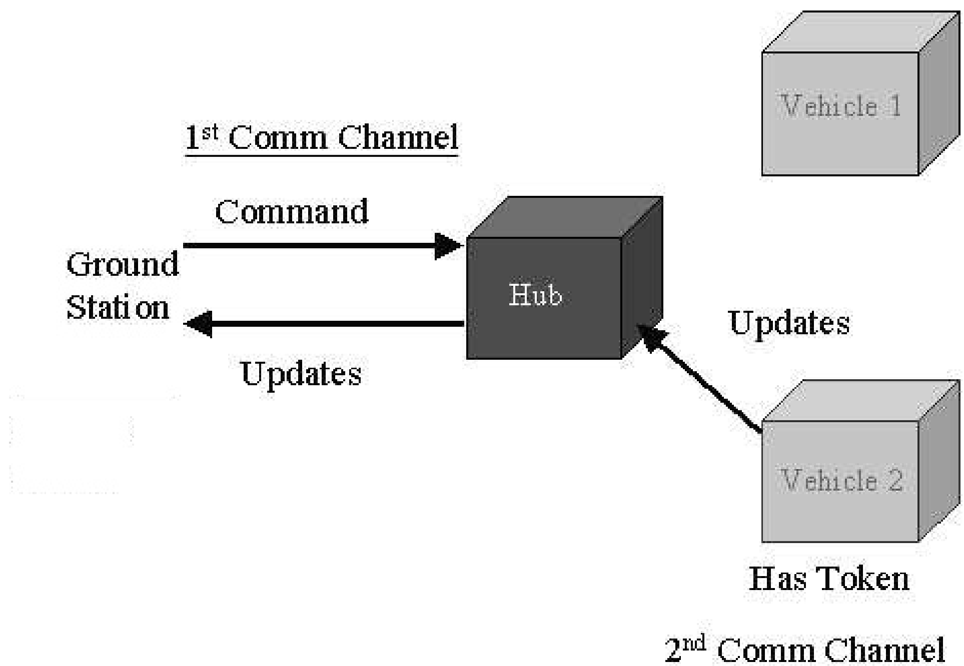


Figure 2.5.4: Sequential Architecture Diagram

Vehicle 2 has the token. The token allows it to communicate to the Hub on the second communication line while the Hub and Vehicle 1 remain silent, awaiting their turns. Once Vehicle 2 completes its communication, the token is passed to Vehicle 1. Vehicle 1 communicates with the Hub while the Hub and Vehicle 2 are silent. Once the control states and other updates have been collected, the Hub makes control calculations and communicates state updates to the Vehicles. Meanwhile, the Hub has direct communication with the ground station. <JEU>

The Sequential architecture assumes that the ground station communicates solely with the Hub. Each vehicle is built exactly the same, so the cluster still meets the interchangeability requirement discussed at the beginning of this document. <JEU>

As long as the transmission rate is sufficiently high, there should not be a problem with the time it takes for one communication cycle to occur. Due to the nature of the polling protocol, the

Sequential architecture requires excess communication code beyond that required for the second option, the Simultaneous architecture. <JEU>

The architecture appears to be reliable from a communications point of view; every vehicle is polled in sequence and there is plenty of opportunity to request retransmission. It is also relatively reliable from a controls perspective because only one vehicle makes the control calculation. As long as each communication channel maintains robustness and reliability, than every vehicle should be well coordinated with the cluster formation. Unfortunately, it also places restrictions on how the control law can be implemented. <JEU>

There also seems to be a lack of redundancy and an inability to correct for emergency situations. If the Hub makes a significant calculation error, there would be very few ways to adjust for it. If the Hub has to be switched for some reason, none of the other vehicles would have a recent set of state data to start from, assuming the chosen vehicle can recognize that it is now the new Hub. <JEU>

2.5.3.3.2 Simultaneous transmission

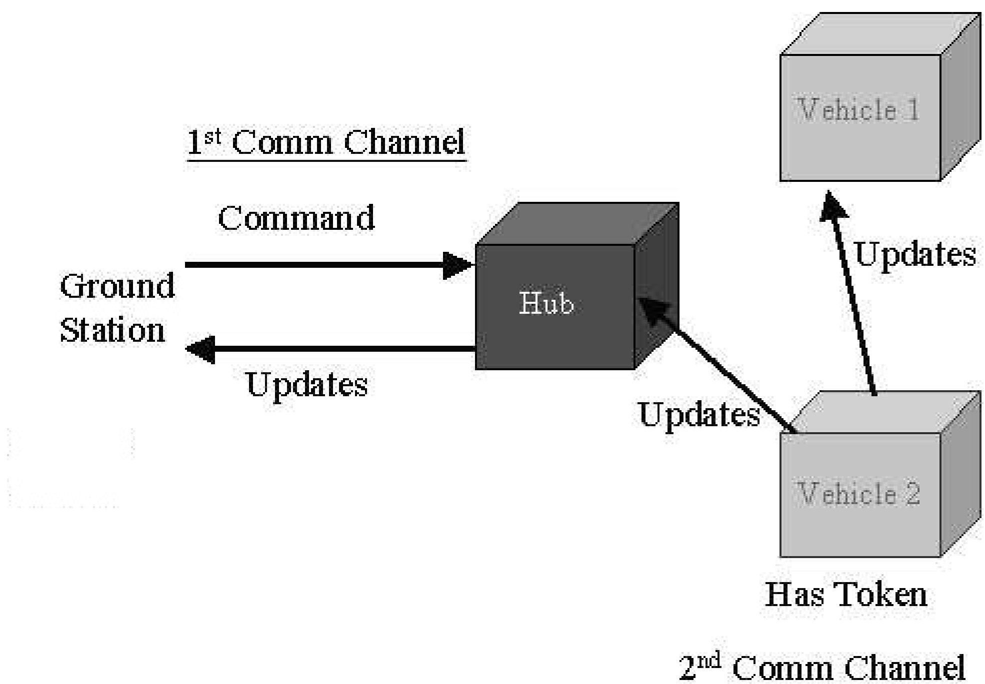


Figure 2.5.5: Simultaneous Architecture Diagram

Vehicle 2 has the token. The token allows it to communicate to the Hub and Vehicle 1 simultaneously on the second communication channel while the Hub and Vehicle 1 remain silent and await their turns. Once Vehicle 2 completes its communication, the token is passed to Vehicle 1. Vehicle 1 communicates with the Hub and Vehicle 2, who remain silent. The token is then passed to the Hub, which communicates its states to the Vehicles. Finally, all vehicles make independent control calculations and move accordingly. <JEU>

The Simultaneous architecture also assumes that the ground station communicates solely with the Hub. The main difference is that each vehicle inactively listens in to the first communication channel chatter in addition to being actively involved in the second communication channel interaction. Once again, each vehicle is built exactly the same, so the cluster still meets the interchangeability requirement discussed at the beginning of this document. <JEU>

The Simultaneous architecture is easier to implement than the Sequential, but is not as reliable. While there is some redundancy inherent in the communication line, the control subsystem is quite vulnerable. Should there be any significant mistake in the control calculation of any vehicle, there could be serious repercussions. If an error is perpetuated, the cluster may not be able to recover before a catastrophic failure occurs. With this design, there is the very real danger that the cluster formation could go out of control and possibly result in collisions. Any collision endangers the flat floor facility. <JEU>

The design allows for the Hub to be switched relatively easily; all vehicles listen in to both channels. However, the Hub isn't actively involved in maintaining the cluster formation, so it may not be useful to switch Hubs in an emergency situation. <JEU>

2.5.3.3.3 Hybrid transmission

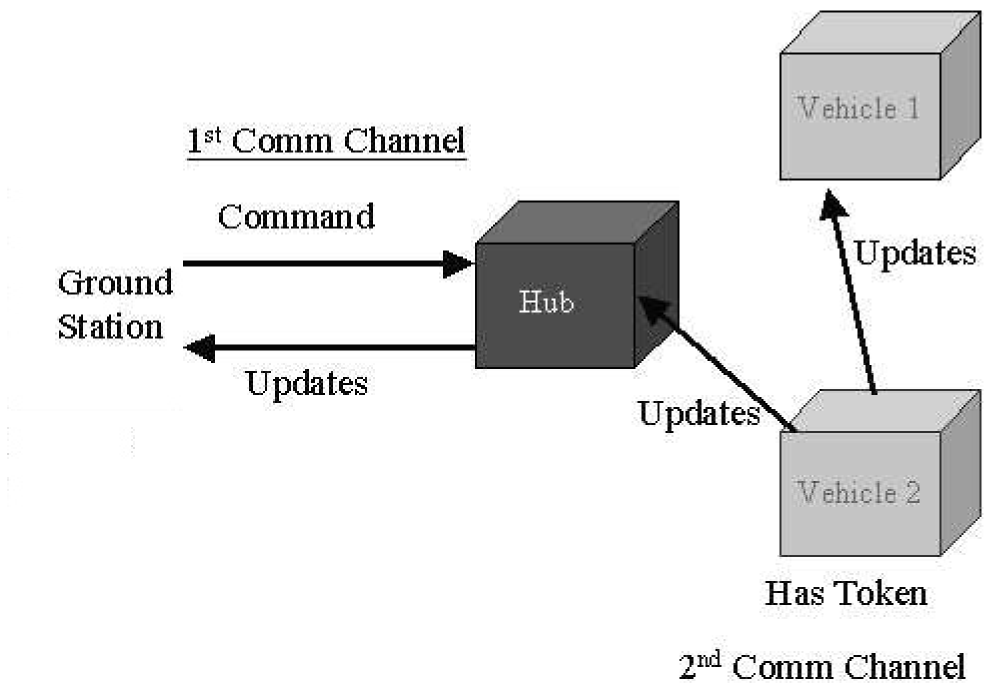


Figure 2.5.6: Hybrid Architecture Diagram

Vehicle 2 has the token. It communicates to the Hub and Vehicle 1 simultaneously on the second communication channel while the Hub and Vehicle 1 remain silent. The token is then passed to Vehicle 1, which communicates to the Hub and Vehicle 2, who remain silent. The hub obtains the token, determines the commanded control vector, and passes the new commands to Vehicle 1 and Vehicle 2. The Ground Station listens in on the second communication channel while actively communicating to the Hub on the first line. <JEU>

The Hybrid architecture assumes two communication lines. The first is for Ground-Hub interaction only. The second is for the cluster communication. All vehicles are equipped to listen in on both channels to meet the interchangeability requirement. <JEU>

This design enables an easy switch of Hubs as needed in emergency situations. All vehicles have the control states of the system, but only one, the Hub, is allowed to command a new state vector. The architecture also allows greater flexibility in communication and control design. The design does not place restrictions on how the control law can be implemented; the control law implementation can even change during the course of the test. However, there is a need for an increased transmission rate, as there is lot of information being passed around in a manner similar to the Sequential design. <JEU>

There is a high degree of redundancy in the system. Emergency situations can be dealt with swiftly. If there is a disagreement between any vehicles on the new state, steps can be taken to determine the correct new state. Similarly, there is plenty of opportunity for a vehicle to request retransmission of faulty data. <JEU>

2.5.3.4 Summary Of Options/Selection Criteria

Not applicable to the communications subsystem architecture. Please see discussion in section 2.5.3.3 for a comprehensive look at the architecture trades. <JEU>

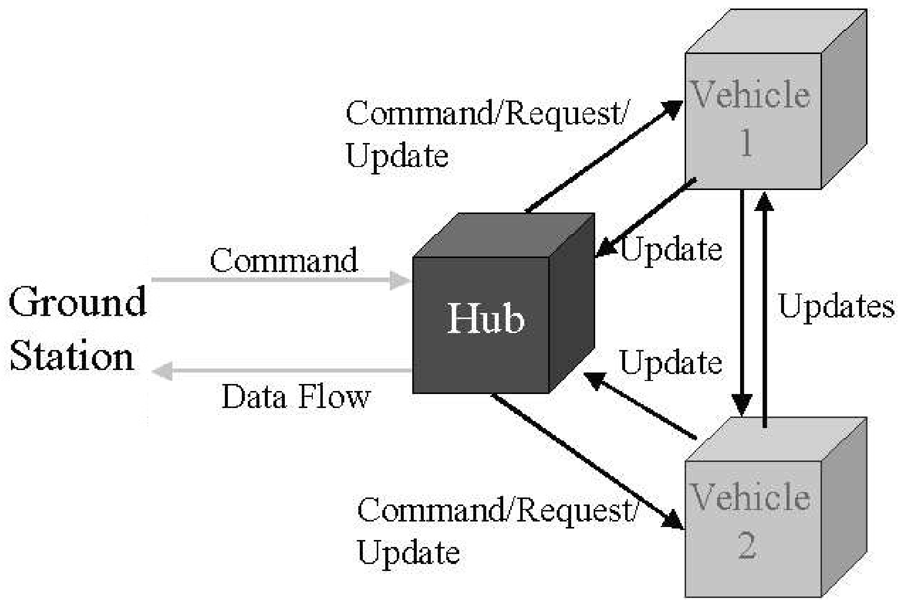


Figure 2.5.7: Current Architecture Design Diagram
The current design choice is the Hybrid architecture. <JEU>

Upon consideration of the architecture options, the communications team decided that the best choice for the EMFFORCE project is the Hybrid architecture. <JEU>

The current design assumes two separate communication channels. The first is for Ground-Hub interaction only. The second is for the cluster communication. All vehicles are equipped to listen in on both channels to meet the interchangeability requirement. The Ground Station initiates the active and inactive listening status of each vehicle upon system startup. The Hub is the only vehicle that actively uses both channels. If all necessary transmissions can be accommodated using one channel only, then the design will be compressed to utilize only one channel. <JEU>

Should an emergency situation arise and the Hub needs to be switched, the Ground Station can command another vehicle to take over as the Hub. Proper use of data framing ensures that the chosen vehicle does not filter out the command from the Ground Station. <JEU>

2.5.4 External Interfacing Needs

There are several external interfacing considerations for the communications subsystem. <JEU>

Foremost among these is the interface with the avionics subsystem. The transceiver module must be able to interface to the processor via digital I/O. Since the communications software must share space on the processor with avionics and control, there needs to be software modularity and a system of standardization for functions that are passed between modules. Since the subsystem requires two transceivers, there should be a sufficient number of I/O ports for both to ensure interchangeability among the vehicles. <JEU>

Communications must also interface with the control subsystem. There should be sufficient flexibility for the control subsystem to implement the control law in whatever manner it is deemed necessary. Once again, software modularity is a key external interfacing issue since communications must share processor space with control. <JEU>

The communications hardware must interface with the structural supports. <JEU>

The communications software must accept data from the metrology board before packaging the information into telemetry and state update packets. <JEU>

2.5.5 Budgets

Table 2.5.2 Budget Estimates for Communications Subsystem <JEU>

Part	Cost ($)	Mass (kg)	Power (W)
Transceiver	$35 each	0.02	0.04
Miscellaneous parts	$100	0.1	-
Replacements/repairs	$70		-
Total (per vehicle)	$275	0.24	0.08
Total (ground station)	$275	0.24	0.08
Total (system)	$1100	0.96	0.32

The communications team estimates that each transceiver will cost around $35 each (estimate provided by SPHERES). Miscellaneous parts expenditures will be approximately $100 per transceiver, with replacements and/or repairs estimated to be another $70 per transceiver. This figure allows for each transceiver to be replaced once during the lifetime of the project with a spare on hand during testing at the Denver Flat Floor facility. If each vehicle is equipped with two transceivers, this puts the estimated cost per vehicle at $275. The ground station is also equipped with two transceivers, and with the requisite equipment and replacement cost, the estimated cost for the ground station is also $275. With three vehicles and one ground station, the total for the system comes to $1100. <JEU>

Mass is computed similarly. Each transceiver is about 0.02kg. Miscellaneous parts are estimated to weigh on the order of 0.1kg. Replacements/repairs should not add mass to the totals. Thus, the communication subsystem will require 0.24kg per vehicle, 0.24kg for the ground station, giving a system total of 0.96kg. <JEU>

The only part currently recognized to draw any appreciable power is the transceiver. Each transceiver draws approximately 0.04W. With two transceivers per vehicle, this gives a total vehicle power draw of 0.08W, the ground station drawing the same. Thus, the total system power draw is 0.32W. <JEU>

2.5.6 Conclusion

The communications subsystem is comprised of hardware, software, and an architecture that links every vehicle to every other one and to the Ground Station. The hardware has been chosen to be the RF Monolithics DR3000-1 transceiver module. The processor for the communications subsystem is to be shared amongst avionics, control, and communications. Software unique to the implementation of the subsystem is to be written by the students involved. As discussed above, the architecture has been chosen to be the Hybrid architecture. <JEU>

For a detailed look at further design considerations, please consult the Appendices. Other design considerations include: data framing, communication channel usage, transmission rate estimation, error detection and correction, channel coding, and automatic repeat request protocols. <JEU>

A Communications System utilizes technology to develop: the overall system architecture; hardware design, development, or selection; software design and development; and the interfacing with other subsystems, with the end goal being predictable and robust message transmission and reception. <JEU>

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2.6 Avionics

2.6.1 Subsystem Overview

The avionics subsystem manages all electronic resources within a single vehicle of the EMFFORCE system. The main focus of the avionics subsystem is to run the control algorithm written by the Control Team. Specifically, the avionics subsystem receives input from metrology sensors and uses the Control Team's algorithm to translate them into electronic signals, which command current to the actuators (electromagnet, EM, and reaction wheel assembly, RWA). <MAS>

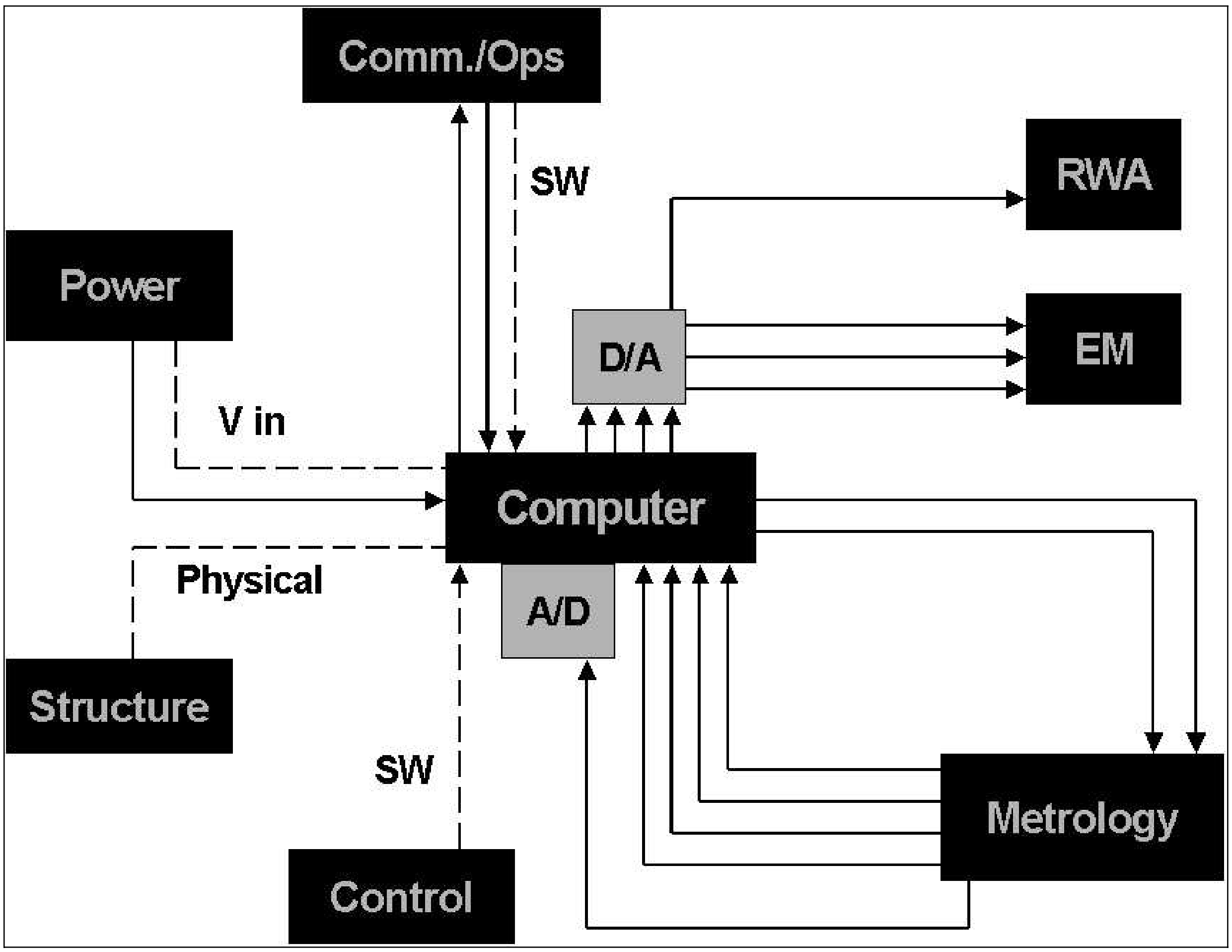

Figure 2.6.1: Avionics Subsystem Diagram

Figure 2.6.1 is a block diagram of the avionics subsystem. It shows both the overall electronic layout of an EMFFORCE vehicle and additional physical interactions of the avionics subsystem with other subsystems. The solid arrows represent data or information flow over electronic wiring; dashed lines indicate non-electronic connections (e.g. power supply, structural interface, and software applications). Each connection is explained in full in section 2.6.6 (avionics external interfacing needs).

The central on-board vehicle computer is the main part of the avionics subsystems. Avionics also includes software, software and hardware support, and other hardware. <MAS>

2.6.2 On-board Computer: Tattletale Model 8.

2.6.2.1 Purpose Of Part

The purpose of the on-board computer is to manage all electronic resources and perform all central calculations for an EMFFORCE vehicle. The on-board computer must allocate manage processing time and data storage space among the control, metrology, communications, EM, RWA, avionics, and even power subsystems. However, the primary task of the computer is to bring in data gathered by the metrology system, run the control loop developed by the control team, and send actuation commands to the EM and RWA subsystems. <MAS>

2.6.2.2 Part Interaction with Subsystem

The on-board computer is the main physical component of the avionics subsystem as well as the “brain” of the entire vehicle. The computer is the hardware bed for the software which organizes computational vehicle processes; the remaining parts of the subsystem must interact with the computer through as software, through a prototyping board or input/output pins located on the computer circuit board. <MAS>

2.6.2.3 Discussion of Trades Analysis

The on-board computer for the EMFFORCE vehicles must adequately meet all the avionics needs for the system to operate. The avionics needs include processing power, data interfaces (digital and analog), support interfaces (structure and power), working memory capacity, and data storage capacity. In addition to satisfying the technical requirements, the EMFFORCE on-board computer must satisfy system constraints, including mass, power consumption, cost and availability, ease of use by the EMFFORCE team, and room for expansion in future applications. <MAS>

Because the time allotted to finding a computer was less than that required by a thorough search of all small computers, the Avionics Team narrowed the field of on-board computer options to those available within the MIT Space Systems Laboratory (SSL). Previous research teams in the SSL have spent considerable time and effort working with small processors ideal for systems similar to EMFFORCE.

The three computers available in the SSL are the self-contained Tattletale Model 8 (TT8) by Onset Computer Corporation, a Motorola C40 series model, and a 6701 model by Sundance, on a SMT 375 board. <MAS>

2.6.2.3.1 Central Processor

The function of the central processor is to run the algorithm written by the controls team. For the EMFFORCE system to perform correctly, the control algorithm must run in real-time. This requires a minimum update frequency of the control loop, which includes at the very least control calculations, actuation instructions, and a matrix describing the state of the EMFFORCE system. The processing power required for the system depends on the number of calculations that must be made in each iteration of the control loop, and the control loop update frequency. <MAS>

Without knowing the control algorithm, the Avionics Team can make only an order-of-magnitude estimate of the control loop calculation requirements. That number is on the order of 1000 or fewer calculations per iteration, updating at a rate of approximately 50 Hz, for a total of approximately 50K calculations per second. <MAS>

Each of the three computers considered by the Avionics Team processes information at a rate well above 50K calculations per second. The weakest computer, the Tattletale, processes approximately 4 million instructions per second (MIPS); the C40 and 6701 process information at 13 and 250 times the rate of the Tattletale, respectively. In fact, through closer inspection the Avionics Team determined that the 6701 holds much more processing power beyond the EMFFORCE system requirements. This extra capability adds weight and size to the computer that violates constraints set on vehicle mass and causes concern about power draw. Therefore, the 6701 was eliminated first from the computer options because it was unsuitable for the project needs and constraints. <MAS>

2.6.2.3.2 Data Interfaces

The data interfaces are introduced in section 2.6.2.2 [Part Interaction with Subsystem], and detailed in section 2.6.6 [External Interfacing Needs]. However, a summary of the data traffic needs for the EMFFORCE vehicle computer is as follows:

- 6+ digital inputs (4x metrology, 2x communications, 1x power; health)
- 3 digital outputs (2x metrology, 2x communications)
- 1-2 analog inputs (metrology)
- 4 analog outputs (actuators)

<MAS>

The Tattletale includes 25 digital input/output ports; eight of these may be reserved for analog inputs, and 14 may be used for timing purposes. However, the Tattletale requires an external D/A converter, because it does not handle analog outputs. The C40 includes only digital data interfaces, and would require both external D/A and A/D converters. <MAS>

2.6.2.3.3 Support Interfaces

The support interfaces for the on-board computer include the power supply, the physical location and position of the computer within the vehicle, and the program upload/download port that connects to the Operations computer. <MAS>

Both the Tattletale and the C40 have a readily accessible power connection and can easily connect to a structural frame. However, the Tattletale is small (~5cm x 7.6cm x 1.27cm) and light, making it more versatile for positioning within the vehicle frame; in contrast, the C40 is built up on both faces of its circuit board, which may cause difficulty when trying to position it for easy access within the vehicle frame. <MAS>

2.6.2.3.4 Working Memory Capacity (RAM)

The principle function of working memory in the EMFFORCE vehicle computer is to temporarily store the variables used in control calculations. The minimum storage must hold the matrix of position and motion variables describing the state of the system as well as all forces and moments applied to the system, and other variables created in the calculation process. A conservative (high) estimate of the memory needed for storing variables is on the order of 16kB of memory. Both the Tattletale and the C40 have well over 16kB memory (256kB and 16MB, respectively). <MAS>

2.6.2.3.5 Data Storage Capacity (ROM)

The permanent or semi-permanent memory in the EMFFORCE vehicle computer primarily serves as storage for system-test program files, which run during vehicle operation. The operator loads at least one test program onto each vehicle's computer, and the test program automatically executes after power-up and initialization of the computer. Assuming a maximum of 1000 lines of code (LOC) for one test program, a conservative estimate of required storage capacity is on the order of 8kB of semi-permanent memory. <MAS>

The Tattletale and C40 computers use FlashMemory, a semi-permanent re-writeable "ROM", as storage space. This allows the EMFFORCE operators to load different test programs to the computer without having to hold all programs in the memory simultaneously. Both the Tattletale and C40 have well over 8kB FlashMemory: 256kB and 640 kB respectively. <MAS>

2.6.2.3.6 Constraint Satisfaction

The budget constraints were the deciding factor in the selection of a single on-board computer for the EMFFORCE vehicles. The most important constraint on the EMFFORCE system is the minimization of mass; only slightly less critical are the cost, ease of use, and availability of the system parts. It is also important that the EMFFORCE system retain the ability to expand and grow into a more complex system in the future, but this goal is secondary to the primary task of demonstrating formation flight. <MAS>

The Tattletale Model 8 satisfies all of these constraints except one. Its mass is well under 0.1 kg, there are user packages (including hardware and software) available in multiple common computer languages, and the MIT SSL has donated four Tattletale computers to the EMFFORCE project free of charge. The cost to repair one Tattletale is on the order of $60; a completely new TT8 computer costs $500. However, the Tattletale does not allow for extensive expansion. Because of its design, the Tattletale processor would have to perform extra calculations to handle floating-point values (see *, Table 2.6.1); these extra calculations mean the EMFFORCE system may run the Tattletale close to its processing limit. Although it satisfies the current EMFFORCE system requirements, the Tattletale might not be sufficient for a more complex application. <MAS>

The C40 has enough processing power to allow for expansion of the EMFFORCE project. However, it lacks an internal A/D signal converter, implying the Avionics Team would need to buy, build, and test more hardware separately. A more important aspect of the C40 is that the version available in the MIT SSL is a custom-fabricated model. Team members of previous MIT SSL projects put together the C40 board in the lab; the board would be virtually impossible for the Avionics Team to reproduce, and prohibitively expensive to order. The C40 would be extremely time-consuming to replicate and repair; it is also heavier and more awkward to work with than the Tattletale. The cost in dollars, time, and effort to use the C40 is not worth its expansion capability. <MAS>

2.6.2.4 Summary of Options/Selection Criteria (Table)

The Avionics Team has selected the Tattletale Model 8 as the central on-board computer of the EMFFORCE vehicles. The Tattletale has adequate processing power, interfaces for data and support, working memory, and data storage to meet the EMFFORCE system needs. It is the easiest to use, and has the lowest mass, power draw, and cost of any computer examined by the Avionics Team. The Tattletale 8 is a relatively low-power computer whose capabilities may not accommodate more complex applications, but the Avionics Team will plan for possible future expansion to a different architecture by using standardized cables and interfacing accessories in hopes that another commercial product will be compatible. <MAS>

Table 2.6.1: On-Board Computer Selection

Feature	Needs	TT8	C40	6701
Calculation and Speed		4 MIPS* 16 MHz	50 MFLOPS*	1 GFLOPS* 167 MHz
I/O	4D, 1A in 1D, 4A out	25D I/O 8A, 14 timing	64 D parallel I/O	
RAM	~16 kB	256 kB	16 MB	16 MB
ROM	~8 kB	256 kB	640 kB	512 kB
Mass	Low	0.028 kg		
Power	Low	1.8 Watts		
Cost	Low	(~$500)	Custom (High)	High
Usability	Easy	Easy	Hard	Medium
Expandability	Fair	Poor	Fair	Good

Difference in units: the TT8 operates in fixed-point calculations only, which are measured in Instructions Per Second. The C40 and 6701 operate in floating-point calculations, which are measured in FLoating-point Operations Per Second. The TT8 cannot work directly with floating-point values; it must convert data to a fixed-point simulation to make calculations and then convert the data back to floating-point values.

2.6.3 Software Environment and Code

2.6.3.1 Purpose of Part

2.6.3.1.1 Software Code

The purpose of the code to be developed by the Avionics Team is to manage the interfacing between vehicle subsystems. The code should be capable of including system updates from the various subsystems and should also route the newly updated information to the subsystems it affects. It also is designed in simple modular manner such that it can include any software written by other subsystems (e.g. communications, controls). <SJS>

2.6.3.1.2 Coding Environment

The purpose of the coding environment is to give the EMFFORCE team members a standardized coding program through which they can create and compile any written code. It also allows for the loading of code onto the Tattletale computer. <SJS>

2.6.3.2 Part Interaction with Subsystem

2.6.3.2.1 Part Interaction: Software Code

The software code is written by the Avionics Team and is then loaded onto the computer board utilizing the coding environments described below. The written code is what manages the information gathered from various subsystems and allows the computer to process the data gathered by the metrology system, to run the control loop developed by the control team, and to send actuation commands to the EM and RWA subsystems. Software code is what allows for system updates and the relay of such updates to the relevant subsystem parts. <SJS>

2.6.3.2.2 Part Interaction: Coding Environment

The coding environment compiles the software code written by the team members. The environment interacts with both the code and the computer; after the environment compiles the code, the code is then transferred to the computer. <SJS>

2.6.3.3 Discussion of Trades Analysis

2.6.3.3.1 Trades of the Coding Environment

The Avionics Team's computer selection included two options for software support: the BASIC package or the C package. In fact, commercially packaged software support for the Tattletale Model 8 was one of its major benefits in usability [2.6.2.3.6-Para.2]. <MAS>

There is a vast consumer base for the C language – much larger than that for BASIC. From this fact stem the two major benefits of using C for the EMFFORCE project: team member familiarity with the language and compatibility with other teams' code. Six to eight members of the EMFFORCE project team will be writing code for the system: the Avionics, Communications, Control, and possibly Metrology Teams. The majority of these team members are familiar with or experienced using the C language. Also, the Control Team uses Matlab Simulink to model the control loop for their subsystem; Simulink can map directly to program code if necessary, and the language it writes in is C. For these reasons, the obvious design choice for computer language is C. <MAS>

The SPHERES project also programmed the TT8 computer in C. The Avionics Team, therefore, decided to use the coding environment software already purchased by SPHERES. The C software support packages for the Tattletale computer include two programs: Metrowerks CodeWarrior for program development and compiling, and Motocross for loading to and running tests on the Tattletale. It is also important to utilize these software environments because it has proven its reliability in the SPHERES project. The Avionics Team has developed some low-level representative tests for the Tattletale using these tools. <MAS, SJS>

2.6.3.3.2 Trades of Software: Creation of Code and Utilizing Code Resources

One must weigh the consequences of writing code from scratch vs. utilizing previously written code. While much of the EMFFORCE code will be project-specific and must be written by the project team members, some of the avionics responsibilities involve tasks for which other code already exists. <SJS>

The usage of previously written code should be considered on a case-by-case basis (a trade analysis must be implemented before each coding decision is made). The Avionics Team must first decide what needs to be accomplished, and what the best method is to accomplish the specific task. <SJS>

The Avionics Team is studying various programs written by members of the SPHERES project to determine if any of this code suits the EMFFORCE project needs. The studying of the code gives the Avionics Team a starting point for writing the code for EMFFORCE. Example software code furthers the learning process of TT8 coding. Also, the time to complete the software design can be decreased if the Avionics Team is able to reuse any code that is both functional and applies to the scope of the EMFFORCE project. Therefore, while the vast majority of the code must be original because it is project specific, code written by another author has been both proven reliable in the past and also can often save time when used with caution. <SJS>

2.6.4 Hardware Support: DAC

2.6.4.1 Purpose of Part

The digital-to-analog converter (DAC) will translate selected digital output signals from the Tattletale into analog signals. This is necessary because although the Tattletale has an internal analog-to-digital converter (ADC) for incoming signals, it does not have a corresponding digital-to-analog converter (DAC) for output signals. Therefore, the Avionics Team must construct or obtain a DAC to produce these signals. <MAS>

2.6.4.2 Part Interaction with Subsystem

The DAC requires a coded procedure modeling a pulse-width modulation (PWM) process, simulating an analog signal with bursts of digital data. However, a DAC is also a small chip which attaches to an electronics board; in this case to the Tattletale. This implies both physical and software interface between the DAC and the on-board computer. <MAS>

2.6.4.3 Discussion of Trades Analysis

The detailed analysis concerning the DAC will occur over the summer of 2002. Research needs to be done on physical vs. software needs, and the Avionics Team needs to check for possible in-house supplies. <MAS>

2.6.5 Subsystem-Specific Electronics Boards

2.6.5.1 Purpose of Part

Although the on-board computer performs all the main control calculations for each EMFFORCE vehicle, there are some processes that are handled outside the central processor. For example, the metrology system may in fact pre-process the data from its sensors, and feed only position and rate information to the avionics subsystem for use in the control software. The power subsystem requires a voltage regulator to distribute its power among the other subsystems; this regulator requires a baseboard. The EM and RWA subsystems may require circuit boards to convert a signal instruction into the actual current they receive. The Avionics Team is responsible for the fabrication of these boards. <MAS>

2.6.5.2 Part Interaction with Subsystem

If any subsystem outside avionics requires its own circuit board, whether for processing needs or as a physical bed for other electronic parts, this circuit board will form the interface between the on-board computer and that subsystem. There may be data transmission or other resource management involved in the connection. It is also possible that an additional subsystem board may reduce the number of I/O ports required in the Tattletale computer. <MAS>

2.6.5.3 Discussion of Trades Analysis

The design is not finalized in all subsystems which may preprocess signals. Therefore, it is not certain which approach will be best for obtaining additional customized circuit boards. The detailed analysis concerning additional electronics boards will occur over the summer of 2002. This includes drawing circuit schematics and ordering original boards for fabrication. However, the Avionics Team is prepared to obtain electronics for up to four additional subsystems at an estimated cost of approximately $1000 per original board. The EMFFORCE system will require several copies of each board: one per vehicle plus sufficient replacement stock. The cost estimate for these boards is therefore approximately $6500. <MAS>

2.6.6 External Interfacing Needs

The avionics subsystem must interface with all other subsystems. Figure 2.6.1 describes the avionics subsystem's interfaces with the system as a whole. Through discussions with each of the other subsystem teams, the Avionics Team has determined that the subsystem needs to interact with each of the other subsystems as explained below: <SJS>

Power. There will be one digital signal input to the computer for a health/low battery indicator. There is also a physical connection that supplies the necessary voltage for Tattletale processing capabilities. <SJS>

Controls. No input/output interfacing is necessary because the controls subsystem consists of software loaded onto the computer. <SJS>

Reaction Wheel Assembly (RWA). One analog actuator will be needed to control the reaction wheel assembly. <SJS>

Electromagnet. The current design of the electromagnet is in Y-pole configuration. For a Y-pole, 3 analog actuation signals will be outputs from the computer (one to each leg of the magnet). <SJS>

Metrology. The design of the metrology subsystem includes ultrasonic sensing for position, infrared sensing for timing, and a rate gyro for determination of angular rate.

- Ultrasonic: Three receivers will be needed; these are all digital inputs to the computer. One digital transmitter (an output) is also needed.
- Rate Gyro: The computer will need to take in one analog signal specifying the angular velocity of the rate gyro. If accelerometers are part of the final design choice, then 2 analog inputs will also be routed from the accelerometers to the computer.
- Infrared: Infrared will be used for timing purposes. One receiver (input) and one transmitter (output), both digital, will be needed for the IR timing. <SJS>

Comm./Ops. Digital inputs and outputs are needed to accomplish the 2-way intervehicle data exchange as described in Section 2.5. <SJS>

Structure. Structure packages the components within a vehicle. The structure will physically interface with the avionics subsystem. That is, the structure system designs casing and supports to hold the TT8 computer and any additional boards. <SJS>

2.6.7 Budgets

Like other EMFFORCE teams, the Avionics Team is responsible for tracking its estimated budgets for money, power, and mass and relaying this information to the systems team. More accurate budgets will be established once the design is further decided upon. For this reason, the avionics estimates are being frequently updated. Table 2.6.2 lists the current budget estimates (as of 12 May 2002) for the avionics microgroup team. <SJS>

Table 2.6.2: Estimated avionics Budgets.

Part	Cost ($)	Power (W)	Mass (kg)
TT8 (2 per vehicle)	1050	3.6	0.057
Original Subsystem Boards	4000	--	4 x 0.028
Additional Subsystem Boards	2500	--	--
TOTAL	7550	>3.6	0.169

This table shows the Avionics Team's budgeting estimates as of 12 May 2002. Subsystem circuit boards will be designed during the CDR period; therefore, details concerning power draw and masses are not yet known. Cost is total system cost while power and mass estimates are per vehicle.

2.6.7.1 Cost Budgets

The Avionics Team believes that one Motorola TT8 computer per vehicle should provide sufficient processor capabilities. Therefore, our current design concept only includes one TT8 per vehicle. The Avionics Team, however, has decided upon the use of two TT8 computers per vehicle if it is found that one TT8 is no longer sufficient. <SJS>

The SPHERES project provided four working Motorola TT8 computers for use on our vehicles. Assuming a 3-vehicle configuration, the Avionics Team will need to purchase 2 more TT8 computers if it is determined that 2 TT8s will be used on every vehicle. Minor repair of TT8 computers cost approximately $60; $500 dollars has been allocated for TT8 maintenance and repair. <SJS>

During Fall 2002, boards will need to be designed and custom-ordered for the metrology, communication, power, and actuation subsystems. Because this design process has not yet begun, only rough cost estimates can be given for the boards. Original boards will cost approximately $1000 apiece while the duplicate boards (8 boards) should cost somewhere in the $200-$400 range each. <SJS>

2.6.7.2 Power Budgets

The Motorola TT8 computers require supplied power. The least favorable scenario in terms of power consumption would be if two TT8s were used per vehicle. In this case, the double TT8 combination would require a total of 3.6W per vehicle. <SJS>

Project EMFFORCE has not yet reached the point where the individual subsystem boards have been designed; therefore, the power draw for such boards has yet to be determined. The Avionics Team will have a more complete power draw estimate during the fall term after the board designs have been completed.. <SJS>

2.6.7.3 Mass Budgets

A single TT8 computer has a mass of 0.028 kg (1.0 oz). If two Tattletales are required, the mass of the computer per vehicle will be 0.058 kg. As explained in section 2.6.7.2, the individual subsystem boards have not been designed. Therefore, the Avionics Team is uncertain of the mass of each of these boards. However, for the purpose of system mass budgets the Avionics Team estimates each additional board will have mass of 0.028kg (1.0 oz) or less. The Avionics Team's estimate of four external subsystem boards brings the total electronics mass to approximately 0.169kg. <SJS, MAS>

2.6.8 Conclusion

The avionics subsystem is the administrator of the EMFFORCE system. It incorporates both hardware and software, and interfaces with every other subsystem, to organize all electronic processes on a single vehicle. The EMFFORCE central on-board computer, the Tattletale Model 8, will handle all central computing for the system. The software and software support will manage all resources supplied by the computer; the external hardware support and additional electronics will preprocess and reformat both incoming and outgoing data for the Tattletale. Through these operations the avionics subsystem will manage communications and metrology data, as well as the current supplied by the power subsystem, to control each EMFFORCE vehicle. <MAS>

2.7 Power

2.7.1 Subsystem Overview

The power subsystem is responsible for providing the necessary voltages and currents to each of the other subsystems. The complete subsystem includes batteries, voltage regulators, amplifiers, and on/off switches. The design presented here will be for a single vehicle – each vehicle on the testbed will have an identical power subsystem. Since power is the underlying force driving the entire system, its design and functionality is crucial to the overall mission success. <TAS>

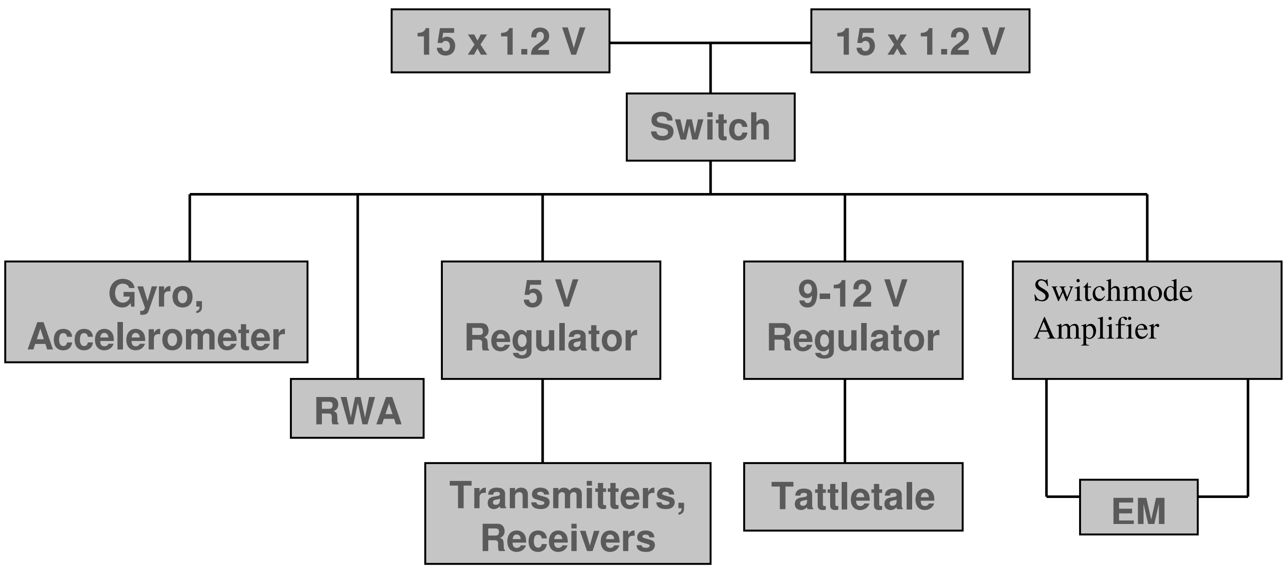

Figure 2.7.1: Power Concept Flowchart
This diagram shows the interfaces between the power supply (1.2 V batteries) and the individual subsystem components. The gyro, accelerometer, and reaction wheel assembly will connect directly to the power supply. The on-board transmitters, receivers, and Tattletale processors will require voltage regulators to buffer the incoming power. Finally, the current through the electromagnet will be controlled with a switchmode amplifier. Each of these components will be further explained in this section. <TAS>

The requirements pertaining to the power subsystem per the Requirements Document are as follows:

- The power supply must be completely contained within the structure [7.2.2.2]. This implies that the power must come from an on-board source such as batteries or solar cells. As explained in section 2.7.2, the final choice is to use rechargeable batteries. <TAS>
- The subsystem must provide sustained power for a minimum of thirty minutes [7.2.1.2]. This will primarily affect the battery selection, since battery chemistry must be chosen to provide the required voltage and current levels for this length of time. <TAS>
- Battery power should be able to be recharged in 30 minutes [7.2.2.1]. This implies that any batteries used must be rechargeable. Due to the limited availability of rechargeable batteries with this capability; this requirement will be slightly amended. An alternative way to satisfy

the intent of this requirement is to have extra battery packs on hand during testing. For example, if a battery pack supplies power for thirty minutes but requires one hour to recharge, then having two battery packs on hand will allow testing to be completed without having to wait for batteries to finish charging. <TAS>

2.7.2 Batteries

2.7.2.1 Purpose of Part

The purpose of the batteries is to provide the source of power to each vehicle. By wiring combinations of batteries in series and parallel, adequate voltages and currents will be provided. <TAS>

2.7.2.2 Interfacing

The batteries will have three different interfaces; connect directly with components from other subsystems, connect to voltage regulators, or connect to a switchmode amplifier. The batteries will also be connected to a main on/off switch, which will allow outside operators to turn the main power on or off. <TAS>

2.7.2.3 Discussion of Trade Analysis

The first trade analysis was conducted to decide between using solar cells or rechargeable batteries. The current requirements for the system are estimated to be on the order of 5 to 7 amps, this means that using solar power is infeasible. The best available solar cells provide currents on the order of milliamps to a maximum of one amp. Also, solar cells are very expensive and often have a long procurement time. For these reasons, the Power Team ruled out solar power as a possibility for the EMFFORCE testbed. <TAS>

After choosing rechargeable batteries, the next trade analysis was deciding which battery chemistry to use. Given the voltage and current demands and using prior knowledge about battery chemistries, the three initial battery types that were considered were Lithium Ion (Li-Ion), Nickel Cadmium (NiCd), and Nickel Metal Hydride (NiMH). Li-Ion batteries offer a high energy density; however, they have low current discharge rates. The highest discharge rate that could be found was 2 amps, which is inadequate for this system. NiCd batteries offer an adequate discharge rate, but they lose efficiency at the high current draws we expect for our system. This would mean the system would require more batteries to supply a given voltage, which would add to the overall mass. The ideal battery chemistry was found to be NiMH. These batteries offer high energy densities, fast discharge rates, and excellent efficiencies at high current draws. They can provide the necessary power for the system at acceptable mass levels. The final downselect for battery chemistry was therefore NiMH. <TAS>

2.7.2.4 Summary Of Options / Selection Criteria

Before choosing the specific type of NiMH battery to use, a good estimate of the power requirements for each subsystem is necessary. The estimates given will be the requirements per vehicle. <TAS>

Using estimates obtained from the previous SPHERES and ARGOS projects, the gyros will each require 0.36 Watts, and the accelerometers will each require 0.18 W. These should operate in the range of 12-18 Volts. The metrology sonic and IR sensors together will require 0.55 W at 3-5 V. These components are expected to draw this much power throughout the duration of the tests. <TAS>

The maximum power draw for the reaction wheel is estimated at ~13 W at 12-18 V. One thing to note is that the reaction wheel is not expected to draw this much power throughout the duration of the tests. At low spin rates, the reaction wheel will require very little power. It will only draw 13 W during complex spin-up maneuvers and for limited amounts of time. However, for the purposes of conducting a conservative analysis, a power draw of 13 W will be assumed throughout the entire testing period. As the system is further designed and built, more accurate estimates for the RW power draw will be obtained. <TAS>

The TT8 Tattletale processor will draw no more than 2 W at 9-12 V. This includes the power draw of the on-board communications transceivers that will be connected to the TT8. The current design calls for the use of only one TT8 per vehicle; however, it is possible that the final design will use two. <TAS>

A proof of concept test for the electromagnet was performed, during which each EM drew a current of 3-4 amps. However, the EM subsystem team has proposed a final current draw of up to 7 amps. Assuming a 12 V current draw, this puts the power draw for the EM at around 84 W. Like the reaction wheel, the maximum power draw for the EM would not be sustained throughout the entire test; however, a constant 84 W draw will be used to make a simple, conservative estimate. <TAS>

The following table summarizes the power requirements for each subsystem component. This is the total power requirement per vehicle.

Table 2.7.1: Power Requirement Estimates

Subsystem Component	Voltage (V)	Power (W)
Gyro	12-18	<1
Accelerometer	12-18	<1
Sonic, IR Sensors	3-5	<1
Reaction Wheel	12-18	13
Tattletale Processor	9-12	2
Electromagnet	12	84
	TOTAL:	**~100**

This table shows the preliminary power estimates for each vehicle. These values will be used to narrow down the appropriate NiMH battery type to use in the power system. <TAS>

One final subsystem component that may require power is an on-board air compressor. This was not included in the power estimates here because it is undetermined whether or not one will actually be used. If the air compressor is used, it will dramatically increase the power requirements of the overall system. This would change the choice of battery and the individual battery configurations. For now, it will be assumed that a compressor will not be used. If it turns out that a compressor will definitely be used, the power subsystem will be redesigned to accommodate this. This may include adding more battery packs in series to produce a higher current draw, or it could mean switching to a battery with a higher energy density. Both of these solutions would result in adding more mass to the power subsystem. <TAS>

The next step in the design process is selecting the specific battery type to be used. The dominating power user is the electromagnet. The current draw for most of the other components can be assumed to be negligible. Assuming a current draw of up to 7 amps for a period of 30 minutes, this requires an energy capacity of 3.5 Amp-hours (Ah) from the batteries. From here an appropriate battery type can be selected. Figure 2.7.1 shows a sample of possible battery types. <TAS>

A preliminary search on the Panasonic website (http://www.panasonic.com) yielded a few suitable battery types. The table below summarizes the results of the search:

Table 2.7.2: Suitable NiMH Battery Types

Model No.	**Voltage (V)**	**Energy Capacity (Ah)**	**Weight (g)**
HHR200SCP	1.2	1.9	42
HHR300SCP	1.2	2.8	55
HHR650D	1.2	6.5	170

This table shows three batteries from the Panasonic website that would satisfy the power requirements for the system. <TAS>

Depending on the finalized power requirements of the system, these batteries can be wired in combination of series and parallel to produce the necessary voltage and currents. For the preliminary power design, the HHR200SCP batteries can be wired into "packs." Each pack would contain 15 batteries in parallel, producing an 18-volt battery pack with an energy capacity of 1.9 Ah. To bring the current capacity up to acceptable levels, two packs can be wired in parallel, bringing the total capacity to 3.8 Ah at 18 volts. <TAS>

The final battery selection will be made after the requirements for each subsystem component are finalized. The battery selection will be one in which an adequate amount of power is provided at a minimum mass. Some other promising NiMH battery types are manufactured by GP Batteries (http://www.gpbatteries.com); their newest model has a capacity of 1.8 Ah, voltage of 1.2 V, and weighs 26 grams. They are also fairly inexpensive and thus would be an excellent candidate for the power subsystem. <TAS>

Finally, battery chargers will have to be purchased. Some chargers will recharge up to four batteries in about an hour, but they are fairly expensive. Chargers that recharge slower (usually overnight) are less expensive but will result in needing more complete sets of batteries on hand during testing. Determining the lowest cost solution will depend on knowing exactly how many batteries are needed per vehicle and how long they will last. <TAS>

2.7.2.5 External Interfacing Needs

As mentioned before, some of the subsystem components contain internal voltage regulators and will be directly connected to the battery source. Other subsystems will require the batteries to connect to a voltage regulator rather than directly to the component. The electromagnet will connect to the batteries through a switchmode amplifier. The batteries will be contained within the main structure of the vehicles. They will be positioned in a symmetric way to distribute the weight evenly across the structure. There will need to be an access point for the main on/off switch somewhere on the main structure. <TAS>

2.7.3 Voltage Regulators

2.7.3.1 Purpose of Part

The purpose of the voltage regulators is to provide a way to step down the voltage of the power source to a level that can be used by the individual subsystem component. They also ensure that the subsystem component sees a constant voltage level, since the voltage level provided by the batteries will tend to decrease as they get depleted.

2.7.3.2 Interfacing

The voltage regulators will reside on an electronic circuit board and will provide a direct connection between the batteries and the subsystem component. <TAS>

2.7.3.3 Summary Of Options

Since the SPHERES project went through the same down-select process for voltage regulators, the final choice will likely be similar to the regulators they chose. That system used the same TT8 processors and similar metrology instrumentation as EMFFORCE. ASTEC AA10B and AA05A models were used, which were 5V and 12V regulators, respectively (http://www.astecpower.com). The same regulators (or ones quite similar) can be used for this project. Figure 2.7.2 shows a sample voltage regulator. <TAS>

2.7.3.4 External Interfacing Needs

As previously mentioned, the voltage regulators will be integrated onto the circuit board of the subsystem component for which they are being used. <TAS>

2.7.4 Switchmode Amplifier

2.7.4.1 Purpose of Part

The swichmode amplifier will be responsible for varying the amount of current going to the electromagnet. It will receive a signal from the Control subsystem that will tell it how to vary the outgoing current to the electromagnet. <TAS>

2.7.4.2 Interfacing

The switchmode amplifier will reside on an electronic circuit board and will provide a direct connection between the batteries and the electromagnet. <TAS>

2.7.4.3 Summary of Options

The main criterion for the switchmode amplifier is that it must be able to provide a high current output (possibly up to 10 amps). Like the voltage regulators, these are commercially available and relatively easy to obtain. One amplifier which satisfies this criteria is the SA60 PWM from Apex Microtechnology (http://www.apexmicrotech.com). The amplifier can handle up to an 80-volt input and can provide a continuous 10-amp output. It has a high efficiency and is commonly used for magnetic coil applications. This model is shown in Figure 2.7.3. For the final subsystem design, this model or one very similar to it will be used. <TAS>

2.7.4.4 External Interfacing Needs

The switchmode amplifier will be directly connected to the battery source. It will interface with the controls, avionics, and electromagnet subsystems. It will receive a voltage signal from avionics and controls, which it will then use to allow the appropriate amount of current through to the electromagnet. <TAS>

2.7.5 Budgets

The power subsystem budget estimates per vehicle are shown below. The estimates include the possibility of having up to three complete battery sets per vehicle. <TAS>

Table 2.7.3 Power Budget Estimates

	Mass (kg)	Cost ($)
30 Batteries (HHR200SCP)	1.26	~100
2-3 Voltage Regulators	~0.05	~60
Switchmode Amplifier	~0.05	~60
Subtotal	1.36	~220
x 3 Sets per Vehicle	--	660
x 3 Vehicles	--	**~2000**

2.7.6 Conclusion

The success of the overall mission is entirely dependent on the success of the power subsystem. The power subsystem design is fairly straightforward and simple, and the type of batteries selected will determine its success. Once final power requirements are obtained from each subsystem, the optimal battery will be chosen and the power subsystem can be finalized.

2.8 Structure

2.8.1 Subsystem Overview

There are three main components of the structure subsystem: the vehicle casing, magnetic shielding, and air carriage. <ALS>

2.8.2 Vehicle Casing

2.8.2.1 Purpose of Part

The purpose of the vehicle casing is to provide physical interfacing capability for all of the subsystem hardware, and to prevent damage to the hardware in case of collision. <ALS>

2.8.2.2 Interfacing

The structural design must be flexible in order to absorb changes in other subsystem design. For this reason the vehicle casing has a modular design. The base holds the electromagnet and is separated from the remaining subsystems by magnetic shielding. The base, in turn, bolts to the main body. The lid, which sits in the main body, latches to the top of the vehicle and holds the electronics. The entire vehicle attaches to the air carriage with wing nuts for ease of manual assembly. <ALS, GG>

2.8.2.3 Discussion of Trade Analysis

The critical property of the vehicle casing is the weight as the weight is the dominant driver of the entire vehicle design. The structure team must fulfill its requirements at the lowest weight possible. While minimizing the weight, issues of cost of the material and machinability also come into play. Currently the structures team is considering aluminum and Lexan plastic as the candidate materials for the vehicle casing.

2.8.2.4 Concept Design

When designing the vehicle casing, the structure team took into consideration the following: accessibility to critical subsystems during operation, accessibility to all subsystems during development phase, thermal considerations regarding the electromagnet, axial symmetry, center of mass location, total structural mass, and manufacturability. <ALS, GG>

During operation the EMFFORCE team may need to access critical subsystems such as power and avionics, in order to replace batteries or reboot the main processor. Other subsystems such as the reaction wheel will most likely not be accessed during operation but must still be easily accessible in case of replacement, repair, and other development. <ALS, GG>

There is a possibility that the electromagnet will overheat. This may affect the structure as well as other subsystems of the EMFFORCE vehicles. Therefore, methods for cooling the electromagnet are considered in the structural design. <ALS, GG>

Since the vehicles will be rotating, an axis of symmetry allows simplification of the system dynamics. Also a low center of mass keeps the system more stable. Because of the properties of electromagnetic forces, it is imperative to minimize the mass of each vehicle. The structure team must minimize the structural mass to accomplish this. Constraints on time, cost and resources also require manufacturability. <ALS, GG>

Since it is critical that the subsystems be accessible during building and development, the vehicle casing is designed with ease of disassembly in mind. The entire vehicle (Figure 2.8.1) is cylindrical with the axis of symmetry aligned with the axis of rotation of the vehicle. The air carriage assembly (shown at the bottom) attaches to the main vehicle casing with wing nuts. <ALS>

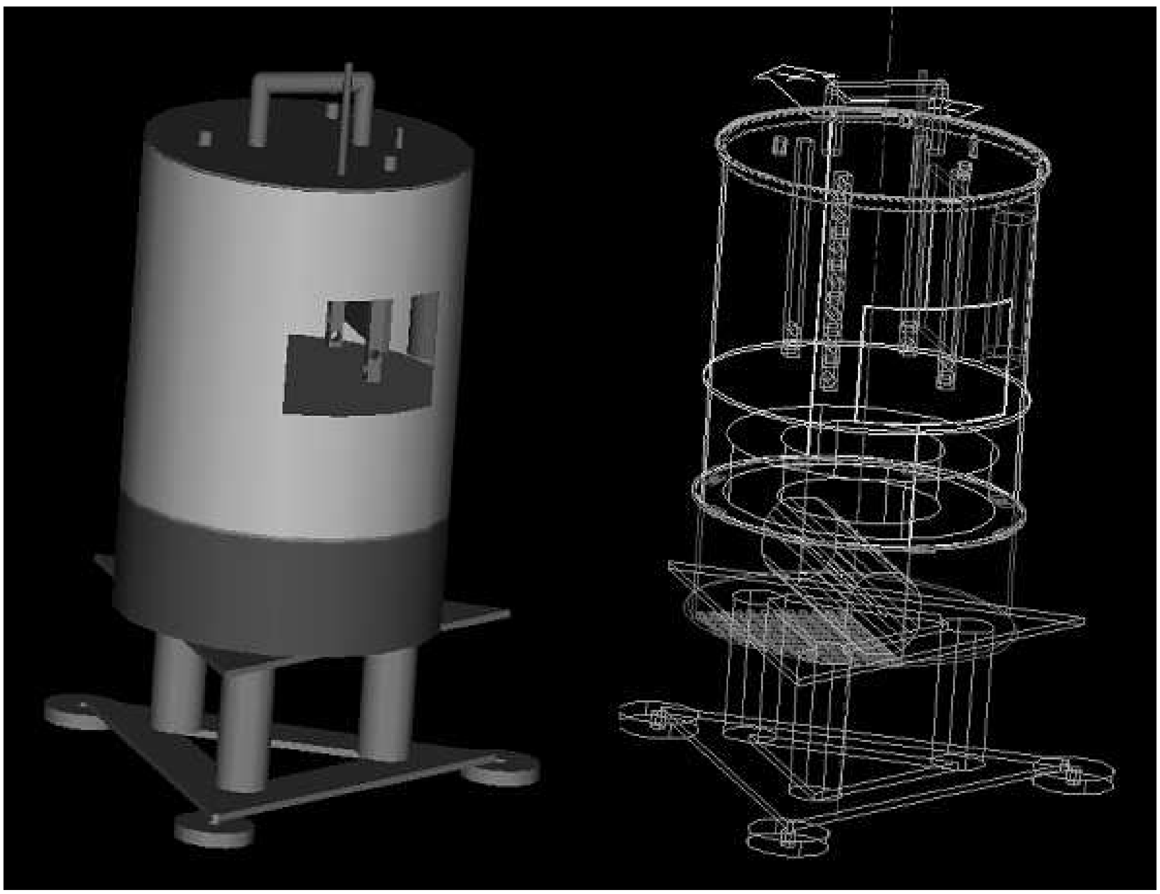

Figure 2.8.1: Vehicle assembly with air carriage <GG>

The base of the vehicle (Figure 2.8.2) contains the electromagnet. The base is grated to provide air flow for convective cooling over the electromagnet. This grating is made of aluminum to allow for additional heat conduction and radiation to the atmosphere in the event of magnet cooling. Directly above the magnet housing, a plate of magnetic shielding material separates the electromagnet from the rest of the subsystems. The reaction wheel assembly is attached to the top of this plate. <ALS>

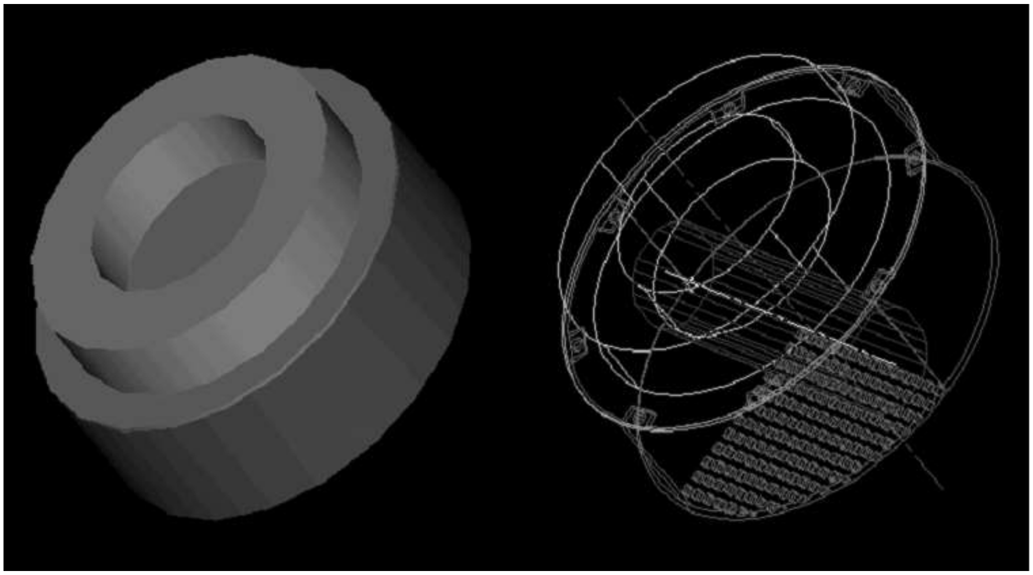

Figure 2.8.2: Base and reaction wheel <GG>

The reaction wheel assembly fits inside the bottom of the body (Figure 2.8.3) when the base is bolted on. The upper portion of the body houses the batteries, which are accessible via access panels in the side of the vehicle. The rate gyros and other internal metrology units sit in the center of the body, aligned with the axis of rotation. Weight-bearing handles are located on the outside of the body for ease vehicle transportation when not in operation. <ALS>

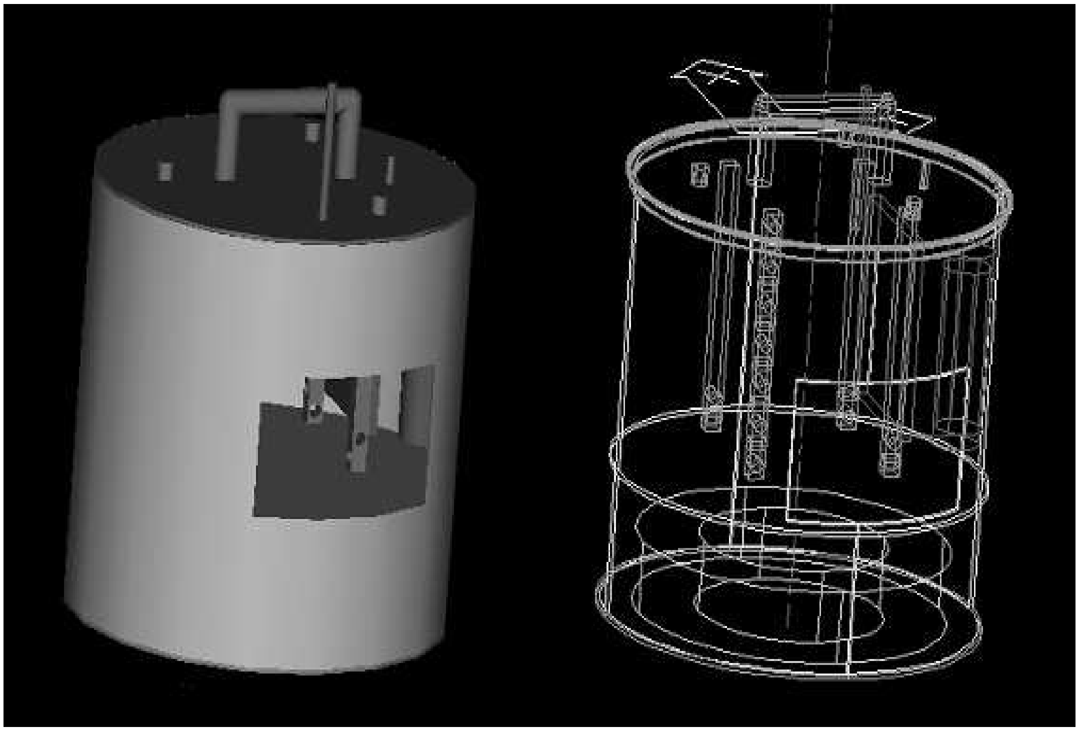

Figure 2.8.3: Body <GG>

The lid (Figure 2.8.4) latches onto the top of the vehicle. Attached to the underside of the lid, a small truss holds the electronics circuit boards for the avionics, communications, and metrology systems. The electronics are connected via one or two power/electronics umbilicals to the rest of the vehicle so that when the lid is removed and replaced, there are a minimum number of connections to worry about. All communications and metrology transmitters and receivers are located on the top of the lid, thereby maintaining direct connection with the electronics on the truss. Also on the top of the lid, a power switch and a reboot button provide manual user interface to the vehicle, and a handle allows easy disassembly/reassembly. <ALS>

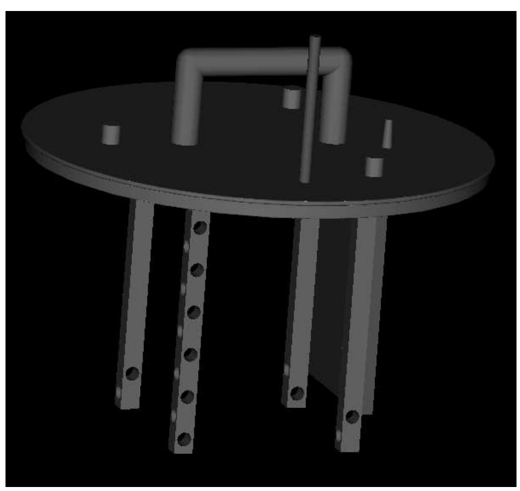

Figure 2.8.4: Lid <GG>

When the vehicle is in the disassembled state, all subsystem teams should be able to access their components easily. In addition, other than the avionics, communications, and metrology teams, who must all share the lid, all teams may access and work on their physical systems independently of the other teams. After maintenance is done, the vehicle is easily reassembled. <ALS>

2.8.3 Magnetic Shielding

2.8.3.1 Purpose of Part

Each EMFFORCE vehicle has various electronic subsystems aboard, as well as an electromagnet. The magnetic shielding exists in order to keep the crucial electronic subsystems from malfunctioning due to interference of the magnetic field. <GG>

2.8.3.2 Interfacing

The magnetic shielding must interface with the vehicle casing of the system. It must interface in a manner in which it successfully blocks the magnetic interference while minimizing mass. <GG>

2.8.3.3 Discussion of Trade Analysis

When choosing the magnetic shielding, trades the structure team needs to consider cost, mass, reliability, and application method. <GG>

2.8.3.4 Summary of Options/Selection Criteria

The structure team will purchase a test kit of shielding products from MuShield. This kit includes foils, plates, and sheets of magnetic shielding material. Upon arrival of this kit the structure team will conduct tests to determine the reliability of each usable material in the described (2.8.3.4) configuration. The team will then decide on the material with the lowest mass that demonstrates robust shielding of the magnetic interference. <GG>

2.8.4 Air Carriage

2.8.4.1 Purpose of Part

The air carriage is a critical component for testing the dynamics of the system. To simulated a space environment, it is necessary to minimize external forces on the system, including those caused by frictional contact with the laboratory floor. The air carriage provides a hydrostatic cushion of air to float the vehicle some distance off the floor. The carriage must maintain sufficient cushion thickness for a given vehicle mass so as to keep the vehicle from touching the facility floor throughout the testing phase, both for steady-state translation and for slight disturbances of cushion thickness. <ALS>

2.8.4.2 Interfacing

The air carriage sits at the bottom of the vehicle and is detachable from the main vehicle body. Its components for each vehicle are as follows: three (3) cylindrical pucks, structural mount for the vehicle, pressure regulator, air supply, and air supply connections. The air supply will most likely be a small household compressor equipped with a tank to act as a capacitor and provide damping. In the event the chosen compressor uses alternating current, a power inverter would be required. If not, a direct battery connection (with a possible voltage regulator) will suffice. <ALS>

In the event that a suitably sized compressor cannot be found, each vehicle will use three (3) refillable carbon dioxide canisters (one tank per puck). Each tank will require its own pressure regulator. <ALS>

2.8.4.3 Discussion of Trade Analysis

When designing the air carriage the structure team will look at the trades between fabricated air carriages and off-the-shelf units. The characteristics that will be important in this comparison include cost and efficiency. Fabricating air carriage systems (specifically, the pucks) at MIT may decrease costs, however it may also decrease efficiency. Manufacturing the pucks provides the distinct advantage of freedom of design and capability for experimentation. Currently, the pucks will be designed by the EMFFORCE team and manufactured at MIT. In the event that the analysis leading to design is too time consuming to provide an optimum design, commercial pucks with advertised specifications may be purchased. This case significantly increases the required structures budget. < ALS, GG >

There are also design trades involved with air tanks and compressors. Though they limit the testing time to a few minutes, air tanks are cheap, light, and require no power draw. This option is still being investigated. The use of a compressor is highly desirable, because the benefits of the increased testing time available far outweigh the mass and power cost. Commercially available compressors run the gamut of mass, power draw, pressure, flow output, and cost. Investigation will be conducted to determine the desired compressor. Tank air supply will be held as a backup plan in the event that a suitable compressor cannot be found. <ALS, GG>

2.8.4.4 Design Stratagem

The design problem for the air carriage is a complicated one. All of the objectives, constraints, and design variables are linked and interdependent. At the same time weight is maximized for a given cushion thickness, for example, it is also of interest to maximize air cushion height (to enable use of a rougher floor) for a given weight. However, a thicker (or thinner) air cushion also introduces other modeling problems such as transitions between compressible (sonic) regions and incompressible regions. The design variables available to accomplish this optimal design are supply pressure, puck radius, and supply orifice. <ALS>

Lubrication theory is the field of fluid mechanics required to describe the dynamics of the sliding air bearings. It makes appropriate assumptions and theoretically should enable the structures team to solve the flow and optimize the design parameters of supply pressure and puck radius. Lubrication theory assumes a cushion thickness, h, that is much, much less than the radius of the puck, R_p. It also assumes a very low Reynolds number, which for a dynamic puck is given by:

$$\mathrm{Re} \propto \frac{\rho_a R_p U_p}{\mu_a}\left(\frac{h^2}{R_p^2}\right)$$

Equation 2.8.1: Lubrication theory Reynolds number for a dynamic puck

where ρ_a is the ambient air density, R_p is the puck radius, U_p is the velocity of the puck, μ_a is the ambient dynamic viscosity, and h is the cushion thickness. (Gross 33) <ALS>

Having just been redirected in the search for an appropriate mathematical model, the air carriage design is currently at a jumping off point. Further analysis will involve solving the governing equations from lubrication theory to develop relationships between the critical parameters: load capacity, cushion height, supply pressure, and puck size. In addition, the structure team must now take into account the effect of compressible effects near the supply orifice and assess the advantages of different puck designs. Examples of such puck designs are shown in Figure 2.8.5. The various designs have different pressure profiles and exhibit different characteristics in stiffness and disturbance rejection. <ALS>

2.8.5 External Interfaces

The structure subsystem must interface with all subsystems except control. Structure must provide the attachments and interfaces for all physical components, while retaining easy access to parts and subsystems during the building and operating phases. <ALS>

The structure team must also ensure that the magnetic shielding is sufficient for the size and field strength of the magnet and will sufficiently protect the electronics. <ALS>

In the event that air compressors are used for the air supply, an interface with the power subsystem will be required. <ALS>

2.8.6 Budgets

The structure team budget estimates are shown in Table 2.8.1.

Table 2.8.1: Structure Team Budget Estimates

	Mass (kg)	Power Draw (V AC)	Cost ($)
Casing (Aluminum)	~0.80	0	~200
Shielding	~0.05	0	200
Carriage	2.30	0	~200
Subtotal	3.15	0	~600
Compressor	~2.00	115	200
Total	~5.15	115	~800

2.8.7 Conclusion

The structure of the vehicle plays an integral part in the physical system. Although the mission of the EMFFORCE team does not directly depend on the structure itself, an efficiently designed physical structure will prove itself a necessity in the success of the testbed. <GG>

3 Implementation

3.1 Budgets

The systems engineering team is responsible for allocating the budgets of money, mass, and power for each of the subsystems. Each subsystem of the EMFFORCE project has reported estimated budgets for each of the categories. The systems group then determines and balances budgets such that EMFFORCE can achieve its project goal. Because the mission objective of EMFFORCE is to demonstrate the feasibility of electromagnetically-controlled formation flight, the budgeting of money, mass, and power must help to ensure that this task can be achieved. For instance, in many cases, certain subsystems can incorporate previously designed technology into the testbed vehicle design to ease budgeting concerns and allow for more accurate budgeting estimate needs. The controls and electromagnet teams have been asked to complete a design that has not be done before. For this reason, it is more difficult to determine a working design and thus determine budgeting for these subsystems. <SJS>

The processes group had set up spreadsheets using Microsoft Excel to aid in the budgeting process. These spreadsheets allow for inputs of estimated expenditures, and graphical outputs can allow the systems engineering team to determine if the EMFFORCE team is on track to complete the project while maintaining necessary budgets. If EMFFORCE appears to be in a “safe zone” as far as money, mass, and power budgeting is concerned, the subsystems can continue with the design process as planned. However, if there is any indication that the team may surpass the budgets allotted, reallocation of subsystem budgets as well as changes in project design will occur. <SJS>

3.1.1 Cost Budget

The EMFFORCE team must work in compliance with the given monetary budget of $50,000. Continuous tracking of the estimated expenditures on both the subsystem and the system level help to ensure that the cost of the project does not exceed this budget that has been given to the team. <SJS>

The current estimated total system monetary budgeting is shown in Table 3.1.1 <SJS>:

Table 3.1.1: Total Estimated Cost for System

	Total Estimated Cost for System ($)
Actuation	**3450**
EM	450
RWA	3000
Formation Flight	**8000**
Controls	500
Metrology	7500
Electronics	**13335**
Comm/Ops	5835
Avionics	7000
Structure/Power	**4050**
Structure	2550
Power	1500
TOTAL	**28835**

This table shows the budgeting estimates for each microgroup, macrogroup, and the total amount of money EMFFORCE anticipates to spend.

Of the $50,000 allotted for EMFFORCE project use, only around $250 have been spent thus far. Our cost budget tracking currently shows that we expect to be under budget by approximately $1500. The Systems Team's cost budget tracking from February 2002 until May 2002 is represented in Figure 3.1.1:

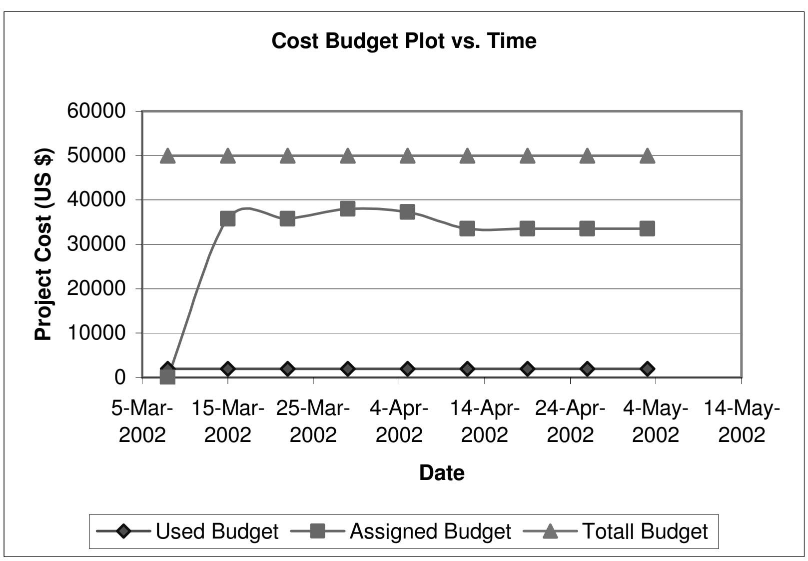

Figure 3.1.1: Cost Budgeting vs. Time

3.1.2 Power Budget

It is necessary to determine subsystem power budgeting to ensure that the vehicles are functional. The Power subsystem is responsible for allocating power to all other subsystems in a vehicle. If it is determined that not enough power or enough different voltages can be supplied to the individual subsystems, then the Systems team must notify the various subsystem teams of the problem, and alterations in subsystem designs may need to occur. <SJS>

The current estimated power needed for each subsystem per vehicle is as follows:

Table 3.1.2: Estimated Power Budgeting

	Estimated Power Needed Per Vehicle (W)
Actuation	133
EM	>120
RWA	13
Formation Flight	1.09
Controls	0
Metrology	1.09
Electronics	3.68
Comm/Ops	0.08
Avionics	3.6
*Structure/Power	—
*Structure	—
Power	Supplies 100% of EMFFORCE power needs
*TOTAL	137.7

This table shows the budgeting estimates for each team and group, and the total amount of power EMFFORCE believes each vehicle will need.

The option of a compressor for the air bearing assembly is still being examined. No power estimates are currently available.

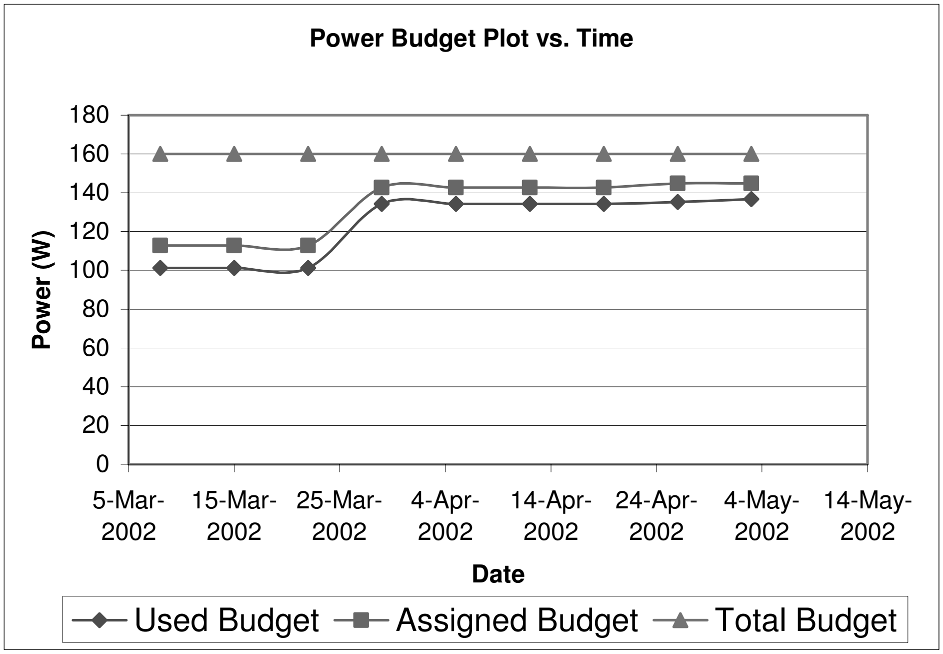

Figure 3.1.2: Power Budgeting vs. Time

3.1.3 Mass Budget

Mass budgeting is crucial to the success of EMFFORCE. The vehicles are electromagnetically controlled; therefore, the greater the total mass of the vehicle, the larger and more powerful the electromagnet will have to be. For this reason, the EMFFORCE project is primarily a mass-driven optimization problem. The Formation Flight, Electronics, and Structures groups are therefore attempting to minimize the masses of their respective subsystems. <SJS>

The current compiled estimated mass budgeting per vehicle follows in Table 3.1.3 <SJS>:

Table 3.1.3: Estimated Mass Budgeting

	Total Estimated Mass per Vehicle (kg)
Actuation	9
EM	8
RWA	1
Formation Flight	0.20
Controls	0
Metrology	0.20
Electronics	0.353
Comm/Ops	0.24
Avionics	0.113
Structure/Power	5.76
Structure	4.45
Power	1.31
TOTAL	15.313

This table shows the budgeting estimates for each microgroup, macrogroup, and the total mass per vehicle.

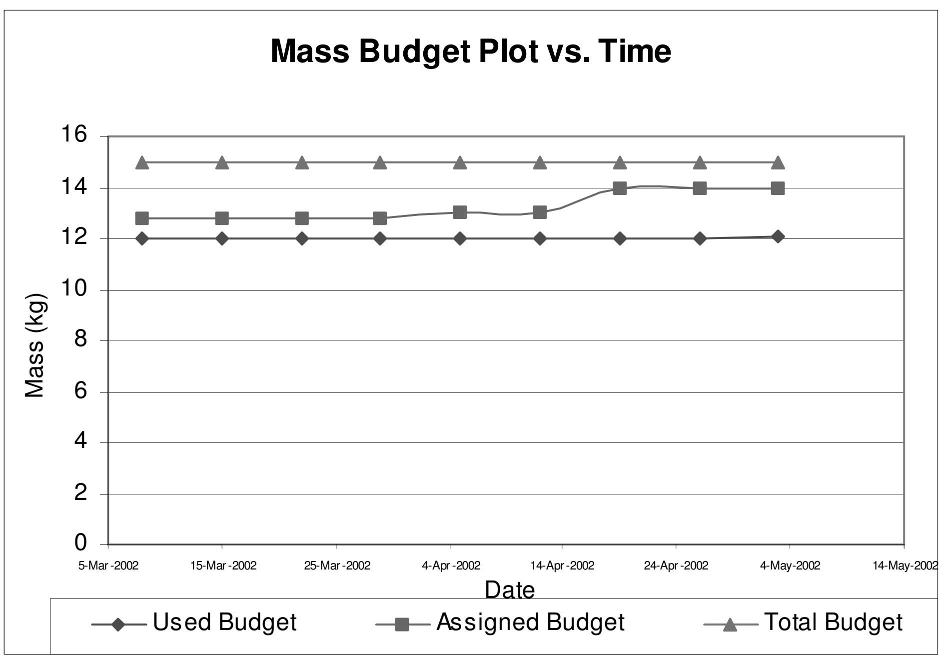

Figure 3.1.3: Mass Budgeting vs. Time

3.2 Parts

Many parts will need to be either purchased or fabricated in order to build the EMFFORCE vehicle testbed. The Processes Group has set up various validation and verification procedures to increase the chance of success for the project. These procedures shall be followed by the EMFFORCE team members and will be enforced by the systems team. The Validation and verification processes are outlined in the following processes documents in the systems team folder: 23-1 Component and System Verification and 23-2 Component Validation. <SJS>

3.2.1 Validation

As defined by the EMFFORCE Processes group, validation is the name for the procedures designed to demonstrate that a newly received part meets design specifications as per the design document. This can also be envisioned as "getting the right part." <SJS, BAB>

All parts will be validated before they are fabricated or purchased. If a part is to be procured, a requisition form (entitled Requisitions Form V1.0) must be completed and the part can be ordered once it has been validated. Purchased parts will be checked against the specifications and tolerances given. Only if the purchased part meets all specifications and tolerances will the part be validated. If a part is to be fabricated, the fabrication can commence only after the validation process is followed. Fabricated parts will be checked against the specifications and tolerances given to the fabricator prior to fabrication. Only if the fabricated part meets all specification and tolerances will the part be validated. <ESS, SJS>

3.2.2 Verification

The EMFFORCE team shall make use of the term "verification" to describe procedures designed to demonstrate that a part or system meets design requirements as per the requirements document. This can be thought of as "getting the part or system right." <SJS, BAB>

The process of verification includes ensuring that the system or subsystem meets requirements and providing a means by which to verify that the requirements are being met. This process occurs in three phases <SJS, BAB>:

Phase One: Determining Requirements Flowdown. Before a system or subsystem is created that team must obtain the applicable system or subsystem requirements and the interface specifications required by other teams or groups. The system designers must also obtain a resource budget. This budget will include mass, power, cost, time, error, flops, etc. As appropriate, each team's design for the system or subsystem must meet all the requirements within the allotted resources. <BAB, ESS>

Phase Two: Test Design. (The layout of the test plan is entitled Test Plan Document, CDIO Form 32-121). As part of designing a particular system or subsystem, the team is required to design a testing procedure for their subsystem. This testing procedure must establish that the system meets all applicable requirements and that all interfaces are within specification. The team itself will decide upon this testing procedure. Any resources used by the team in the designed test will be taken out of that team's resource budget, and must be accounted for in the subsystem design. <SJS, BAB, ESS>

Phase Three: Verification of Results (entitled Verification Review Document, CDIO Form 32-122.) Once the test designed in Phase Two has been performed, the team will evaluate the data brought forth by the test and check the aquired data against the requirements and constraints. Only if all requirements and resource constraints are met may the team verify the system or subsystem. <SJS, BAB, ESS>

If a part is found to be non-compliant, a noncompliance document (CDIO Forms 23-291 and 23-292) that can be found in the systems folder must be completed.

3.3 Schedules

3.3.1 Overall Schedule

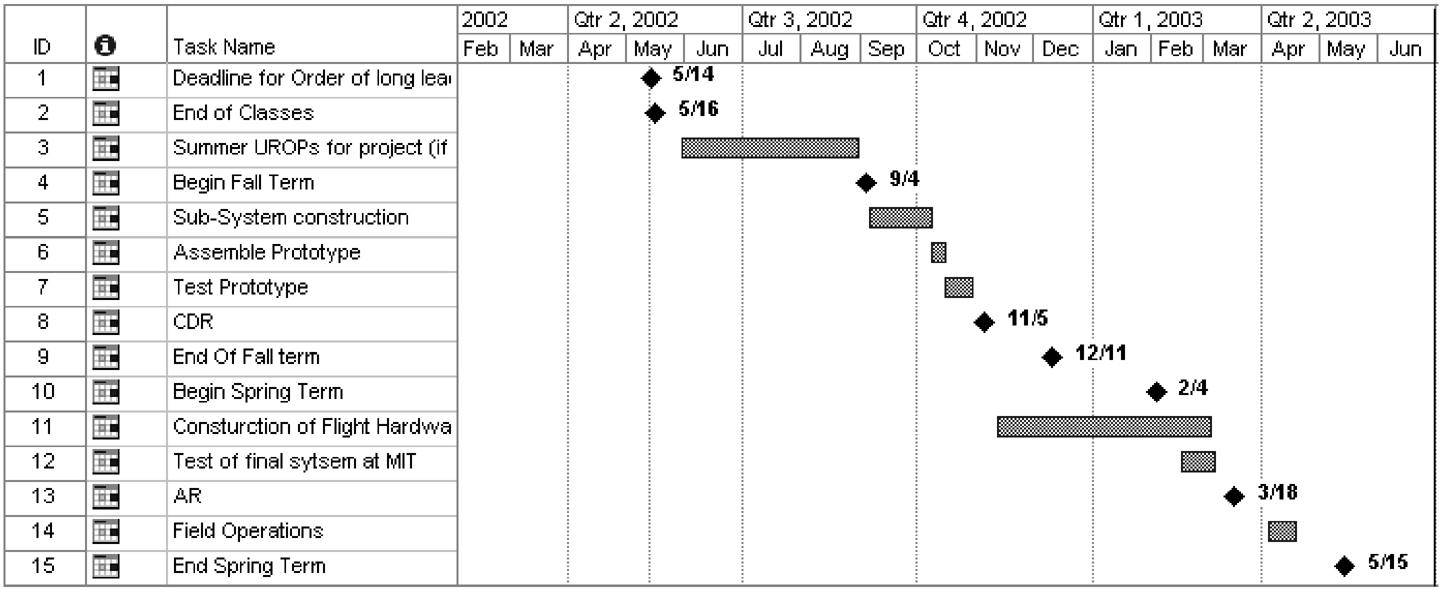

Figure 3.3.1: Overall Schedule

Above is a schedule of major deadlines for the EMFFORCE team.

3.3.2 Detailed Schedule: PDR to CDR

3.3.2.1 June 2002 through August 2002 (Summer Period)

By 17 May 2002 the EMFFORCE team will finish the design document. The design document will then be put under configuration control. Subsystems should also validate any items that they need and should order them so that the orders can be processed and shipped over the summer 2002. Students may also be working on their portions of the EMFFORCE project over the summer as UROP students in MIT's Space System Laboratory. <SJS, APA>

3.3.2.2 Fall 2002

Figure 3.3.2 depicts the schedule of major events for the Fall 2002 semester. This schedule is subject to change as new developments arise.

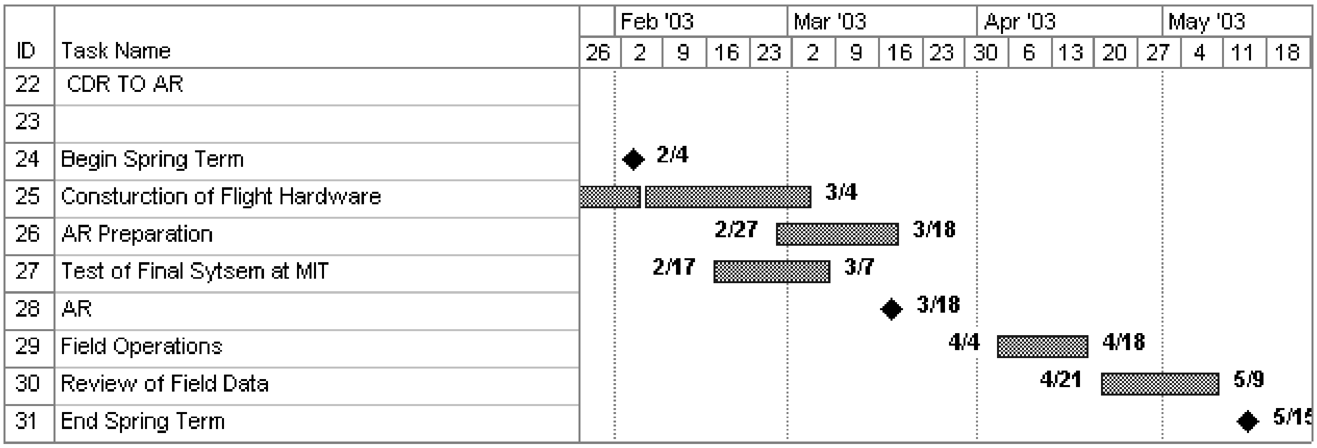

Figure 3.3.2: Schedule through CDR

This is a schedule of major deadlines the EMFFORCE team must meet from now until the Critical Design Review.

UROP's and the procurement of long lead items should be completed by the beginning of the semester. Also during the fall term, prototypes of complete subsystems will be assembled to test interfaces and provide initial data on the entire system.

Construction of "flight hardware" will commence after CDR and may continue during IAP. Though not shown in the schedule above, due to the fact that CDIO does not technically meet as a class during IAP, this flight hardware construction scheduling is essential and should be taken into consideration. <APA, SJS>

3.3.3 Projected Schedule CDR to AR

As mentioned in the previous section, the construction of flight hardware (the final EMFFORCE product formation flight test vehicles) will commence at the end of the fall term and may proceed over IAP. Final testing will provide data to be presented at the Acceptance Review. Field operations will be conducted at the Denver flat floor facility during early to mid-April 2003. Figure 3.3.3 shows the major events from the Critical Design Review until the Acceptance Review as they stand now. Once again, long-range scheduling is subject to change. <SJS, APA>

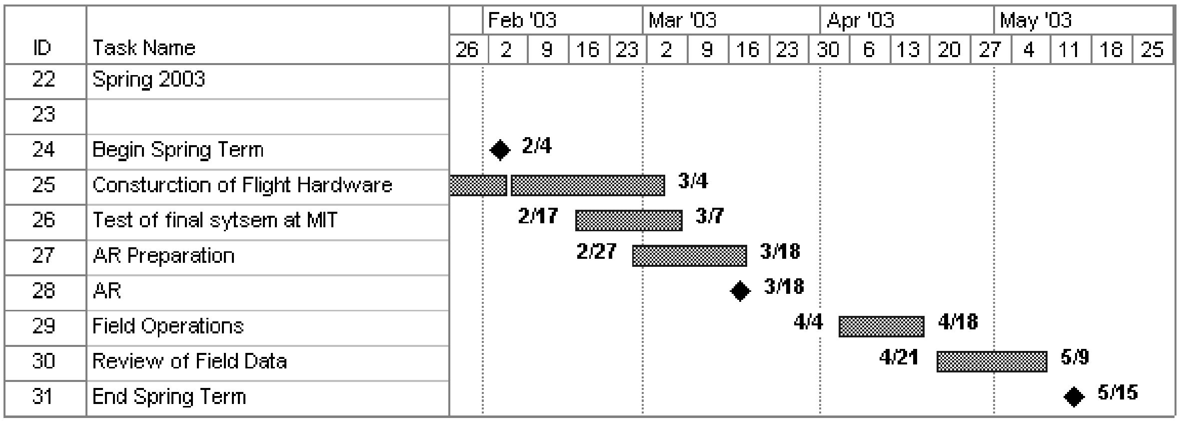

Figure 3.3.3: Projected Schedule CDR to AR

The above schedule depicts the major deadlines for the EMFFORCE team from the Critical Design Review period until the EMFFORCE Acceptance Review

3.4 Operations

3.4.1 Operations Overview

The ultimate goal of the CDIO program is to successfully operate the completed EMFFORCE testbed at a flat floor facility in Lockheed Martin's Technology Development Lab in Denver. All subsystems must not only work as designed, but must come together into a complete operational system that can perform useful research in a deployed location. <ESS>

The EMFFORCE mission is to *demonstrate* the feasibility of EMFF. This can only be done through planned experimentation with coordinated data collection and analysis. Every member of the team must know exactly what is going on, and be able to perform the mission and overcome in real-time whatever setbacks may occur while Project EMFFORCE is deployed to Denver. <ESS>

3.4.1.1 Priorities

The following priorities are set forth by Operations Team to guide all operational planning and implementation:

- **Safety**. Safety is paramount, as the well-being of our team members is more important than completing the project. The EMFFORCE team must also safeguard the testing facility and associated equipment against damage from system malfunction. Personal injury or severe infrastructure damage will negate any mission successes that may have been achieved. <ESS>
- **Equipment Longevity**. Equipment longevity must be promoted at all levels. The two most valuable system resources, time and money, both suffer when parts break and need to be either repaired or replaced. Conservative stewardship of materiel will pay off in the long run. <ESS>
- **Mission Completion**. Mission completion, which includes the satisfaction of all operational requirements listed for the system (given in the introduction) and is determined by the system test program. The objective of the project is to make the testbed work and prove the feasibility of EMFF. <ESS>
- **Efficiency**. Efficiently planning and conducting operations will save time and money. The EMFFORCE Team should do as little work and spend as little money as possible without jeopardizing the above priorities. <ESS>

3.4.1.2 Mission

The mission of the Operations Element of the EMFFORCE Team is threefold:

- **Operations-oriented Development.** Guide the development of the EMFFORCE project with respect to the operational architecture. The operational architecture is just as important as any other subsystem architecture, and interfaces closely with all subsystems. **<**ESS>
- **Field Operations.** Develop the Field Operations Plan for the transportation of the class to the Denver Test Site. The EMFFORCE team must be able to move itself and the vehicle to the test site as efficiently and safely as possible. **<**ESS>

- **Test Program.** Develop the Test Program Operations Plan that will be executed at the test site. The program will determine if the EMFFORCE Team has accomplished the mission, and will provide evidence to support that finding. <ESS>

This version of the Design Document specifies the operational architecture design and outlines the major elements of the Operations Plan designs. The formal EMFFORCE Operations Plan that contains the Field and Test Program Operations Plans will be completed as the system matures, towards the end of Fall 2002. <ESS>

3.4.2 Operations-oriented Development

At the end of the development cycle, the vehicles will need to operate in the field. However, there is a lengthy development process during which it may be possible to lose sight of the end-state. The EMFFORCE Team must therefore incorporate planning for the eventual operation of the test bed into every aspect of system development, beginning with the earliest design stage. In order to accomplish this, an operational architecture must be specified and updated parallel to the architectures of the other subsystems. By integrating operational considerations into all aspects of product development, the EMFFORCE team seeks to minimize the costs of operation and maximize the probability of success. <ESS>

3.4.2.1 Scope and Architecture Overview

The operational architecture is the responsibility of the Operations Element of the Communications and Operations Team. All hardware not physically part of the test vehicles and all procedures employed outside of the laboratory development environment are included in this architecture. The Operations Element is also responsible for interfaces with external organizations and facilities. It is necessary that all subsystem teams maintain an interface with this operational architecture to promote successful operation of the test bed in the end-state. <ESS>

The operational architecture must account for all operational constraints and actively promote the Operational Priorities listed in subsection 3.4.1.1. It accomplishes this by establishing discrete operational states, system health monitoring procedures, failure minimization procedures, and emergency operational states. <ESS>

3.4.2.2 Operational Constraints

When operating the EMFFORCE testbed outside of the MIT development laboratories, additional constraints are placed on the system. Failure to account for these constraints early on will lead to costly revision later in the development cycle. <ESS>

The flat floor testing facility at the Lockheed Martin Technology Development Laboratory in Denver, CO is a unique testing environment that brings unique constraints to the project. The maximum pressure at any point on the floor is 500 psi (3.5 Mpa). EMFFORCE personnel may walk on the floor with restricted footwear. The floor is protected as a clean environment; personnel will have to wear lint-free clothes and guard against other types of contamination according to the clean room procedures at the facility, thus adding more time to test preparation. <ESS>

The laptop ground station must be able to monitor the appropriate RF frequencies and must have a source of power to sustain operations. The ground station must record data in real-time as it is generated. <ESS>

The batteries used by the vehicles will need to recharge, and the Operations Element and Power Team must secure the necessary resources on-site. <ESS>

Other constraints will be added as development continues, and must be incorporated into the final design. <ESS>

3.4.2.3 Normal Operational States

To facilitate work division and modularity, the Operations Element has characterized the operation of the testbed by several system operational states. These states are independent, self-contained, and mutually exclusive; the system may move from one to another only when directed to do so by the operator or when the software detects pre-programmed conditions that authorize and mandate a change of state. The states direct software, hardware, and operator actions, thus unifying all elements of the system in a combined operational architecture. <ESS>

- **Safe Mode.** In Safe Mode, the system powers down all actuation subsystems while not changing the status of the avionics, communications, metrology, and control subsystems. If the system detects certain faults, it will enter Safe Mode. This prevents the system from going further out of control, but preserves data for analysis. Operators may also place the system into Safe Mode by hitting the Big Red Button located on the top of each vehicle. <ESS>

- **Initialization.** In this state, the vehicle powers up the electronics and checks for faults before the operators place the vehicle on the floor. With the vehicles near the entrance but off the test floor, an operator manually toggles the master power switch, which turns on the avionics subsystem. The communications subsystem is also activated, and the ground station designates a vehicle as the hub, illuminating an LED on the selected vehicle. The system runs automatic diagnostics of avionics and communications functions and transmits the results to the laptop ground station. If a fault is detected, the system enters Safe Mode. If the diagnostics detect a communications fault, the avionics illuminate an LED and the operators may dump the data via serial port to the ground station. If all avionics and communications diagnostics complete successfully, the system informs the operators that it is ready for deployment. <ESS>

- **Deployment.** Deployment activates the metrology and air carriage subsystems and guides the vehicles to their initial positions. EMFFORCE personnel place the vehicles manually on the floor. The ground station transmits the planned mission to the vehicles, including initial position, desired steady state flight parameters, and other variables. The metrology subsystem is activated and runs its own diagnostics. If a fault is detected, the system enters Safe Mode. Otherwise, an operator activates the air carriage subsystem while other operators move to monitoring positions on the test floor. The metrology subsystem takes data to assist the operators in moving the vehicles to the commanded initial positions. The operators then position the vehicles in the commanded initial positions. When the metrology subsystem indicates that the relative vehicle positions are acceptable and stable, the Control system is activated in diagnostic mode and the actuation system is activated in standby mode. System health monitoring devices are also powered on and begin to provide health telemetry to the ground station. Once diagnostics have been completed successfully, i.e., the system has determined that the control system can communicate as designed with the actuation devices, the operator may initiate Spin-up by command from the ground station. <ESS>

- **Spin-up.** At the command to initiate spin-up, the actuation devices leave standby mode and act upon commands from the control subsystem. The control subsystem commands the actuation subsystem to steer the system towards the steady state goal by using the Spin-up algorithm. The system leaves Spin-up mode when it either has reached the steady state or is commanded to safe mode by operator input or the fault detection system. <ESS>
- **Steady-state Rotation.** When metrology indicates that the system is within the desired steady-state parameters, the system automatically enters steady-state rotation mode without operator input. In this mode, the control algorithm changes to maintain the desired rotational velocity. The system may exit this mode upon an operator command to De-spin or enter Safe Mode, or upon an automatic command to enter Safe Mode resulting from operator inattention. <ESS>
- **De-spin.** De-spin switches the control algorithm again to bring the vehicles to rest from the Steady-state Rotation Mode. This is the fault remediation method used while control is still possible, as it should bring the system to rest with the minimum chance for damage. After the vehicles have completed De-spin, they are placed in Safe Mode for recovery by operator command. <ESS>
- **Recovery.** Upon entering Safe Mode, the operators will attempt first to bring the vehicles to rest and then move them off the floor. Once the vehicles are off the floor, the air carriage is powered down. If there are no faults, the vehicles may be powered down to the Off state by using the master power switch. <ESS>
- **Off.** The state where none of the electronics systems is drawing current and the air carriage is inactive. <ESS>

3.4.2.4 System Health Monitoring and Operator Interface

Critical variables are monitored by the subsystems and transmitted to the operations ground station. These health variables include electromagnet core and wire temperatures, air carriage delivery pressure, reaction wheel speed and vibration, power supply voltage and amperage, and control error for the eighteen system state variables. These critical variables may fall into one of three ranges classified as Green, Yellow, or Red. The several subsystem teams are responsible for placing monitoring equipment to report the status of these critical variables. <ESS>

The safety officer is responsible for monitoring this data in real-time during operation. Green is the normal operating range for all variables, which will be determined by a combination of experiment and design. The ground station laptop displays the variables, and provides warnings to the operator if any reach the Yellow level. The safety officer in conjunction with the test supervisor may choose to ignore the warning, or may take corrective action. If any of the variables reach the Red level, the system will either de-spin or enter Safe Mode without an explicit override from the ground station. <ESS>

3.4.2.5 Failure Minimization

During development, equipment longevity is an operational priority. The EMFFORCE team has a tight budget and cannot afford to waste money on preventable equipment destruction. Therefore, all laboratory testing must follow a documented test plan, which should be well-considered and minimize risk. <ESS>

The consequences of failure in the field are even greater than in the lab, because the necessary repair facilities might not be available and the time budget will be tightly constrained. To make the operation successful, things need to go right on the first try as much as possible. Thorough testing and system integration practice prior to departure will serve this end. <ESS>

In order to perform effective field maintenance, the vehicles are designed with operational considerations in mind. Access panels and removable modules provide easy access for maintenance technicians. The modules themselves and all the subunits are interchangeable, making field replacements more expedient. Finally, all Teams are expected to track failures carefully during testing and prepare documentation on failure modes to aid in rapid diagnosis in the field. <ESS>

3.4.2.6 Fault Remediation and Emergency States

While the initialization and deployment diagnostics seek to detect faults before the system is fully activated, thus minimizing the impact of the failure, many factors may lead to emergency conditions requiring fault remediation during operation. <ESS>

Safe Mode is implemented to prevent further damage as a result of a failure. On the actual test floor, it is conceivable that the control and/or actuation systems may fail to maintain controllability. There must be a mechanism in place to bring the vehicles safely to rest. If the system is no longer controllable, it automatically enters Safe Mode. Operators on the floor must catch the vehicles and manually bring them to rest for recovery. <ESS>

De-spin Mode may be commanded by the operator to prevent a problem from becoming a fault. If, for example, the magnet core temperature or air carriage delivery pressure enters the Yellow range, the operator may command an immediate De-spin rather than concluding the test. By bringing the vehicles to rest in a controlled manner, the risk of damage is minimized. <ESS>

3.4.3 Field Operations

Only after a successful deployment to and assembly at the test site can the actual system test program begin. To get to Denver, EMFFORCE needs a Field Operations Plan. The following is an overview of the important elements that will be included in the Field Operations Plan, including personnel, materiel, and facilities considerations. <ESS>

3.4.3.1 Personnel

Personnel, the most valuable resource in the EMFFORCE program, require a lot of work to get from one point to another. For the deployment of the EMFFORCE Team to Denver, the Operations Element will have to arrange for all travel, lodging, food, and scheduling considerations. <ESS>

The EMFFORCE Team will be divided into three travel groups for the deployment. The Advance Team will consist of 3-4 personnel arriving in Denver 6-18 hours ahead of the Equipment Group in order to secure transportation and lodging. Transportation will consist of two 15-passenger vans, one for cargo and the other for personnel. Depending on the remaining budget, the Advance Team may also secure food for the main group. It is easier to make these arrangements with a small group unencumbered by cargo. The Equipment Group of 12-15 personnel will travel with the EMFFORCE cargo and will arrive in Denver the evening before scheduled testing. The Follow-on Team of 2-4 personnel will leave Boston around 0600 on the day of testing and arrive in Denver around mid-morning. <ESS>

Once the EMFFORCE Team is reassembled, all personnel must be fully prepared to do their individual parts for the test program. All personnel must also be adequately prepared to troubleshoot the system in the field, and this will require training and documentation. The Operations Element especially will need to be very familiar with the ground station interface. <ESS>

3.4.3.2 Materiel

The test vehicles will need to be broken down and securely packaged to prevent damage. The Equipment Group will transport them via commercial airline. The Equipment Group will need to bring all necessary spare parts, diagnostic and repair tools, and other operations support equipment into the field. The Operations Team and Systems Group will create an inventory of what needs to go; Systems Group will track the deployment mass and volume budgets. <ESS>

Upon arrival in Denver, the equipment will be unpacked and visually and electronically inspected for damage during transport and for completeness. It should be possible to bring the vehicles up through Deployment Mode without specialized laboratory facilities. If any problems are found, the Follow-on Team will be notified and will try to gather any necessary equipment prior to their departure. <ESS>

3.4.3.3 Facilities

Prior to and upon arrival at the Lockheed facility, EMFFORCE will have to coordinate with the appropriate Lockheed personnel to arrange for facility use and support. The scheduling of time at the facility will have a direct impact on both arrival times and the length of tests that can be implemented. Therefore, it is advantageous for the EMFFORCE Team to know exactly what will happen as far in advance as possible. <ESS>

To this end, Operations element will negotiate a contract with Lockheed Martin that specifies exactly which services will be received, when they will be received, and who the points-of-contact are in Denver. <ESS>

3.4.4 Test Program

The EMFFORCE Team is utilizing the Denver Test Facility because the Flat Floor Facility there is the only one in the country that will provide opportunity to adequately evaluate the complete system with respect to its operational requirements of far-field EMFF. Simply getting to the site is very expensive, and every effort must be made to ensure that the time spent there is fully utilized. <ESS>

Therefore, the test program must be completely specified well before deployment to ensure that it will accomplish the mission objectives, which are laid out in the requirements document. Every trial to be executed should be pre-loaded into data files for transmission to the test vehicles. Plans must also be made to vary the test program if the schedule begins to slip, such as prioritizing the tests and criteria to evaluate when skipping certain tests may be justified. <ESS>

The measurable outcomes must be tracked and accounted for in the early stages of the test program design. The test program itself will be made up of a series of tests to demonstrate these requirements, and there will likely be a limited schedule with which the Operations Element can work. All aspects of the operation must be accounted for, including set up of the facility, time required for repairs, modification, and battery recharging. <ESS>

The test program will be the first time the full system has been evaluated, and will be the first true simultaneous verification of all the subsystem models. While most concepts should have been demonstrated in lab, the combination of all systems brings new complexities to the planning process. Similarly, the test program will be the first time the planning and craftsmanship of the full system have been evaluated, and the results, if positive, will be a good indicator that EMFF is indeed feasible. <ESS>

The protocols and procedures designed to prepare the class for the test program require extra paperwork and close coordination between teams. The procedures must be reviewed extensively by all Teams to ensure nothing is overlooked. <ESS>

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5 Appendices

Appendix A: Systems

A.1 Variable Assignments

Table A.1.1 Variable Assignments

Symbol	Description of Quantity
α	Dimensionless aspect ratio $L_{core}/2r_{core}$
α_B	Angle from vehicle A to B measured from "North" of vehicle A
α_C	Angle from vehicle A to C measured from "North" of vehicle A
B	Resulting magnetic field
β_A	Angle from vehicle B to A measured from "North" of vehicle B
β_C	Angle from vehicle B to C measured from "North" of vehicle B
Co	Gauge factor = i/(pi r^2)
D	Translated vehicle distance (sorry hard to explain)
γ_A	Angle from vehicle C to A measured from "North" of vehicle C
γ_B	Angle from vehicle C to B measured from "North" of vehicle C
H	Applied magnetic field
h	Air cushion thickness
$H_{cluster}$	Angular momentum of cluster
H_{RW}	Angular momentum of RW
I	Moment of inertia of cluster about CG
i	Current
I_0	Moment of inertia of vehicle
I_{RW}	Moment of inertia of RW
L_{coil}	Total length of coil wire
L_{core}	Length of the core
μ_0	Permeability of free space
μ_A	Magnetic moment of magnet A

μ_a	Ambient dynamic viscosity
μ_B	Magnetic moment of magnet B
μ_C	Magnetic moment of magnet C
m_{coil}	Mass of the coil
m_{core}	Mass of the core
m_o	Mass of entire system except coil and core
m_{RW}	Mass of RW
m_{tot}	Total vehicle mass
N	Number of turns around the core
n	Number of vehicles in cluster
P	Air cushion pressure distribution
P_a	Ambient pressure
P_{RW}	Power of reaction wheel
P_s	Supply pressure
ρ_a	Ambient density
ρ_{Al}	Density of Aluminum
ρ_{coil}	Density of the coil
ρ_{coil}	Radius of the coil wire
ρ_{core}	Density of the magnet core material
r_{core}	The radius of the core
Re	Reynolds number
R_p	Air bearing max radius
r_p	Air bearing radius
ρ_{res}	Resistivity of the coil
r_{RW}	Radius of RW
s	Separation distance between outermost vehicles in cluster
s_{AB}	Distance from center for vehicle A to B

s_{AC}	Distance from center for vehicle A to C
s_{BC}	Distance from center for vehicle B to C
s_{US}	Distance between ultrasonic sensors on a vehicle (equilateral triangle form)
τ_{mag}	Torque induced by magnet
t_{ring}	Thickness of RW ring
τ_{RW}	Torque of reaction wheel
U_p	Puck velocity
U_r	Air flow radial velocity
V_{core}	Volume of magnetic core
Ω	Rotation rate of cluster
Ω_{RW}	Rotation rate of reaction wheel
x	Distance from magnet center to point in field

Appendix B: Electromagnet

B.1 Calculations of System Masses vs. Applied Magnetic Field

Appendix C: Controls

Appendix C.1 Derivation of Poles for Steady State

Force Balance

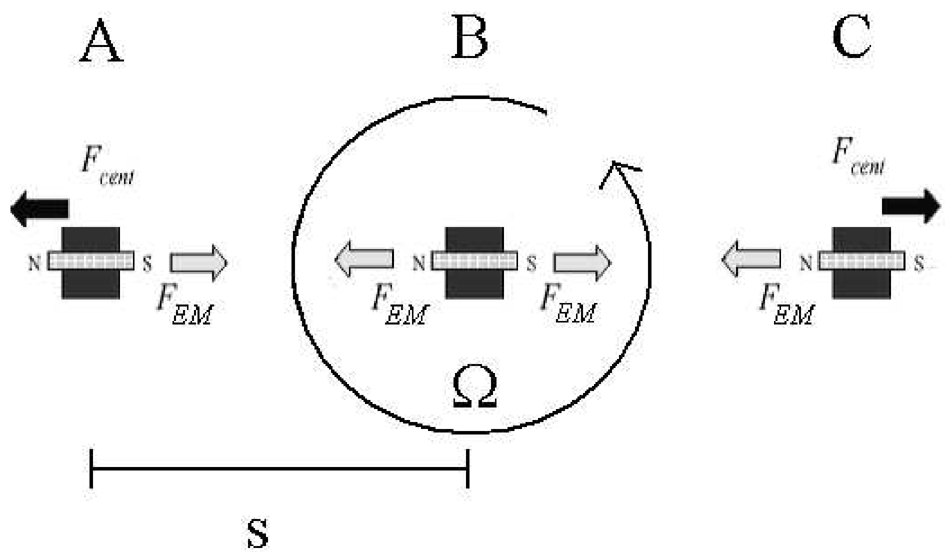

Figure C.1.1 Three Vehicle Steady State Force Balance

Assume the three vehicles have the same magnetic moments, so $\mu_A = \mu_B = \mu_C = \mu_{avg}$.

Equation C.1.1 $$F_{cent.} = \frac{mv^2}{s} = m\Omega^2 s = \frac{mh^2}{s^3}$$

Equation C.1.2 $$F_{EM} = \frac{c_0\mu_{avg}^2}{s^4} + \frac{c_0\mu_{avg}^2}{(2s)^4}$$ **where** $c_0 = \frac{3\mu_0}{2\pi}$

Equation C.1.3 $$m\ddot{s} = F_{EM} - F_{cent.} = \frac{c_0\mu_{avg}^{\;2}}{s^4} + \frac{c_0\mu_{avg}^{\;2}}{(2s)^4} - \frac{mh^2}{s^3}$$

Add a perturbation

$$m(\ddot{s}_0 + \Delta\ddot{s}) = \frac{17c_0(\mu_{avg} + \Delta\mu_{avg})^2}{16(s_0 + \Delta s)^4} - \frac{mh^2}{(s_0 + \Delta s)^3}$$

$\ddot{s}_0 = 0$ because there is no force at s_0

$$md\ddot{s} = \frac{17c_0\mu_{avg}^2(1 + \frac{d\mu}{\mu_{avg}})^2}{16s_0^4(1 + \frac{ds}{s_0})^4} - \frac{mh^2}{s_0^3(s_0 + \Delta s)^3}$$

Binomial Expansion $(1 + x)^n = 1 + nx +$ higher order terms

$$md\ddot{s} = \frac{17c_0\mu_{avg}^2(1 + 2\frac{d\mu}{\mu_{avg}})(1 - 4\frac{ds}{s_0})}{16s_0^4} - \frac{mh^2(1 - 3\frac{ds}{s_0})}{s_0^3}$$

$$md\ddot{s} = \frac{17c_0\mu_{avg}^2(1 + 2\frac{d\mu}{\mu_{avg}} - 4\frac{ds}{s_0} - 8\frac{d\mu ds}{\mu_{avg}s_0})}{16s_0^4} - \frac{mh^2(1 - 3\frac{ds}{s_0})}{s_0^3}$$

Neglect Higher Order Terms

$$md\ddot{s} = \frac{17c_0\mu_{avg}^2(1 + 2\frac{d\mu}{\mu_{avg}} - 4\frac{ds}{s_0})}{16s_0^4} - \frac{mh^2(1 - 3\frac{ds}{s_0})}{s_0^3}$$

Cancel Force Balance Terms

$$\text{Since } F_{EM} \square F_{cent.} \square \frac{17c_0\mu_{avg}^2}{16s^4} \square \frac{mh^2}{s^3} \square 0 \text{ when } \ddot{s}_0 \square \; 0$$

$$md\ddot{s} \square \frac{17c_0\mu_{avg}^2(2\frac{d\mu}{\mu_{avg}} \square 4\frac{ds}{s_0})}{16s_0^4} \square \frac{3mh^2\frac{ds}{s_0}}{s_0^3}$$

Grouping the Terms:

$$\mu_{avg}^2 \square \square \frac{16smh^2}{17c_0}$$ derived from Equation C.1.3

Equation C.1.4

$$md\ddot{s} \square \frac{mh^2}{s_0^4} ds \square \square 2\frac{mh^2}{\mu_{avg}s_0^4} d\mu$$

Taking the Laplace Transform (Using S as the Laplace variable for clarity)

$$mS^2 \square \frac{mh^2}{s_0^4} \square 0$$

Equation C.1.5 $S \square \square \sqrt{\frac{h^2}{s_0^4}} \square \square \Omega$

Appendix C.2 Derivation of Poles for 16.62x Setups

Appendix C.2.1 Derivation of Poles for Stable 16.62x Setup

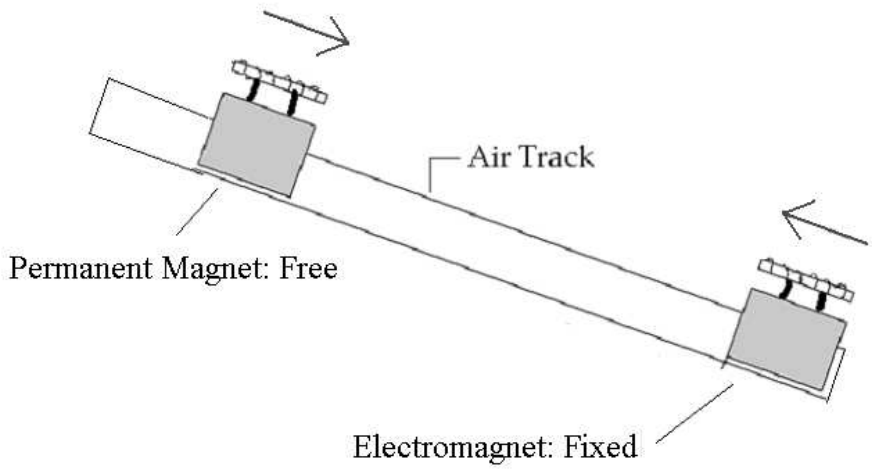

Figure C.2.1.1 16.62x Stable Setup

Force Balance

Equation C.2.1.1 $F_{EM} = F_{grav}$

Equation C.2.1.2 $F_{EM} = \frac{c_0 \mu_{avg}^2}{s^4}$ where $c_0 = \frac{3\mu_0}{2\pi}$

Equation C.2.1.3 $F_{grav} = mgSin(\theta)$

where m is the mass of the free magnet, g is gravitational acceleration, and θ is the angle of the track

$$m\ddot{s} = F_{EM} - F_{grav} = \frac{c_0 \mu_{avg}^2}{s^4} - mgSin(\theta)$$

Add a perturbation

$$m(\ddot{s}_0 + d\ddot{s}) = \frac{c_0(\mu_{avg} + d\mu)^2}{(s_0 + ds)^4} - mgSin(\theta)$$

$\ddot{s}_0 = 0$ because there is no force at s_0

$$m d\ddot{s} \square \frac{c_0 \mu_{avg}^2 (1 \square \frac{d\mu}{\mu_{avg}})^2}{s_0^4 (1 \square \frac{ds}{s_0})^4} \square mgSin(\square)$$

Binomial Expansion $(1 \square x)^n \square 1 \square nx \square$ higher order terms

$$m d\ddot{s} \square \frac{c_0 \mu_{avg}^2 (1 \square 2\frac{d\mu}{\mu_{avg}})(1 \square 4\frac{ds}{s_0})}{s_0^4} \square mgSin(\square)$$

$$m d\ddot{s} \square \frac{c_0 \mu_{avg}^2 (1 \square 2\frac{d\mu}{\mu_{avg}} \square 4\frac{ds}{s_0} \square 8\frac{d\mu ds}{\mu_{avg} s_0})}{s_0^4} \square mgSin(\square)$$

Neglect Higher Order Terms

$$m d\ddot{s} \square \frac{c_0 \mu_{avg}^2 (1 \square 2\frac{d\mu}{\mu_{avg}} \square 4\frac{ds}{s_0})}{s_0^4} \square mgSin(\square)$$

Cancel Force Balance Terms

$$\text{Since } F_{EM} \square F_{grav} \square \frac{c_0 \mu_{avg}^2}{s^4} \square mgSin(\square) \square 0 \text{ when } \ddot{s}_0 \square 0$$

$$m d\ddot{s} \square \frac{c_0 \mu_{avg}^2 (2\frac{d\mu}{\mu_{avg}} \square 4\frac{ds}{s_0})}{s_0^4}$$

Grouping the Terms

Equation C.2.1.4 $m d\ddot{s} \square \frac{4 c_0 \mu_{avg}^2}{s_0^5} ds \square \frac{2 c_0 \mu_{avg}}{s_0^4} d\mu$

Taking the Laplace Transform (Using S as the Laplace variable for clarity)

$$mS^2 \square \frac{4 c_0 \mu_{avg}^2}{s_0^5} \square 0$$

Equation C.2.1.5 $S \Box \Box \sqrt{\frac{4c_0 \mu_{avg}^2}{m s_0^5}} i$

Appendix C.2.2 Derivation of Poles for Unstable 16.62x Setup

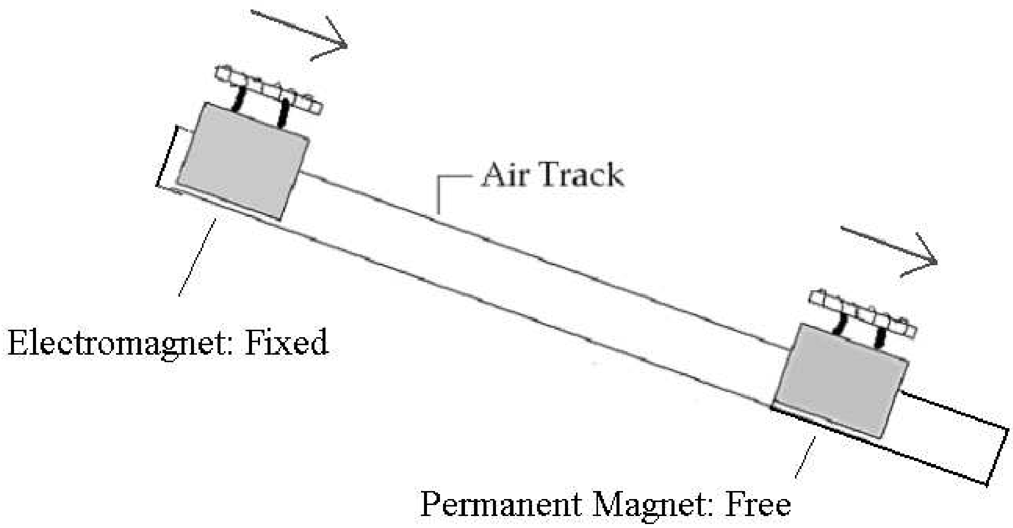

Figure C.2.2.1 16.62x Unstable Setup

Force Balance

Equation C.2.2.1 $F_{EM} \Box F_{grav}$

Equation C.2.2.2 $F_{EM} \Box \Box \frac{c_0 \mu_{avg}^2}{s^4}$ where $c_0 \Box \frac{3\mu_0}{2\Box}$

Equation C.2.2.3 $F_{grav} \Box mgSin(\Box)$

where m is the mass of the free magnet, g is gravitational acceleration, and $\Box$ is the angle of the track

$$m\ddot{s} \Box F_{EM} \Box F_{grav} \Box \Box \frac{c_0 \mu_{avg}^2}{s^4} \Box mgSin(\Box)$$

Add a perturbation

$$m(\ddot{s}_0 \Box d\ddot{s}) \Box \Box \frac{c_0 (\mu_{avg} \Box d\mu)^2}{(s_0 \Box ds)^4} \Box mgSin(\Box)$$

$\ddot{s}_0 = 0$ because there is no force at s_0

$$m d\ddot{s} = -\frac{c_0 \mu_{avg}^2 (1 + \frac{d\mu}{\mu_{avg}})^2}{s_0^4 (1 + \frac{ds}{s_0})^4} + mgSin(\theta)$$

Binomial Expansion $(1 + x)^n = 1 + nx +$ higher order terms

$$m d\ddot{s} = -\frac{c_0 \mu_{avg}^2 (1 + 2\frac{d\mu}{\mu_{avg}})(1 - 4\frac{ds}{s_0})}{s_0^4} + mgSin(\theta)$$

$$m d\ddot{s} = -\frac{c_0 \mu_{avg}^2 (1 + 2\frac{d\mu}{\mu_{avg}} - 4\frac{ds}{s_0} - 8\frac{d\mu ds}{\mu_{avg} s_0})}{s_0^4} + mgSin(\theta)$$

Neglect Higher Order Terms

$$m d\ddot{s} = -\frac{c_0 \mu_{avg}^2 (1 + 2\frac{d\mu}{\mu_{avg}} - 4\frac{ds}{s_0})}{s_0^4} + mgSin(\theta)$$

Cancel Force Balance Terms

$$\text{Since } F_{EM} + F_{grav} = -\frac{c_0 \mu_{avg}^2}{s^4} + mgSin(\theta) = 0 \text{ when } \ddot{s}_0 = 0$$

$$m d\ddot{s} = \frac{c_0 \mu_{avg}^2 (4\frac{ds}{s_0} - 2\frac{d\mu}{\mu_{avg}})}{s_0^4}$$

Grouping the Terms

Equation C.2.4 $$m d\ddot{s} = \frac{4 c_0 \mu_{avg}^2}{s_0^5} ds - \frac{2 c_0 \mu_{avg}}{s_0^4} d\mu$$

Taking the Laplace Transform (Using S as the Laplace variable for clarity)

$$mS^2 - \frac{4c_0\mu_{avg}^2}{s_0^5} = 0$$

Equation C.2.5 $$S = \pm\sqrt{\frac{4c_0\mu_{avg}^2}{ms_0^5}}$$

Appendix C.3 State Space Analysis

State Space Equation

Equation C.3.1
$$\begin{bmatrix} \frac{\dot{s}}{s_0} \\ \frac{\ddot{s}}{s_0} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ \Omega^2 & 0 \end{bmatrix} \begin{bmatrix} \frac{s}{s_0} \\ \frac{\dot{s}}{s_0} \end{bmatrix} + \begin{bmatrix} 0 \\ -2\Omega^2 \end{bmatrix} \frac{\Delta\mu}{\mu_{avg}}$$

of form

$$\dot{x} = Ax + Bu$$

Want to minimize J, where J is a cost function.

Equation C.3.2
$$J = \int_0^{\infty} [x^T R_{xx} x + u^T R_{uu} u] dt$$

Equation C.3.3
$$u = -R_{uu}^{-1} B^T P x = -Fx$$

Equation C.3.4
$$R_{xx} + PA + A^T P - PBR_{uu}^{-1} B^T P = 0$$

Variable Definitions

$$R_{uu} = \rho \qquad R_{xx} = \begin{bmatrix} \gamma & 0 \\ 0 & 0 \end{bmatrix} \qquad P = \begin{bmatrix} P_{11} & P_{12} \\ P_{12} & P_{22} \end{bmatrix}$$

Plug into Equation D.3.4

$$\begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} \gamma & 0 \\ 0 & 0 \end{bmatrix} + \begin{bmatrix} P_{11} & P_{12} \\ P_{12} & P_{22} \end{bmatrix} \begin{bmatrix} 0 & 1 \\ \Omega^2 & 0 \end{bmatrix} + \begin{bmatrix} 0 & \Omega^2 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} P_{11} & P_{12} \\ P_{12} & P_{22} \end{bmatrix} - \begin{bmatrix} P_{11} & P_{12} \\ P_{12} & P_{22} \end{bmatrix} \begin{bmatrix} 0 \\ -2\Omega^2 \end{bmatrix} \frac{1}{\rho} \begin{bmatrix} 0 & -2\Omega^2 \end{bmatrix} \begin{bmatrix} P_{11} & P_{12} \\ P_{12} & P_{22} \end{bmatrix}$$

Three distinct equations result

Equation C.3.5
$$0 = \gamma + 2P_{12}\Omega^2 - 4\frac{\Omega^4}{\rho} P_{12}^2$$

Equation C.3.6
$$0 = P_{11} + P_{22}\Omega^2 - 4\frac{\Omega^4}{\rho} P_{12}P_{22}$$

Equation C.3.7
$$0 = 2P_{12} - 4\frac{\Omega^4}{\rho} P_{22}^2$$

Solve Equation C.3.5 for P_{12}

$$P_{12} = \frac{\rho}{4\Omega^2}\left[1 + \sqrt{1 + 4\frac{\square}{\rho}}\right]$$

Plug into Equation C.3.6 and solve for P_{22}

$$P_{22} = \sqrt{\frac{\rho}{2\Omega^4}\frac{\rho}{4\Omega^2}\left[1 + \sqrt{1 + 4\frac{\square}{\rho}}\right]}$$

Both values must be positive to be real, therefore

$$P_{12} = \frac{\rho}{4\Omega^2}\left[1 + \sqrt{1 + 4\frac{\square}{\rho}}\right] \quad \text{and} \quad P_{22} = \sqrt{\frac{\rho^2}{8\Omega^6}\left[1 + \sqrt{1 + 4\frac{\square}{\rho}}\right]}$$

Solve Equation C.3.6 for P_{11}

$$P_{11} = \Omega^2\sqrt{\frac{\rho^2}{8\Omega^6}\left[1 + \sqrt{1 + 4\frac{\square}{\rho}}\right]}\sqrt{1 + 4\frac{\square}{\rho}}$$

From C.3.3

$$F = -\frac{1}{\rho}\begin{bmatrix}0 & 2\Omega^2\end{bmatrix}\begin{bmatrix}P_{11} & P_{12}\\ P_{12} & P_{22}\end{bmatrix} = -\frac{2\Omega^2}{\rho}\begin{bmatrix}P_{12} & P_{22}\end{bmatrix}$$

if $\frac{\square}{\rho} \to 0$, $\quad P_{12} = \frac{\rho}{4\Omega^2}[2] = \frac{\rho}{2\Omega^2}$

$$P_{22} = \frac{\rho}{2\Omega^3}$$

$$F = -\frac{2\Omega^2}{\rho}\begin{bmatrix}\frac{\rho}{2\Omega^2} & \frac{\rho}{2\Omega^3}\end{bmatrix} = -\frac{1}{\Omega}\begin{bmatrix}\Omega & 1\end{bmatrix}$$

$$\dot{x} = Ax + Bu = Ax + BFx = (A + BF)x = A_{CL}x$$

where $A_{CL} = \begin{bmatrix}0 & 1\\ -\Omega^2 & 0\end{bmatrix} + \begin{bmatrix}0\\ 2\Omega^2\end{bmatrix}\left(-\frac{1}{\Omega}\begin{bmatrix}\Omega & 1\end{bmatrix}\right) = \begin{bmatrix}0 & 1\\ -\Omega^2 & -2\Omega\end{bmatrix}$

solutions of $\quad |SI - A| = \begin{vmatrix}S & -1\\ \Omega^2 & S + 2\Omega\end{vmatrix}$

yield $(S + \Omega)^2 = 0$, two closed loop poles at $-\Omega$.

if $\frac{\square}{\rho} \gg 1$, $\quad F = -\frac{2\Omega^2}{\rho}\begin{bmatrix}P_{12} & P_{22}\end{bmatrix} = -\left[\frac{1}{2}\left(1 + \sqrt{1 + 4\frac{\square}{\rho}}\right) \quad \frac{\sqrt{2}}{2\Omega}\sqrt{1 + \sqrt{1 + 4\frac{\square}{\rho}}}\right]$

$$\dot{x} = Ax + Bu = Ax - BFx = (A - BF)x = A_{CL}x$$

where

$$A_{CL} = \begin{bmatrix} 0 & 1 \\ -\Omega^2 & 0 \end{bmatrix} - \begin{bmatrix} 0 \\ 2\Omega^2 \end{bmatrix} \begin{bmatrix} \frac{1}{2}\left(-1 + \sqrt{1 + 4\frac{\lambda}{\rho}}\right) & \frac{\sqrt{2}}{2\Omega}\sqrt{-1 + \sqrt{1 + 4\frac{\lambda}{\rho}}} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\sqrt{1 + 4\frac{\lambda}{\rho}} & -\Omega\sqrt{2}\sqrt{-1 + \sqrt{1 + 4\frac{\lambda}{\rho}}} \end{bmatrix}$$

solutions of $$\left|SI - A_{CL}\right| = \begin{vmatrix} S & -1 \\ \sqrt{1 + 4\frac{\lambda}{\rho}} & S + \Omega\sqrt{2}\sqrt{-1 + \sqrt{1 + 4\frac{\lambda}{\rho}}} \end{vmatrix}$$

yield two closed loop poles at:

$$s = \sqrt[4]{\frac{\lambda}{\rho}}(1 \pm i)$$

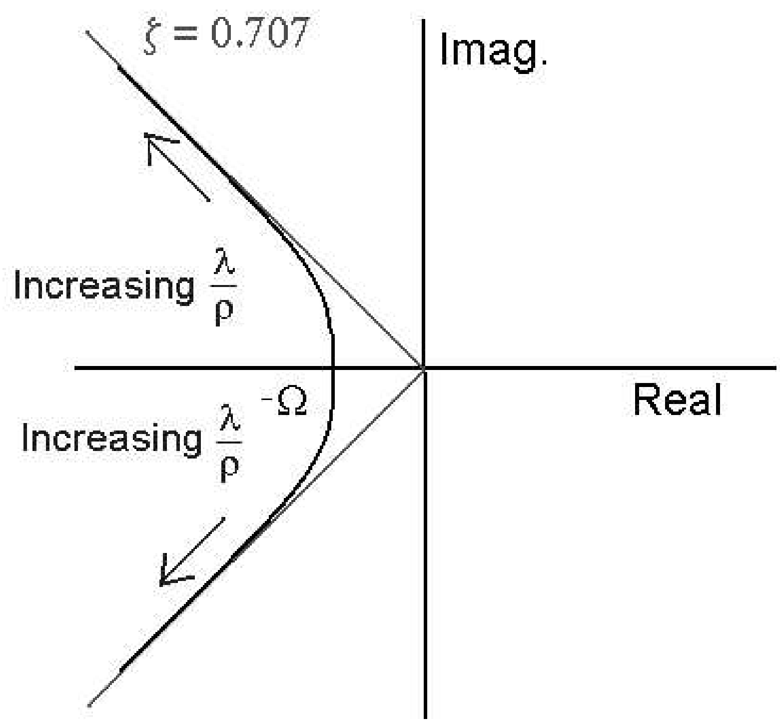

Figure C.3.1 Plot of Position of Closed Loop Poles

Appendix D: Communications

D.1 Data Framing

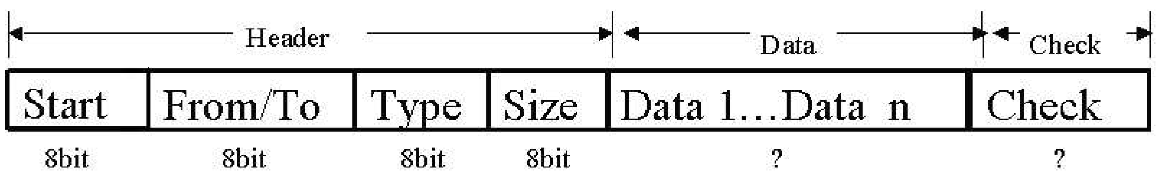

Figure D.1.3: Data Framing
This figure demonstrates the proposed data framing protocol for the EMFFORCE communications subsystem. <JEU>

Data framing determines how data is to be packaged prior to transmission. It is necessary to design the data framing architecture as soon as possible to aid in structuring the framing coding algorithm. It is also an essential part of any communications system design. <JEU>

The current protocol is demonstrated in the above figure and is described in more detail below <JEU>:

- Start byte: This byte says: "This is the start of a data packet. Pay attention!" The start byte may also incorporate a global time stamp. <JEU>
- From/To: This byte ensures that a piece of info is routed to the right recipient and says which vehicle (or the Ground Station) sent the info. If a vehicle receives a data packet that is not intended for it, the information is filtered, and after a delay period, deleted. The delay period is merely to ensure that if the Ground Station switches the Hub, that the new Hub has enough information to keep propagating the formation. <JEU>
- Type: The data type tells the recipient what type of data to expect. The type could include: a command, health information, control state updates, a request, a retransmission, or the token. <JEU>
- Size: The size (# of bytes of data) tells the recipient how many bytes to expect before the packet is completed. <JEU>
- Error-checking: Provides a way of ensuring accurate data. If the data is not accurate, then there should either be enough information in the check byte to determine what the correct data is, or a retransmission of the original data should be requested. It may also be possible to use some error-checking/error-correction methods within the header itself. The implementation of such a system depends on error probabilities and the limits on the rate of information transmission. <JEU>

Finally, there is a possibility that the header can be compressed to cut down on the size of the packet (and hence, the time of transmission). <JEU>

Currently, it is desired to use one byte for each section of the header since the TT8 UART channel operates in 8-bit pieces and because it results in encoding flexibility. <JEU>

To / From	Ground	Hub	Vehicle 1	Vehicle 2
Ground	-	000 0	101 0	010 1
Hub	111 1	-	100 1	001 1
Vehicle 1	-	110 0	-	-
Vehicle 2	-	011 0	-	-

Figure D.1.4: Preliminary Coding Scheme for From/To Header

The above table shows a preliminary coding scheme for the From/To chunk of the Header. Only those transmission paths that will be used for the Hybrid subsystem Architecture have been assigned codes. <JEU>

The current code minimizes bit errors by encoding with a 2-bit difference between adjacent levels. Hence, if a packet arrives from the Hub, there is a 2-bit difference in the code determining for which vehicle (or the Ground Station) the packet was intended. Hence, it is highly unlikely that a packet will arrive from one place claiming to have come from another. <JEU>

The From Ground encoding scheme is slightly different. This communication path will only be used if it is necessary to give Hub status to another vehicle or to apply any other emergency intervention procedure. Since this will (hopefully) happen very rarely, it is safe to leave the code as not quite a 2-bit difference. In addition to a simple parity check, the From/To header can be matched with the type of command to determine whether the Ground Station is indeed switching Hub status within the cluster. If the header and the type match, then the vehicle will heed the command, but if the header and the type do not match, then the vehicle will ignore the command. <JEU>

Also, the current code enables a second layer of bit-error detection by utilizing a simple 1-bit modulo2 parity check-sum. Thus, the From/To byte will look something like: 00001111. <JEU>

The preliminary breakdown of data types and the coding schemes to go with them are as follows <JEU>:

Ground to Hub:

- User command (111 1)
- Emergency command (100 1)

Hub to Vehicles:

- Hub command (110 0)

- Hub request (001 1)
- Token busy (1111 0)
- Token free (1110 1)

Hub to Ground:

- Test data (011 0)
- Health updates (000 0)

Vehicles to Hub:

- Health update (101 0)
- State update (010 1)

Ground to Vehicles

- Emergency Intervention (11111 1)
- Hub switch (111111 0)

Once again there exists a 2-bit difference between adjacent levels and a single bit check sum. <JEU>

There are a few differences. First, the token ring commands are assigned an extra 1. This will allow the vehicle that receives the token to immediately know if it is able to talk or if the token is being used by another vehicle. The use of a free token and a busy token is in accordance with normal token ring design. <JEU>

The Type byte will look something like: 00001001. <JEU>

The free token will look like: 00011101. <JEU>

The busy token will look like: 00011110. <JEU>

If there is an emergency, and the Ground Station must send a command to one of the vehicles, then an extra 1 on top of the free token should alert the vehicle being queried that it has been sent a command from the Ground. <JEU>

The Emergency intervention will look like: 00111111. <JEU>

If a Hub switch is required in the cluster, than two extra 1's on top of the busy token should alert the vehicle being queried that it is now the Hub. <JEU>

The Hub switch will look like: 01111110. <JEU>

A comparison of the Hub Switch, the From/To header, and the parity checks should enable the receiving vehicle to know whether it is being switched to Hub on purpose or by accident. If it is by accident, then the Vehicle ignores the request. <JEU>

These assignments only hold true if the current 8-bit framing is maintained. <JEU>

D.2. Communication Channel Usage

Currently, there are 6 variables in the state vector (the x and y positions, the angle orientation, and the derivatives thereof), and 4 variables to the actuators (3 voltage/current commands to the EM and 1 to the RWA) per vehicle. Preliminary calculations using a spreadsheet suggest this will result in about 800 bits being transmitted per cycle. This number is with 10% retransmission and includes framing bytes. The cluster communication channel will also be carrying about 500 bits/cycle to deal with health updates necessary for ensuring cluster survival. <JEU>
Also, it is expected that the channel connecting to the ground station will be around 400 bits/cycle or about that order of magnitude. However, since the requirements are as yet still undefined for the data that will be transferred over this link, a better estimate cannot be made. <JEU>

These estimates are made for one complete cycle of the system (as generalized in architecture trades). <JEU>

D.3. Transmission Rate Estimation

Since the control runs at 50 Hz (e.g.: how frequently the systems/states are measured), and since the rate at which health data is measured is set at a max of 10 Hz (estimate), we can estimate the transmission rate of the channel. This was found to be around 45 kbps when considering the estimated needs of both control and health data. <JEU>

$$800 \text{ bits/cycle} * 50 \text{ cycles/sec} + 500 \text{ bits/cycle} * 10 \text{ cycles/sec} = 45\text{kbps}$$

D.4. Error Detection/Correction

In the current design, the Header utilizes single-bit parity checks in each section to detect bit errors. <JEU>

As in SPHERES, it is hoped to use a set of 8-bit check sums to detect errors in the data chunk. SPHERES used two (2) 8-bit check sums. <JEU>

Also, clever code will minimize timeout errors and errors associated with “broken” packets (packets that have chunks lost in transmission). <JEU>

Currently, the only scheme to correct errors is to request retransmission from the sender. Codes should exist to allow for detection AND correction. As of this publication of this document, further research is required to determine what these codes are and whether these codes should be implemented for this project. However, it may be possible to enhance the current coding scheme (as discussed in Appendix F.1) to obtain correction capabilities. <JEU>

D.5. Channel Coding

Channel coding is the addition of redundant bits to improve accuracy. There are several different ways to improve accuracy (communication accuracy is very important for this design). The main types of channel coding are <JEU>:

- Repetition codes
  Repetition codes are what they sound like. They repeat the data at least once. <JEU>

- Block codes

  Data is broken into equal length blocks. Each block is "mapped" onto larger blocks. An example is the famous Hamming Code. <JEU>

- Systematic codes

  Systematic codes have a data part and a redundant part. Block codes can be systematic codes as long as they have a data part and a redundant part. Systematic codes are linearly independent and can be written as a generator matrix such that every codeword is a linear combination of the rows of the generator matrix. Using the generator matrix, one can also find a matrix that gives a parity check. <JEU>

Currently, it is preferred that a systematic code be used since it will make the code needed to implement communications the scale of this project more efficient. <JEU>

D.6. Automatic Repeat Request Protocols (ARQ's)

Automatic Repeat Request Protocols (ARQ's) are designed to automatically request retransmission should there be an error in the data that has been sent. There are three potential ARQ protocols: Stop and Wait, Go Back N, and Selective Repeat. <JEU>

The characteristics of each are listed below <JEU>:

- Stop and Wait

  Stop and wait transmits one packet at a time, then waits for an acknowledgement (ACK) before sending another packet. The protocol is easy to implement, but is not efficient when the delay is greater than the transmission time. <JEU>

- Go Back N ("Sliding Window")

  Go Back N transmits new packets before all previously sent packets are acknowledged (Ack). A benefit is the ability to implement bi-directional piggy-backing, where a request number can be sent along with an acknowledgement and vice-versa. The protocol is relatively easy to implement, but the entire window must be resent upon discovery of an error. <JEU>

- Selective Repeat

  Selective repeat only retransmits packets that are in error or are lost. The protocol requires buffering to achieve this capability. A consequence of being able to retransmit packets that are in error or are lost is that the protocol requires more coding than Go Back N. A major benefit is that Selective repeat is better than Go Back N when using a large transmission window. <JEU>

The preliminary selection is Go Back N since it allows for bi-directional piggy-backing, is relatively easy to implement, and is fairly efficient (less efficient than Selective Repeat, but is much easier to implement). Should a large transmission window be chosen, or should the Go Back N method prove to not be efficient enough, it is possible to modify the code for Go Back N to achieve Selective Repeat. <JEU>