Trade Analysis and Requirements Review

<BAB>

Welcome to the Trade Analysis and Requirements Review for Project EMFFORCE (ElectroMagnetic Formation Flight Of Rotating Clustered Entities).

CDIO Space Systems Product Development
MIT Aero/Astro

Introduction
Requirements
System Trades
Subsystems
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REQUIREMENTS
Oscar Murillo
Leah Soffer
Maggie Sullivan

ARCHITECTURE
Jesus Bolivar
Darien Crane
Geeta Gupta
Timothy Sutherland
Lindsey Wolf

PROCESSES
Andre Bosch
William Fournier
Erik Stockham
Jennifer Underwood

DATABASES
Amilio Aviles
Amy Schonsheck
Stephanie Slowik
Melanie Woo

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<BAB>

The CDIO Space Systems Product Development Class met as a team for the first time five weeks ago. At this meeting we were presented with the challenge of demonstrating the feasibility of using electromagnetic control for formation flight of satellites. Since then the team has been working diligently to understand the problem and quantify any relevant requirements and trades. To this end, the class organized it self into the following groups: Requirements, Processes, Architecture, and Databases. The Requirements team was formed to identify all customer requirements and constraints and to levy other pertinent requirements as dictated by the nature of the project. The Processes team was formed to act as a systems engineering team so as to coordinate the other teams. In addition, the processes team set up the processes by which the class would conduct the remainder of the project. The Architecture team was formed to quantify the design trades in order to identify important metrics. In the process of doing so, the Architecture team also drafted design possibilities and investigated these possibilities. The Databases team was formed to construct a database of possible parts and manufacturers. This database will become invaluable in determining whether to make or buy a particular part. This database will also enable the project team to select parts that meet requirements. Once the TARR has passed, the class will be divided into subsystem groups with a systems group coordinating the project.

MIT Aero/Astro

Introduction

Erik Stockham

<JEU>

Welcome to the Introduction portion of the Trade Analysis and Requirements Review for Project EMFFORCE (ElectroMagnetic Formation Flight Of Rotating Clustered Entities).

TARR Purpose

MIT Aero/Astro

Introduction
•**Purpose**
•Background
•Motivation
•Mission
•Approach
•Overview

Requirements
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- Formally accept Requirements Document
- Present system and subsystem trade analyses
- Outside expert review of current progress
  - Provide impetus for generation of new action items

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<BAB>

The purpose of the TARR is explicit in its name, Trade Analysis and Requirements Review. Specifically, the class hopes to review the requirements that have been levied and the trade analyses that have been conducted. The purpose of presenting this to an audience is twofold:

1. To require the class to polish their work by having to make it presentable to an outside audience.

2. To seek outside view of our work as it stands.

The class realizes that we do not have all the answers and hopes that through this exercise we will gain further understanding and new insight into the project.

Formation Flying Satellites

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- Use of a cluster of satellites flying in formation
- New mission capabilities
- SPHERES demonstrated feasibility

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<BAB & ESS & WDF>

Formation flight of satellites is defined as the use of a cluster of satellites maintaining a designated formation in Space Flight. 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. SPHERES demonstrated the initial feasibility of the use of a group of satellites in formation flight and we hope to expand on this research with our project.

Electromagnetic Control

- The use of electromagnets as the force generator that will control the vehicles
- Control achieved by varying the current in the coil of the magnet

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BAB

Electromagnetic control of satellites essentially means that we will be using electromagnets as the force generators to control the relative position, attitude, and angular rate of a cluster of satellites. This control can be achieved by varying the current in the coil of an electromagnet to vary the B field the electromagnets provide.

Advantages of Formation Flying Satellites

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- Smaller vehicles
  - Cheaper to launch
- Redundancy
  - Mission doesn't fail if one fails
- Reconfigurable
  - Can tailor for mission specs

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BAB

A number of current satellite missions are considering multiple spacecraft architectures for a variety of reasons. First, multiple spacecraft can be separated to large baselines thereby improving angular resolution for imaging, astrometry, and planet detection. Second, each spacecraft in the formation can be smaller than a single spacecraft designed to perform the same mission and thereby provide easier packaging, launch, and deployment. Third, since inter-spacecraft interfaces are soft (e.g., communications, optics, control, metrology), if a spacecraft fails, it can easily be removed from the formation and replaced with a functioning spacecraft. Fourth, as technology improves, replacement spacecraft can be launched and integrated into the array thereby evolving the formation's capabilities without the costly "block changes" typical of past programs. (Miller, D. et. al., EMFF for Sparse Aperture Telescopes)

Applications of Formation Flying Satellites

- Interferometry
  - Increased resolution
- Servicing
- Upgrade and maintenance
- Deployment and system assembly
- Large and reconfigurable apertures

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BAB

One of the main arguments for utilizing satellite formation flight for surveillance and imaging applications is the fact that large sensor apertures can be synthesized without the need for correspondingly large physical structures. In the case of interferometry, larger apertures lead to higher resolution. But other advantages to formation flight are equally compelling: these include the possibility of dynamically changing the formation geometry to respond to evolving mission sensing requirements or to address multiple missions, and the capability of replacing failed formation elements on orbit more efficiently and economically than heretofore. (from NRO proposal)

Challenges of Current Formation Flying Satellite Technology

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- **Command and control**
  - Must control multiple vehicles' inertial position and motion
- **Drawbacks of propellant for ACS**
  - Consumable fuel limits endurance
  - Gas plumes contaminate IR and other imaging instruments
  - Ion plumes potentially contaminate sensitive equipment

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BAB

While these benefits are clear, there are several drawbacks. As one explores the design of these systems in more depth, one recognizes that there is a miss-match between the geometric requirements that the formation must achieve and the way in which that geometry is controlled. Specifically, the relative separations between spacecraft, not the absolute inertial position in space, is important. However, thrusters actuate inertial degrees-of-freedom. In addition, precision formation flight of the satellites in the array requires that precious propellant be expended to maintain the formation geometry. This has several implications. First, propellant is a consumable which, once depleted, renders the satellite useless. Second, the impingement of a thruster plume on a neighboring spacecraft can cause a dynamic disturbance to its stability, deposit particulates on sensitive optics, induce inadvertent charging, and actually ablate material off the spacecraft thereby causing permanent damage. Third, for missions such as NASA's Terrestrial Planet Finder (TPF), the propellant plume can put a thermally bright haze across the line-of-sight of the telescope. For example, micron particles at room temperature can blind TPF even if the particles are many kilometers away. Furthermore, low speed plume exhaust will tend to be attracted to the spacecraft creating a local pollution haze through which the telescope must look. (adapted from Big Sky presentation)

Advantages of Electromagnetic Formation Flight

- Proposed Electromagnetic Control
  - No thrusters
    - Energy comes from Solar arrays
    - Longer life (fewer/no consumables)
    - No contamination of IR imaging
    - No damaging plume
  - Relative position/motion vs. inertial position/motion

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BAB

To overcome some of the difficulties of current FF technology, the use of electromagnets for formation control has been suggested. Research has been conducted into the control models of such a system by the MIT Space Systems Laboratory (SSL).

As earlier discussed, one of the undesirable aspects of formation flight is the use of thrusters. EMFF would eliminate the use of thrusters for position in the formation. This would lead to longer life, no contamination of IR imaging, and no damaging plume. In addition EMFF would lead to better control of the formation. Specifically electromagnets control relative position instead of inertial position and it is this relative positioning capacity that we seek.

- Control Problem
  - Unstable system
  - Rotating system
  - Distributed
    - Moving one vehicle affects all vehicles
- Disadvantages of Electromagnets
  - Heavy
  - Weak
    - Force drops off as fourth power of separation distance

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ESS & BAB

There are also challenges with using Electromagnets for control of Formation flight. The first of which, is that it has never been done before. The problem of controlling satellites using electromagnets is also formidable. The details of the electromagnetic effects with multiple poles in multiple planes gets exponentially complicated with the number of satellites and degrees of freedom that need to be controlled. The system is inherently unstable and has the added difficulty that the control of each satellite is coupled with the motions of every other satellite in the constellation. Electromagnets are also very heavy and have a force which drops off proportional to the separation distance to the fourth.

EMFF Mission Statement

MIT Aero/Astro

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- To determine the feasibility of electromagnetic control of formation flying satellites.
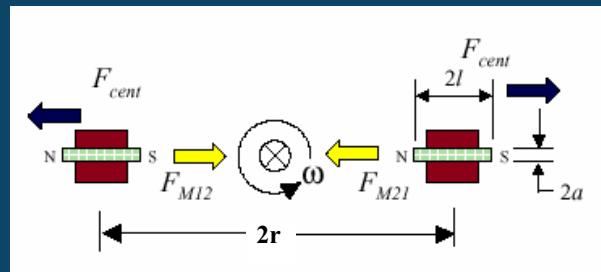
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ESS & BAB

This is the mission statement for our project. It will be fully explained in the Requirements Document and in the requirements section of this Review.

CDIO Program Approach

- Conceive and Design EMF^2 testbed in Spring 2002
- Implement testbed in Fall 2002
- Operate completed testbed in Spring 2003
  - small flat surface at MIT
  - Large smooth floor test facility in Denver

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ESS & BAB

In order to achieve our mission, there are several steps we must progress through. The first stage of the project will be the conception and design of the EMF^{2}ORCE testbed in the spring of 2002. The design will be finalized in the fall of 2002 and construction and testing of subsystems will occur. In Spring of 2003, the subsystems will be integrated into the final system and tested first at MIT and then at the Lockheed Martin flat floor test facility in Denver, Colorado.
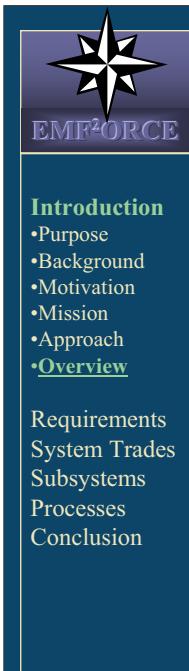
TARR Overview

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- Requirements
- System-level trades analysis
  - Driving mathematics of EMFF
- Subsystem trades analysis
  - Product specifications
- CDIO processes
  - Methodologies
  - Plan for project completion

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ESS & BAB

The outline for today's presentation will include a discussion of the system's requirements by the Requirements team. Followed by a discussion of the large scale system level trade analysis and equations presented by the Architecture team. We will then go into the trade analysis at the subsystem level provided by a combination of the Architecture and Databasing Teams. Finally, the Processes team will explain the procedures that will be used by the class to ensure the successful completion of this project. We will follow the presentation with a question and answer session.

Requirements Review

Maggie Sullivan

Leah Soffer

BAB, JEU

Welcome to the Requirements Review portion of the Trade Analysis and Requirements Review for Project EMFFORCE (ElectroMagnetic Formation Flight Of Rotating Clustered Entities).

Requirements Introduction

- Customer Requirements
- Mission Statement
- Constraints on the Problem
- System Requirements
  – Functional and operational
- Subsystem Requirements
  – Functional and operational
- Additional Notes

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MS

The Requirements Team presentation is primarily the Requirements Document mapped onto slides and detailed for the audience.

Each requirement in this presentation is referenced to the Document and, where applicable, to one or more Customer-originated documents.

There are a few points recommended by the customer proposals and by the staff that are not requirements but guidelines, and recommendations for design approaches. These are noted at the end of the Requirements presentation as a springboard for the top-level system trade analysis.

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- Multiple vehicles
- Formation flying maneuvers representative of real-world applications
  – Dynamically changing geometry
  – Replacement elements
- Electromagnetic control testing

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MS

The primary sources of Customer Requirements are the Executive Summary EMFF Proposal by MIT SSL (hereafter referred to as E-S), and the Technical-Management Proposal by MIT Space Systems Laboratory (MIT SSL) and Lockheed-Martin Advanced Technology Center (LM-ATC) (hereafter referred to as T-M). Both documents are in response to National Reconnaissance Office (NRO) document 000-02-R-0008. (The NRO is the source of funding for the project.)

•Multiple Vehicles (T-M, page 4, col. 2b): "This testbed will consist of **small prototype satellites**, …" (EMF^{2}ORCE Requirements Document [RD] 2.1)

•Representative Formation Flying Maneuvers:

•"… these [advantages to formation flight] include … **dynamically changing the formation geometry** to respond to evolving mission sensing requirements or to address multiple missions," (E-S, p.1, col. 1a) [RD 2.2.1].

•"… the capability of **replacing failed formation elements** on orbit…" (E-S, p.1, col. 1a) [RD 2.2.2].

•Electromagnetic Control Testing: there are several aspects of EM control which the EMF^{2}ORCE project must address [RD 2.3].

- Replace thrusters
- Control 3 degrees of freedom (DOF), translate to 6 DOF
- Robust controller
  - Disturbance rejection
  - Reposition vehicles
  - Restoring forces

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MS

•Replace thrusters: "The EMFF system would replace the traditional thrusters in maintaining the geometry of the formation in space or in evolving it in response to changing surveillance requirements," (E-S, p.1, col. 1a) [RD 2.3.1]

•Degrees of Freedom (DOF): "As part of the EMFF program, this class will design, build, test, and operate a testbed that will allow for three and six DOF EMFF," (T-M, p.4, col. 1a) [RD 2.3.2]. The class interpretation of this statement is as follows

>•The system shall operate in two dimensions.

>•Each **individual vehicle** shall have **three controlled DOF**: two of translation and one of rotation (X, Y, θ).

>•The **system** shall control all **relative DOF**. The six possible DOF for two vehicles are as follows: linear separation distance, "skew" separation, direct translation of the formation, rotation of each individual vehicle, and rotation of the formation. However, since the forces in an EMFF system are all internal to the system, the formation cannot translate its own center of mass. Therefore, our System Functional Requirements will show that **EMF²ORCE shall control all relative system DOF**.

>•Since the applications of this system involve space-based satellites, eventually the idea will be implemented in a three-dimensional environment. Therefore, EMF²ORCE shall show **potential for translation to control six individual DOF** (in 3-D: X, Y, Z, θ, φ, Ψ).

•The system shall have a robust control design and implementation that provides for the following:

>•Disturbance rejection: "… design that will have the capability to **counteract any disturbance force** that the satellite formation will encounter…" (T-M, p.1, col. 2b) [RD 2.3.3.1]

>•Vehicle repositioning: "have enough control authority to **reposition satellites within the formation**" (T-M, p.1, col. 2b) [RD 2.3.3.2]

>•Restoring forces: "… **using magnets to generate the necessary restoring forces** [to remain stable for a sufficiently long time]," (E-S, p.1, col. 1b) [RD 2.3.3.3]

Large-scale concerns such as the effect of the Earth's magnetic field or valid orbital metrology techniques are not addressed by EMF²ORCE. These points are outside the scope of our project; they will be tackled by the MIT SSL and LM-ATC.

Mission Statement

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Demonstrate the feasibility of electromagnetic control for formation flying satellites.

- Demonstrate
- Feasibility
- Electromagnetic
- Formation Flying

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LS

This is the objective of our project as created to fulfill the customer requirements.

Mission Statement - Demonstrate

- <u>Demonstrate</u> implies operating an electromagnetic formation flight testbed in a scaled mode representative of a real world application.

  – Shall operate in 2D

  – Shall be easily translated to 3D environment

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LS

This part of the mission statement stems from the customer requirements that the system should perform representative formation flying maneuvers [2.2], and be composed of vehicles that control three individual degrees of freedom (DoF) in EMFF (X, Y, θ) and demonstrate potential for translation to 6 individual DoF (X, Y, Z, θ, ϕ, Ψ [2.3.2]

•The testbed will be operated in a 2D flat floor facility. [3.1.1]

•The design should easily be extended to 3D and 6 degrees of freedom, but it is not required to be demonstrated by this project. [3.1.2]

Mission Statement - Feasibility

- <u>Feasibility</u> implies that the project is limited by the ability to design a functional controller and the constraints levied on the class.

  – Control system shall be designed to stabilize system

  – Budget and schedule limitations

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LS

•This stems from customer requirement 2.3, stating the system should facilitate testing and verification of electromagnetic control. The presence of electromagnets in a rotating system present the potential for instability. In this project, it must be proven that the system can be stabilized by using electromagnets to control the formations. [3.2.1]

•This stems from the schedule constrain [4.1], and budget constraint [4.2]. Though the use of electromagnetic control may be possible, it must be researched and implemented within 15 months and within the set budget. [3.2.2]

Mission Statement - EM Control

- <u>Electromagnetic control</u> implies the design and implementation of a controller using:
  - No thrusters
  - Angular momentum storage

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LS

This part of the mission statement comes from the customer requirement that the system must implement an electromagnetic control system to replace traditional thrusters. [2.3.1]

•Because this project is exploring an alternate method of control, thrusters may not be used at all. [3.3.1]
•Angular momentum must be used in conjunction with the electromagnets to create motion. [3.3.2]

Mission Statement - FF Satellites

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- <u>Formation flying satellites</u> implies a testbed composed of multiple rigid bodies that must exhibit the functionality of a real cluster of satellites in formation flight.

  – Shall sense other vehicles

  – Shall implement user commands

  – Shall maintain degree of autonomy

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LS

This part of the mission statement comes from the customer requirements to perform representative formation flying maneuvers [2.2], and utilize a robust controller [2.3.3]

•The vehicles must determine their own relative position and communicate it to the other vehicles [3.4.1]

•A ground station will send commands to the formation. [3.4.2]

•The system must maintain a minimal degree of autonomy by successfully carrying out preprogrammed test plans without user intervention. [3.4.3]

- Schedule
- Budget
- Human resources
- Testing facility
- Self-contained
- Recorded test data
- Safety

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0M/ LS/ MS

•The system must be designed, built, tested, and fully operational by May 2003. [4.1]

•There is a financial cap of $50,000. [4.2]

•The team responsible for this project includes the MIT CDIO-3 students and staff. [4.3]

•The system must operate in available test spaces. The preliminary test facility shall be a flat-floor area at MIT, less than 10 sq. ft. The culminating   system tests shall be at the Lockheed flat-floor facility in Denver, CO. which means the system must be transportable, able to maneuver freely on the flat   floor, and within the floor dimensions of 20ft by 30 ft. [4.3]

•As a self contained vehicle, it cannot have any external unbilicals during testing for power, gas, or communication [4.5]. The test duration shall be limited by on-board resources. [4.6]

•Test must be documented and data recorded for offline analysis and validation of customer requirements. [4.7]

•Safety must be preserved at all levels of work throughout the project timeline. [4.8] This includes individuals involved in construction and testing must insure safety, each vehicle shall not damage other vehicles or its test environment, and the system shall not be damaged in transport.

Musts:
- Stability with at least three vehicles
- Control in each relative DOF

Shoulds:
- Representative 5 rotation maneuver
- Far field

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LS/ MS

•The system must demonstrate stable maneuverability using at least three vehicles. This requirement, [5.1.1.1] stems from the customer requirements [2.1, 2.3.3].

•Control each relative system degree of freedom This requirement, [5.1.1.3] is derived from [2.3.2]. It implies the system must be demonstrated in 2 dimensions with identifiable transition to 3 dimensions. Also, it cannot control absolute motion of center of mass.

• The system should complete a representative five-rotation system maneuver as stated in [5.1.2.1] based on customer requirement [2.2.1], This maneuver will include one rotation for spin-up from rest to a separation distance of at least 2 meters. Then, it will complete three rotations at a constant angular rate of 6 degrees of arc per second for a 2 meter separation distance. Finally, it will have one rotation to de-spin to rest.

•The system should operate in the far field of EM control as stated in [5.1.2.2] This stems from customer requirements [2.2, 2.3] The "far field" interpretation implies a separation distance of at least 10 times electromagnet length. Any different interpretation will lead to inconsistencies with the 2 meter separation distance.

- Test time 5 minutes
- No umbilicals
- Identical interchangeable vehicles
- Send/record test data
- Respond to other satellites
- Respond to user input
- Demonstrate autonomy
- Maintain safety

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LS

•The system shall operate without needing recharged batteries or gas resupply for a period of time useful to perform several tests, as stated in [5.1.1]. This comes from the constraints [4.6, 4.7] Based on the five-rotation maneuver, duration of a single test is 5 minutes so stability can be demonstrated, data recorded, and significant maneuvers can be performed.

•Operate with no external umbilicals as stated in [5.2.2] from constraint [4.5] This means the power supply must be on-board, wireless communication must be used, and all other resources (such as gas supply) must be self-contained.

•Each vehicle must be identicle to the others in the system. This allows mission flexibility in that each vehicle can perform any task. Also, the vehicles must be able to be replaced. Identicle vehicles allows for easy replacement, as well as cost efficiency through standardized parts. This is requirement [5.2.3] as derived from [2.2.2]

•Each vehicle shall record flight data including position and health. The data will be sent to a ground station for inflight analysis, as well as recorded for later download and analysis. These are requirements [5.2.4, 5.2.5], which come from the constraints [4.7, 4.8.2]

•The system shall respond to other satellites in formation in real time at a distance of at least 2 meters to demonstrate far field, but no greater than 8 meters due to size of testing facility. These requirements [5.2.6, 5.2.7] come from [2.2]

•The system shall respond to user input from a ground station within 0.1 seconds as stated in [5.2.8] stemming from [2.2]

•The system shall demonstrate a basic level of autonomy [5.2.9] The system will receive user input from a ground station but must then executed the maneuver without further user input. It must maintain stability, reject disturbances, and reposition the vehicles without additional user input. This requirement stems from the customer requirement [2.2.1]

•The system must not be damaged during testing as stated in [5.2.10]. This comes from the constraints [4.8.1, 4.8.2]

MIT Aero/Astro

- Center of mass location
- Lightweight, air carriage dependent on vehicle weight
- Protection
- Shielding
- Standardized parts

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LS

•Location of center of mass of each vehicle must not destabilize moving system. It must have a low center of mass so each vehicle is not top heavy and inclined to tip while moving. This requirement [6.1.1.1] is derived from [5.1.1.1]

•The structure should be lightweight to minimize cost. The design of the air carriage will depend on the mass of the vehicle. Requirement [6.1.1.2] is derived from [4.2, 4.5]

•A form of bumpers or robust structure is required to protect the vehicle from collisions within testing environment. Requirement [6.1.1.3] is from constrain [4.8.2]

•Shielding for the onboard electronics must be provided so the force from the magnet does not interfere with the components. Requirement [6.1.1.4] stems from constraint [4.8.2]

•The system must utilize standardized parts for interchangeability, ease of manufacturing, and ease of repair. This requirement [6.1.1.5] stems from [5.1.1.2]

floor.

- Stable movement at specified height
- Accessible resources in under 1 minute
- Accessible subsystems for repair/maintenance
- Ports for downloading telemetry
- No umbilicals

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LS

•The air carriage must support the full weight of the vehicle. The system must remain stable when it is raised from the ground by the air carriage. The height required to be lifted is determined by the roughness of the test space. The height must clear the degree of roughness. This requirement [6.1.2.1] is derived from [4.2.2.2, 5.1.1.1]

•The on-board power supply and gas supply must be easily accessible. It shall take less than a minute to access the different resources so they can be replenished and renewed without wasting test time. This requirement [6.1.2.2] stems from the constraint [4.6]

•On-board subsystems should also be located so they can be readily accessed. The computer system, sensing system, and other subsystems should be easily accessed for repair or maintenance without disturbing other subsystems. This is requirement [6.1.2.3] stemming from constraint [4.6]

•Each vehicle must contain ports to download health and position telemetry after test run for later analysis. This is requirement [6.1.2.4] from constraint [4.7]

•During testing, the system may not contain umbilicals that would alter angular momentum. This suggests onboard fuel supply, gas supply, and wireless communication. This is requirement [6.1.2.5] stemming from [5.2.2]

Functional

- One backup power supply per vehicle
- Sustain power for 30 minutes
- Have a minimum overall lifetime of 1 year

Operational

- Recharge in 30 minutes
- Self-contained

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OM/ LS

Functional Requirements

•Each vehicle must contain one onboard power supply and one spare. The power supplies must be chargeable and reusable to save money. While one is being, the other can charge. This requirement [6.2.1.1] is from constraint [4.6]

•Each power supply must sustain power for 30 minutes. This is to allow time for multiple tests without renewing power. This is requirement [6.2.1.2] is from [5.2.1]

•The batteries shall be usable (still able to be recharged) for at least one year, or the length of design and testing. This requirement [6.2.1.3] is derived from the constraints [4.1, 4.2]

Operational Requirements

•The power suppy shall be recharged in 30 minutes to allow for continual testing. This is requirement [6.2.2.1] is from constraint [4.6]

•Power supply completely contained within structure. Requirement [6.2.2.2] stemming from [5.2.2.1]

To allow the system to run freely on the testing environment the power must be internal. An untethered in-flight power supply is necessary to simulate space-like dynamics – outside forces will affect the dynamics and stability of individual vehicles through friction and balance.

The testing time will generally be less than 30 minutes. Spin up and Spin down times will be less than 5 minutes, and stable flight will generally last less than 5 minutes. It is desired that multiple test be run on the same power unit.

The recharge time is set so that at no time will we be unable to perform a test because we do not have a power unit. This is coupled with the requirement that we have 2 power units per vehicle.

The requirement of a 1 year overall life is set so that we do not have to replace the units while in our testing phase. Our testing phase will be less than 1 year, however, power units tend to deteriorate as time progress, resulting in a less efficient power supply.

Introduction

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- Controllable in all relative DOFs
  - Relative position tolerance
  - Angle tolerance
- Sized for far field
- Stability
  - Magnet response time
  - Magnet location
- Infinite solenoid approximation

ElectroMagnetic Formation Flight Of Rotating Clustered Entities   30

LS

•Each vehicle shall control three degrees of freedom. In a multiple vehicle configuration, there will be many degrees of freedom, both relative and absolute. Absolute degrees of freedom, such as translation of center of mass of system, will be impossible. Only relative degrees of freedom will be controlled, as stated in requirement [6.3.1.1] traced to [5.1.1.2]

> •Both relative position and angle will be controlled to a certain tolerance. These are dependent on the separation distance and the angular rotation rate. These are requirements [6.3.1.1.1, 6.3.1.1.2] with suggested separation distances and rotation rates listed in [5.1.2.1.2]

•The size of the electromagnet determines the strength, and the ratio of the separation distance to length of magnet determines satisfaction of the far field requirement. The electromagnet must be sized to satisfy far field requirement. This is requirement [6.3.1.2] as derived from [5.1.2.2]

•One function of the electromagnet besides controlling motion is to induce stability This requirement [6.3.1.3], along with the details regarding stability below, are derived from requirement [5.1.1.1]

> •Responsiveness of the magnet must be sufficient to respond to small changes and maintain stability.

> •The magnet location must be determined to not disturb system stability. In a moving system, the magnet of one vehicle can create a torque on other vehicles if the magnets are not located near the midpoint of the vehicle.

•Many equations used to model the system assume the magnet is an infinite solenoid. The magnet should approximate an infinite solenoid for this reason and to limit fringe effect of the field lines.

Actuator: Operational

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- Shield electronics from magnet
- Limit magnet weight for maneuverability
- Size magnet for test space

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LS

•Shielding from the electromagnet to protect onboard electronics. This is requirement [6.3.2.1] , which is derived from [6.1.1.4, 4.8.2]

•The magnet weight is limited by the weight able to be supported by carriage and move freely on test floor. This is requirement [6.3.2.2] derived from [4.4.2.2, 6.1.1.2]

•Magnet size determines vehicle size, which is limited by test space. This requirement [6.3.2.3] comes from [4.4]
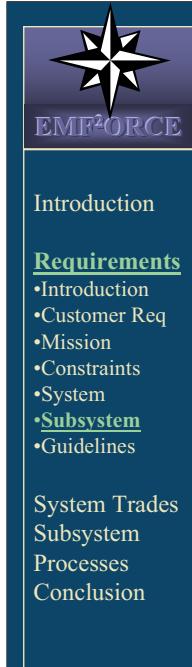
Metrology

MIT Aero/Astro

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- Functional
  - Full field of view
  - Range
  - Relative tolerances
- Operational
  - Work with avionics to interpret data
  - Robustness to withstand transport
  - Budgets

ElectroMagnetic Formation Flight Of Rotating Clustered Entities   32

MS

Sources for listed requirements are referenced in brackets [x].

Functional Requirements:
- Full field of view within testing facility (360 degrees in two dimensions)
- Sensing presence of other vehicles to a distance compatible with test facilities
- Determining separation distance of other vehicles to a linear tolerance dependent on linear controllability [6.3.1.1.1]
  - Goal: sense to one-tenth the control tolerance
- Determining relative attitude (direction) of vehicle to an angular tolerance dependent on angular controllability [6.3.1.1.2]
  - Calculate angle between vehicles
  - Goal: sense to one-tenth the control tolerance
- Other items: angular rate of formation, speed of relative linear motion (closing distance)

Operational Requirements: Subsystem shall:
- Communicate with avionics to calculate positions from sensor data
- Withstand transport to remote testing facility
- Cheap enough to replace, since we don't have the tech on-site to fix…
- Fall within all budgets regarding cost, weight, size

Avionics: Functional

- Manage subsystems
  - Timing
  - Memory
- Run preprogrammed test procedures
- Store test data

ElectroMagnetic Formation Flight Of Rotating Clustered Entities   33

MS

Sources for listed requirements are referenced in brackets [x].

Functional Requirements

• Coordinate timing and allocate memory among metrology, actuators, power subsystems [5.2.1, 5.1.2.1]

•Implement preprogrammed test runs [5.2.9]

   •Interpret metrology data [6.4.2.1]

   •Control power to actuators [6.2]

•Store test data for later analysis [5.2.4]

Avionics: Operational

- Realtime processes
- Store health records
- Emergency memory backup
- Software operations
- Budgets

ElectroMagnetic Formation Flight Of Rotating Clustered Entities   34

MS

Sources for listed requirements are referenced in brackets [x].

Operational Requirements
•Process in realtime to represent a real-world situation [5.2.6, 5.2.8]
•Take health records for realtime reports to operators [5.2.5]
•Have emergency backup storage in case of unplanned shutdown [5.2.10]
•Run software operable by project HR [5.2.11]
•Fall within all budgets regarding cost, weight, power, size [4.2, 4.4]

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- • Vehicle-vehicle
  - – Metrology and control
- • Ground-vehicle
  - – Test initiation
  - – Emergency intervention
- • Vehicle-ground
  - – Selected health and test data
- • Self-contained system

ElectroMagnetic Formation Flight Of Rotating Clustered Entities   35

MS

Sources for listed requirements are referenced in brackets [x].

Communication: Functional Requirements

•Send information and instruction automatically from vehicle to vehicle [5.2.9]

    •control/metrology purposes to maintain relative position and motion knowledge

•Send information and instruction on command from ground to vehicle [5.2.10]

    •begin preprogrammed tests, implement emergency intervention procedures

•Send flight health data to "ground" operator [5.2.4, 5.2.5]

    •Monitoring test and vehicle progress

    •left to design team: at regular intervals or on request

•Have no protruding antennae [might interfere w/dynamics; 5.2.2.2]

- Timing
  - Real world representation
  - System safety
- Range
  - Test floor dimensions
  - Test floor-operator distance
- Budgets

MS

Sources for listed requirements are referenced in brackets [x].

Communication: Operational Requirements

•Process in realtime to represent a real-world situation [5.2.5, 5.2.6, 5.2.8]

•Cover a range 50% larger than test facility [allow for distance to ground, plus safety and recovery] [5.2.7, 5.2.10]

•Fall within all budgets regarding cost, weight, power, size [4.2, 4.4]

"Explore innovative approaches to electromagnetic design and power reduction"

ElectroMagnetic Formation Flight Of Rotating Clustered Entities   37

MS

There are many points addressed in the customer requirements documents and discussed in class which do not specifically qualify as "requirements." Among these are recommendations to make use of new technology to support the electromagnetic system, including power supply and shielding or cooling systems. Other new areas include the EM control itself, with brand-new control algorithms based on different magnetic dipole configuration. These and other concerns received the attention of the Trade Analysis teams, both system and subsystem level.

System Trade Analysis Review

Lindsey Wolf

Timothy Sutherland

<JEU>

Welcome to the System Trade Analysis Review portion of the Trade Analysis and Requirements Review for Project EMFORCE (ElectroMagnetic Formation Flight Of Rotating Clustered Entities).

The customer and functional requirements have been put forth in some detail. Now it's time to show how these requirements flow down into the EMFFORCE system.

System Analysis Overview

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- Force balance analysis
  – Obtain relations for core mass, vehicle mass, magnetic moment, and radius of separation.
- Dipole assumptions/constraints
- Torque wheel analysis
  – Obtain relations for mass and radius of torque wheel.
- Electromagnet time constant
  – Find expressions for inductance and resistance.
- Voltage/power analysis
  – Compare to time constant analysis.

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<JB, TS, LW, GG>

These are the primary system trades necessary to provide a preliminary architectural analysis.

Looking at the relevant force equations, we will be able to manipulate them into equations for core mass, vehicle mass, and magnetic moment. These equations will be based off given values for radius of separation.

We will make certain dipole assumptions and use these to analyze some of the various constraints to the problem.

Using conservation of angular momentum equations, we will get an idea for the necessary moment of inertia for the torque wheel. From there, mass and radius estimates can be made depending on the shape of the torque wheel.

By deriving equations for inductance and resistance, we can figure out the time constant of the electromagnet. This is important in determining how fast the response of the system will be.

Finally, we will conduct a voltage and power analysis and compare these equations to the time constant equation.

Configuration Assumptions

- 2D configuration
- Two vehicles
- One iron core magnet per vehicle
- One reaction wheel per vehicle
- Separation distance 2r = 1 m
- Angular rotation ω about system center of mass

2r
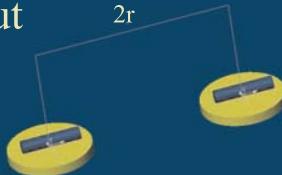
ElectroMagnetic Formation Flight Of Rotating Clustered Entities   40

<JB, TS, LW>

These are the basic assumptions needed to begin architectural analysis. The simplest configurations were used for ease of analysis.

An iron core is used because it is a magnetic material with well known properties.

Force Balance

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- Magnetic force must be balanced by centripetal force:

$$F = \frac{3\mu_o \mu_A \mu_B}{2\pi (2r)^4} = m\omega^2 r$$
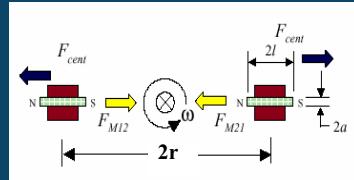
- Manipulate the force balance to get magnetic moment of electromagnet:

$$\mu_{magnet} = \left[\sqrt{\frac{32}{3} \frac{\pi \cdot m_{veh}}{\mu_0}} \right] \omega \cdot r^{5/2} = \frac{2.15\, V_{core}}{\mu_0}$$

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<TS, LW>

During rotation, the centripetal force must balance the electromagnetic force from each magnet. This is necessary to keep the satellites from either flying apart or coming together. This balance is shown in the first equation.

Magnetic moments of each satellite (A and B) are assumed to be equal. The equation is rewritten in terms of the magnetic dipole moment, mu_magnet. The magnetic moment that will be provided by the magnet is equal to the quantity 2.15*(volume of the iron core)/mu_nought. This relation provides the necessary core volume for given values of mass, angular rotation and separation. The value 2.15 Tesla is the magnetic saturation value for iron. Magnetic saturation is the maximum obtainable field strength for a material. We will aim to operate slightly below the saturation point during testing, but for purposes of analysis we use the value of 2.15.

Mu_nought is the permeability of free space, and is a constant.

Determination of Core Mass

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- Using the relation for material density, substitute the following values into the magnetic moment equation:

$$\mu_o = 4\pi \cdot 10^{-7} \quad \text{m kg s}^{-2} \cdot \text{A}^{-2}$$
$$r = 0.5 \quad \text{m}$$
$$\varpi = \frac{2\pi}{15} \quad \text{s}^{-1}$$
$$\rho = 7000 \quad \text{kg} \cdot \text{m}^{-3}$$

$$V_{core} = \frac{m_{core}}{\rho}$$

$$m_{core} = \left(\frac{32}{3} \pi m_{vehicle} \; \mu_o \right)^{1/2} \varpi r^{5/2} \frac{7000}{2.15}$$

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<TS, LW>

The magnetic moment equation was manipulated to provide an equation for the mass of the iron core. This equation gives a relation between the mass of the magnetic core and the total vehicle mass (including the core mass).

A value of 7000 kg/m^3 was used as the density of iron.

A radius of 0.5 m was used because a separation distance of 1 m was assumed.

The value for omega used in this analysis is 2pi/15 rad/sec. The actual value will be mandated in the Requirements Document.

Core Mass vs. Vehicle Mass

MIT Aero/Astro

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Core Mass (Kg)

Configuration not Possible

$m_{core} = m_{vehicle}$

$m_{core} = \left(\dfrac{32}{3} \pi m_{vehicle} \, \mu_o \right)^{1/2} \varpi r^{5/2} \dfrac{7000}{2.15}$

Mass Vehicle (Kg)
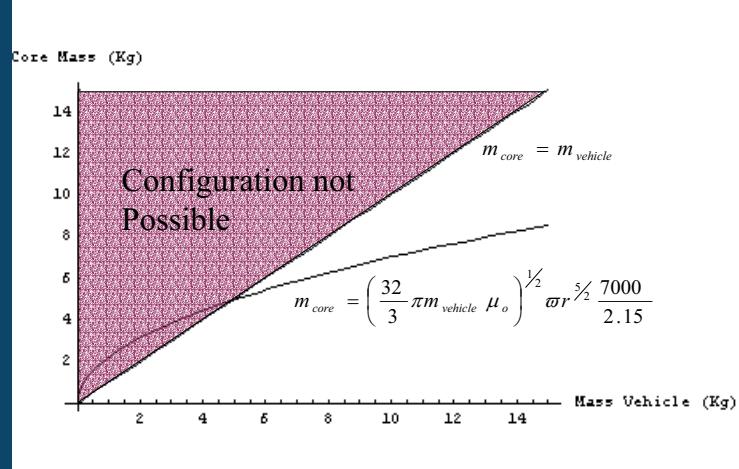
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<JB, TS, LW>

The x-axis represents the total mass of the vehicle, which includes the mass of the magnetic core. The y-axis represents the mass of only the magnetic core. Due to this definition of 'total mass,' it is not possible to have a core mass greater than the vehicle's total mass. The straight line on the graph is the line core_mass = vehicle_mass. Therefore, all configurations shown in the darkened area are not possible.

The curve shown on the graph represents the core mass as a function of vehicle mass. The point where the curve crosses the straight line is the smallest possible configuration, where the entire vehicle mass consists of only the core mass (leaving no room for any other components). All other possible configurations are located along the curve to the right of this point.

The separation distance between the curve and the straight line represents the available mass for all other system components.

Core Mass vs. Vehicle Mass vs. Radius

MIT Aero/Astro

Adding radius to the previous graph as a third dimension:

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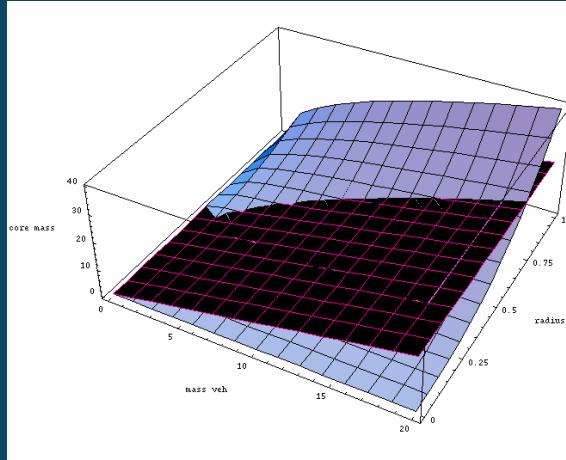
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<JB, TS, LW>

This graph shows the previous graph with the added dimension of radius of separation.

Vehicle configuration options are feasible until the radius of separation increases to a certain critical value. This point is shown on the graph where the curve (core_mass as a function of vehicle_mass and radius) breaches the flat plane (core_mass = vehicle_mass).

Feasible options are only those for which the curve lies beneath the flat plane.

Spin-up Representation

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• Magnetic force diagrams before and during spin-up
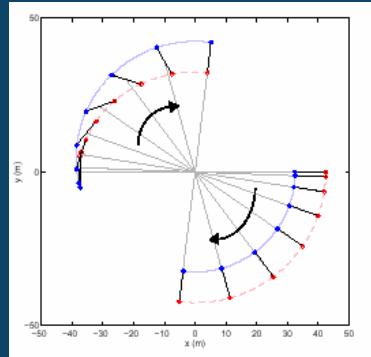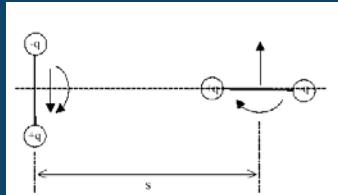
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<JB,TS, LW>

The diagram on the left depicts two stationary dipoles just before spin-up. The straight arrows represent net forces on each dipole. The curved arrows represent net moments on each dipole.

The diagram on the right depicts the two dipoles as they begin to spin up. The dipoles begin perpendicular to each other. 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 an applied torque from the torque wheels. The dipoles initially move in the directions of their respective net forces. As they begin to move the applied torque is decreased to induce centripetal motion. As centripetal force increases, the applied torque continuously decreases, which allows the rotating dipoles to slowly become aligned along the same axis. At the point when there is no more applied torque, the dipoles are perfectly aligned and the centripetal force equals the magnetic force. The system is now in steady-state.

- Infinitely long solenoid
  - α is aspect ratio

$$\frac{\ell}{2\,a} = \alpha \approx 10$$

- Operation in far field
  - May need to relax to preserve design freedom

$$\frac{2\,r}{\ell} = \beta \approx 10$$

- $m_{magnet} \cong .5\, m_{total}$
  - Magnet mass is large portion of system mass

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<LW>

These assumptions are constraints which the system would ideally satisfy. However, by fixing all these parameters, design freedom is removed from the system. The design would be fully constrained. Therefore, some of these assumptions must be relaxed through the course of the design process.

Alpha is the aspect ratio. To satisfy the assumption that the solenoid is infinitely long, alpha should be at least 10.

ℓ is the length of the solenoid.

a is the radius of the solenoid.

Beta is a parameter that measures the far-field capability of the system. To satisfy the assumption of operation in the far-field, beta should be ~10.

2r is the distance of separation, as defined in configuration assumptions.

It is also assumed that the magnet comprises a significant proportion of the total vehicle mass (one half of the total vehicle mass). This is a rough estimate based on the properties of electromagnets. The assumption is based specifically on the fact that electromagnets are heavy and weak.

Dipole Assumptions/Constraints

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• Combining previous constraints: $\dfrac{\ell}{2a} = \dfrac{2r}{\ell} \approx 10$

$$r = 100\ a$$

• Applying to original force balance:

$$a = \frac{\left(3.2 \times 10^{11}\right)\left(m\ \omega^2\right)}{1200\ \ \pi \cdot B^2}$$

• System is over-constrained
  – ω is defined by the Requirements Document
  – 'a' is automatically defined by system mass
  – No choice for geometry of system
• Must relax one of the constraints

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<LW>

Here both the far-field approximation and the infinite solenoid approximation are applied, as shown in the first equation. When these two constraints are applied simultaneously, r=100a.

The analysis begins with the original force balance equation. The relation r=100a is plugged into the force balance equation, as is the relation for magnetic moment, mu=BV/mu_nought. Here B is the applied magnetic field strength and V is the volume of the magnetic core. The relation for 'a' is found by simplifying the resulting expression.

The expression for 'a' shows that the system is over-constrained. 'a' is only a function of omega and m. Omega is defined for the system in the Requirements Document. Therefore, 'a' is only a function of the mass of the system. As 'a' is directly related to l and r through the constraints, this means that for every mass of the system, there is a corresponding system geometry that is defined on the basis of the dipole assumptions.

Since it is not ideal to have system geometry defined solely by total mass, it is necessary to relax one of the constraints placed on the system. It is most likely that the far-field assumption will be relaxed, because some of our testing facilities may not capable of running tests in the far-field.

Torque Wheel

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- Counter torque is required to initiate formation rotation
- Torque wheel must satisfy conservation of angular momentum:

$$H = \varpi_{formation} m_{vehicle} r_{formation}^2$$

$$= \varpi_{reactionwheel} m_{reactionwheel} r_{reactionwheel}^2$$

- Known parameters:
  - $\omega_{reactionwheel}$ (structural constraint)
  - $\omega_{formation}, r_{formation}$ (from Requirements Document)
- Can solve for mass and radius of torque wheel

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<JB, TS, LW>

It is assumed that the torque wheel is a ring. The moment of inertia, I, is represented as: $I = mr^2$.

In order to satisfy the conservation of angular momentum, the angular momentum of the vehicles in steady-state rotation must be equal to the angular momentum of the torque wheels at the instant spin-up begins.

The parameters omega_reactionwheel, omega_formation, and r_formation are given properties of the system. Therefore, the conservation of angular momentum relationship provides a method to find the mass and radius of the reaction wheel as a function of total vehicle mass.

Electromagnet Time Constant

- Looking at equations that govern overall system dynamics:
  - System time constant = rotation rate of the system, ω.

- To control the system, electromagnet time constant must be less than the system time constant.

- Electromagnet time constant is L/R.
  - Need to find equations for inductance and resistance.

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<TAS>

The time constant of the electromagnet is an important factor, since a small time constant means a faster response from the electromagnet. Looking at the equations of the dynamics of the system, the natural system time constant is equal to the rotation rate of the entire formation. The time constant of the electromagnet should thus be smaller than this value. The equation for the electromagnet time constant is L/R (inductance/resistance), so we need to find equations for these now.

Electromagnet Time Constant

- The inductance of the electromagnet is:

$$L = n^2 \mu_{core} V$$

where μ_{core} is the magnetic permeability of the core material and n is the number of turns per unit length (N/ℓ).

- The induced magnetic field of the magnet is:

$$B_{mag} = n \mu_{core} i$$

- Substituting:

$$L = \frac{B_{mag} \, nV}{i}$$

ElectroMagnetic Formation Flight Of Rotating Clustered Entities   50

<JB, TAS>

Here the equations for inductance and induced magnetic field are combined to produce an equation for inductance in terms of induced magnetic field, number of wire turns per length, volume of the core, and current.

Electromagnet Time Constant

• For a wire with length s, resistivity ρ and radius r_{wire}, resistance is described by:

$$R = \frac{\rho \cdot s}{\pi \cdot r_{wire}^2}$$

• Using the standard wire gauge relationship:

$$\frac{i}{\pi \cdot r_{wire}^2} = c_0$$

• Due to geometry, $s = N*2\pi a$:

$$R = \frac{2\pi\rho N c_0 a}{i}$$

• Recall:

$$\mu_{mag} = \frac{B_{mag}(\pi a^2 \ell)}{\mu_0}$$

$$\frac{\ell}{2a} = \alpha$$

$$a = \left(\frac{\mu_{mag}\mu_0}{B_{mag}2\pi\alpha} \right)^{1/3}$$

\<TAS\>

Here an initial equation for resistance is given. Next, the relationship for standard wire gauges is noted. For most wires, the maximum current it can carry divided by pi*wire_radius^2 is a constant. The value of this constant is the same for most all wire gauges. The length of the wire is then put in terms of number of turns and core diameter. This yields an expression for resistance in terms of material resistivity, number of turns, radius of the core, and current.

It is possible to find an expression for the radius of the core. Recalling the two given equations, the necessary radius of the core can be written as a function of magnetic moment, induced magnetic field, and alpha (the aspect ratio of the core).

Electromagnet Time Constant

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- Combining the above expressions yields the equation for L/R:

$$\frac{L}{R} = \frac{1}{2\rho c_0}\left(\frac{\mu_{magnet}\mu_0}{2\pi}\right)^{\frac{1}{3}} B_{magnet}^{\frac{2}{3}} \cdot \alpha^{-\frac{1}{3}}$$

- Want L/R as low as possible for maximum control and stability.

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<TAS>

By combining the equations for inductance and resistance, the result is the equation shown. The time constant L/R is a function of resistivity, magnetic moment, the induced magnetic field in the core, and the aspect ratio.

It is now possible to plug in values and see how the time constant varies with respect to different parameters.

Time Constant vs. Aspect Ratio

Assuming the following values:

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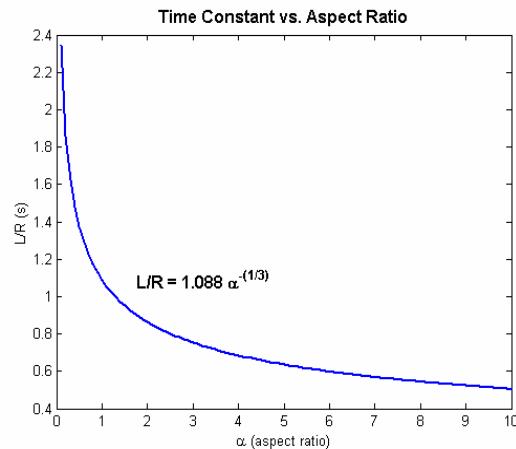
$$\rho = 1.724 \cdot 10^{-8} \ \Omega \cdot m$$
$$c_0 = 2.25 \cdot 10^{6} \ A \cdot m^{-2}$$
$$\mu_{magnet} = 645 \ A \cdot m^{2}$$
$$\mu_0 = 4\pi \cdot 10^{-7} \ N \cdot A^{-2}$$
$$B_{magnet} = 2.15 \ T$$

Time Constant vs. Aspect Ratio

$L/R = 1.088 \ \alpha^{-(1/3)}$

L/R (s) vs. α (aspect ratio)

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<TAS, JB, LW>

This is the graph of time constant vs. aspect ratio. The values assumed are:

Rho: the resistivity of copper wire

C_o: this value was computed using data from standard 20, 22, and 24 gauge wire.

Mu_magnet: this value was computed from the earlier equation mu_magnet = 2.15*Volume_core/mu_nought.

Mu_nought: this is the permeability of free space.

Bmagnet: this is the saturation point for iron.

This graph shows that by increasing the aspect ratio of the magnet, the time constant will also be increased.

We expect to be operating at an aspect ratio of ~10, meaning the time constant of the electromagnet should be around 2.3.

Time Constant vs. Resistivity

Assuming the following values:

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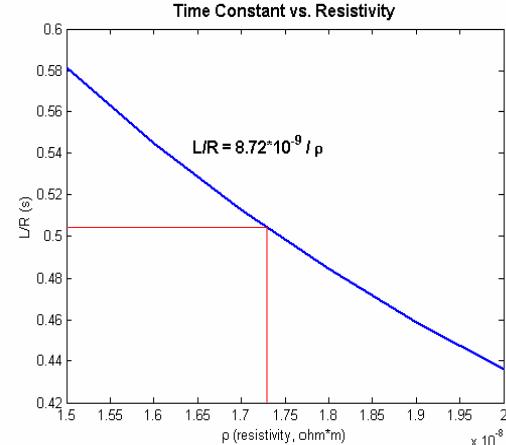
$$\alpha = 10$$
$$c_0 = 2.25 \cdot 10^6 \ \text{A} \cdot \text{m}^{-2}$$
$$\mu_{magnet} = 645 \ \text{A} \cdot \text{m}^2$$
$$\mu_0 = 4\pi \cdot 10^{-7} \ \text{N} \cdot \text{A}^{-2}$$
$$B_{magnet} = 2.15 \ \text{T}$$

L/R = 8.72*10^{-9} / ρ

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<JB, TS, LW>

This is the graph of time constant vs. resistivity. The values assumed are the same as before, except here an aspect ratio of 10 is chosen, and the resistivity is allowed to vary.

This graph shows that a reduction in the time constant may be achieved using wires with higher resistivities. The resistivity of copper is shown since that is the most readily available type of wire.

Applied Voltage

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- Resistance:

$$R = \frac{2\pi\rho N c_0 a}{i}$$

- Ohm's law:

$$V = iR$$

- Recall value for core radius:

$$a = \left(\frac{\mu_{mag}\mu_0}{B_{mag} 2\pi\alpha} \right)^{\frac{1}{3}}$$

- Obtain final voltage equation:

$$V = 4\pi\rho\, nc_0 \left(\frac{\mu_{mag}\,\mu_0}{2\,B_{mag}\,\pi} \right)^{\frac{2}{3}} \alpha^{\frac{1}{3}}$$

ElectroMagnetic Formation Flight Of Rotating Clustered Entities   55

<JB, TS, LW>

This derivation for voltage is the voltage that must be applied to the system.

The resistance given is that previously derived from the wire gauge relationship and wire geometry.

'a' is the radius of the core, which was previously derived.

B_m is the induced magnetic field, measured in Tesla.

Voltage vs. Aspect Ratio

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Assuming the following values:

Voltage vs. Aspect Ratio

$V = 1.15 \cdot \alpha^{(1/3)}$
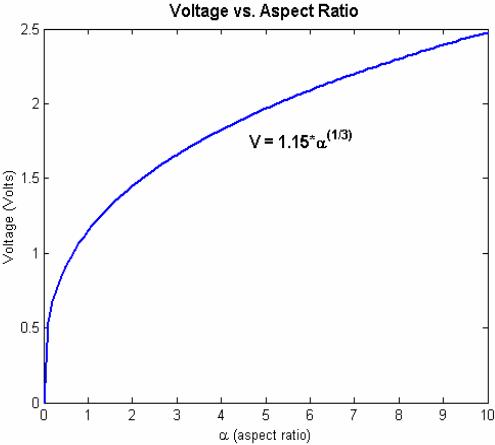
$c_0 = 2.25 \cdot 10^6 \ \text{A} \cdot \text{m}^{-2}$

$\mu_{magnet} = 645 \ \text{A} \cdot \text{m}^2$

$\mu_0 = 4\pi \cdot 10^{-7} \ \text{N} \cdot \text{A}^{-2}$

$B_{magnet} = 2.15 \ \text{T}$

N = 465 turns
(22 gauge wire)

$\ell = 0.3 \ \text{m}$

$\rho = 1.724 \times 10^{-8}$

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<LW>

This plot of voltage vs. aspect ratio shows that voltage increases exponentially with aspect ratio. For an aspect ratio of 10 (according to infinitely long solenoid approximation) a voltage of ~2.5 volts is required.

Voltage vs. Resistivity

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Assuming the following values:

Voltage vs. Resistivity

$V = 1.15 \cdot \alpha^{(1/3)}$

$c_0 = 2.25 \cdot 10^6 \ \mathrm{A \cdot m^{-2}}$

$\mu_{magnet} = 645 \ \mathrm{A \cdot m^2}$

$\mu_0 = 4\pi \cdot 10^{-7} \ \mathrm{N \cdot A^{-2}}$

$B_{magnet} = 2.15 \ \mathrm{T}$

$N = 465$ turns
(22 gauge wire)

$\ell = 0.3 \ \mathrm{m}$

$\alpha = 10$
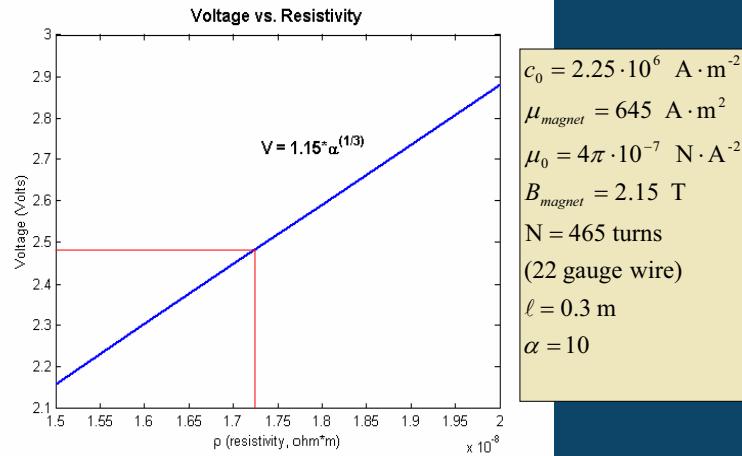
ElectroMagnetic Formation Flight Of Rotating Clustered Entities

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<JB, TS, LW>

For 22 gauge wire, N=465 due to geometry.

This plot shows a linear relationship between resistivity and required voltage for a given B field. So, while resistivity does not have a large effect on time constant (shown before), it has a more substantial effect on the required voltage, and should be taken into consideration in this case.

Power Required

- Current:

$$i = \frac{B_{mag}\, \ell}{\chi \mu_0 N} \qquad \chi = \frac{B_{mag}}{B_{applied}}$$

  – χ is magnetic susceptibility

- Power:

$$P = iV$$

- Using expanded voltage equation, obtain final power equation:

$$P = \frac{4\pi\rho\, c_0}{\chi} \left(\frac{B_{mag}}{\mu_0} \right)^{\frac{1}{3}} \left(\frac{\mu_{mag}}{2\pi} \right)^{\frac{2}{3}} \alpha^{\frac{1}{3}}$$

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<JB, TS, LW>

The current is derived from the definition of magnetic field, where B = (mu_nought)(chi)(ni). Chi is the magnetic susceptibility, which is a material property. Chi is equal to the ratio of the induced magnetic field to the applied magnetic field.

Using the relationship for power (P=iV) and the previously derived voltage expression, the final power equation is found. This equation dictates how much power the system requires.

Power vs. Aspect Ratio

MIT Aero/Astro

Assuming the following values:

$c_0 = 2.25 \cdot 10^6 \ \text{A} \cdot \text{m}^{-2}$

$\mu_{magnet} = 645 \ \text{A} \cdot \text{m}^2$

$\mu_0 = 4\pi \cdot 10^{-7} \ \text{N} \cdot \text{A}^{-2}$

$B_{magnet} = 2.15 \ \text{T}$

$N = 465 \ \text{turns}$

(22 gauge wire)

$\ell = 0.3 \ \text{m}$

$\chi = 5000$

$\rho = 1.724 \times 10^{-8}$

$P = .2548 * \alpha^{(1/3)}$
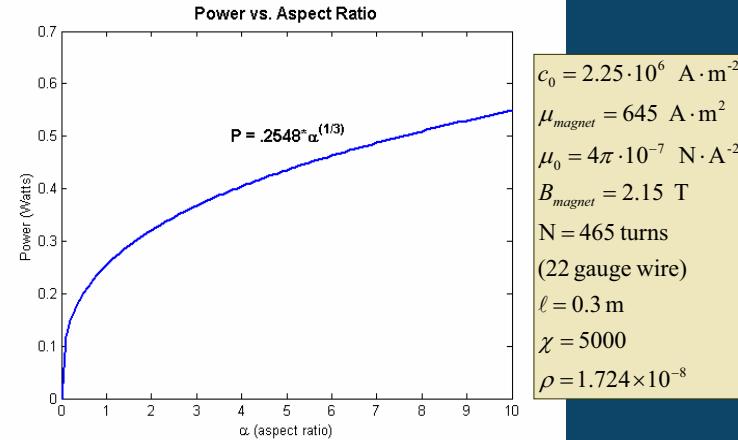
ElectroMagnetic Formation Flight Of Rotating Clustered Entities

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<LW>

The graph shows power vs. aspect ratio. For an aspect ratio of 10 (which satisfies the infinitely long solenoid assumption) this plot predicts a required power of ~0.55 Watts. Here we assumed a 22 gauge copper wire, with a resistivity given in the table at the right.

Power vs. Resistivity

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Assuming the following values:

Power vs. Resistivity

$P = .2548*\alpha^{(1/3)}$

Power (Watts) vs. ρ (resistivity, ohm*m) $\times 10^{-8}$

$c_0 = 2.25 \cdot 10^6 \; \text{A} \cdot \text{m}^{-2}$

$\mu_{magnet} = 645 \; \text{A} \cdot \text{m}^2$

$\mu_0 = 4\pi \cdot 10^{-7} \; \text{N} \cdot \text{A}^{-2}$

$B_{magnet} = 2.15 \; \text{T}$

$N = 465$ turns
(22 gauge wire)

$\ell = 0.3 \, \text{m}$

$\chi = 5000$

$\alpha = 10$
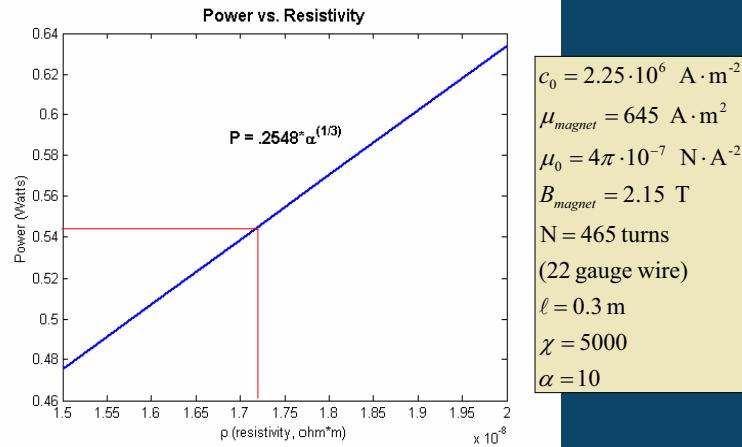
ElectroMagnetic Formation Flight Of Rotating Clustered Entities
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<LW>

There is a linear relationship between power and resistivity. The red lines show the power estimate when a 22 gauge copper wire is used. The resistivity of copper wire is shown in the parameters at the right as rho. This graph shows a similar power estimate as is predicted by the power vs. aspect ratio graph, approximately 0.55 Watts.

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•Torque Wheel
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- Power is directly related to the time constant, L/R
  - Both are proportional to α
  - Increase power to decrease L/R

$$\frac{L}{R} = \frac{1}{2\rho c_0} \left(\frac{\mu_{magnet} \mu_0}{2\pi} \right)^{\frac{1}{3}} B_{magnet}^{\frac{2}{3}} \cdot \alpha^{-\frac{1}{3}}$$

$$P = \frac{4\pi\rho c_0}{\chi} \left(\frac{B_{mag}}{\mu_0} \right)^{\frac{1}{3}} \left(\frac{\mu_{mag}}{2\pi} \right)^{\frac{2}{3}} \alpha^{\frac{1}{3}}$$

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<LW>

The expressions for L/R and P are given again here. It is clear that power is directly related to the time constant. This is an interesting relationship to consider when designing a control system, as the goal is to minimize the time constant. Power may be a limiting factor in control system design.

System Trades Summary

- Found core mass as a function of vehicle mass (force balance equations).
  - Certain values of core mass were invalid.
  - A maximum allowable radius of separation exists.
- Both far field and infinitely long solenoid assumptions over-constrained the system.
  - Relax one constraint (most likely far field).
- Found required moment of inertia of the torque wheels (conservation of angular momentum).

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<TAS>

After analyzing the governing equations for the system, several major design tradeoffs were noted.

An equation for core mass was found in terms of total mass of the system and radius of separation. Here, we saw that some total mass values below a certain point were invalid because the iron core would have been heavier than the total mass (which includes the iron core). If you increased the total mass of the system beyond this critical point, the percentage of total mass taken up by core mass decreased, leaving larger amounts of mass available for all other components. These relations were then plotted on a 3-D graph, where radius was allowed to vary. This showed that for values of radius above a certain point, the values for core and total mass were invalid.

An analysis was made on the far-field and infinitely long solenoid assumptions. This analysis showed that when these assumptions are both put into place, the system is over-constrained, leaving no freedom for the selection of core radius. Freedom is restored if one of these assumptions is relaxed, which will likely be the far-field assumption.

By looking at the conservation of momentum equations, the required moment of inertia for the torque wheel could be found. Depending on the geometry of the torque wheel, estimates of radius and mass could then be made.

System Trades Summary

- Found electromagnetic time constant (inductance and resistance equations).
  - Time constant most easily changed by varying the aspect ratio of the electromagnet.
- Found equations for voltage and power.
  - Also a function of aspect ratio.
- Showed that decreasing the time constant increases the necessary power.
- What now?
  - Apply these trades to the various subsystems.

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<TAS>

By finding equations for inductance and resistance, the time constant of the electromagnet was found (L/R). This equation showed that the time constant depended mostly on aspect ratio of the magnet, and somewhat on the resistivity of the wire used in the coils. However, since it is difficult to obtain wires with abnormally high resistivities, it is easiest to vary the aspect ratio in order to vary the time constant. The objective of varying the time constant is to make it as small as possible in order to provide as much control as possible over the system.

Equations for voltage and power were then derived. These equations also depended primarily on aspect ratio and resistivity. Through comparison with the time constant equation, it was shown that any effort to reduce the time constant would result in higher power requirements.

The next step in the design process is to apply these overall system trades to the individual subsystem designs.

EMF²ORCE will be composed of the following subsystems:

- **Avionics**: provides necessary computational power
- **Communication**: transmits data between vehicles and ground base
- **Metrology**: measures attitude and position of vehicles through onboard sensoring system

ElectroMagnetic Formation Flight Of Rotating Clustered Entities   64

<TAS>

The overall system will be divided into six major subsystems:

Avionics: these are the onboard computers that will run the program codes and control the system as a whole. They will also act as an interface between the communication, metrology, attitude control, and power systems.

Communication: this subsystem will be responsible for transmitting data from vehicle to vehicle and from each vehicle to the ground base. Some of the different types of data to be transmitted include telemetry, system health, and attitude and position measurements.

Metrology: this is the method by which attitude and position of each vehicle will be determined. Onboard sensors will be used to make these measurements, which will then be passed to the control system.

- **<u>Attitude Control</u>**: combines previous three subsystems with electromagnets and torque wheels to control attitude and relative positions.
- **<u>Power</u>**: provides the necessary voltage and current needed to operate the system
- **<u>Structure</u>**:
  - <u>Basic structure</u>: holds all components together
  - <u>Magnetic shielding</u>: shields avionics from potential damage due to the magnetic field
  - <u>Air carriage</u>: provides a frictionless way to operate vehicles on the testbed

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<TAS>

Subsystems (cont):

Attitude Control: the attitude and relative position of each vehicle will be controlled by the electromagnets. By varying the current through each electromagnet, the vehicles can be controlled to perform complex configurations, including spin-up and spin-down maneuvers. This subsystem will also include the torque wheels which will provide the necessary angular momentum reactions.

Power: this will provide the necessary currents and voltages to the other subsystems.

Structure: there are three components to the main structure – the basic structure, the magnetic shielding, and the air carriages. The basic structure will be responsible for holding all the system components together and forming the outer shell of the vehicles. Magnetic shielding will most likely be necessary to protect the avionics and sensors from possible damage due to the presence of a strong magnetic field from the electromagnet. Finally, air carriages will be needed to produce a frictionless environment in which to perform operation tests on the vehicles.

Design Concept

<TAS, JEU, ESS>
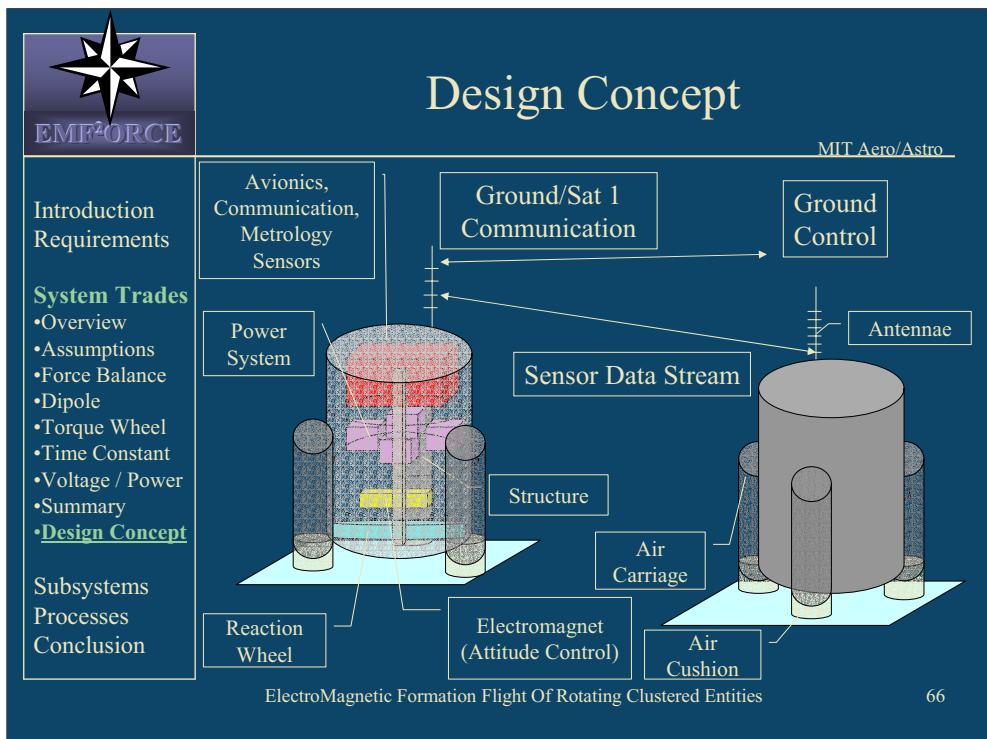
Here is an artistic rendition of what the final vehicles may look like. This representation does not reflect any detailed analysis of the potential layout of the various subsystems, but rather a basic preliminary design incorporating these subsystems into a coherent structure. The subsystems are all contained within the outer structure. The air carriages are fixed to the outside of the vehicle. The arrows show the different lines of communication between the ground base and each vehicle.

MIT Aero/Astro

Subsystems Trade Analysis Review

Amilio Aviles

Stephanie Slowik

<SJS>

This begins the Subsystem Trade Analysis and Review which will be prevented by Amilio Aviles, and Stephanie Slowik.

Subsystem Trades Overview

EMF²ORCE

• Component classification and subsystem breakdown

• Trade analysis for each component

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<SJS>

The subsystems of the testbed have been determined. Metrics have been established for each subsystem so that components with the most desirable parameters have been researched. A thorough trade analysis has been done on each component. The Databasing team has been in direct contact with various vendors and manufacturers of components to discuss pricing, procurement time, and component specification information. At the current time, it appears as if the majority of our components can be bought COTS (Commercial Off The Shelf), with the exception of the casing, the airbearings, and the Electro-Magnets.

Subsystem Flowdown

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Requirements
System Trades

Subsystems
•Overview
•**Flowdown**
•Avionics
•Communication
•Metrology
•Attitude Control
•Power
•Structure

Processes
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Mission objective

Avionics — Communication — Metrology — ACS

Power Amp — Ground Comm — Inertial Metrology — Actuation
On-board Computer — Inter-device Comm — Relative Metrology — Reaction
Software — Omnidirectional — Separation distance — De-spin
Signal Conditioning
Power — Structure
Simulated Solar Cells — Carriage
EM Shielding
Frictionless mount

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<ALS, SWS, AA, MW, WDF >

The following diagram shows the flowdown of the subsystems and the various components of each has determined from the mission objective. The six subsystems include Avionics, Communication, Metrology, Attitude Control System, Power, and Structure. We have collected information on various possible components for each subsystem and will provide a preliminary recommendation for each component. A more detailed flowdown will be developed when the final design has been determined.

Avionics, Communications and Metrology Subsystems

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•**Metrology**
•Attitude Control
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Avionics, Communications, and Metrology Subsystems
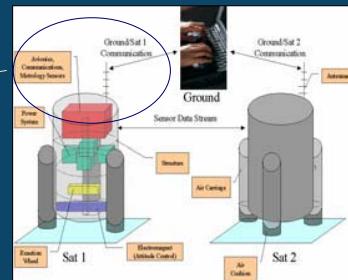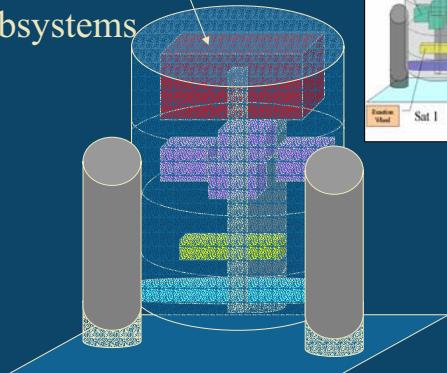
ElectroMagnetic Formation Flight Of Rotating Clustered Entities

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<GG, JEU, WDF>

We will begin our discussion of the unit's subsytems with the Avionics, Communications, and Metrology down select.

Avionics Candidates

- HandyCricket
- Tattletale/TIM-DIO (SPHERES)
- TI-C40
- TI-C6701
- Tiny Processors (DARPA)

ElectroMagnetic Formation Flight Of Rotating Clustered Entities

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<DA,AA>

The candidates for the avionics system are listed above.

- Processor Speed

- Mass

- Memory

- Power Consumption

- Cost

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<AA, DC, GG>

The processor speed is important because it must operate quickly and efficiently enough for our satellites to do the following tasks when needed: take inputs from sensors, understand commands, coordinate communication with other satellites and ground station, control actuators, etc. Mass, cost, and power are all criteria which need to be minimized in order to keep the power consumption, mass, and cost of the entire vehicle low.

Candidate Specifications

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Processor	Speed (MHz)	Mass (Kg)	Memory (KB)	Cost (US $)
Handy Cricket	N/A	N/A	32	49
TattleTale	16	.028	256	1190
TI-C40	60	<.03	None	313
TI-C6701	167	<.03	128	119
Tiny Processors (DARPA)	Unfortunately, this information is not currently available to us, however we will further investigate this possibility when the information is available.			

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<DC, AA, GG>

This table compares the five selection metrics of the candidate systems. Some information was not available. Note that some systems are complete and ready to program, while others are simply microprocessors and require auxiliary hardware in order to function within the range of required applications.

Final Downselect

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•Communication
•Metrology
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Processor	Pros	Cons	Downselect Decision
Handy Cricket	-Incorporates IR Communication -Programmable	-IR may be extraneous -Limited clock speed	No
TattleTale	-Used on SPHERES -Adequate Clock Speed	-Comparatively Expensive	No
TI-C40	-Fast Clock Speed	-No Memory- requires auxiliary	No
TI-C6701	**-Very Fast Clock Speed**	**-Small Memory Capacity**	**YES**
Processors (DARPA)	-Incorporates RF componets	-Still under development	No

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<DC, AA>

This table shows the final downselection process. The pros and cons of each system are indicated, resulting in a final selection. This selection process was used because most candidates were easily ruled out based on infeasibility issues. Note that the final selection does require auxiliary hardware. Although this is the final selection currently made, it is not set in stone and is also dependent on the development of other sub-systems.

Possible Design Options

- Radio Frequency

- Infrared

- Umbilical

- Ultrasonic

- Laser

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<GG, AA>

RF communication using some frequency of radio waves

Infrared uses modulation of IR beam to transmit information (like a TV remote control)

Umbilical external cable attaches physically to the vehicles

Ultrasonic uses sound waves to transmit information

Laser uses modulation of a laser beam to transmit information.

Design Metrics

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- **Feasibility** – can this system be applied to the formation flying satellites
- **Bandwidth** – how much information must be transmitted
- **Mass/size** – can the system fit in our satellites w/out adding a lot of mass
- **Power**
- **Cost**
- **Range**

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<GG>

From these criteria we can rule out infrared or laser because they both require accurate aiming amongst satellites. In our final system, it will be difficult to have specific points on satellites face each other. This makes these systems less feasible and therefore undesirable.

We have therefore down-selected the communications architecture to radio-frequency.

<GG>

Because we are currently unsure of how much data we need to transmit we wish to maximize our bandwidth.

Power consumption must remain low to keep the power supply simple and adequate for an extended period of time.

Mass and volume must be minimized in order to keep the mass and size of the entire vehicle small.

Rejected Design Options

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System Trades

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•Metrology
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- Infrared & laser – highly directional, limits mobility of vehicles
- Umbilical – does not meet requirements, interferes with dynamics
- Ultrasonic – expensive, harder to implement

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<GG, AA>

Infrared and laser communications require a direct line of sight between the emitter and the sensor. Rotation of the vehicles might disrupt the data stream.

Umbilical will require physical connection to vehicles which might interfere with their free motion. Umbilical might become entangled for a rotating formation of vehicles.

Ultrasonic are semi-directional. Signals could easily interfere with signals from ground station or other vehicles.

- Bandwidth is estimated by
  - The amount of data and how often we want to transmit the data, known as the bit-rate

    (Amount of floating point numbers wish to transmit)

    X (64 bits per floating point number)

    X (number of times per second we want to transmit these number)

    = (Bit rate)

- Noise and the encoding create additional system needs
  - Therefore multiply this bit rate estimate by two

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<GG>

This is how bandwidth is calculated, but because we will most probably need to transmit several floating point numbers several times a second we know we will want a high bandwidth. We do not do the calculations of the bandwidth needed instead we will look to choose an architecture that maximizes this criterion.

Other Factors

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- Communications system must be able to connect to main processing board and should also be able to connect to the metrology system.

- System must also be able to communicate with the ground station. (laptop)

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<GG>

These are other criteria that should be considered when finally down selecting a particular RF system.

SYSTEM	Power (mW)	Data Rate (Kbps)
TR 100	36	115
TR 3003	36	115
DR 3100	36	19.2
RF 2938	330	N/A
RF 2968	180	1000

<AA,GG>

These chips are estimated as within one cubic centimeter and 6 grams of each other, we consider these estimates negligible and therefore do not include them in the table.

The first three are from RF Monolithics (www.rfm.com)

The last two are from RF Microdevices (www.rfmd.com)

Mass and volume for all chips are very similar, so no valuable comparison could be made using those parameters.

Final conclusion will be tentative pending price information which we have requested. Obviously the RF2969 Chip provides the best bandwidth, however it also requires more power. Our final decision will be tentative on how the final design fits together, if it can supply enough power, and how much bandwidth is enough.

We will also need to check for compatibility with the avionics and metrology systems.

- Optical devices
  – Infrared
  – Laser

- Ultrasonic devices

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<LW>

Optical devices: IR ranging devices measure distance by sensing reflection of IR waves. Laser ranging devices measure distance by one of two methods. The first is measuring the time-of-flight of the laser to reach the target and return. This method is used mainly for larger distances (> 1 m). The second method is the triangulation method, which is used for smaller distances (< 1 m).

<http://www.acroname.com/robotics/parts/R19-IR02.html>

<http://www.acuityresearch.com/prodov1.html#AR4000>

<http://www.ipm.fhg.de/english/fields/pp_monitoring/production/optical-ranging.html>

Ultrasonic devices: Work by sensing the reflection of high frequency sound waves. The devices function by one of two methods. The first is a triangulation method, which requires at least three transmitters and one receiver (time-of-flight method). The second method measures the phase difference in the signal between the transmitter and receiver (phase-coherence method).

<http://www.cs.nps.navy.mil/people/faculty/capps/4473/projects/chang2/Simple.htm>

Rejected Design Options

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- GPS-like system – very expensive to create an indoor GPS system

- Laser ranging – very expensive, only provides position between ground station and satellite system (global metrology system)

- Radio interferometry – unavailable on small scale needed for testing

- Electronic whiteboard technology – cannot track multiple targets

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<AA, LW>

GPS-like system: There is no commercially available indoor GPS-like system. The system would require transmitters mounted inside the testing facility and a receiver on each of the satellites. The technology is still experimental, thus we would need to design our own system, which would be both time consuming and expensive. Therefore, this option is not feasible.

Laser Ranging: Laser ranging is a technology that provides position measurement between a ground station and a body in space. It is not practical for our purposes for two reasons. First, we are testing in an indoor facility. A large laser is not needed to provide global metrology (position measurement between the system and a ground station). Second, it is very expensive. Use of laser ranging would exceed the scope of the project's budget.

<http://almagest.as.utexas.edu/~rlr/mlrs.html>

Radio Interferometry: Radio interferometry determines position by a triangulation method. It requires three antennae to determine the position of a body with a radio emissor. It is not feasible for use on this project, because the radio interferometry systems are not available on a small scale suited to our test environment.

<http://www.drao.nrc.ca/science/vlbi/principles/principles.shtml>

Electronic Whiteboard: Intended for use on board of ~1x2 m. The system uses a combination of IR and Sonic sensors to determine the location of the pen on the board. The system has high accuracy and works in realtime, but it cannot track multiple targets. Several systems cannot be used in overlapping regions.

Design Metrics

EMF²ORCE

- Range (maximize)
- Precision (minimize)
  - Linear – must be precise to .015 m
  - Angular – must be precise to +/- 1 arcsec
- Power needed (minimize)
- Cost (minimize)
- Mass (minimize)

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<LW>

Range is the maximum distance away from the sensor at which another object can be sensed.

Precision is measured both in distance (linear) and angular position (angular). Requirements are those specified in the Requirements Document.

Precision is specified as the allowed tolerance for each measurement. Therefore, minimizing the 'Precision' variable will yield a very precise system.

Power needed is the power that must be supplied in order for the sensors to function.

Metrology System Candidates

	IR	Laser	Sonic
Range	.1-.8m	0-17m	.15-2.7m
Precision	N/A	.00254 m	.01 m
Angle	~0 deg	~0 deg	~28 deg
Power	~.25 W	~2 W	N/A
Price	$21	N/A	$119
Mass	.003 kg	.624 kg	~.03 kg

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<AA, LW>

Infrared: Sharp GP2D02 Infrared Ranger.

Precision information not available.

<http://www.acroname.com/robotics/parts/R19-IR02.html>

Laser: Acuity Research AR4000 Laser Ranger.

Only available laser ranger for the scale we are working on – it is highly accurate, and meant for scientific measurement and machine control.

No pricing information given, assumed to be very expensive (hundred-thousands $).

<http://www.acuityresearch.com/prodov1.html#AR4000>

Ultrasonic: Ultrasonic Owl Scanner – Sonar Sensing Kit.

Sensor is mounted on a servo, and can therefore effectively cover an arc of 90 degrees.

Power draw information not available.

*Price includes computer interface and software, actual price should be cheaper.

<http://www.robotstore.com/catalog/display.asp?pid=217>

Prices are measured on a per unit basis.

Power needed is the maximum power possibly drawn by the sensing system.

Angle measures the angular range of the device.

Final Design Choice

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- Ultrasonic sensing device
  - Meets all criteria from Requirements Document
    - Maximum range of 2 m between bodies
    - Minimum precision of .015 m
  - Negligible mass compared to system mass
  - Affordable (although more expensive than IR sensors)

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<LW>

The current final design choice is the ultrasonic sensing device due to the fact that it satisfies all requirements.

The infrared sensors do not satisfy the maximum required range of 2 m. However, they are much more affordable than either the laser or the ultrasonic devices. They also have a much smaller mass that either of the other range finders. Additionally, they have a very small power draw. It is possible that a higher quality IR sensor is available, and may provide a better metrology solution.

The laser range finders are the most precise solution. However, they are not feasible due to the fact that they have a large mass and are exceedingly expensive.

Attitude Control Subsystem

ACS
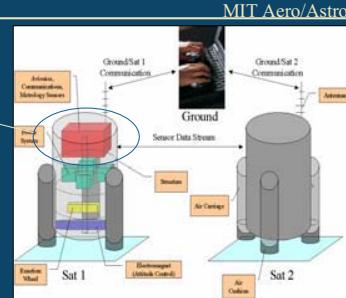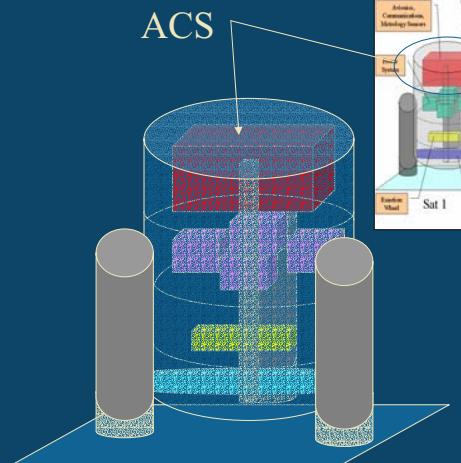
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< GG, JEU, WDF>

We will now move on to the downselect of the attitude control system.

ACS: Torque Wheels vs. CMG

Torque Wheel	CMG
• Commercially available	• Experimental
• Several vendors interested	•No vendors found
• Variety of specifications avail.	• FUSE failure
• Heavy, slightly unwieldy	•Small, light, accurate, versatile

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<ALS>

Our two options for mechanical attitude control are torque wheels and control moment gyros, or CMG's.

Upon first investigation, CMG's appeared a better option because they are small, light, accurate and versatile – more so than the traditional torque wheel.

Further study however, revealed that CMG's are still an experimental technology. They are not commercially available. In fact, the only real usage to date of a CMG system was on NASA's FUSE sattelite – recently publicized because of the failure of its attitude control system.

Torque wheels will be more readily available and provide more options.

ACS: Torque Wheels

• Provide resistance to EM torques enabling better control

• Most use magnetic bearings

Specifications (30 kg vehicle)

• Moment: 0.1-2.0 N-m-s

• Weight: 0.7-4.5 lbs.

• Peak power: 1-27 W

• Size: 4x6 in. – 4x6 ¾ in.

•Nominal speed: 3000-8000 RPM

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<ALS>

Torque wheels are required for our system to help control the actuation forces provided by the electromagnets.

It is interesting to note that most commercially available torque wheels use magnetic bearings. The far field effects of these magnets is not currently known and interference with the B-field of the electromagnetic actuators will be investigated.

Shown are ranges of some typical specifications for torque wheels appropriate for a 30kg unit. 30 kilograms was a very preliminary rough estimate drawn from the preliminary architecture brainstorms. As the mass changes and is finalized, so too will these specifications.

Electromagnets
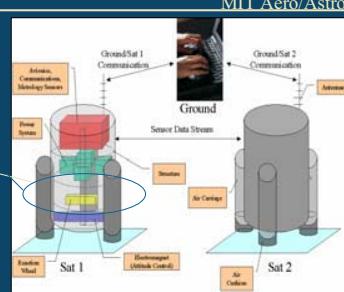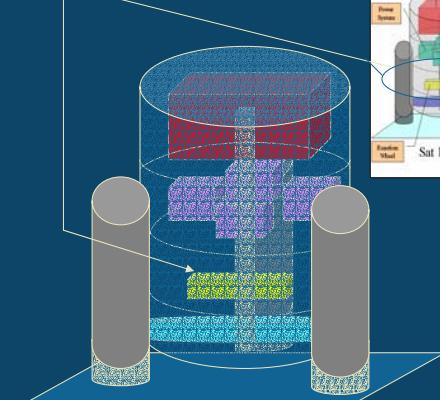
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< GG, JEU, WDF>

The most important component in the system which demonstrates the feasibility of electromagnetic control of formation flight is the electromagnet. This begins the discussion of possible materials to be used to construct the system's electromagnet.

- Core material selection criteria
  - Permeability
  - $B_{saturation}$
  - Cost and availability
- Material candidates
  - Ferromagnetic materials with high permeabilities
- Material downselect
  - High-permeability materials with low $B_{saturation}$ values
  - Rare, exotic materials difficult and costly to obtain and/or machine

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<MSW>

EM Core Material Trade Analysis:

The core material selection criteria included permeability, $B_{saturation}$, cost, and availability. Permeability is a measure of the material's magnifying effect on the magnetic field. $B_{saturation}$ is extremely important for our application because it is a measure of what field strength we can obtain when the core is saturated. Cost (and subsequently, availability) is important because of budgetary constraints to our program.

A wide variety of ferromagnetic materials were considered for the EM core ranging from materials commonly used in industrial applications to rare, specialty materials. There were two main reasons for materials to not be selected. First of all, many of the materials with very high permeabilities had low values for $B_{saturation}$, well below those that would probably be required for our testbed. Secondly, many of the high-permeability materials were quite rare. This made them extremely costly and also difficult to machine since there were no vendors with the correct equipment and expertise.

ACS: EM Core Material

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Material	Permeability	$B_{saturation}$ [gauss]	Density [g/cm^3]	Cost
Low Carbon Steel (99% Fe)	Moderate	21,000	7.87	Low
AlNiCo	High	10,000	6.9-7.3	High
Permalloy 80 (80% Ni, 15% Fe)	Extremely High	7,500	8.74	High

• Low Carbon Steel (AISI 1010)
  • High $B_{saturation}$
  • Low Cost
  • Wide Availability

http://www.grouparnold.com/mtc/
http://www.oz.net/~coilgun/theory/materials.htm
http://www.matweb.com

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<MSW>

EM Core Material Trade Analysis:

A wide variety of soft ferrous materials were considered for use as the electromagnet core. This table represents some of the more likely candidates based on permeability, $B_{satuaration}$, density, and cost.

Low carbon steel was chosen for its high value for $B_{saturation}$ and wide availability. After speaking to several of the electromagnet and ferrite material vendors, it was clear that low carbon steel (specifically, AISI 1010 or AISI 1020) would be the most likely choice. Although other materials have extremely high permeabilities, their values for $B_{saturation}$ were too low for our application. Additionally, these exotic materials (such as permalloy and supermalloy) are extremely expensive and not widely available. Low carbon steel is what is commonly used in industrial applications and presents less of a machining challenge for manufacturers.

Power Subsystem
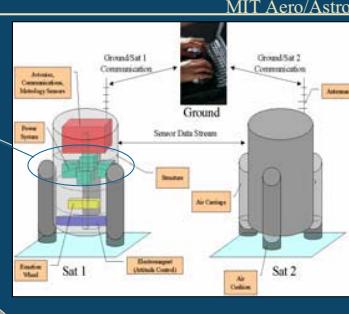
ElectroMagnetic Formation Flight Of Rotating Clustered Entities

< GG, JEU, WDF>

A major limitation to the successful design of the system is the ability to provide the necessary power to the electromagnets while still maintaining a low system mass.

- Available options:
  - Batteries
  - Solar cells
  - Beamed energy
- Metrics:
  - High energy density (J/kg)
  - Feasibility
    - Using beamed energy not feasible for our purposes

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< SJS, WDF>

The available options for providing the necessary power to our vehicles include Batteries, Solar Cells, or some form of beamed energy. The metrics used to downselect these potential options include energy density and feasibility. It is important to have a high energy density to help reduce the mass of the overall system while still providing the necessary power. It is also important to make sure any system we choose is within the scope of this design project. Beamed energy is not feasible for this project and therefore has been ruled out as an option.

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•Relatively low cost ($4 - $300 per battery, depending on properties chosen)
•Ease of replacement for testing purposes
•Lightweight (0.0005 – 0.8 kg per cell, depending on design)

Disposable Batteries
•Longer discharge time
•Lower cost per cell
•Must buy new cells to replace

Rechargeable Batteries
•Discharges quicker
•Need to buy fewer cells (can recharge between tests)

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<SJS>

Batteries can be procured both COTS (Commercial over the shelf) or custom-made. For our purposes, it would save procurement time as well as cut down the cost of the power subsystem if the batteries were bought COTS. COTS batteries are usually 1.5 V per battery cell, and cells can be connected in series or parallel to achieve the desired voltages and/or currents. Batteries seem a viable option due to their low cost (from single digit to double digits per cell, depending on type of battery), their ease of replacement (they can be easily removed when they can no longer achieve the desired voltage and be replaced with new batteries), and their small mass (each cell is between 0.5 and 2 grams).

We can either utilize dry cell disposable batteries, or we could choose to utilize rechargeable batteries. A rechargeable battery has a shorter average lifetime and a higher cost per individual cell than does a disposable battery. However, testing can be done with fewer rechargeable batteries because each cell can be recharged. If disposable batteries are used, on the other hand, more individual cells must be bought to replace cells that have been discharged during testing.

Image found at http://www.panasonic.com/industrial/battery/oem/chem/lithion/

Power Options: Solar Cells

•Flexible Thin Film Solar Module Cells
•Suitable for indoor use (compatible with the Denver flat floor testbed)

•Iowa Thin Film Technologies manufactures such cells.
  •3.2 V per cell: can be soldered together in series or parallel to achieve desired voltage and current
  •0.1m x 0.03m per series of cells
  •$10 - $35, depending on model

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<SJS>

Solar cells are another option for supplying power to each vehicle. There are many lightweight solar cells that can be bought COTS that suit our purposes. Flexible thin film solar module cells can be easily obtained from Edmund Scientific (information about manufacturers such as Iowa Thin Film Technologies has been collected and examined) for a cost of $6.95 - $19.95, depending on design, per cell. Most of the models of solar film are designed with 3.2V for each cell, and similar to batteries, can be connected in either parallel or in series to obtain the necessary voltages and currents.

Image can be found at: www.iowathinfilm.com

Power Options:Voltage/DC Regulators

MIT Aero/Astro

• Need for different output voltages to supply power to different subsystems

• $40-$75 per regulator

• In contact with manufacturers of voltage regulators: General Semiconductor, Siemens, Seiko

• Specific type of Voltage Regulator TBD as system design is further determined

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<SJS>

Voltage/DC regulators may be necessary power supply components for our testbed vehicles. The regulators keep batteries from overheating. They also allow for different output voltages to supply power to different subsystems. The cost is $40-$75 dollars per regulator, and Seiko has recently developed tiny, low mass regulators that suit our purposes.

• **Cost:** wish to minimize the cost of the project.

• **Mass:** mass should be minimized

• **Ease of replacement:** if problems arise, can the option be replaced during testing?

• **Reliability:** have the options proved to be reliable?

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<SJS>

As we wish to minimize cost and mass of the entire vehicle, we wish to minimize the mass of the power subsystem.

The power option chosen should prove to be easily replaceable during testing periods.

The power option should be reliable because if there is no power to drive any of the other subsystems, testing cannot occur.

Power Options: Downselect

Option	Pros	Cons	Decision
Batteries	•Easily Replaceable •Low cost (~ $5 per cell) •Rechargeable •Compatible with indoor use •Familiar with operation	•Difficult access for replacement, inside unit packaging	**YES**
Solar Film	•Lightweight •Closely simulate satellites	•May not work in test facilities •More expensive •Team unfamiliarity with operation	**NO**

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<SJS>

For our power subsystem, we wish to minimize cost and mass, while keeping in consideration ease of replacement during testing as well as feasibility.

Batteries are easily replaceable and the CDIO3 team members are all familiar with battery powered systems.

Solar film is a new topic to the CDIO3 team. It is more expensive, however the film is extremely lightweight and can closely simulates a satellite's power system (easing the transition from testbed to satellite system). Although manufacturers and vendors claim that solar cells can be utilized in indoor facilities, there is some uncertainty as to whether the given lighting is sufficient at both the Denver Flat Floor facility as well as the MIT glass testing plate.

Batteries are the better option because we can be certain that they will work. Although they are higher mass than the solar film, their mass is still low enough to keep our entire vehicle design low-mass. It is not safe to assume that the solar film will properly work at the testing facilities, and buying lighting systems would only further increase our project cost.

Battery Downselect: Metrics

EMF²ORCE

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•**Cost**: We wish to minimize the cost.

•**Voltage Profile**: What is the relationship between voltage output and time?

•**Safety Factor**: Are there any known safety concerns?

•**Memory Effects**: For secondary batteries, does recharging the battery before complete discharge create a loss of power?

•**Lifetime**: What is the average lifetime of each type?

•**Energy Density**: How much energy can the battery supply relative to its weight or volume?

•**Mass**: We wish to minimize the total vehicle mass.

•**Self-Discharge Rate**: How much charge is lost over time?

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<SJS>

Different types of batteries were examined and a trade analysis downselect was done to find the current battery choice as of TARR. The following metrics were chosen:

Cost: The cost of each battery cell. A lower cost will receive a higher rating.

Voltage Profile: The relationship of its voltage over time of discharge. A flat voltage profile curve is less desirable than a sloped voltage profile; a battery with a flat voltage profile must be replaced as soon as the voltage is no longer steady.

Safety Factor: Are the chemicals utilized in the battery cells known to be safe? For instance, there has been concern with Li-ion batteries due to the volatile interaction between Lithium and water. The safer the battery is known to be, the higher the rating it will receive.

Memory Effects: This is only a concern with rechargeable aka secondary batteries. (All primary batteries, therefore, automatically receive a "5" in this category). Often times when a battery is recharged before it is completely discharged, it will lose a portion of its memory. NiCad batteries suffer considerably from memory loss.

Lifetime: How long a battery can last while being used. A longer lifetime is desired.

Energy Density: How much energy the battery can supply relative to its weight or volume. This is an extremely important factor, therefore it is weighted most heavily in the battery downselect process.

Mass: The mass per battery cell. We wish to keep the mass at a minimum.

Self-Discharge Rate: How much charge is lost over time. While Alkaline batteries only discharge 2% a year, NiMH batteries discharge 3% per day.

Batteries: Downselect

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Type	Pros	Cons	Decision
Li-ion	•Rechargeable •Desirable voltage profile •Highest E •Low self-discharge rate •No memory effects	•Safety concerns •Highest Cost	YES
Alkaline-1	•Lowest cost •Most desirable voltage profile •Very low discharge rate	•Greater mass than newer cell technology •One-time usage	NO
NiMH	•Rechargeable •Low mass	•Greater cost per cell •Highest self-discharge rate	NO
NiCad	•Rechargeable •Long cycle life •Lowest cost for rechargeable batteries	•Undesirable voltage profile •Lowest E •1% per day self-discharge rate	NO

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<SJS>

Cost: A lower cost is more desirable.

Voltage Profile: Flatter voltage curves can shorten acceptable usage life for a battery; it is more desirable to have a battery with a more constant sloped curve profile.

Safety Factor: Some batteries have known safety concerns.

Memory Effects: We do not want memory loss effects.

Lifetime: A longer lifetime is desired.

Energy Density: A high energy density is the primary concern in selecting battery type.

Mass: We wish to keep the mass at a minimum.

Self-Discharge Rate: Low discharge rates are desirable.

The choices are in order from most desired option at this point in time to least desired.

Structure Subsystem

<GG, JEU, WDF>
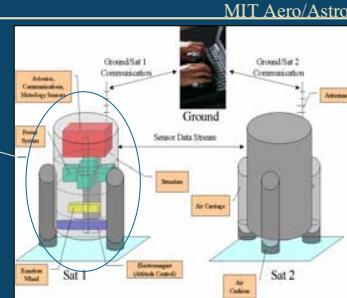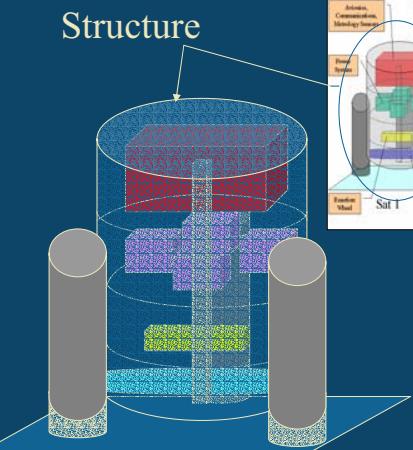
The final subsystem of the design is the structure and air carriage.

Structure Subsystem

- Unit packaging
  - Encases unit and protects it from damage
- EM shielding
  - Protects electronic components from the effects of the electromagnet
- Air carriage
  - Maintains air cushion under unit to reduce friction

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<ESS, WDF>

The Structure subsystem serves several purpose. First, it must support and encase all other subsystems and provide the physical means to connect each of the various subsystems. The structure must also provide EM shielding for all of our sensitive electrical components. Finally, the structure also includes the air carriage will be used to elevate the vehicle off of the flat floor and provide for frictionless testing.

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- Magnetic properties
- Density
- Strength
- Thermal properties (conversion to space, cooling)
- Method of manufacture
  - Ability to machine
  - Feasibility of outside manufacture

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<AS>

When choosing the material for the main structure, several things must be taken into consideration:

The material must not be ferrous, since this could potentially disrupt the magnetic field of the electromagnet.

The density and strength of the material will be of crucial importance, and will factor into one of the design metrics later.

To make the transition into 3-D space easier, a material with robust thermal properties may want to be chosen.

The manufacturing method will play a crucial role in the final downselect. Metal materials would require welding and machining and would require a number of man-hours from the team. Plastic would be made with a mold, and may require fewer man-hours. However, this would probably be contracted out to a vendor, in which case the cost may be higher than if we use metal and do the work ourselves.

<TAS>

Material Selection Metric

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- Metric
  - Require minimal mass with maximum strength
  - Metric determined from equation for plate deflection:
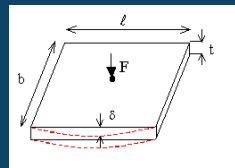
$$\delta = \frac{Cl^3 F}{Ebt^3}$$

$$M = \rho btl$$

$$M = \left[C\left(\frac{F}{\delta}\right) l^6 b^2 \right]^{\frac{1}{3}} \cdot \left(\frac{\rho}{E^{1/3}}\right)$$

Want to minimize $\longrightarrow$ $M \propto \left(\frac{\rho}{E^{1/3}}\right)$

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<TAS>

Our structural design criteria are based on the idea of having a cylindrical satellite body with multiple layers that stack on top of each other. For the most part, we don't have to worry about any significant loading on our structure. The biggest loads and deflections will be seen on the lower flat panels of the cylinder, since they will be supporting most of the weight of the structure. Therefore, we use the equations for bending of a flat plate in order to come up with design metrics.

The equations given are usually used for a square plate, whereas ours will most likely be round. However, this will just affect the value for the constant C, which depends on geometry and the way the plate is supported. The mass will still be proportional to density/modulus^1/3, so the metric still holds for a circular plate. Our main objective will be to minimize this value, since that will produce the structure with the least amount of mass.

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Material	density (kg/m³)	modulus (Gpa)	density/E^(1/3)	CTE (micro	Therm conduc
Aluminum alloy, general	2700	70	0.655	24	190
Magnesium alloy, general	1800	45	0.506	26	80
Titanium alloy, general	4700	110	0.981	8.7	7
Zinc alloy, general	7000	85	1.592	30	105
Stainless steel, Type 400	7700	200	1.317	10.2	24.2
Stainless steel, Type 300	8030	200	1.373	16.6	16.4
Iron superalloy	7920	201	352 1.	16.5	17.6
Nickel superalloy	8420	207	1.423	12.4	14.8
ABS polymer, molded	1050	2.4	0.784	90.6	0.15
Acetal copolymer, 30% glass fib.	1610	7.7	0.815	37	0.32
Acrylic	1180	3.3	0.793	72.9	0.2
Polyester, rigid	1650	6.7	0.875	135	0.17
Polycarbonate/PET	1220	2.2	938 0.	69.5	

•Other considerations:
  - Cost
    - Manufacture method
• Final downselect pending further analysis

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ALS

Shown here is a table of material properties. The table includes several types of metals and plastics. The parameters of interest here are density, modulus, the design metric of density/modulus^1/3, coefficient of thermal expansion, and the thermal conductivity. Note that for plastics, the flexural modulus and not the tensile modulus is used.

Using only the design metric, Aluminum and magnesium alloys as well as several types of plastics are the ideal choices. Parameters not taken into consideration here are cost and ease of manufacture. Further downselect of materials requires further investigation.

EM Shielding

• High permeability metals
• Available in foils, sheets, bars, plates and tubing
• "Sample kit" ~$200

	Dims.	Thickness
Foil	Up to 16" wide	0.002-0.010"
Sheet	24x30", 36x120"	0.015-0.060"
Plate	Up to 10" wide	0.135" and up
Tubing	0.080-2.25" dia.	Custom

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ALS

High permeability shielding materials are available in these forms.

Air Carriage

- Require low-friction support system to simulate 2D microgravity
- Air bearings provide best option
- Flat pad air bearing allows x-, y-translation, yaw rotation, as shown
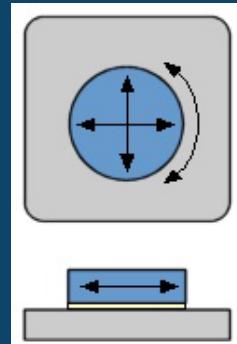
Flat pad bearing

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<DC, AS>

Some sort of system is required to reproduce microgravity in 2 dimensions. Supporting the system with a cushion of high-pressure CO_2 will allow the system to translate with low friction. A simulated profile of the pressurized cushion can be seen in the upper right corner. The air bearings can provide the required support, using onboard CO_2 canisters to provide pressurized gas.

Flat Pad Air Bearing
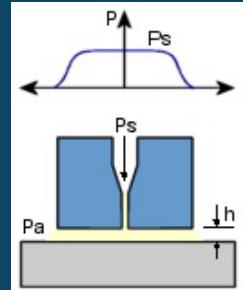
Pressure profile

•Creates cushion of air for frictionless translation and rotation
•No umbilical; self contained unit
• Hydrostatic pressure from tank
•Pressure drops off at edges of bearing, as shown

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<DC, AS, WDF>

Air bearings operate by creating a cushion of air for frictionless translation and rotation. These systems will be self-contained with replenishable CO_2 canisters. This eliminates the need for an umbilical cord which may cause unwanted forces acting on the system. The diagram shows how the air pressure drops of at the edges of the bearing but is mostly constant across the surface of the bearing.

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- Require at least three bearings for stability
- Each bearing must support 1/3 of total system weight
- Efficiency factor = 0.3 to account for edge effects
- Force required per bearing:

$$\frac{M_{total} \cdot g}{3} = \eta_{bearing} \cdot P_{supply} \cdot A_{bearing}$$

- Yields ⟶ $P_{\textbf{supply}} = \dfrac{M_{total} \cdot g}{3 \cdot \eta_{bearing} \cdot A_{bearing}}$

ElectroMagnetic Formation Flight Of Rotating Clustered Entities   109

<DC, AS>

Three air bearings are required to ensure stability. Thus, each bearing must support 1/3 of the total weight of the system. To calculate the required area of each bearing, the above equation is used with a .3 efficiency factor to account for pressure loss at the fringes of the bearing. The required supply pressure is then a function of bearing area only.

Air Bearings Specifications

Typical specifications
• Linear accuracy: 10 µin/in, 100 µin / 36 in
• Rotary accuracy: +/- 1 µin TIR
• Linear repeatability: +/- 10 µin
• Rotary repeatability: 1 µin

Part	Radius (mm)	Thickness (mm)	Load Capacity (N)	Stiffness (N/mm)
FP-C-10	25 mm	12.5 mm	88	17,500
FP-C-15	38 mm	12.5 mm	220	28,000
FP-C-020	50 mm	15.8 mm	330	52,500

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<DC,AS>

Assuming a 60 psi supply pressure, this table lists the specifications for several sizes of bearings. General manufacturer specifications are also listed. The smallest air bearing listed is sufficient to support the expected weight of the system.
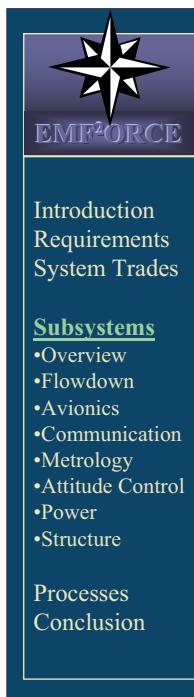
Subsystems Summary

- Flowdown
- Avionics
- Communication
- Metrology
- Attitude Control
- Power
- Structure

ElectroMagnetic Formation Flight Of Rotating Clustered Entities 111

<WDF notes>

This concludes our discussion of the subsystems' trade analysis. We began by explaining the flowdown from requirements, which generated each subsystem and then went to explain the metrics and downselect for the subsystem's components.

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Processes
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•Config Control
•Timelining

Conclusion

Processes Review

Andre Bosch

JEU

Welcome to the Processes Review portion of the Trade Analysis and Requirements Review for Project EMFORCE (ElectroMagnetic Formation Flight Of Rotating Clustered Entities).

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- Validation and Verification
- Budget Tracking
- Configuration Control
- Timelining and Project Management

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<BAB WDF>

The goal of the processes team was to develop the procedures which will guide the project to completion. These procedures include the development of a validation and verification system. A process for the tracking of budgets both financial budgets and resource budgets. Also, the creation of a system for configuration control. Finally, we developed a detailed timeline which will carry the project from present day to completion in the Spring of 2003.

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• Validation: Procedures designed to demonstrate that a newly received part meets design <u>specifications</u> as per the design document. *"Getting the right part."*

•Verification: Procedures designed to demonstrate that a part or system meets design <u>requirements</u> as per the requirements document. *"Getting the part right."*

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<BAB WDF>

Validation procedures have been developed that will demonstrate that a newly obtained part meets the design specifications. The essentially means "Getting the right part". Validation procedures will be used to make sure components, subsystems, and the final system meet all the design requirements as specified in the requirements document.

Validation Process

MIT Aero/Astro

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Conclusion

- Did we get the right part?
  - Machined Parts
    - Check critical dimensions and tolerances
  - Commercial Off-the-Shelf (COTS)
    - Check for compliance with manufacturer's specifications
    - Check critical dimensions and tolerances
- Document the part as valid
  - List all actual dimensions and tolerances

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<BAB, ESS>

Abstract: Parts will need to be either purchased or fabricated for the project's final product. To ensure a successful final product it is imperative that a process be in place to validate the quality of the purchased or fabricated part prior to investment of project resources in this part.

1.   **Validation for Fabricated Parts.**

1.1.   **Definition.** Fabricated parts are parts that will be constructed or implemented by members of the project at a variety of production facilities. These facilities include but are not limited to laboratories, workshops, machine shops, and computer labs.

1.2.   **Validation Process.** 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.

1.3.   **Documentation.** Prior to inclusion in a subsystem, every fabricated part must be verified and documented as verified on CDIO Form 23-212.

2.   **Validation for Purchased Parts**

2.1.   **Definition.** Purchased parts are parts that are purchased by members in the group from a variety of sources. These sources include but are not limited to companies, manufacturers, and stores.

2.2.   **Validation Procedure.** Purchased parts will be checked against the specifications and tolerances given by the entity from which they come. Only if the purchased part meets all specifications and tolerances will the part be validated.

2.3.   **Documentation.** Prior to inclusion in a subsystem, every purchased part must be verified and documented as verified on CDIO Form 23-211.

2.4.   **Non-Compliance**. Purchased parts that do not meet the specification of the entity from which they are purchased will be returned to the entity from which they are purchased for a full refund. Non-compliance will be documented on CDIO Form 23-291.

Verification Process

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- Determine the applicable requirements
- Design a test to prove the requirements are met
  - Concurrent with system design
  - Must be submitted to Systems Group before construction
- Evaluate test data against requirements and draft verification review
- Submit the verification review

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<BAB, ESS>

Abstract: Once systems and subsystems are created it becomes necessary to ensure that the system meets requirement and interface specifications. To this end, a procedure by which systems and subsystems are tested against the requirements becomes necessary.

1. **Definition.** The process of verification includes ensuring that the system or subsystem meets requirements and also providing a means by which to verify that the requirements are being met.

2. **Verification Process.** The verification process occurs in three phases.

2.1. **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 such things as: mass, power, cost, time, error, flops, etc. This group's design for the system or subsystem must meet all the requirements within the allotted resources.

2.2. **Phase Two: Test Design**. 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.

2.3. **Phase Three: Verification of Results.** Once the test designed per subparagraph 2.2 has been performed the team will evaluate the data brought forth by the test and check that data against the requirements and constraints. Only if all requirements and resource constraints are met may the team verify the system or subsystem.

3. **Verification Documentation.**

3.1. **Test Plan Document CDIO Form 23-111.** As part of the test design the subsystem design team will submit a test plan document which outlines the functional requirements of the subsystem and the tests that will be performed to the subsystem to verify that these requirements have been met.

3.2. **Verification Review Document CDIO Form 23-121.** The subsystem design team is required to document all applicable test data.

Budgets Overview

MIT Aero/Astro

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Conclusion

- Budgets for cost, mass, power, labor, volume, FLOPs (Floating-point Operations per Second), and Error will be tracked
- Sub-teams manage their own budgets
- Weekly reports to the Systems Team

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<ESS, WDF>

In order to ensure that the system is meeting the specified design constraints it will be important to track various budgets. Official control of budget information is placed in the hands of the System's Team. The system's team will assign budgets to each sub-team as they see fit. Sub-teams will be responsible for managing their own budgets and reporting non-compliance to the System's Team.

<WDF>
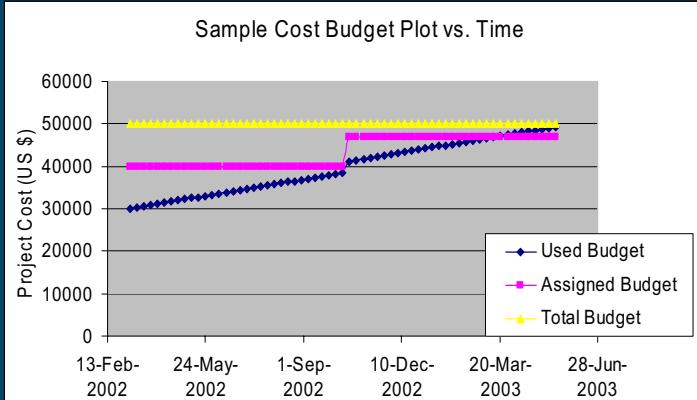
Using an Excel Spreadsheet the System's team will be able to quickly enter in each Sub-team's current budget data and get instant feedback on budget status for all parameters. This includes a week by week plot of all tracked items to allow observance of spending trends. All reallocations of budget numbers must be decided by the Systems Team. Plot shows a sample plot of the project cost versus time. This plot has the actual value used, the amount that has been allocated and the total budget. A similar plot is generated for every parameter (mass, power, labor and volume).

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Conclusion

- **FLOPS budgets depend on operating modes**
  - Startup, steady control, formation change
- **Error tracking consists of holding control tolerances**
  - Sources of error in position and angular rate
    - Accuracy of metrology
    - Accuracy of control law
    - Stability of electromagnets

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<WDF>

FLOPS budgets will depend on operating state, and will be set by the hardware purchased. It will be important for software and avionics to be sure to test all possible combinations of computing modes to ensure that FLOPs usage remains under budget.

Error tracking currently only consists of position and angular rate errors. These errors can be results of accuracy problems in the metrology equipment or software. Stability of the electromagnets and there properties. The accuracy of the electromagnetic and system dynamics models.

Configuration Control

MIT Aero/Astro

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Conclusion

- One official version of all group documents
  – Essential for efficiency and mission completion
  – Eliminates confusion over current version of documents
- Major documents tracked by Chief Systems Engineer
- Other documents tracked by Systems Group

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<ESS>

PROCESSES DOCUMENT 22-1

CONFIGURATION CONTROL

Purpose: This document will describe the process by which project and subproject configuration will be controlled by the proper authorities.

Abstract: Configuration control is essential in systems engineering applications. All groups and teams must be working with the most current information, but it is essential that this information is the same for all teams. The Chief Systems Engineer will place major documents under configuration control. The Systems Group will control smaller documents.

Tracking Interfaces

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Conclusion

- How the subsystems are mated together into the final project
- Documentation of all subsystem inputs and outputs is required
  - Power connections
  - Information flow
  - Structural attachments
- Critical to success of final project

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<ESS>

PROCESSES GROUP INSTRUCTION 22-11

INCLUSION OF INTERFACE SPECIFICATIONS IN ARCHITECTURE DESIGN

1. The most important aspect of systems integration during the latter stages of the systems design project will be the interfaces between the various subsystems. Therefore, it is critical that all inputs to and outputs from each subsystem are well documented.

2. When designing an abstract for a subsystem, the interfaces must be summarized in an interface specification document (CDIO Form 22-112). Types of interfaces may include but are not limited to:

a. Physical design and specification of power connections

b. Electronic Communications between various subsystems

c. Structural connections and attachments from the subsytems to the main structure

3. This interface documentation should be included in the design of the final architecture, which will be included in all formal reviews.

Preliminary Design Phase Execution Objectives

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Conclusion

Team Goals:
- Assurance of task completion
  – Weekly briefing to team by systems group
- Provide warning of potential problems ahead
  – Consistent weekly updates to timeliner
- Maintain strong communication lines
  – Avoids misconceptions on progress and needs
- Sustained time commitment

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<JEU>

For any plan, it's important to consider problems encountered before and to take steps to prevent them from occurring again. There were many problems with Timelining the project encountered during the first six weeks.

In this capacity, the Processes Group proposes the following four Team Goals.

1. Assurance of Task Completion

    The briefing gives an opportunity for the whole Team to get on the same page, so to speak.

2. Provide Warning of Potential Problems Ahead

    Consistent updates to the TimeLiner allow for consistent checks on progress, and thus allows the Team to be informed of potential future problems
    with task completion and ensures the issue is addressed immediately.

3. Maintain Strong Communication Lines

    Provides open forum for group interaction to avoid problems with task dependencies.

4. Sustained Time Commitment

    Each team member should plan on placing a sustained emphasis (time and effort) on their portion of the project to accomplish all tasks on schedule.

Preliminary Design Phase
Organizational Chart
MIT Aero/Astro

Introduction
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•**Timelining**

Conclusion

Systems Group

EM Hardware Group
Attitude Control Group
Formation Flight Group
Structures and Power Group

EM Team (2)
RWA Team (2)
Avionics Team (2)
Control Team (2)
Metrology Team (2)
Comm/Ops Team (2)
Str/Pwr Team (3)

EM, RWA Teams
•Design
•Trades
•Implementation

Control Team
•Control
•Software

Comm/Ops Team
•Comm to Ground
•Comm b/w Vehicles
•Testing Procedures
•Documentation

Avionics Team
•Electronics
•Power
•Computer Hardware

Metrology Team
•Relative Position
•Angular
•Data to ACS

Structures Team
•Detailed Design
•Physical Interfaces

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<JEU, ESS, WDF>

In the next week, the project will move into the Preliminary Design Phase (PDP). In order to ensure the progress of the project through the PDP the Processes team recommends that the class be divided into the following groups and teams. There will be four groups each of which will have on representative on the System's Group. These Groups are: EM Hardware, Attitude Control Group, Formation Flight Group, and the Structures Group. These groups will then be furthered divided teams whose specific responsibilities are all detailed above

Timeline To Preliminary Design Review (PDR)

MIT Aero/Astro

Introduction
Requirements
System Trades
Subsystems

Processes
• Verification
• Budget
• Config Control
• **Timelining**

Conclusion

Task Name	W1	W2	W3	W4	W5	W6	W7	W8	W9
Address TARR Action Items	03/21 ——— 04/02								
Flowdown Requirements		04/01 ┃ 04/04							
Define Interfaces		04/01 ┃ 04/05							
Subsystem Design			04/02 ——— 04/16						
Fabrication/Procurement Plans		04/01 ——— 04/09							
Procurement Order Deadline					┃ 04/16				
Prototyping						04/18 ——— 04/30			
Tests & Model Comparisons							04/23 ┃ 04/30		
Alter Hardware Designs							04/23 ┃ 04/30		
PDR Preparation and PDR							04/23 ——— 05/07		

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<JEU>

The main focus of the Plan to Execute the Preliminary Design Phase (PDP) is a projected timeline to the PDR on 7 May.

This timeline lists major tasks to be accomplished by each Sub-System Team (or Group). The tasks differ in Developing their Sub-System Designs. These diverging tasks are included on a separate page (and backup slide).

The Gantt Chart beside the Major Task List shows the proposed time allocation for each task for each group. Many things must be run in parallel within each group for the tasks to be accomplished on time. There is some flexibility within groups to assign more detailed timelines and tasks to individual members, but it is absolutely critical that each individual and group stay aware of the overall timeline. This is to be directed and verified by the Systems Group.
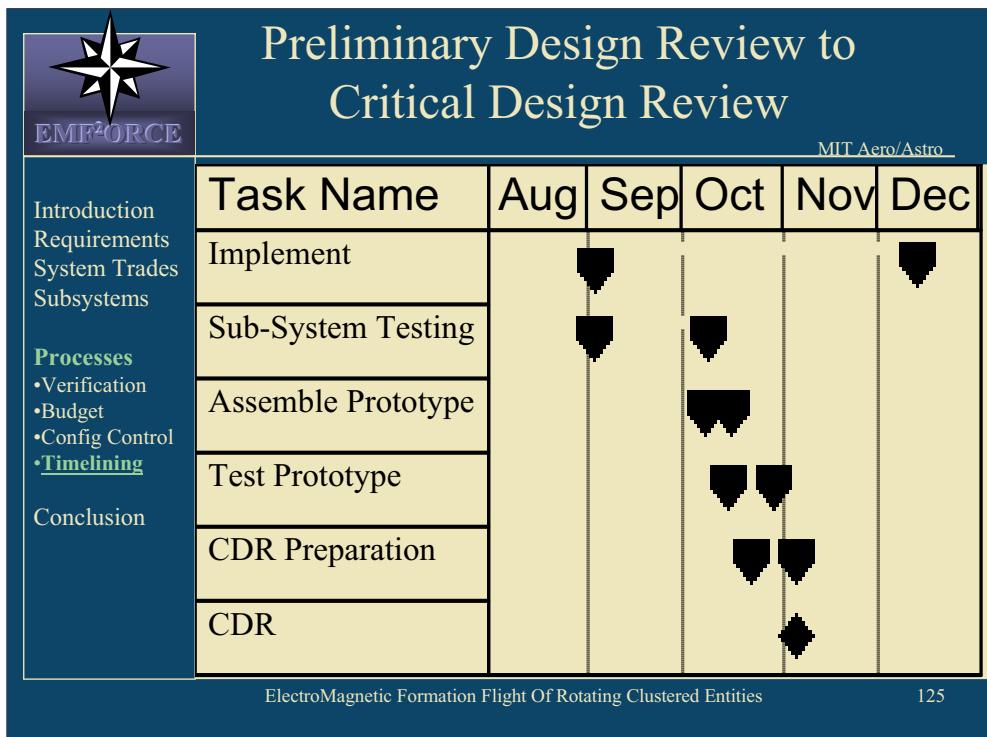
Preliminary Design Review to Critical Design Review

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Conclusion

Task Name	Aug	Sep	Oct	Nov	Dec
Implement					
Sub-System Testing					
Assemble Prototype					
Test Prototype					
CDR Preparation					
CDR					

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<JEU>

Finally, it's important to look ahead to the other major milestones, such as CDR and AR. This is a timeline from the completion of the Preliminary Design Review to the wrap-up of the Critical Design Review in November 2002. There is not much detail because much has yet to become apparent. However, there are some things that can be considered now as major sections of the project. These are shown above in the task list and Gantt chart. The Gantt chart describes the proposed timeline of events as seen currently.

The Long-Term Procurement phase of the project occurs over Summer break 2002 (May 2002 – August 2002).

Note: Past the PDR, all of the dates are rough estimates.
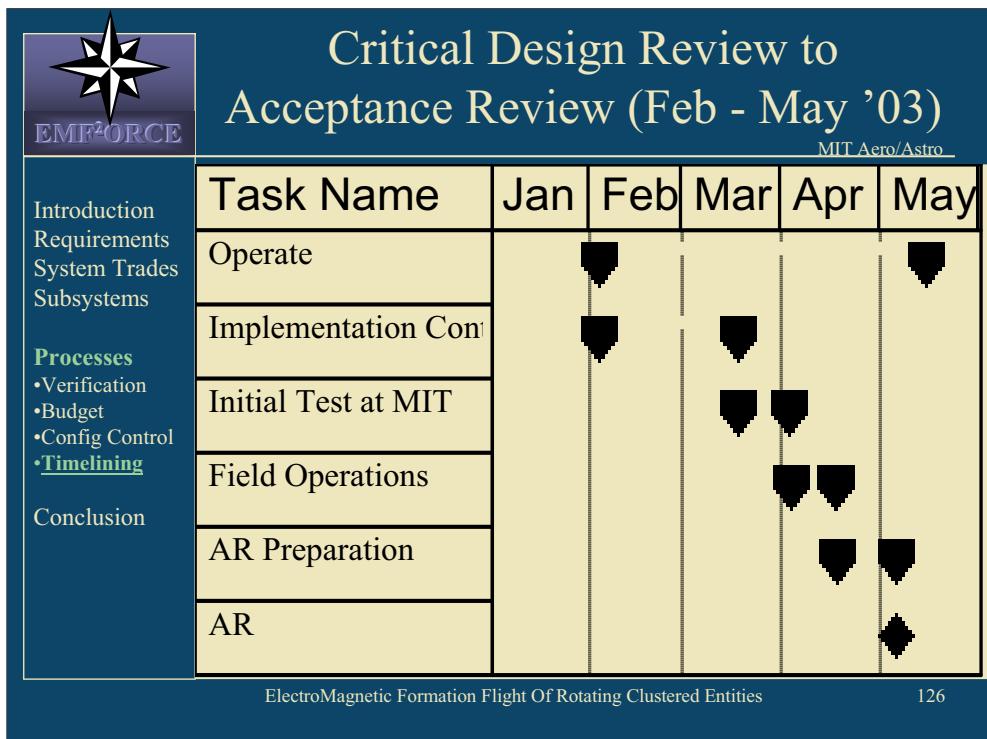
Critical Design Review to Acceptance Review (Feb - May '03)

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•Verification
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•Config Control
•Timelining

Conclusion

Task Name	Jan	Feb	Mar	Apr	May
Operate		▼			▼
Implementation Con		▼	▼		
Initial Test at MIT			▼ ▼		
Field Operations				▼ ▼	
AR Preparation				▼	▼
AR					◆

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<JEU>

Finally, it's important to look ahead to the other major milestones, such as CDR and AR. This is a timeline from the completion of the Critical Design Review to the Acceptance Review in May 2003. There is not much detail because much has yet to become apparent. However, there are some things that can be considered now as major sections of the project. These are shown above in the task list and Gantt chart. The Gantt chart describes the proposed timeline of events as seen currently.

The Flight Hardware Development Phase of the project occurs between December 2002 and the beginning of February 2003.

Note: Past the PDR, all of the dates are rough estimates.

Conclusion and Summary

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- Motivations for EMFF
- Requirements and Scaling
- Systems Trade Analysis
- Subsystem Trade Analysis
- Processes
  - Timeline set through PDR
  - Formal configuration control applied to the Requirements Document

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<BAB, ESS, WDF >

We began with an explanation of the details and motivation behind our project. We then detailed the requirements and constraints that our design will be verified against. An overall System's Trade Analysis was presented which detailed many of the key trades for this design. We then listed our metrics and recommended components for each of the various subsystems. Finally we detailed the processes and procedures that will be used to carry through project forward towards completion.

Questions

MIT Aero/Astro

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Conclusion

?

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< ESS, WDF>

We would like to thank all of you for sharing your valuable time with us today. We will now take questions from the audience.

Back-Up Slides

<JEU>

This is the backup slide section of the presentation. These slides are only meant to be shown should a question be raised that these slides can help clarify.

Accelerometers & Gyros

Introduction
Requirements
System Trades

Subsystems
•Flowdown
•Avionics
•Communication
•**Metrology**
•Attitude Control
•Power
•Structure

Processes
Conclusion

- Accelerometers
  - Single axis
  - High accuracy
  - Size: ~4x4x7 mm, .5 g
  - Price: $425
- Gyros
  - Small, lightweight
  - Price: $88

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<AA>

Acceleration information will help to make the system controllable. This is desirable since the system will be inherently unstable.

Accelerometers are highly accurate scientific measurement devices.

The gyro shown is an off-the-shelf, low accuracy, angular acceleration measurement device.

Battery Downselect: Comparison

Introduction
Requirements
System Trades

Subsystems
•Flowdown
•Avionics
•Communication
•Metrology
•Attitude Control
•**Power**
•Structure

Processes
Conclusion

	Weight	Alkaline-2	Alkaline-1	NiMH	NiCad	Li-ion	Lithium	Zn-C
Cost	5%	5	5	3	4	3	4	2
Voltage Profile	15%	3	5	3	2	4	3	5
Safety Factor	5%	4	4	4	3	2	2	3
Memory Effects	10%	2	4	4	2	5	5	5
Cycle Life	20%	2	3	4	5	4	5	3
E-Density	30%	3	3	3	2	4	3	2
Mass	10%	3	3	4	3	4	4	4
Discharge	5%	5	5	1	2	4	4	3
TOTAL	100%	2.95	3.45	3.35	2.85	3.95	3.75	3.35

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<SJS>

Cost: A lower cost will receive a higher rating.

Voltage Profile: Flatter voltage curves will receive a lower score and higher scores will be given to those with the more constant sloped curve profiles.

Safety Factor: Those batteries with known safety concerns will receive lower ratings.

Memory Effects: The greater the memory loss, the lower the score.

Lifetime: A longer lifetime is desired.

Energy Density: A high energy density is the primary concern in selecting battery type.

Mass: We wish to keep the mass at a minimum.

Self-Discharge Rate: The lower the discharge rates, the higher the batteries will score.

<SJS>

Subsystem Task Breakdown

MIT Aero/Astro

ElectroMagnetic Formation Flight Of Rotating Clustered Entities

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<JEU>
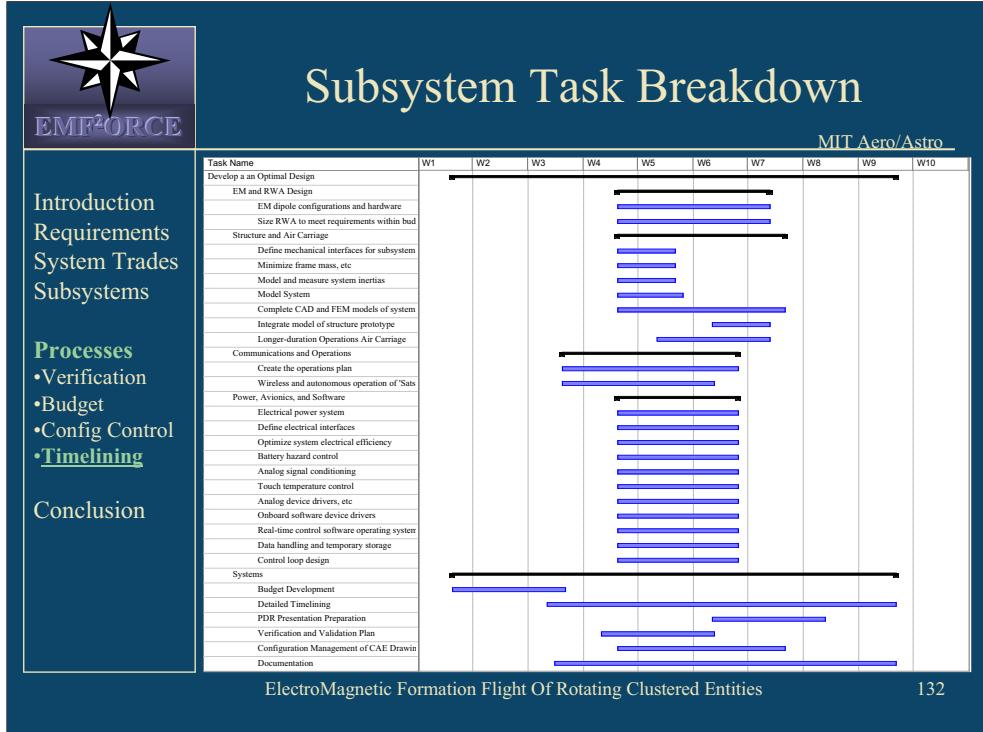
This is the timeline to PDR broken down by required subsystem tasks. Essentially, these describe the major tasks that need to be accomplished to develop an optimal design for each subsystem.

Detailed Timeline to AR

ElectroMagnetic Formation Flight Of Rotating Clustered Entities

<JEU>
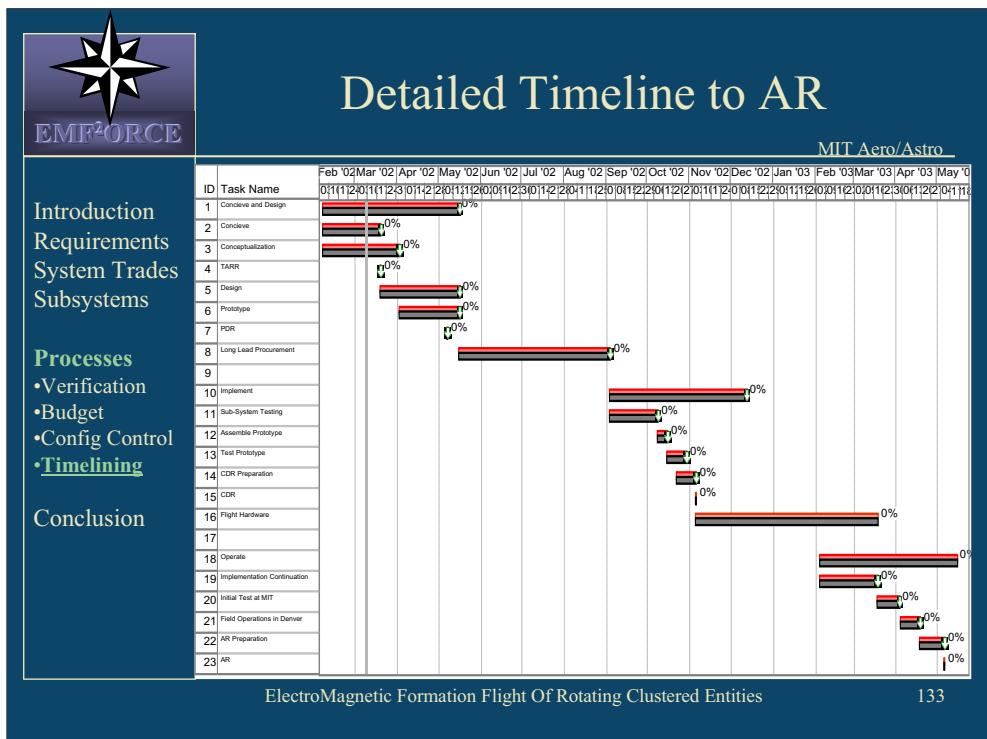
This Gantt chart demonstrates the timeline of major tasks and phases of the project from start to completion (designated by the approximate date of the Acceptance Review).