

ElectroMagnetic Formation Flight Of Rotating Clustered Entities

EMFFORCE



Critical Design Review

December 5, 2002

33-116

Department of Aeronautics and Astronautics

MIT

<ALS>

Welcome to the Critical Design Review for the EMFFORCE team.

Introduction



André Bosch

05 December 2002

EMFFORCE - CDR

2



EMFFORCE

CDR Purpose

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Present design progress to date
- Identify and address concerns for completion of project
- Demonstrate plans for implementation and operation phases
- Show budget and schedule trends and predictions
- Get approval to enter build phase

05 December 2002

EMFFORCE - CDR

3

<ALS>

The purpose of the Critical Design Review is mainly to present the team's design progress and identify and address concerns regarding the team's ability to complete the project. In addition, the team will present plans for the final phases of the project (to take place over the next term), show trends of the budgets and schedules, and get approval to enter the build phase.



EMFFORCE

Presentation Overview

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Introduction
 - Background, requirements, overview
- Subsystems Reports
 - Actuation, Electronics, Testbed
- Systems Report
 - Budgets, Integration, Schedule
- Q&A and laboratory tour

05 December 2002

EMFFORCE - CDR

4

<MAS>

The EMFFORCE CDR presentation consists of three parts: introduction, progress reports on each subsystem, and a progress report from the Systems team. Following the presentation the EMFFORCE team will answer any further questions before leading guests on a tour of the lab, where team members will demonstrate aspects of their subsystems through tests and explanations.



EMFFORCE

Background and Motivation

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Space-based telescopes limited in size by launch constraints
- Can increase resolution by using multiple small apertures widely spaced
- Formation flight one solution to holding widely spaced apertures together

05 December 2002

EMFFORCE - CDR

5

<MAS>



EMFFORCE

Application: NASA TPF

Introduction

Subsystems

- EM
- RWA
- Power
- Structure
- Metrology
- Avionics SW
- Comms
- Avionics HW
- Control
- Operations

Systems

- Terrestrial Planet Finder: multi-satellite formation detecting extrasolar planets by interferometry and spectral analysis
- One concept: rotating system
 - 5 spacecraft
 - 2m diameter optics
 - 12.5m and 25m separations
- Design architecture chosen by 2006



Image is taken from NASA's Web site:
<http://www.nasa.gov>.

05 December 2002

EMFFORCE - CDR

6

<MAS>

“TPF will take the form of either a coronagraph operating at visible wavelengths or a large-baseline interferometer operating in the infrared.

“During almost 20 years of study, design concepts have alternated between interferometric arrays and coronagraphs. In recent years alternative architectures have emerged with the potential to achieve similar science goals. These opened up the possibility of new mission concepts and additional precursor missions.

“In December of 2000, JPL and four study teams consisting of aerospace industry companies and university investigators, with advice from the Science Working Group, selected the most promising architectures for more detailed definition and analysis. These architectures were studied in detail, and the results were presented during a Final Technical Review a year later.

“Final selection of a TPF architecture will occur in 2006, based on the science and technology progress of the next four years.”

-from “What is TPF?”

http://planetquest.jpl.nasa.gov/TPF/tpf_what_is.html

“Design Concept: Interferometer (Lockheed Martin) Light from four or more telescopes on a common structure (right) or separate, free-flying spacecraft will be combined to suppress, or null, starlight in Lockheed Martin's interferometric mission concept. “

-from “Sample Mission Concepts”

http://planetquest.jpl.nasa.gov/TPF/tpf_sample.html



EMFFORCE

EMFFORCE Mission

Introduction

Subsystems

- EM
- RWA
- Power
- Structure
- Metrology
- Avionics SW
- Comms
- Avionics HW
- Control
- Operations

Systems

Demonstrate the **feasibility** of
electromagnetic control for
formation flying satellites

05 December 2002

EMFFORCE - CDR

7

<MAS>

EMFFORCE is a proof-of-concept project. Its purpose is to develop technology for application to future space-based systems. The two most important concepts EMFFORCE must link are electromagnetic control of satellites, and untethered formation flying vehicles.

The mission of Project EMFFORCE reflects this goal.



EMFFORCE

Electromagnetic Control

Introduction

Subsystems

- EM
- RWA
- Power
- Structure
- Metrology
- Avionics SW
- Comms
- Avionics HW
- Control
- Operations

Systems

Electromagnets and momentum storage device replace thrusters

Advantages	Challenges
No obscuring plumes	Coupled control law
Independence from fuel	Relative control only
Small adjustments easy	Electromagnets unconventional

05 December 2002

EMFFORCE - CDR

8

<MAS>

Electromagnetic control requires two-part actuation: electromagnets to provide the force and system torque for repositioning, and a reaction wheel to hold angular momentum, which provides restoring torque to the vehicles.

There are distinct advantages and also some challenges to EM control.

Advantages:

- Regular thrusters produce plumes from gas jets used to reposition vehicles. These plumes could damage the system optics as well as interfere with imaging precision. Electromagnetic control produces no such plumes.
- The lifetime of thruster-based propulsion systems is limited by the amount of propellant on board. Electromagnetic propulsion is infinitely renewable (assuming a solar power supply).
- Thrusters are difficult to use in small increments; the jet bursts are often quite imprecise and therefore impractical for the station-keeping required by a formation-flying cluster. Electromagnetic control is ideal for this kind of small, gradual repositioning maneuvers.

Challenges:

- The control law governing an EM control system is highly complex due to coupling.
- Since there is no external force involved with electromagnets, the system can control only relative degrees of freedom (DoF) – not inertial.
- Electromagnetic control of free-flying vehicles is an untested technology and requires extensive experimentation to understand the behavior of the system.



EMFFORCE

Formation Flight

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Geometry is adaptable; expands mission capability
- Formation is able to overcome failure of a single vehicle
- Vehicles easier to launch, replace, reconfigure
- Control of many satellites difficult
 - Large amounts of fuel consumed by “station-keeping” maneuvers and array rotation

05 December 2002

EMFFORCE - CDR

9

<MAS>

There are several advantages to using a formation of free-flying satellites over using a rigid framework of multiple apertures for a large space-based telescope.

- Adaptable geometry
- Robustness – overcome partial failure
- Ease of launch (weight reduction); replacement and reconfiguration possibilities
- Conventional control of a formation-flying group of satellites is very difficult due to thruster imprecision.



EMFFORCE

Functional Requirements

Introduction

Subsystems

EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations

Systems

System must complete tests representative of application

- 7 minute rotational maneuver
 - 2 or 3 vehicles
 - 2 minutes spin-up, 2 minutes spin-down
 - 3 revolutions at 1 RPM
 - 2 meters minimum separation
- Other tests: disturbance rejection in linear arrangement

05 December 2002

EMFFORCE - CDR

10

<MAS>

Functional requirements - based on MIT SSL technical documents



EMFFORCE

Operational Requirements

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- gas carriage and power must support vehicle for 20 minutes of operation
 - 1 or 2 tests plus margin
- Vehicles must operate freely: no tethers
- System must remain intact during and after tests without causing damage to operators or environment
- System must be portable in preparation for field operation

05 December 2002

EMFFORCE - CDR

11

<MAS>

Operational requirements – based on application as well as on facilities and resources available to the EMFFORCE team



EMFFORCE

Constraints and Optimization

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Observe constraints: labor, cost limits
 - Work force: 180 student hrs/week
 - Cost cap: \$50,000
- Optimize EMFFORCE vehicle (considering associated resources):
 - Mass (EM strength, power supply, gas carriage support)
 - Power (battery life)
 - Computation (processor speed, memory)

05 December 2002

EMFFORCE - CDR

12

<MAS>

Constraints imposed on funding and labor require the EMFFORCE team to optimize certain characteristics of the system.



EMFFORCE

Testbed Summary

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- 3 vehicles, each having:
 - 19 kg mass, 20 min power duration, 2 electromagnets, 1 reaction wheel
- Gas carriage: 20 min duration supporting a 19 kg vehicle
- Operational environment
 - 1.2m x 1.8m glass surface at MIT
 - 5m x 10m facility at Lockheed
- Communication and processing
 - 2 internal microprocessors (metrology, avionics/control)
 - Inter-vehicle communication via RF channel
 - External “ground station” computer (operations, records)
- Metrology per vehicle
 - 1 rate gyro
 - 3 ultrasonic (US) receivers synchronized using infrared (IR) pulses

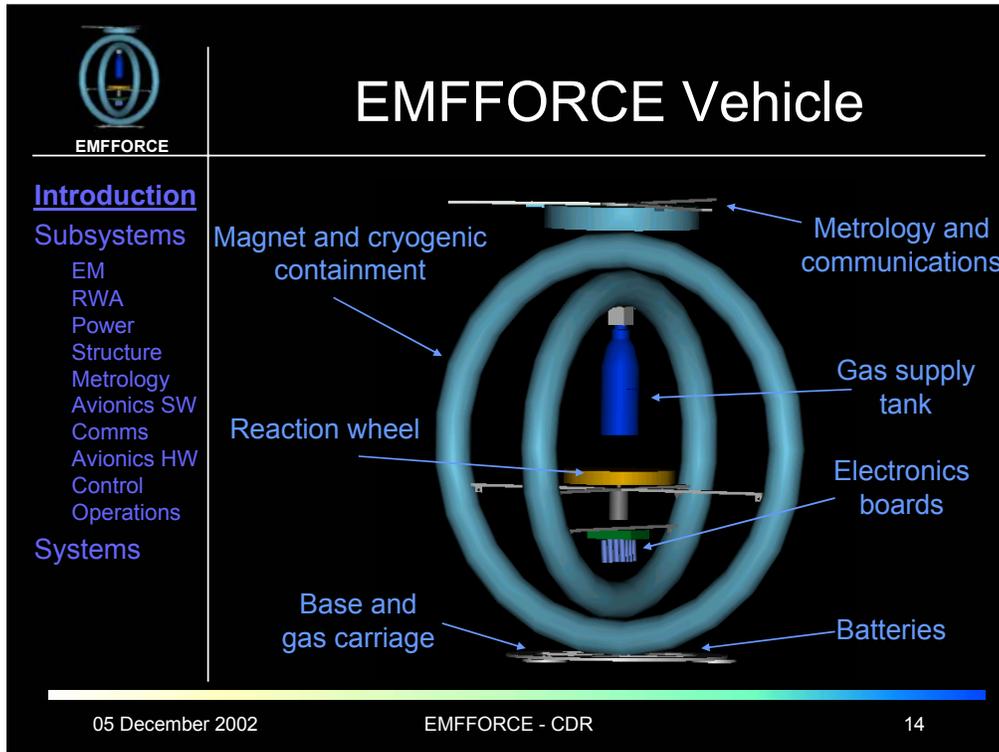
05 December 2002

EMFFORCE - CDR

13

<MAS>

A high-level summary of the EMFFORCE testbed.



<ALS>

This is a computer rendering of one of the EMFFORCE vehicle. All physical subsystems are noted on the drawing.



EMFFORCE

Subsystem Breakdown

Introduction

Subsystems

EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations

Systems

Electronics

- Avionics
- Communications
- Metrology

Actuation

- Electromagnet
- Reaction wheel
- Power
- Structure

Testbed

- Control
- Operations
- Systems

05 December 2002

EMFFORCE - CDR

15

<ALS>

The subsystems have been divided into three main groups. The subsystems within each group work closely together and share the most critical interfaces. The electronics group consists of the avionics, communications, and metrology subsystems. The actuation group consists of the electromagnet, reaction wheel, power, and structure subsystems. Together these two groups form the hardware and software of the vehicle. To achieve the project mission, a third group is required to implement these vehicles in a testbed. The testbed group consists of the control, operations, and systems subsystems.

Electromagnet



Jesus Bolivar

05 December 2002

EMFFORCE - CDR

16



Overview

- 2 Perpendicular Electromagnet Coils
 - Superconductor Wire
- Coil Casing
 - Liquid nitrogen cooling system for superconductor coils
- Liquid Nitrogen Reservoir
 - Provides system with supply of liquid nitrogen

05 December 2002 EMFFORCE - CDR 17

<MSW>

The electromagnet subsystem is composed of 2 large perpendicular electromagnet coils oriented vertically, the coil casing, and the liquid nitrogen reservoir.

The electromagnet coils produce the force and torque necessary to spin up the system. The coils are made of superconductor wire that must be operated below 110K so they are contained within a casing that immerses the coil in liquid nitrogen at 70K. The liquid nitrogen reservoir contains the supply of liquid nitrogen to replenish the nitrogen that boils off during operation.



Requirements

<p>Introduction</p> <p>Subsystems</p> <p><u>EM</u></p> <p>RWA</p> <p>Power</p> <p>Structure</p> <p>Metrology</p> <p>Avionics SW</p> <p>Comms</p> <p>Avionics HW</p> <p>Control</p> <p>Operations</p> <p>Systems</p>	<ul style="list-style-type: none"> • Electromagnet coils must produce force and torque for <ul style="list-style-type: none"> – Translational movement – Disturbance rejection – Steady state rotation rate of 1 rpm for 3 rotations – Vehicle separation distance of 2 meters • Electromagnet casing must <ul style="list-style-type: none"> – Maintain superconductor coils at temperature below 110K for duration of test – Provide structural rigidity for vehicle <ul style="list-style-type: none"> • Hardware mounted to inner casing, outer casing, and liquid nitrogen reservoir
---	---

05 December 2002
EMFFORCE - CDR
18

<MSW>

The electromagnet coils must produce force and torque necessary for translational movement, disturbance rejection and rotation of the vehicles. The system is required to rotate at 1 rotation per minute (or 6 degrees of arc per second) at steady state for a minimum of 3 rotations. The separation distance of the vehicles is 2 meters measured from the centerline of a vehicle to the centerline of adjacent vehicle(s).

The electromagnet casing is required to keep the superconductor coils at temperatures below 110 K in order for the wire to exhibit superconducting properties (0 resistance). To do so, it keeps the coil immersed in 70K liquid nitrogen for the duration of the test. The electromagnet casing is also required to provide structural rigidity for the vehicle since it is the outer structure. The casing must provide mount points for other subsystem hardware (such as metrology transmitters and receivers, gas carriage, reaction wheel, etc.). The casing will be made out of insulating foam and epoxy. To strengthen the foam against damage and for vehicle structural rigidity, the foam is wrapped with fiberglass and epoxy.



EMFFORCE

EM Design History

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

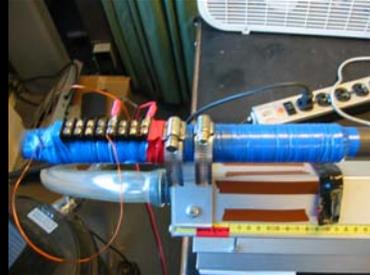
Avionics HW

Control

Operations

Systems

- Ferromagnetic core wrapped with copper coil
 - Steel core extremely heavy
 - Difficult to model field strength
- Large copper coil
 - Eliminated heavy core
 - Easier to model
 - Could not meet requirements due to current limitations through copper wire



05 December 2002

EMFFORCE - CDR

19

<MSW>

The original design for the electromagnet was a ferromagnetic iron core wrapped with a copper coil. This design was eventually discarded for several reasons. The iron core was extremely heavy. The last mass estimate for the iron core alone was nearly 8 kg. It was also very difficult to model the near-field effects of this ferromagnetic core design.

The next design for the electromagnet was a large copper coil. This eliminated the heavy ferromagnetic core from the original design. Additionally, it is much easier to model the B-field around the coreless coil design. However, the copper was unable to carry safely the amount of current necessary to satisfy the requirements due to resistance and heating issues. In order to alleviate this problem, a different material for the coil had to be found that allowed much higher levels of current to be passed through the wire.

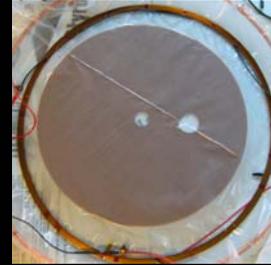


EMFFORCE

EM Design History

Introduction
Subsystems
EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations
Systems

- Final Design: High-temperature superconductor coil
 - Eliminated heavy core
 - High current
 - Almost no resistance in wire at temperatures below 110K
 - Easier to model than ferromagnetic core electromagnet
 - Needs cooling system to keep superconductor below 110K



05 December 2002

EMFFORCE - CDR

20

<MSW>

The final electromagnet design uses high-temperature superconductor wire instead of copper in the large coreless coil design. This eliminated the heavy ferromagnetic core which is a design more translatable to space application. It would be costly and inefficient to launch a satellite using a large, heavy core as part of its actuation system. This coreless design, like the previous copper wire design, is easier to model than the electromagnet with a ferromagnetic core.

The superconductor can safely carry over 10 times the amount of current that the copper wire can due to its superconducting properties below 110K. At those temperatures, the wire has zero resistance negating the current and heating problems that caused the copper wire design to not meet the requirements. However, this does add the additional requirement that the superconductor wire be encased in a container that will keep it at a temperature below 110K.



EMFFORCE

EM Coil Design

Introduction
Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- American Superconductor Bi-2223 Reinforced High Temperature Superconductor Wire
 - Dimensions
 - 4.1 mm wide
 - 0.3 mm thick
 - 85 m length pieces
 - Critical Current
 - 115 amps, 9.2 kA/cm²
 - Below 110 K
 - Coil properties driven by requirements. Next step: Solve for the coil properties using equations of motion

05 December 2002

EMFFORCE - CDR

21

<MSW>

The wire that was chosen for the electromagnet coil was American Superconductor's Bi-2223 Reinforced High Temperature Superconductor Wire. They are the only large American manufacturer of high-temperature superconductor wire applicable to the project. For added strength, the decision was made to go with the reinforced wire.

The wire is tape-like with a width of 4.1 mm and a thickness of 3 mm. 85 m lengths of wire were obtained from the manufacturer.

The primary reason that the superconductor was chosen was for the high amount of current that could be safely passed through the wire. For this wire, 115 amps may be passed through the wire below a temperature of 110K since the wire does not have resistance at low temperatures.



EMFFORCE

EM Coil Design

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

• Radial Force

$$F_x = \frac{3}{4\pi} \frac{\mu_o \mu_A \mu_B}{s^4} (2 \cos \alpha \cos \beta - \sin \alpha \sin \beta)$$

• Tangential Force

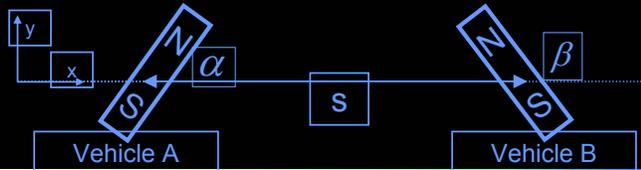
$$F_y = \frac{3}{4\pi} \frac{\mu_o \mu_A \mu_B}{s^4} (2 \cos \alpha \sin \beta - \sin \alpha \cos \beta)$$

$\mu_o = 4\pi * 10^{-7}$ T-m/A: permeability constant

μ : magnetic moment

α, β : dipole angles

s : separation distance between vehicle centerlines



05 December 2002

EMFFORCE - CDR

22

<MSW>

In order to determine the necessary size of the coil, consider the radial and tangential force acting on two vehicles at a separation distance of s (between vehicle centerlines). Each vehicle is simply modeled as a dipole. The dipoles are oriented at angles α and β from their connecting centerline.

Force is dependent on the electromagnet properties (number of turns, current, and loop radius), separation distance, and dipole angles.



EMFFORCE

EM Coil Design

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Set radial force equal to centripetal force due to spinning cluster

$$F_x = ma_{centripetal} = m\omega^2\left(\frac{s}{2}\right)$$

- Tangential force required to provide angular acceleration

$$F_y = m\dot{\omega}\frac{s}{2}$$

05 December 2002

EMFFORCE - CDR

23

<MSW>

Set the radial force (magnetic) equal to the centripetal force due to the spinning cluster in order to counteract it.

The tangential force is what is required to provide angular acceleration. Set the tangential force (magnetic) equal to the mass times the angular acceleration times the radius (1/2 separation distance).



EMFFORCE

EM Coil Design

- Introduction
- Subsystems
 - EM**
 - RWA
 - Power
 - Structure
 - Metrology
 - Avionics SW
 - Comms
 - Avionics HW
 - Control
 - Operations
- Systems

- Solve for magnetic moment μ
 - Both vehicles identical
 - Perpendicular configuration

$$\mu = \left(\frac{32\pi}{3} \frac{m \left(\frac{s}{2}\right)^5 \sqrt{4\dot{\omega}^2 + \omega^4}}{\mu_o} \right)^{\frac{1}{2}}$$

- Solve for μ at required steady-state rotation rate of 1 rpm
 - Mass estimate: $m = 20 \text{ kg}$
 - Separation distance requirement: $s = 2\text{m}$

$$\mu = 2418 [\text{Amp-turns} * \text{m}^2]$$

05 December 2002

EMFFORCE - CDR

24

<MSW>, <JB>

Assuming that the dipoles are in a perpendicular configuration (Beta = 0 degrees) and that both vehicles have identical coils, we obtain the above equation for magnetic moment. This equation shows that the magnetic moment (and thus, the coil properties) are dependent on the mass of the vehicle, separation distance, angular velocity, and angular acceleration.

Solve for the required magnetic moment of the coil for steady state (no acceleration) rotation at 1 rpm and a separation distance of 2 meters which was set by the requirements. The required magnetic moment is 2418 Amp-turns*m².

In order to meet the requirements, the coil must be sized such that it exceeds this required magnetic moment.



EMFFORCE

EM Coil Design

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Allowing for a 25% increase in mass and separation distance:

$$\mu = 4723 [\text{Amp-turns} * \text{m}^2]$$

- Determine coil properties by solving for μ where $\mu = nIA$.
 - n : number of wire turns. I : current. A : area enclosed by coil.
- The max current was set to $I=100$ A. Safety margin from the critical current of 15A.

05 December 2002

EMFFORCE - CDR

25

<MSW>,<JB>

Taking a look at the magnetic moment dependency on mass and separation distance, we find that the required strength is dependent on separation distance to the 2.5 power. Thus, an increase in separation distance greatly increases the required strength of the coil. Likewise, mass increases the required magnetic moment but only to the ½ power.

Allowing for a 25% increase in mass and separation distance for safety, the required magnetic moment is 4723 Amp-turns*m².

Having found the required magnetic moment for a coil at steady-state rotation of 1 rpm, we then solve for the coil properties where the magnetic moment is equal to the number of turns of the coil times the current times the area of the coil.

Since the superconductor critical current is 115 amps, we set the current at a lower value of 100 amps. In order to have a safety gap of 15 amps.



EMFFORCE

EM Coil Design

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- 2 perpendicular coils to vary field direction

- Outer Coil

- .835 m diameter
- 100 turns

$$\mu = 5476 \text{ [Amp-turns} * m^2]$$

- Satisfies requirements with margin allowing for 25% increase in mass and separation distance.

- Inner Coil

- .67 m diameter
- 120 turns (same length of wire as outer coil)

$$\mu = 4231 \text{ [Amp-turns} * m^2]$$

- Satisfies requirements

05 December 2002

EMFFORCE - CDR

26

<MSW>

The final design incorporates 2 perpendicular, vertically-oriented coils into each vehicle in order to increase the ability to vary the direction of the magnetic field.

Both the outer and inner coil are sized such that they exceed the magnetic moment necessary to meet the requirements. Additionally, the outer coil exceeds the required magnetic moment for the mass and separation distance increased by a 25% margin for safety.

The outer coil has a diameter of .835 m with 100 turns. This gives it a magnetic moment of 5476 [Amp-turns*m²] with 100 amps of current. The inner coil has a diameter of .67 m with 120 turns. This gives it a magnetic moment of 4231 [Amp-turns*m²].



EMFFORCE

EM Coil Design

Introduction
Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

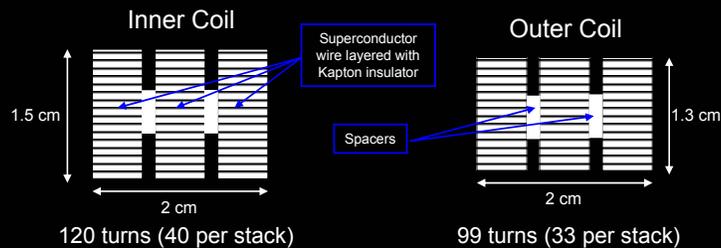
Avionics HW

Control

Operations

Systems

- Each coil comprised of 3 “stacks” of superconductor wire
 - More compact containment system
- Wire insulated with Kapton adhesive tape to prevent shorting



05 December 2002

EMFFORCE - CDR

27

<MSW>

Each coil is comprised of 3 “stacks” of superconductor wire instead of 1 tall “stack” of wire. This allows for a more compact containment system to surround the rings keeping in mind that the inner ring must fit entirely inside the outer ring.

The stacks are separated by spacers and they are tightly attached to the container at certain points. The separation between the stacks allows the liquid nitrogen to be in contact with more surface area of the wire, providing a more uniform distribution of temperature inside the coil. This is critical for the operation of the wire, due to the fact that if the temperature goes above 110k the wire’s resistance will increase.



EMFFORCE

Containment System Design

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Requirements:
 - Keep the wire immersed in liquid nitrogen.
 - Insulate from the environment the wire and the liquid N₂.
 - Non-conductive material.
 - Stiff enough to support liquid N₂ container and its own weight.

05 December 2002

EMFFORCE - CDR

28

<JB>

The superconducting wire must be immersed in liquid N₂, in order to operate as desired. To do this a containment system is needed for the wire and for the liquid N₂.

The containment system must keep the the liquid nitrogen, as isolated as possible from the environment. Because better insulation will allow for slower boil off, less liquid nitrogen will be needed and thus the EM subsystem will be lighter.

For the same reason as above and because of the high current going through the superconducting wire, the material of the container needs to be non-conductive.

Finally, due to the size of the coil, most of the subsystems will be attached in some form to the container. The containment system will be the main structural component of the system, therefore it needs to have attach points and be strong enough to support the weight of the different components.

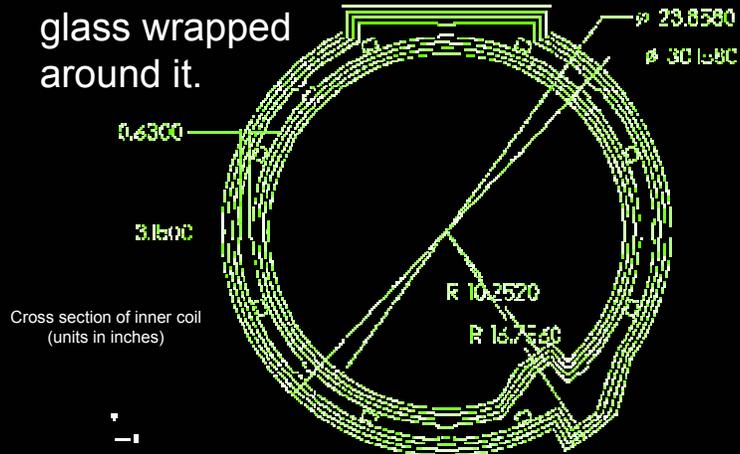


EMFFORCE

Containment System Design

- Introduction
- Subsystems
 - EM
 - RWA
 - Power
 - Structure
 - Metrology
 - Avionics SW
 - Comms
 - Avionics HW
 - Control
 - Operations
- Systems

- Foam with fiber glass wrapped around it.



05 December 2002

EMFFORCE - CDR

29

<JB>

Foam is a very good insulator and easy to machine into complex shapes. Fiber glass wrapped around it adds rigidity, which helps satisfy the requirement for the structure of the system. Manufacturing software (Mastercam 8) was used with a milling machine.



EMFFORCE

Containment System Design

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems



Section of container

05 December 2002

EMFFORCE - CDR

30

<JB>

In this picture, the details of the spacers on the side and bottom are shown. This is the male part of the container. Another part that has the mirror shape of this one, attaches to the top creating more space for the liquid N₂.



EMFFORCE

Containment System Design

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

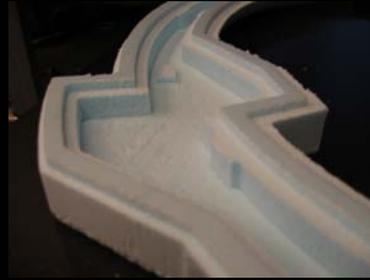
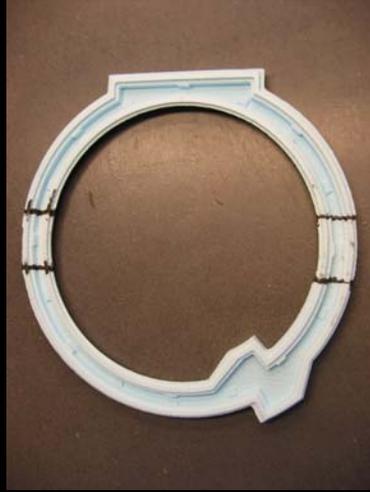
Comms

Avionics HW

Control

Operations

Systems



Top view of half of
the Container

05 December 2002

EMFFORCE - CDR

31

<JB>

In the picture on the left, the black lines are due to the epoxy. The container is manufactured in 4 pieces because the milling machine that we are using is not big enough to cut the whole container in one piece.

The picture on the right show's the details of the spacing left for the wire's clamp, where the interface with the power subsystem will be located.



EMFFORCE

EM Coil Testing

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

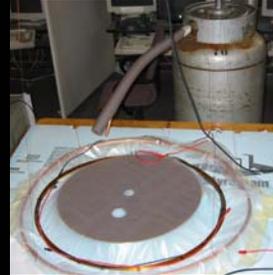
Control

Operations

Systems

B-field measurements

- Inner coil stack
 - .67 m inner diameter
 - 40 turns
 - $I = 30$ amps
- Axial and Radial B-field measurements taken at varying radii.



05 December 2002

EMFFORCE - CDR

32

<JB>

The purpose of the first test was to make sure that the wire could super conduct at the operating temperature of 77K and to compare our model for the B field of a coil against the actual B field produced by the super conducting wire in the coil.

To accomplish this, the axial and radial B field was measured using a gauss meter. The tested coil was the size of the inner coil but it was just one stack with 40 turns. Finally a current of 30 amps was used in the test.



EMFFORCE

EM Coil Testing

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

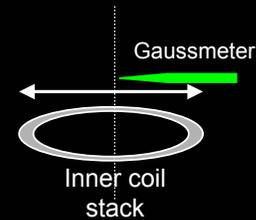
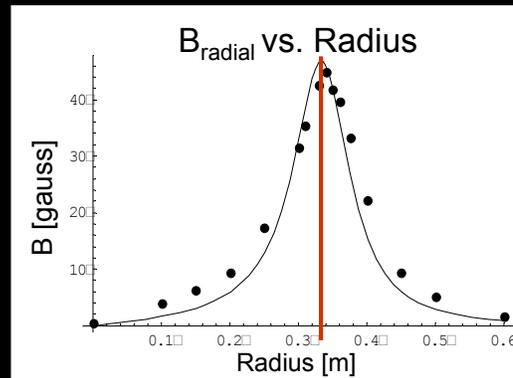
Avionics HW

Control

Operations

Systems

- Magnetic field measurements at varying radii
- B-field in radial direction



05 December 2002

EMFFORCE - CDR

33

<MSW>

B-field (magnetic field) measurements were taken for the component in the radial direction of the coil. To do so, the gauss meter was held parallel to the plane of the coil. The height was held constant at .055 meters, and the radius was varied from the center (at 0) to .60 meters (outside of the coil).

The experimental data is plotted against the model for the radial component of the B-field for the given parameters.

The red line denotes the coil which has a radius of .335 meters. As expected, the radial component of the field is greatest nearest to the coil.

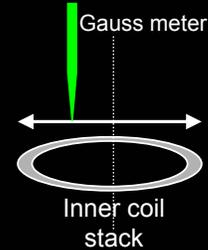
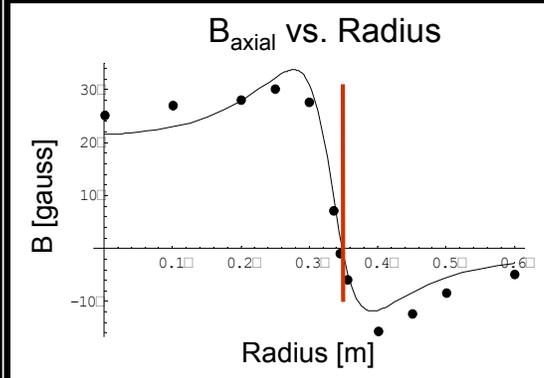


EMFFORCE

EM Coil Testing

- Introduction
- Subsystems
- EM**
- RWA
- Power
- Structure
- Metrology
- Avionics SW
- Comms
- Avionics HW
- Control
- Operations
- Systems

- Magnetic field measurements at varying radii
- B-field in axial direction



05 December 2002

EMFFORCE - CDR

34

<MSW>

B-field (magnetic field) measurements were taken for the component in the axial direction of the coil. To do so, the gauss meter was held perpendicular to the plane of the coil. The height was held constant at .055 meters, and the radius was varied from the center (at 0) to .60 meters (outside of the coil).

The experimental data is plotted against the model for the axial component of the B-field for the given parameters.

The red line denotes the coil which has a radius of .335 meters. As expected, the radial component of the B-field switches direction from the inside of the coil to the outside of the coil.



EMFFORCE

EM Coil Testing

Introduction
Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

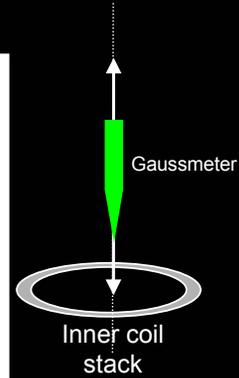
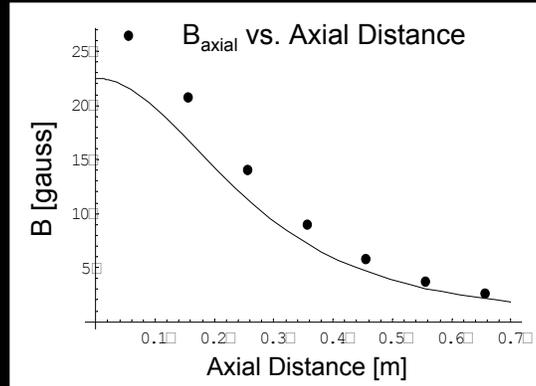
Avionics HW

Control

Operations

Systems

- Magnetic field measurements at varying axial distances
- B-field in axial direction



05 December 2002

EMFFORCE - CDR

35

<MSW>

B-field (magnetic field) measurements were taken for the component in the axial direction of the coil. To do so, the gauss meter was held perpendicular to the plane of the coil. The measurements were taken at the center of the coil along its axis, and the height was varied from the center of the coil (0) to .65 m.

The experimental data is plotted against the model for the axial component of the B-field for the given parameters.



EMFFORCE

EM Container Testing

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Open foam cup
 - Foam contracted but contained the liquid nitrogen
- Two-part square foam container, no epoxy
 - Foam did not maintain tight seal, liquid N₂ leaked
 - Warping from contraction occurred
- Two-part ring-shaped foam container, standard epoxy
 - Container leaked at epoxy seal; epoxy was brittle and cracked
 - Warping from contraction occurred



05 December 2002

EMFFORCE - CDR

36

<MSW>, <JB>

After the testing of the magnetic field, the development of the containers started. First, a simple cup of foam was filled with liquid N₂, in order to make sure that the foam would not chatter and leak during operation. Although it shrank a bit, it did contain the liquid and did not have any leaks.

After a successful first test, a Two-part square foam container with no epoxy was tested to see if with just a press fit of the two parts would be enough to create a seal. From this test, it was concluded that there is a lot of warping and contraction, and that the press fitting does not create a seal.

For the next round of testing, 5-minute epoxy was applied to the fins located on the edges. The system contained the liquid for about 2 minutes before the epoxy chattered and leaked. Warping was not observed in this test, thanks to the ring shape.



EMFFORCE

EM Container Testing

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Two-part open cup, cryogenic epoxy
 - Contained liquid N₂
 - Epoxy did not crack or become brittle.
- Two-part toroid, cryogenic epoxy, fiberglass wrapped
 - Contained liquid N₂ for 10 minutes
 - Failure attributed to holes in the seal due to uneven foam edges
 - Fiberglass added significant rigidity container
- Two-part open container, cryogenic epoxy, two copper pipes
 - Contained liquid N₂
 - Seal around pipes did not fail



05 December 2002

EMFFORCE - CDR

37

<MSW>, <JB>

In the last test it was determined that the 5 minute epoxy could not sustain the cryogenic shock. The epoxy was shrinking at a higher rate than the foam and this broke the seal in the fins.

The purpose of the next test was to make sure that the new epoxy could withstand the cryogenic shock. A small cup glued with epoxy on one side was built and tested and it worked well.

After the epoxy problem was solved, the shape of the container needed to be improved for the fiber glassing process. Considering this issue, a toroid shape container was built and tested. Due to uneven edges the seal failed. But in this test, the machining process for the new shape and the fiber glassing process were learned.

Finally, our last test consisted of the container on top of the coils with the extra liquid N₂. The purpose was to check for leaks and test the piping adhesiveness to the epoxy, which turned out to be quite good in making a seal.



EMFFORCE

EM Container Testing

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Results

- Foam and cryogenic epoxy can contain liquid N₂ for the duration of test and more.
- Fiberglass can be used to provide added rigidity and to allow mount points to be secured to container.
- Cryogenic epoxy may be used to secure copper pipes to foam.

05 December 2002

EMFFORCE - CDR

38

<MSW>,<JB>

The results of our tests helped us a great deal in the design of the container. Not only was our selection of materials tested to guarantee that it was the right one, but the shapes and different ways to machine and wrap the foam were learned by the group in the process.

From the test it was concluded that the foam and the cryogenic epoxy can contain liquid N₂ for the duration of test. The only problem with the epoxy is that the curing time is from 16 to 24 hours. Also the epoxy may be used to secure the copper pipes to the foam, and in this configuration the epoxy did not break.

The fiberglass is strong enough to provide the rigidity needed from the containers and it allows mount points to be secured to container in any place were it is needed.



EMFFORCE

Concerns and Mitigations

Introduction
Subsystems
EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations
Systems

- Heat paths in sealed container.
 - Epoxy
 - Soldering and connections between stacks of wire.
- Robustness of containers.
- Schedule

05 December 2002

EMFFORCE - CDR

39

<JB>

The part that needs the most work is the containment system of the EM. From the last test that we performed we observed that there foam is effective insulating the inside of the container, but a relatively large amount of heat coming from the epoxy joints was observed (we observed more bubbles in this section in the liquid nitrogen).

This could have an impact on the weight of the system, since the liquid nitrogen would boil at a faster rate and therefore more volume would be needed to keep the wire submerged at all times during operation.

On the other hand, if we decide to pressurize the container and use the boiling nitrogen to drive the gas pucks. The epoxy's heat path could be an advantage since we could need a greater mass flow of nitrogen than with the current configuration.

In case the container needs to be insulated better, a different kind of epoxy could be use. An epoxy that can be exposed to the same temperatures and with worse conductive properties was found.

The soldering between the wires does not have superconductive properties. This brings up two issues that are highly coupled. One is that it will cause a rise in the resistance of the overall coil, and the second is that there will be a heat produced in the soldering spots. As it was mentioned before, the second issue might not be a problem but an advantage, depending if we decide to go later with the pressurization of the container or not.

The problem with the increase in resistance is that we might not have enough voltage to drive the current through the coils. To solve this two options are being considered, the voltage into the coils could be raised the soldering could be eliminated and instead the ends of the wires could be overlapped a certain distance and clamped together.

The amount of soldering material used will directly impact the amount of the extra resistance added to the coils, and since there is no way to determine this with enough precision. This will not be determined until the coils are tested with the soldering on them.

Another issue that it is important to pay attention to, is the robustness of the containers. The EM subsystem is composed of different material, which are exposed to a variation of temperature from room temperature to 40 K. This variation will make these materials shrink and expand every time they are used. It is important to determine how many times the containment system can withstand this cycle without failing.

The manufacturing of the containers is a time consuming process. For every container tested there at least six to ten hours of only manufacturing time. There is also the time to epoxy the different parts which is about an hour and finally the curing time which is from sixteen to 24 hours for every layer of epoxy. Due to this the schedule could become a problem for us. In order to deal with this issue, it would be possible to hire someone to do the machining so that the manufacturing time can be reduced. Also, a convection oven could be used to heat the parts after the epoxy is applied in order to reduce the curing time. For every 10 K of temperature increase the curing time is reduced by 50%.



EMFFORCE

Cost Budget

Introduction
Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

Development		Final Product (System)	
Item	Cost (\$)	Item	Cost (\$)
Plexiglas	250	Superconductor Wire	23,715
Pipes, Fittings, Tools	100	Kapton Insulator Tape	294
		Pipes, Fittings	100
		Cryogenic Epoxy	600
SUBTOTAL:	350	SUBTOTAL:	24,709
TOTAL SUBSYSTEM BUDGET:			25,059

05 December 2002

EMFFORCE - CDR

40

<MSW>,<JB>

For our cost budget, \$350 were spent in development. That includes pipes, fittings, tools and plexiglas for the wrapping of the coils.

The cost for the final product for the whole system is of \$24,709. Most of the cost is driven by the high temperature superconductor wire, which is an expensive technology but it was needed for the functioning of our subsystem.



EMFFORCE

Mass Budget

Introduction
Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

Item	Unit Mass (kg)	Qty.	Per Vehicle (kg)
Superconductor Wire / Kapton EM Coil	2.9	2	5.8
Coil Container	1.0	2	2.0
Liquid N ₂ Reservoir	.5	1	.5
Pipes, fittings	N/A	N/A	.4
TOTAL Subsystem Mass:			8.7

05 December 2002

EMFFORCE - CDR

41

<JB>

Reaction Wheel



Jesus Bolivar

05 December 2002

EMFFORCE - CDR

42



EMFFORCE

RWA Overview

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

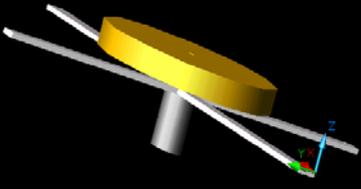
Comms

Avionics HW

Control

Operations

Systems



- Urethane Fly Wheel
- Electric Motor
- Mounting Frame

- Purpose
 - Store angular momentum
 - Provide counter-torques to electromagnets
 - Provide angular control authority

05 December 2002
EMFFORCE - CDR
43

<WDF>

The reaction wheel assembly (RWA) consists of three components. First, a fly-wheel molded from a high density urethane (the large yellow disk). Second, an electric motor (the silver cylinder) manufactured by AstroFlight Inc. Finally, an aluminum mounting frame that will attach the motor to the main vehicle structure.

The reaction wheel assembly is designed to achieve three specific tasks. First, the assembly must store the angular momentum created during the spin-up of the system. Thus conserving the total angular momentum of the system. Second, in order to keep the electromagnetic poles aligned in the appropriate orientation the RWA must provide torques to counter the torques generated by the electromagnet forces. Finally, the RWA provides the control algorithm with a method for controlling the angular position of each vehicle.



EMFFORCE

RWA Requirements

Introduction
Subsystems
EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations
Systems

- Flywheel Requirements
 - Store system angular momentum (H)
 - Maximum wheel velocity at 7000 RPM
 - Maximum wheel diameter of 0.5 m
 - Non-metallic
- Motor Requirements
 - Generate initial torque of 0.1 Nm

05 December 2002

EMFFORCE - CDR

44

<LLW>

The angular momentum for the system is that generated when the system is at a two-vehicle configuration, with 2m separation distance between the vehicle centers. The system will be rotating at 1 RPM.

The maximum angular velocity of the wheel is set to preserve the structural integrity of the flywheel. The tensile strength of the flywheel is such that it is not capable of sustaining speeds above the set maximum RPM.

The flywheel diameter is limited by the size of the electromagnetic coils and the packaging of the vehicles. At the height in the vehicle where the RWA is stored, the maximum available diameter for the flywheel is 0.5m.

It is essential that the flywheel be constructed of non-metallic material due to the fact that it will be spinning in an electric field. It has been determined that eddy currents will be induced in any conductive material placed within the magnetic coils. The presence of these eddy currents will stop the relative rotation of the fly-wheel, similar to a "viscous effect."

The motor must be able to provide the "start-up" torque, the maximum torque required by the system during operation. The start-up torque for a two-vehicle configuration spinning at 1 RPM has been determined to be 0.02 Nm. Torques can also be controlled by adjusting current flow through the electromagnetic coils.



EMFFORCE

Wheel Design

- Introduction
- Subsystems
 - EM
 - RWA
 - Power
 - Structure
 - Metrology
 - Avionics SW
 - Comms
 - Avionics HW
 - Control
 - Operations
- Systems

Determine Angular Momentum stored for 2 vehicles, 2 m separation, 1 RPM

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

Given vehicle mass is 18 kg and moment of inertia for a vehicle is approx. 0.9 kg m²:

I_{tot} is 37.8 kg m²

$$H_{tot} = I_{tot} \cdot \Omega$$

Total angular momentum is 3.96 kg m²/s

05 December 2002

EMFFORCE - CDR

45

<WDF>

The design of the fly wheel is dictated by the angular momentum that it must store for a given maneuver. Our current test plan calls for the ability to perform a spinup with two vehicles at a separation of two meters rotating at 1 RPM. The first step is to develop an estimate of each vehicles mass moment of inertia about the z/2 (spin) axis perpendicular to the plane of the array. This was done by estimating the mass moment of inertia of each of the vehicles components about the center of rotation of the vehicle. For the current vehicle design the mass moment of inertia is approx. .9 kg m². Using the parallel axis theorem allows the calculation of the system mass moment of inertia from the vehicle mass and vehicle mass moment of inertia. By multiplying the system mass moment of inertia by the spin rate of the system we arrive at the total angular momentum that must be stored by reaction wheel.



EMFFORCE

Wheel Design (cont)

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

$$H_{tot} = 2 \cdot H_{wheel} = 2 \cdot I_{wheel} \cdot \Omega_{wheel}$$

- Max speed of the wheel is limited by material properties

$$\sigma_{max} = \frac{3+\nu}{4} \cdot \rho \cdot \Omega_{wheel}^2 \left(R_o^2 + \frac{1-\nu}{3+\nu} R_I^2 \right)$$

- Failure occurs at 15,000 RPM
- Deformation occurs at 7,000 RPM
- Chose system operating point at 2,000 RPM
- Mass moment of inertia of wheel is 0.01 kg m²

05 December 2002

EMFFORCE - CDR

46

<WDF>

The moment of inertia created by the spinning vehicles must be stored in the two vehicles reaction wheels. For the purpose of these calculations, it is assumed that the spin-up maneuver chosen equally distributes the angular momentum between the two reaction wheels. If different maneuvers are performed we intend to spin the two wheels at different operating speeds. The maximum spin rate of the wheels is limited both by the motor performance and the wheels material properties. Our motors are capable of spinning at upwards of 20,000 RPM and thus the limiting factor is the wheel material properties. Using the above equation for the stress found in a spinning disk and the known material properties of the wheel it can be calculated that the wheels will fracture at 15,000 RPM and begin to deform at 7,000 RPM. In order to remain well below this limit, we chose a system operating point of 2,000 RPM. This limit keeps the wheels well below any failure limit and still allows for margin to provide any necessary control authority. At this operating point the mass moment of inertia of each wheel must be approximately .01 kg m². This value was thus used to set the geometry of the wheel.



EMFFORCE

- Introduction
- Subsystems
 - EM
 - RWA
 - Power
 - Structure
 - Metrology
 - Avionics SW
 - Comms
 - Avionics HW
 - Control
 - Operations
- Systems

Wheel Design (cont)

- Moment of Inertia of the wheel set by geometry
$$I_{wheel} = \frac{\rho \cdot \pi}{2} [h_{ring} \cdot (r_{rw}^4 - r_{disk}^4) + h_{disk} \cdot r_{disk}^4]$$
- For $I_{wheel} = 0.01 \text{ kg m}^2$
 - $r_{rw} = 0.124 \text{ m}$
 - $r_{disk} = 0.100 \text{ m}$
 - $h_{disk} = 0.015 \text{ m}$
 - $h_{ring} = 0.030 \text{ m}$



05 December 2002

EMFFORCE - CDR

47

<WDF>

The mass moment of inertia of the wheel is calculated from the wheel's geometry. The most efficient use of mass to achieve a high mass moment of inertia is to position as much mass as possible far from the center of the disk. Taking into consideration practical manufacturing capabilities the following dimensions were chosen to provide the necessary geometry. Wheels of the following dimensions were ordered from Advanced Urethane Solutions who are casting the wheels from high density urethane and will ship the completed wheels to us.



EMFFORCE

Motor Torque Requirement

- Introduction
- Subsystems
 - EM
 - RWA
 - Power
 - Structure
 - Metrology
 - Avionics SW
 - Comms
 - Avionics HW
 - Control
 - Operations
- Systems

- Definition for magnetic moments:
$$\mu_A \mu_B = \frac{32\pi}{3} mr^5 \sqrt{4\omega^2 + \omega^4}$$
- Dipole angle:
$$\alpha = -\cos^{-1}\left(\frac{\omega^2}{\sqrt{4\omega^2 + \omega^4}}\right)$$
- Torque:
$$\tau = \frac{-1}{4\pi} \frac{\mu_0 \mu_A \mu_B}{(2r)^3} 2 \sin \alpha \rightarrow \tau = \frac{-4}{3} \omega mr^2$$
- Boundary conditions:

$$\omega(0) = 0$$

→

$\tau = 0.02 \text{ Nm}$

05 December 2002

EMFFORCE - CDR

48

<LLW>

The first equation gives the definition for the product of the magnetic moments of two dipoles. The electromagnets used in the project are not dipoles, but the coreless coils create fields like “effective dipoles,” so dipole modeling techniques are used here.

The second equation gives the relationship for the dipole angle, alpha. This angle measures the rotation of the dipole from the x-axis. Alpha is depicted in the diagram at the bottom of slide 21. For these calculations, it was assumed that beta (the other dipole angle) is zero.

Assuming that the dipoles are only able to translate and rotate in the x-y plane, the torque relationship shown above can be derived. In the x-y-z coordinate system, the torque is about the z-axis. Using the relationships for magnetic moment and dipole angle, the torque equation was simplified.

Finally, boundary conditions were applied to give a quantitative value for the torque required by the RWA motor. It was assumed that in the initial state (before spin-up) there is no angular velocity. According to the system requirements, the system will spin at a rate of 1 RPM, which drives the end boundary condition. Applying these conditions gives a required torque of 0.02 Nm. Margin was built into this calculation, and the motor was selected under a requirement to provide 0.1 Nm of torque.



EMFFORCE

Selected Motor

Introduction
Subsystems
EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations
Systems

- Astroflight Direct Drive Cobalt Airplane Motor
- Specifications:

Max Current	35 Amps
Max Shaft RPM	12,000 – 15,000
Torque (at 10 A)	0.1 Nm
Mass	0.31 kg
Length	0.0635 m
Diameter	0.0427 m

05 December 2002

EMFFORCE - CDR

49

<LLW>

The selected motor is an Astroflight Astro Cobalt 25 Airplane motor. A complete list of the motor's specifications can be found online at: <http://astroflight.com/sport1020.html>. The selected motor is p/n 625.

At 10 Amps the motor is capable of providing 0.1 Nm of torque (see next slide for the calculation). At the maximum current of 35 Amps, the motor is capable of providing 0.34 Nm. These estimates are found using the given torque constant of the motor.

At a mass of 0.31 kg, the selected motor is the least massive of the motors researched.



EMFFORCE

Motor Power Requirement

Introduction
Subsystems
EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations
Systems

- Torque drives current requirement: $\tau = ki$
- Required current: $i = 10.2$ Amps
- $V_{tot} = V_{BackEMF} + V$
- Voltage: $V = iR$, $R_{arm} = 0.093 \Omega \rightarrow V = 0.95$ V
- Voltage due to Back EMF: 2.06 Volts
- Required voltage: $V_{tot} = 3.01$ Volts
- Required power: $P = 31$ Watts

05 December 2002

EMFFORCE - CDR

50

<LLW>

The required current determined here is based on a required torque requirement of 0.1 Nm. This is five times the calculated required torque, building in an operational margin for the motors.

The voltage due to back EMF was calculated using a design angular velocity (maximum) for the wheel of 2000 RPM and the motor speed provided in the manufacturer specifications, 971 RPM/Volt. This is a peak voltage, as the maximum value for angular velocity was used to calculate it.

The total required voltage is the voltage required to overcome the armature resistance at the operational current plus the voltage required to overcome the back EMF. The value for the resistance in the armature is provided by the motor manufacturer.

The required power is then calculated using the relationship $P = iV$. Again, this is a peak power requirement, as the voltage and current calculated are those required for situations with maximum torque and maximum wheel angular velocity.

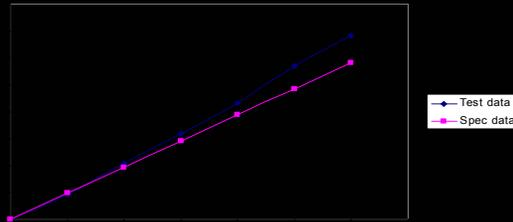


EMFFORCE

Testing – Voltage Profile

Introduction
Subsystems
EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations
Systems

- Motivation: Confirm motor specifications
- Measured angular velocity using a strobe
- Better performance than provided specs



05 December 2002

EMFFORCE - CDR

51

<LLW>

It was important to verify the provided motor performance specifications because these specs are used as variables for control inputs. The torque output of the motor is also an essential parameter, and testing is in progress to obtain a torque-current profile.

This test was done by clamping the motor to a table and varying the voltage input to the motor. The motor angular velocity was measured using a strobe light.

The spec data was found from the given 971 RPM/volt. Although the motor is designed to operate with up to 18 volts input, the range was limited here to that which will be practically used in the EMFFORCE project. Although this test found that the actual motor performance is better than the specified performance, the specifications were still used as the basis for calculations, again adding margin to the design.



EMFFORCE

Testing – EM Field

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Motivation: Verify that motor performance does not vary during operation in an EM field
- Varied current through coil from 0 – 30 Amps
- No variation in performance



05 December 2002

EMFFORCE - CDR

52

<LLW>

The motor was placed in a foam holder, and then in the liquid nitrogen bath that holds the electromagnetic coil. The motor was turned on by itself. Current was then applied to the electromagnetic coil. Both the voltage supplied to the motor and the current applied to the magnet were varied, in turn. The motor was also rotated so that it was aligned perpendicular to the induced B-field. No difference in motor performance was noted in any of the different conditions.



EMFFORCE

RWA Mass/Power Budgets

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

Item	Mass Per Vehicle (kg)	Voltage (V)	Current (A)	Power (W)
Flywheel	1.2	-	-	-
Motor	.31	3.01	10.2	31
Subsystem TOTALS:	1.51	3.01	10.2	31

05 December 2002

EMFFORCE - CDR

53

<LLW>

The masses per vehicle represent one flywheel and one motor per vehicle. The budgets for voltage, current, and power reflect the calculations shown in the previous slides. The system totals shown here fit into the system requirements set for the vehicles.



EMFFORCE

RWA Cost Budget

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

Item	Development (\$)	Cost Per Item (\$)	Qty.	Total (\$)
Fly Wheel	432	47	3	573
Motor	27	140	3	420
Subsystem TOTAL:				1020

05 December 2002

EMFFORCE - CDR

54

<LLW>

The cost budget shows development costs for the flywheel. This was a fixed rate to cover the set-up for the manufacture of the wheel. After this initial set-up fee, the wheels cost \$47 each, as shown in the chart. There were no developmental costs for the motors.



EMFFORCE

RWA Concerns

- Introduction
- Subsystems
 - EM
 - RWA
 - Power
 - Structure
 - Metrology
 - Avionics SW
 - Comms
 - Avionics HW
 - Control
 - Operations
- Systems

Concern	Mitigation
Wheel Fracture	Design Margin, physical limits on motor inputs
Safety Hazard of Wheel	Addressed by Ops
Wheel Saturation	Margin designed into H storage calculations
Motor Overheating	Long duration testing planned

05 December 2002

EMFFORCE - CDR

55

<LLW>

The concerns listed mainly involve the flywheel. Testing on the wheels has not yet been done because the wheels have not yet been delivered. Throughout the design process of the wheel, extra margin was built into the design to assure that the wheel will neither fracture nor saturate during operation.

In terms of the safety of the wheel, the Operations team has addressed this problem. The wheel will have a guard around it to prevent injury to anyone on the test floor.

Motor overheating is not an expected problem, but a possible one. A long duration test will be completed by the end of the term to address this issue.

Power



Geeta Gupta

05 December 2002

EMFFORCE - CDR

56



EMFFORCE

Power Subsystem

Introduction
Subsystems
EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations
Systems

- Objective: provide necessary voltage and current levels to other subsystems
- Two distinct designs:
 - **Actuation:** Electromagnet, Reaction Wheel
 - **Electronics:** Avionics, Communications, Metrology

05 December 2002

EMFFORCE - CDR

57

<TAS>

The objective of the power subsystem is to provide the necessary levels of voltage and current to each of the other subsystems. The power is separated into three branches: electromagnet, reaction wheel, and electronics. The electromagnet and reaction wheel branches are the actuation branches. The electronics branch is responsible for providing power to the avionics, communications, and metrology subsystems.



EMFFORCE

Requirements

- Must be completely self-contained (no external cords)
- Batteries must be rechargeable
- Battery lifetime must be at least 20 minutes
- Electronics branch must continue to operate even if EM & RW (actuation) batteries are drained

Introduction
Subsystems
EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations
Systems

05 December 2002 EMFFORCE - CDR 58

<TAS>

These are the four main requirements for the power subsystem.

-The power supply must be completely contained within the structure of each vehicle. This implies that the power must be supplied from an on-board source (i.e. batteries)

-Any batteries used must be rechargeable. The purpose of this requirement is to lower the overall cost by avoiding the need to purchase thousands of batteries over the lifetime of the project. Rechargeable batteries are also more environmentally friendly than disposable batteries.

-The subsystem must provide sustained power for at least twenty minutes. This lifetime corresponds with initial estimates for the expected lifetime of the gas bearing system. It also allows for several tests to be run without having to replace the batteries.

-The electronics branch must continue to function even if the actuation branch batteries are drained. The electronics subsystems must be able to pass commands and record data regardless of the status of the actuation branches. This requirement implies that there will be two distinct, separate power systems on board each vehicle.



EMFFORCE

Battery Selection

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Important characteristics:
 - Total energy per battery [mAh]
 - Energy density [mAh/kg]
 - Maximum current discharge capacity for each battery type
 - Charge/discharge characteristics, memory effects

05 December 2002

EMFFORCE - CDR

59

<TAS>

The main selection criteria for the batteries was the total energy per battery. Because of the twenty minute lifetime requirement, the batteries had to have enough stored energy to be able to last that long.

There were also other issues important in the battery selection. Choosing batteries with the highest energy density minimizes the total battery mass. The maximum current discharge capacity was also important. The electromagnet requires up to 100 Amps of current, so finding batteries with a high enough discharge rating was essential. Finally, the charging and discharging characteristics of the batteries was important. Some batteries can be permanently damaged if they are over-charged, so these were avoided. Also, some batteries have what is known as a "memory effect." A battery has a memory effect if complete discharge is required before re-charging. Finding batteries with no memory effect was desirable.



EMFFORCE

Actuation Battery Selection

Introduction
Subsystems
EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations
Systems

- Battery selection: 9000mAh rechargeable NiMH D-cells
- Features:
 - High energy density (53 mAh/kg)
 - 45 Amp max. continuous current discharge, up to 120 Amps momentarily
 - No memory effects, long service life (300-1000 charge/discharge cycles)

05 December 2002

EMFFORCE - CDR

60

<TAS>

After researching different battery chemistries, Nickel Metal Hydrides (NiMH) offered the highest energy densities. The design of the actuation branches was dominated by the requirements for the electromagnet. The batteries chosen for this were 9000mAh D-cells manufactured by GoldPeak Industries. The maximum current for the electromagnet is estimated to be 100 Amps. These D-cells have a maximum current rating of 35 Amps, which is higher than any of the other batteries researched. Connecting three D-cells in parallel will provide over 100 Amps to the electromagnet when needed. These batteries have no memory effect, meaning they can be recharged at any time without any decrease in performance. Their service life is long – they can undergo several hundred charge/discharge cycles without a decrease in performance.

The reaction wheel requires a much lower maximum current (on the order of 10-20 Amps). Although it would be sufficient to use slightly less powerful and lighter batteries, the reaction wheel will use the same batteries as the electromagnet. This will permit interchangeability of individual batteries between the two branches, which is more beneficial than the small amount of weight that could be saved. In the event that weight became a more important issue, then lighter batteries could be substituted in for the reaction wheel branch.

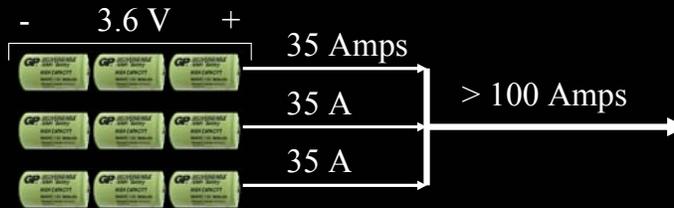


EMFFORCE

EM Branch Design

Introduction
Subsystems
EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations
Systems

- 100 Amps required @ 2 – 5 Volts
- Combine in series and parallel:



- MOSFET controller – pulse width modulated signal to drive current

05 December 2002

EMFFORCE - CDR

61

<TAS>

The electromagnet will require up to 100 Amps of current. Because of its superconducting properties, there is virtually zero resistance across the magnet. This means that only a small voltage (2-5 Volts) is required to drive the current through the magnet. (In fact, most of the resistance in the system is due to the internal wiring and circuitry). The power requirements for the electromagnet can be met by placing the batteries in combinations of series and parallel. Placing three batteries in series produces a voltage difference of 3.6 volts, which is sufficient to drive the magnet. Since this "cell" can still only output 35 amps, wiring three cells in parallel will allow three times as much current, thus providing over 100 Amps when necessary.

The EM branch uses a MOSFET controller to control the current to the magnets. This is shown on the next slide.

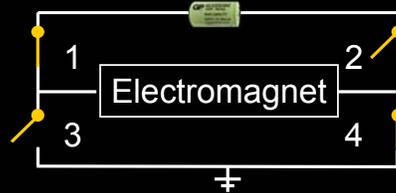


EMFFORCE

EM Branch Design

Introduction
Subsystems
EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations
Systems

- MOSFET controller – uses H-bridge circuit to control current through gates



- Gates 2+3 open, 1+4 closed → current in forward direction (pictured)
- Gates 1+4 open, 2+3 closed → current in reverse direction

05 December 2002

EMFFORCE - CDR

62

<TAS>

This is a simple representation of the H-bridge circuit used to control the direction of current through the magnet. The gates are driven by the pulse-width modulated signal from the controller. The PWM signal fluctuates between “up” and “down” at a certain frequency. The signal has a duty cycle between 0 and 100%. At 50% duty cycle, the PWM is up 50% of the cycle and down 50% of the cycle. A 75% duty cycle would be up 75% of each cycle and down 25%. When the signal is in the up position, the current is commanded to flow forward through the magnet. This is accomplished by closing gates 1+4 and opening gates 2+3 in the diagram above. When the signal is in the down position, the current flows backwards through the magnet. This is accomplished by closing gates 2+3 and opening gates 1+4.

For duty cycles above 50%, the net flow of current through the magnet is in the forward direction. For duty cycles below 50%, the net flow of current is in the reverse direction.



EMFFORCE

RW Branch Design

Introduction
Subsystems
EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations
Systems

- 10 Amps required @ 3 – 5 Volts



- If higher voltage needed, add more batteries in series
- Uses same MOSFET controller as EM branch

05 December 2002

EMFFORCE - CDR

63

<TAS>

The design of the reaction wheel branch is almost identical to the electromagnet branch. The same MOSFET controller will be used to drive the current with the PWM signal. The expected current draw for the reaction wheel is 10 amps, so a single cell of batteries in series will be sufficient. The estimated voltage requirement is between 3 and 5 volts, which will be satisfied by connecting four batteries in series. If it is determined that a higher voltage is required, more batteries can be added in series.



EMFFORCE

Electronics Branch Design

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Battery selection: 1800mAh rechargeable NiMH AA-cells
- Features:
 - High energy density (69 mAh/kg)
 - 5 Amp max. current discharge
 - No memory effects, long service life (500-1000 charge/discharge cycles)

05 December 2002

EMFFORCE - CDR

64

<TAS>

Nickel Metal Hydrides were also chosen for the electronics branch. The electronics branch requires around 1 Amp of total current, at three separate voltages. The batteries chosen for this were 1800mAh AA-cells manufactured by GoldPeak Industries. Approximately 12 AA batteries will be wired in series, and will be connected to three voltage regulators: 3.3, 5, and 12 Volts. These batteries also have no memory effect and a long service life (over 500 charge/discharge cycles).

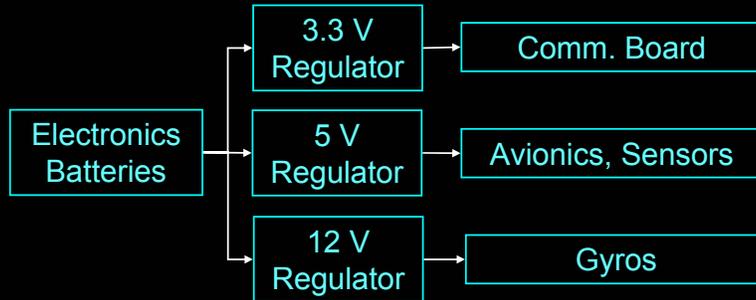


EMFFORCE

Electronics Branch Design

Introduction
Subsystems
EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations
Systems

- <1 Amp required @ 3.3, 5, 12 Volts
- Use 12 batteries in series, voltage regulators



05 December 2002

EMFFORCE - CDR

65

<TAS>

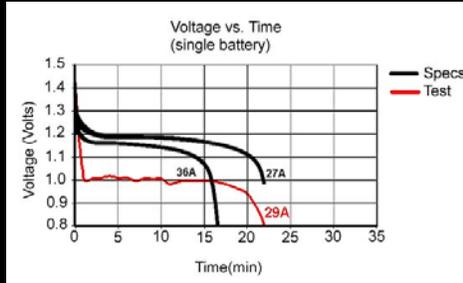


EMFFORCE

Test Results

- Introduction
- Subsystems
 - EM
 - RWA
 - Power**
 - Structure
 - Metrology
 - Avionics SW
 - Comms
 - Avionics HW
 - Control
 - Operations
- Systems

- Validate manufacturer's lifetime specifications



- 0.8 Volts considered stopping point
- Lifetime specs matches well, despite lower voltage levels than expected
- Voltage data matches better when using multiple batteries in series

05 December 2002

EMFFORCE - CDR

66

<TAS>

This is a test of the maximum battery lifetime.



EMFFORCE

Test Results

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

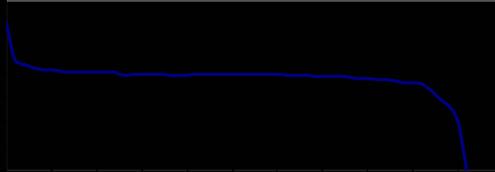
Comms

Avionics HW

Control

Operations

Systems



- Lifetime requirement far exceeded
- Extended lifetime due to due to battery recharging on “down” part of duty cycle

05 December 2002

EMFFORCE - CDR

67

<TAS>



EMFFORCE

Power Subsystem Budgets

Introduction
Subsystems

EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations

Systems

Item	Unit Mass (kg)	Qty.	Mass per vehicle (kg)	Total Cost (\$)
D-cells	0.170	13	2.21	1200
AA-cells	0.027	12	.33	250
Controllers	0.1	3	.3	450
Volt. Regs.	0.1	3	.3	100
Sensors	0.1	2	.2	200
Misc.	-	-	.1	300
TOTAL MASS PER VEHICLE:			3.44	-
TOTAL SUBSYSTEM BUDGET:				2500

05 December 2002

EMFFORCE - CDR

68

<TAS>



EMFFORCE

Power Concerns

- Introduction
- Subsystems
 - EM
 - RWA
 - Power**
 - Structure
 - Metrology
 - Avionics SW
 - Comms
 - Avionics HW
 - Control
 - Operations
- Systems

Concern	Mitigation
Difficulties with running 100 Amps through circuitry	Use separate controllers for each battery cell if needed
Buildup of heat in circuit components, batteries	Use heat sinks wherever possible
Long charge time for D-cell batteries (~16 hours)	Have extra complete sets of batteries on hand (and charged)

<TAS>

Structure



Geeta Gupta

05 December 2002

EMFFORCE - CDR

70



Structure Overview

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Physical interfacing of subsystems
 - Provide structural “backbone” of vehicle
- Subsystem packaging/magnetic shielding
 - Prevent magnet from interfering with electronics and vice versa
- Gas carriage provides pressurized cushion of gas for near frictionless translation over a flat floor

05 December 2002
EMFFORCE - CDR
71

<GG, ALS>

The EMFFORCE packaging is meant to hold together the various subsystems of the total system in a functional manner that allows for efficient use of volume and mass, as well as practical interfaces. The packaging must ensure that all subsystems have the necessary physical conditions to function correctly; the electromagnet must not interfere with the electronics, and the metrology subsystem must have a 360 degree unobstructed view of the vehicle’s surroundings.

The gas carriage portion of the structure will provide near frictionless translation over the test facility floor. It is important to minimize external forces on the vehicle so that the system’s force balance is undisturbed and also so that a space environment is simulated. The test facility floor may have a variety of surface finishes: very smooth, such as glass or Lockheed’s flat floor facility; or not as smooth, such as the floor of MIT’s Lobby 7. Lobby 7 could provide a valuable test surface for pre-Denver testing.



Requirements

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Feasible Packaging
 - Rotational symmetry; keep center of mass to within 1cm of center of EM field.
 - Center of mass kept low for stability
- Shielding
 - Provide sufficient shielding to prevent interference from electromagnet generating field strength up to 0.03 Tesla.
- gas Carriage
 - Must provide gas supply sufficient for 20 minutes of operation

05 December 2002
EMFFORCE - CDR
72

<GG, ALS>

The requirements associated with the EMFFORCE packaging relate to the feasibility of the design. In order to maintain simplicity in maneuvering and handling, as well as to avoid control problems the packaging must be rotationally symmetric. The structures team must avoid a top-heavy design in order for stability, as well as take into consideration where the forces will act on the vehicles.

The packaging must include some sort of shielding (if necessary) to avoid magnetic interference between the magnet, electronics and other subsystems on board.

The gas carriage must provide as long a test duration as possible. The minimum requirement is 20 minutes.



EMFFORCE

Design History

Introduction

Subsystems

- EM
- RWA
- Power
- Structure
- Metrology
- Avionics SW
- Comms
- Avionics HW
- Control
- Operations

Systems



- Symmetrical Design
- Use volume inside rings to package subsystems

- Obstacles
 - Four attachment points on rings vs. three attachment points due to pucks
 - Mounting methods
 - Rings on base
 - Subsystems inside rings
 - Keep mass MINIMAL

05 December 2002
EMFFORCE - CDR
73

<GG>

In order to fulfill the requirements the preliminary conceptual design used a spherical volume formed by the two electromagnet rings to house the reaction wheel and other subsystems. The rings sat on a triangular plate attached to gas pucks.

Although the conceptual design maintained rotational symmetry and kept the reaction wheel in the center of the generated force field, mounting methods that kept the mass minimal needed to be developed. A geometrical location for the power subsystem batteries also needed developing.



EMFFORCE

Design History

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

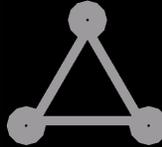
Control

Operations

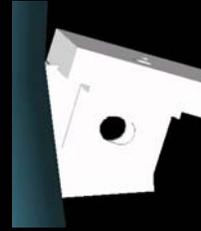
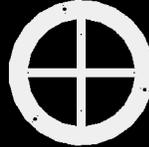
Systems

- Circular base used to decouple four-point to three point attachment.
- Provides ample space for mounting batteries

rejected design



selected design



- Mount cross braces directly to fiber-glassed foam containers with L-brackets
- Use similar fiber-glassed brackets to mount gas tank to rings and rings to base.

05 December 2002

EMFFORCE - CDR

74

<GG>

To find four points at which to connect the rings and base plate and maintain as much rotational symmetry as possible we designed a circular ring base plate. In order to overcome attachment point obstacles and keep minimal mass, L brackets were specially designed to attach four connection points on the rings to a circular base. L brackets will be attached to the foam rings using cryogenic epoxy as well as fiber glass strips. These L brackets will also support braces suspended inside the rings to hold the avionics board, and reaction wheel assembly.



EMFFORCE

Packaging Design – Attach Points

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

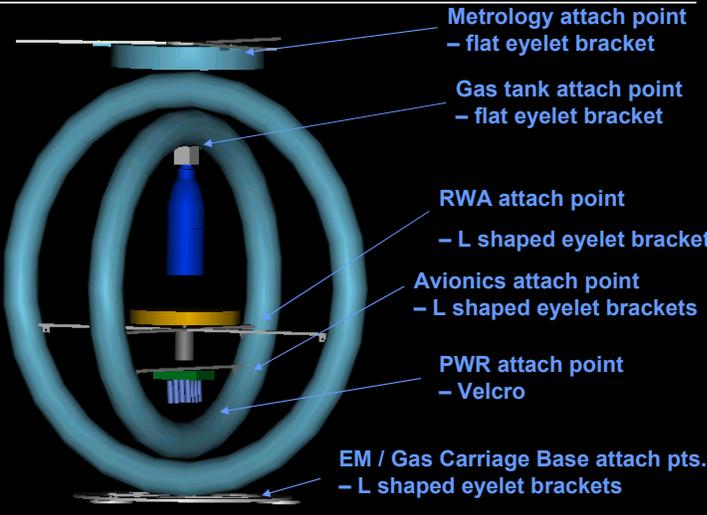
Comms

Avionics HW

Control

Operations

Systems



05 December 2002
EMFFORCE - CDR
75

<GG>

All the attachment points are described above. Special brackets are designed and attached to the rings using the previously described method for the metrology system, gas tank, RWA, avionics, and base plate attachment points. The power subsystem will be secured using Velcro to the base plate for easy replacement between tests.



EMFFORCE

Gas Carriage Design

Introduction
Subsystems
EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations
Systems

- CO₂ gas supply: rechargeable compressed gas tank
- High pressure regulator: reduces 860 psi to 30-60 psi
- Three 100 mm diameter pucks evenly spaced around base ring
- Pucks not rigidly attached
- Backup tanks



05 December 2002

EMFFORCE - CDR

76

<ALS>

The final gas carriage system consists of several components. The gas supply source is a tank of compressed CO₂. These tanks are rechargeable. The tanks discharge high pressure CO₂ gas at approximately 860 psi. This high pressure is then reduced to operational pressure of 30-60 psi by a regulator. The lower pressure gas is then pushed through three single-aperture, 100 mm diameter pucks evenly spaced around the base ring.

The circular base of the packaging allows the gas carriage pucks to interface with the rest of the vehicle. The pucks are attached to the ring by two 6-32 screws. However, they are not rigidly attached. Rather, they are loosely screwed on and then separated from the ring by springy "shock-absorbing" washers. This allow the gas carriage puck to maintain coplanarity despite any mass or force imbalance that may occur in the vehicle above. A similar system was employed on the SPHERES earth-bound testbed with great success.

EMFFORCE owns several backup tanks should a sequence of testing be required without time to recharge the tanks.



EMFFORCE

Puck Designs

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Motivation: increase vehicle mass, test time, and/or gap height by optimizing puck design
- Varied puck design parameters:
 - Number of outlet apertures
 - Radius of apertures
 - Diameter of puck
- Designed a cap for ease of plumbing multiple aperture pucks

05 December 2002

EMFFORCE - CDR

77

<ALS>

The structures team hoped to choose a puck design that would optimize the critical design variables. To do this, a matrix of prototype pucks were manufactured varying those parameters affect performance: number of apertures, the radius of those apertures, and the overall puck diameter. To ease the plumbing of multiple aperture pucks, a cap adapter was devised to require only one fitting per puck, regardless of aperture size.



EMFFORCE

Puck Prototypes

- Introduction
- Subsystems
 - EM
 - RWA
 - Power
 - Structure**
 - Metrology
 - Avionics SW
 - Comms
 - Avionics HW
 - Control
 - Operations
- Systems



- 1 aperture, Vary puck diameter
- 3 apertures, vary radius
- 5 apertures, vary radius
- 6 apertures, vary radius

05 December 2002

EMFFORCE - CDR

78

<ALS>

All of the prototype pucks are shown here.



EMFFORCE

Cap Configuration

Introduction
Subsystems
EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations
Systems

- Single aperture: simplifies plumbing
- 3.175 mm circular recess to give all apertures access to gas supply
- O-ring seals gasflow inside recess
- Cap attaches to puck with 5 screws



05 December 2002

EMFFORCE - CDR

79

<ALS>

The cap was designed to simplify plumbing to a multi-aperture puck. This cap design is a universal adapter for any of the prototypes created. There is a recess so the gas can flow freely to all of the apertures in the puck, and an o-ring seals the cap so that there is no leakage. The cap attaches to the top of the puck with five screws.

The top photo shows the underside of the cap, the side that would face the puck. The bottom photo shows a top view of the cap attached to a puck.



EMFFORCE

Puck Test Results

- Introduction
- Subsystems
 - EM
 - RWA
 - Power
 - Structure
 - Metrology
 - Avionics SW
 - Comms
 - Avionics HW
 - Control
 - Operations
- Systems

- Chatter experienced with all capped designs
- Possible explanations
 - Aerodynamic disturbance in recess
 - Apertures too large
 - Prototype pucks unpolished
- Able to test with single aperture pucks
 - Unpolished 100 mm diameter puck at 70 psig

Weight (kg)	Gap (mm)
6	0.13
7	0.08
10.5	0.03

- Indicates that design sufficient for 31.5kg vehicle on glass, potential for rougher surface

05 December 2002

EMFFORCE - CDR

80

<ALS>

Unfortunately, a chattering phenomenon was experienced with all of the developed designs using the cap configuration. This phenomenon was a mode of instability predicted by previous research on gas lubricated bearing called “pneumatic hammer.” The structures team was unable to determine the exact source of the instability. The most probable explanation is that the cap design introduced some form of aerodynamic instability. This explanation is supported by the fact that the baseline design (used by SPHERES quite reliably) also experienced chatter when coupled with the cap.

Other contributing factors could have been the fact that the apertures in the multi-aperture pucks were too large or that the pucks were unpolished. Every aperture was the same diameter as the one aperture in the single aperture pucks. This made the total area available to the gas flow three, five, or six times that of the one aperture pucks. Further prototype and testing would have included multi-aperture pucks with apertures sized proportionally to the number of apertures. The surface finish of the pucks is less likely a problem, as unpolished pucks functioned perfectly well in later testing.

In light of test results and schedule constraints, multi-aperture puck designs were ruled out.

When the structures team ruled out the cap configuration, the single aperture pucks (of varying diameters: 80mm, 100mm, 120mm) were threaded and tested. No chatter was experienced with any of these designs. It was shown that the weight-carrying capacity of the puck increased with diameter, but the 100mm puck was more than sufficient for this project. It was determined that a larger diameter would be a waste of material. Shown above is the gas cushion gap height for different weights. Six kg per puck implies an 18 kg vehicle – currently the mass estimate. This indicates that there is plenty of margin with regard to the gas carriage capability in the vehicle mass.



EMFFORCE

Shielding Test Results

Introduction
Subsystems
EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations
Systems

- Tested Electronics in magnetic field
 - 1500 Amp-turns, 30 cm diameter magnet
 - Tested various combinations for effects on DR2000 transmission
 - DR2000 and TT8 located singly and jointly in magnetic field
 - Varied orientations and rotational velocities
- No discernable effect on packet transmission
 - Agrees with theoretical conclusion

05 December 2002

EMFFORCE - CDR

81

<ESS>

Shielding Test

Goal: determine if DR2000 and TT8 can function normally in magnetic field in order to evaluate need for shielding of electronic components

Results: shielding should not be required for the Avionics or Communications subsystems

Procedure:

We ran the communications initial system test in the presence of a strong magnetic field created by the preliminary super-conducting magnet model. This test consists of two nodes, each with a laptop, a TT8 microprocessor, and a DR2000 comm board. One TT8 runs a packet transmission program that requires a keyboard input to send a string through the attached DR2000. The other node receives the packet, processes it, and outputs it to the laptop.

The magnetic field was created by a super-conducting magnet of 40 turns running at approximately 40 amps.

In various phases of the test, the TT8, the DR2000, and then both boards together were placed in the magnetic field, rotated within the field, and held in different orientations.

The packet transmissions were not distorted or interrupted. This indicates that no shielding will be required. However, we are not sure if the increased field strength present in the real magnet will affect this determination.

This result agrees with the theoretical assessment that the magnetic field should not affect the operations of the solid state electronics present in these electronics components. The sizes of the electrical channels are so small that no discernable eddy currents are expected. The board manufacturer, OnSet Computer, also indicated that no magnetic field effects would be expected



EMFFORCE

Structures Mass Budget

Introduction
 Subsystems
 EM
 RWA
 Power
Structure
 Metrology
 Avionics SW
 Comms
 Avionics HW
 Control
 Operations
 Systems

Item	Unit Mass (kg)	Qty.	Per Vehicle (kg)
Base Plate	0.90	1	0.90
Brace 1 (avionics)	0.15	1	0.15
Brace 2 (RWA)	0.3	1	0.30
Brackets + Assembly Hardware	0.35	-	0.35
Tank	1	1	1.0
Regulator	0.32	1	0.32
Pucks	0.25	3	0.75
Plumbing	0.75	-	0.75
TOTAL Subsystem Mass:			4.52

05 December 2002

EMFFORCE - CDR

82

<ALS, GG>

Above is the mass budget for the entire structure subsystem.

Packaging mass includes the base plate, the two braces, brackets as previously described and nuts and bolts

The gas carriage contributes tank, regulator, pucks, and plumbing fittings to the total mass. The tank is aligned along the axis of rotational symmetry so that it contributes minimum to the moment of inertia of the vehicle.



EMFFORCE

Structures Cost Budget

Introduction
 Subsystems
 EM
 RWA
 Power
 Structure
 Metrology
 Avionics SW
 Comms
 Avionics HW
 Control
 Operations
 Systems

Development			Final Product (System)		
Item	Qty	Cost (\$)	Item	Qty	Cost (\$)
Dry Ice	1	40	Tanks	1	250
Airman compressor	1	10	Regulators	3	110
Feeler Gages	1	68	Plumbing	1	195
1/4" aluminum sheet metal	2	150	1/8" aluminum sheet metal	1	100
Shielding Sample Kit	1	189	1/16" aluminum sheet metal	1	100
Misc Plumbing	1	200			
SUBTOTAL:		957	SUBTOTAL:		975
TOTAL SUBSYSTEM BUDGET:					1932

05 December 2002

EMFFORCE - CDR

83

<GG, ALS>

Above is the monetary budget for the structures system.

Research and development expenditures were largely due to some different ideas for gas supply that were tested and rejected over the summer. The regulators turned out to be a more significant cost than originally predicted.

The quarter inch aluminum was used for prototyping and found to be too heavy for the actual system. Instead eighth inch aluminum will be used for the base providing enough rigidity. The sixteenth inch aluminum will be used for the fabrication of the eyelet brackets.



EMFFORCE

Structure Concerns

- Introduction
- Subsystems
 - EM
 - RWA
 - Power
 - Structure**
 - Metrology
 - Avionics SW
 - Comms
 - Avionics HW
 - Control
 - Operations
- Systems

Concern	Mitigation
Foam rings may not support cross-braces and subsystems	Run tests; have back-up design
Electromagnet may interfere with electronics when field is stronger	Keep shielding kit to use if necessary (+0.2 kg)
Tanks may not provide estimated test time with new pucks, different pressures	Test full gas carriage for new time estimate, experiment with pressure control

05 December 2002

EMFFORCE - CDR

84

<GG, ALS>

There are still a few remaining concerns from the structures team. The biggest concern is that the foam rings will not be able to support the cross braces and the torque exerted on them due to the forces and torques generated by the electromagnet and reaction wheel.

In the case that the electromagnet does interfere with the electronics when the EM field is stronger the structures will utilize the shielding kit originally purchased to block and interfering forces.

The puck is the one component of the gas carriage that has changed significantly in design. The EMFFORCE pucks are larger than the pucks used for SPHERES. Because the fluid dynamics of lubrication theory are so complicated, analytical model development was not possible under the given time constraints. There is concern that a trade has been made between mass carrying capability and test time. Since the larger pucks are able to carry more mass, the structures team hypothesizes, based on qualitative analysis of the fluid dynamics and previous lab experience, that gas flow will need to be increased to maintain sufficient gap height. If the gas flow is increased, the tank gas will be depleted in a shorter amount of time. To determine the possible range of operation, the structures team's next step is to conduct tests in order to gain new time estimates for varying operating pressures. During these tests it will also be beneficial to measure the separation gap height to determine what operating pressure (and correlating test time) is required for alternative surfaces. The ability to float the vehicle over a coarser surface allows the EMFFORCE team greater flexibility in test facility.

Metrology



Oscar Murillo

05 December 2002

EMFFORCE - CDR

85



EMFFORCE

Metrology Overview

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Determine position and orientation of each vehicle within the system
- Uses IR and ultrasonic transmitters and receivers on each vehicle
 - 1 ultrasonic transmitter and 3 ultrasonic receivers
 - 4 IR transmitter arrays and 3 IR receiver arrays
- Time difference of IR receive and ultrasonic receive determines distance
- Orientation of ultrasonic receivers determines angle
- Rate gyros are used to supply angular rates about vertical axis

05 December 2002

EMFFORCE - CDR

86

<OM>

The general goal of the Metrology system is to determine the position and orientation of each vehicle in the system. The system design uses IR and Ultrasonic transmitters and receivers to do these estimations. The basic algorithm for the system uses the time difference of the IR and Ultrasonic signals to determine the distance of the other vehicles. In addition, the orientation of the 3 receivers help determine the angle from which the signal came.



EMFFORCE

Requirements

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Determine separation distance
 - Goal: sense to 1 cm
- Determine relative attitude (direction) of vehicle
 - Resolution of distance sets angle resolution to 0.7°
- Full field of view : 360 degrees in the horizontal plane
- Detect other vehicles at distances compatible with field tests
 - Max of 4 meters
- Refresh rate compatible with control system requirements
 - Timing sequence of system refreshes at 10 Hz

05 December 2002

EMFFORCE - CDR

87

<OM>

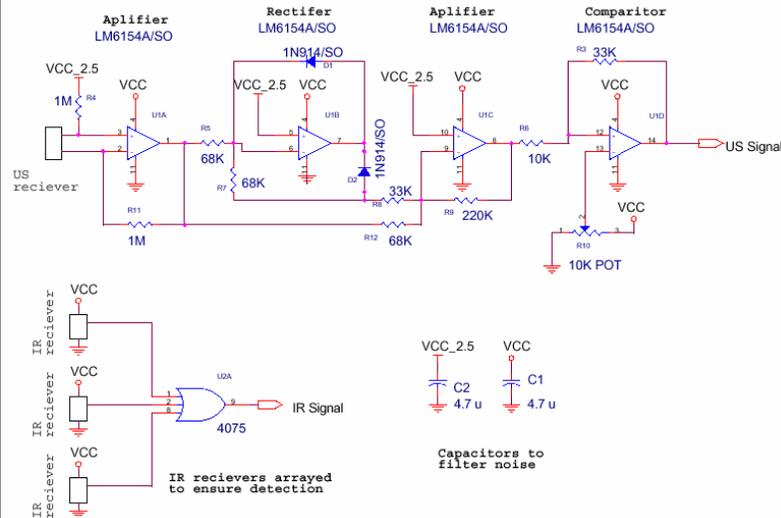
Extracted from the requirements of the overall project, the goal of the metrology system is to accurately calculate relative distance and attitude of each vehicle and the orientation of the system. Per the requirements document, accurately is defined as 1/10 of the control tolerance for both distance and angular readings. In addition, the metrology system needs to have a field of view of 360° in a 2-D plane. Next, the system needs a detection range compatible with test facilities. These test facilities include the test facility at MIT and the Lockheed flat floor facility in Denver, CO. Finally, the system needs to meet refresh rate requirements set forth by the control team, currently set at 10 Hz.



EMFFORCE

Hardware Design: Receiver Circuit

- Introduction
- Subsystems
 - EM
 - RWA
 - Power
 - Structure
 - Metrology**
 - Avionics SW
 - Comms
 - Avionics HW
 - Control
 - Operations
- Systems



05 December 2002

EMFFORCE - CDR

88

<AA>

The Receiver board will contain both the ultrasonic and infrared receivers.

The Ultrasonic signal is first amplified, then rectified, amplified again, and finally put through a comparator, so that the analog audio signal is sent to the tattletale as a digital signal. Since the metrology system determines, time of flight, the only data of importance is the time of the initial reception of the US signal.

At least one IR receiver will also be on the receiver board. More may be added to ensure detection of IR pulse.

Capacitors have been placed across the power bus to decrease noise.



EMFFORCE

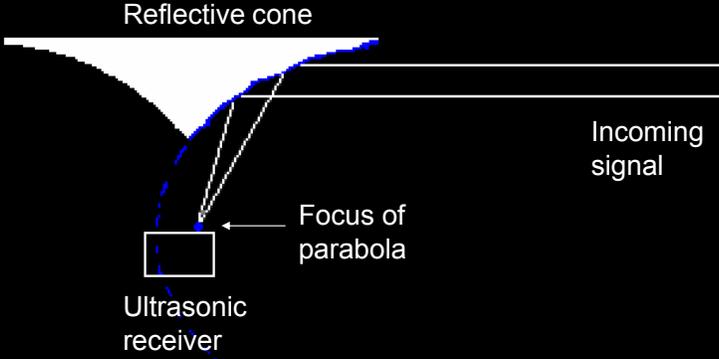
Hardware Design: Reflective Cones

Introduction

Subsystems

- EM
- RWA
- Power
- Structure
- Metrology
- Avionics SW
- Comms
- Avionics HW
- Control
- Operations

Systems



- Reflects incoming US waves and focuses them into receiver

05 December 2002
EMFFORCE - CDR
89

<AA>

The reflective cones reflect the planar wave emitted by the ultrasonic transmitter and focus it on the receiver. The purpose of the cones is to make directional receivers effectively omni directional (in the plane).

The shape of the reflective cone is made by rotating a section of a parabola around the y axis. The equation of the parabola is $y^2=4(7.059\text{mm})(x+4.906\text{mm})$ from $x=0$ to $x=39\text{mm}$ (x will be the radius of the cone). This equation is taken from the basic formula for a parabola, using measurements of the reflective cones from the Mimio electronic whiteboard system to solve for the constants.

This exact shape has not been made and tested, but initial testing seems to indicate that minor differences in shape should not greatly effect the efficiency of the reflective cones.

Initial testing indicates that the cones decrease the range of the receivers by about 30%.

Changes in angle do not appear to effect the range readings for the receivers (cones do make accurate omnidirectional receivers).

 EMFFORCE	<h2>Hardware Design: Transmitters</h2>	
Introduction Subsystems EM RWA Power Structure <u>Metrology</u> Avionics SW Comms Avionics HW Control Operations Systems	<h3>40kHz Omni-Directional Ultrasound Transmitter</h3>	<h3>High-Power Infrared Emitters</h3>
	<h4>US40KT-01</h4>	<h4>PDI-E804</h4>
	<ul style="list-style-type: none"> •1 per vehicle •Sound pressure output: 0.025 Pa/V •Max Voltage: 300 V 	<ul style="list-style-type: none"> •4 arrays of 4 to 6 transmitters •Power Dissipation 160 mW •Peak Forward Current 3.0 A •Beam directionality ~120 deg
05 December 2002	EMFFORCE - CDR	90

<AA>

The transmitter board will consist of one ultrasonic transmitter and 4 arrays of infrared emitters. The arrays will consist of 4 to 6 emitters depending on final range requirements. Boards will be designed to hold up to 6, but will only be populated with enough to meet requirements.

The transmitter board will be laid out to attach to the communications board because they share a mounting point at the center of the top of the vehicle.

The Transmitter board will take signals output by the metrology tattletale. The US signal will be amplified through a transformer before being used to actuate the Piezo Electric transmitter.

The US transmitters will be taken from Mimio pens. The Infrared emitters will be purchased.



EMFFORCE

Hardware Design: Rate Gyro

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

Bandwidth (-90°)
>50 Hz

Threshold/ Resolution
0.004°/sec

Output voltage
0 to +5 Vdc

- Gyro determines inertial angular rate of individual vehicle
 - Rate data used for control algorithm
- Gyro connects to avionics tattletale (not metrology)

05 December 2002

EMFFORCE - CDR

91

<AA>

We will be using the BEI Gyrochip II. This gyro was donated by project SPHERES.

The gyro is 25.65mm wide by 25.65mm high by 68.58mm long.

The rate gyro will be polled directly by the avionics tattletale rather than the metrology board. This allows the control algorithm to poll the gyro as often as necessary. It won't need to wait for the MSA. The gyro will be polled at between 1 to 10 Hz, depending on processing load on avionics board.

Hardware Design: Structure

EMFFORCE

Introduction
Subsystems
EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations
Systems

Transmitter

Receiver

.38m

.22m

Attachment bolt hole

Receiver

- Maintains proper orientation for receivers
- Provides attachment to main vehicle

05 December 2002 EMFFORCE - CDR 92

<AA>

The structural support for of the metrology system is part of the metrology subsystem. The structure is a large Y shape. The US transmitter is placed at the center along with the communications board. The US receivers are placed at the ends of the Y. The receivers and transmitter will be bolted to the structure.

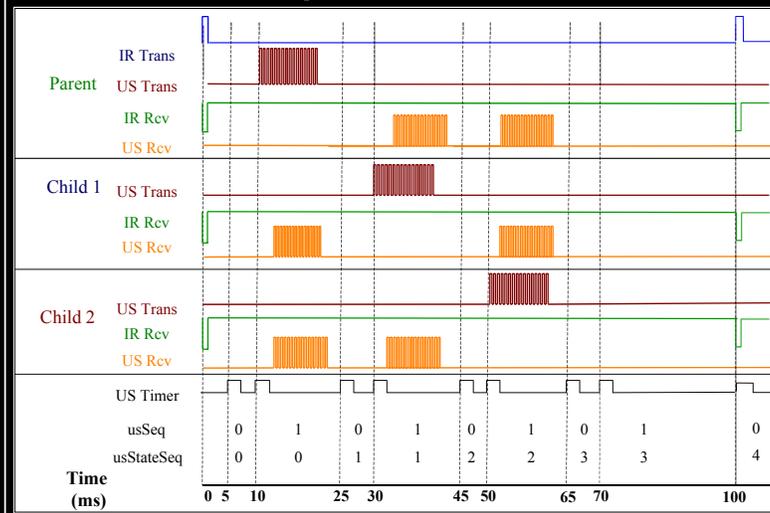
The size of the structure is determined by the size of the vehicle. Increasing the distance between the receivers increases the resolution of the system. Thus it was decided to put the receivers as far from the center as possible without extending past the edges of the vehicle.

The final material down select has not yet been completed. The structural support will either be 1/8 inch aluminum stock or 1/4 inch balsa wood struts.



Software Design: Timing Sequence

- Introduction
- Subsystems
 - EM
 - RWA
 - Power
 - Structure
 - Metrology**
 - Avionics SW
 - Comms
 - Avionics HW
 - Control
 - Operations
- Systems



05 December 2002

EMFFORCE - CDR

93

<OM>

The current design of the system uses a Tattletale 8 processor (TT8), which is capable of handling ultrasonic and infrared transmitters and receivers. All code is written in C, which is easily uploaded on the TT8 via a serial connection with a PC. The following timing sequence was created to map out the sequence of events for the metrology system.

The first even begins with the master vehicle. Each vehicle is assigned master, slave 1, or slave 2 prior to the test. This label is available to each vehicle and can be set prior to each test over the communications port or prior to software load. The master vehicle emits an IR pulse. Each vehicle then receives the pulse (assumed to be instantaneous since the speed of light is much greater than the speed of sound) and causes an interrupt to be triggered on the TT8.

The IR triggered interrupt begins a timer that sets the TPU pin high or low at given times. When the TPU pin is set high, a second interrupt is triggered causing the TT8 to do a sequence of events based on timing and vehicle ID.

Two counters are used to track the sequence of events. One counter, usSeq, oscillates between 0 and 1, switching back and forth each time the timer interrupt is triggered. A second counter, usStateSeq, increments by 1 each time usSeq resets to 0.



EMFFORCE

Software Design: Distance Determining Algorithm

Introduction

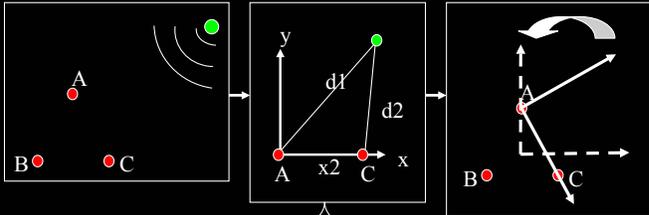
Subsystems

- EM
- RWA
- Power
- Structure
- Metrology
- Avionics SW
- Comms
- Avionics HW
- Control
- Operations

Systems

```

graph LR
    Start([Start]) --> Step1[Determine 2 closest sensors]
    Step1 --> Step2[Calc coordinates in sensor frame]
    Step2 --> Step3[Rotate, translate to body frame]
    Step3 --> Step4[Calc distance and angle]
    Step4 --> End([End])
  
```



$$\begin{aligned}
 x^2 + y^2 &= d_1^2 \\
 (x - x_2)^2 + y^2 &= d_2^2 \implies x = \frac{x_2^2 + d_1^2 - d_2^2}{2x_2} \\
 & \qquad \qquad \qquad y = \sqrt{d_1^2 - x^2}
 \end{aligned}$$

05 December 2002
EMFFORCE - CDR
94

<OM>

As a result of the transmitter and receiver code, each sensor will have a distance to each (3 sensors x 2 vehicles = 6 distances). These distances will then help the vehicle to determine a distance and angle from center of the vehicle sending the signal to the center of itself. The following algorithm is then used to determine the distance and angle.

Since only two sensors are needed to determine the two unknowns (distance, r , and angle, θ) the two sensors that read the closest distance are used. By eliminating the 3rd sensor we are able to get an initial idea of where the signal came (reducing the signal origin to a certain range). A temporary frame of reference is set to the two sensors, with the origin at one sensor and the second sensor $(x_2, 0)$ away. Since the distance is known to each sensor, you can determine the coordinates of the originating signal relative to the temporary frame. Once that coordinate is determined, the frame is then rotated and translated so that the frame of reference is centered at the center of the vehicle. The coordinates are then converted from Cartesian to polar so that an r and θ are known.



EMFFORCE

Testing/Verification

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Range test, required range 4 m
 - With an array of 5 IR emitters, range exceeds 4 m
- Time of flight measurement test
 - Distance correlates linearly with time of flight (I.e. no ring up effects)
- Timing error due to angular offset
 - No noticeable effect on time of flight due to rotation of transmitter or changing bearing angle over 180 deg

05 December 2002

EMFFORCE - CDR

95

Range test: using oscilloscope to read outputs of IR and US receivers, moved transmitter away until signal was undetectable

Time of flight measurement test: using oscilloscope read outputs of IR and US receivers and measure time difference between reception of IR and US compare that to the distance between receiver and transmitter. The relation proved to be linear over the test range.

Timing error due to angular offset: first rotated the transmitter to verify that no variation in signal reception. Then placed the transmitter at 1 meter from receiver at various angles from original time of flight test. The time of flight correlated exactly (within accuracy of test) to the time of flight test. Thus there seems to be no effect on range determination due to angle changes.

Upon review, tests may not have been accurate enough, further testing is suggested.



EMFFORCE

Mass Budget

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

Item	Unit Mass (kg)	Per Vehicle (kg)
Reflective Cone	0.040	0.120
US Receiver	0.012	0.036
US Receiver Circuitry	0.025	0.075
Adjustment Screws (3/receiver)	0.009	0.081
Transmitter with Circuit	0.034	0.034
Structure	0.103	0.103
Rate Gyro	0.040	0.040
TOTAL Subsystem Mass:		0.489

05 December 2002

EMFFORCE - CDR

96

<OM>

The overall mass of the system is less than 1/2 a kilogram. The biggest contributor to this weight is the reflective cones and the main structure.



EMFFORCE

Cost Budget

Introduction
 Subsystems
 EM
 RWA
 Power
 Structure
 Metrology
 Avionics SW
 Comms
 Avionics HW
 Control
 Operations
 Systems

Development		Final Product (System)	
Item	Cost (\$)	Item	Cost (\$)
Material for Cones	60	Rate Gyro (donated)	0
Material for Support	20	IR Emitters (up to 24/vehicle)	75
Wire, Nuts, bolts, etc	20	US/IR Receiver (donated)	0
		US/IR Receiver Circuits (3/vehicle)	90
		US/IR Transmitter Circuits	30
SUBTOTAL:	100	SUBTOTAL:	195
TOTAL SUBSYSTEM BUDGET:			685

05 December 2002

EMFFORCE - CDR

97

<OM>

The financial budget is much smaller than expected. The rate gyro was obtain from the Spheres Team. In addition, the Virtual Ink Corporation was generous enough to donate the US/IR transmitters and receivers. What's left is the procurement of the circuit boards needed to the US and IR sensors. We've include development costs to construct reflective cones (allows the US receivers to be omni-directional), support materials, and additional wire, nuts and bolts.

Testing indicated that the IR emitters on the Mimio pen are not strong enough to work at the range we need. Using other emitters (which were used on SPHERES) does achieve the range we need. The new IR emitters will be arranged in arrays of 4-6 emitters facing in 4 directions. This calls for 16 to 24 emitters per vehicle. The emitters cost approximately \$1 each.



EMFFORCE

Metrology Concerns

- Introduction
- Subsystems
 - EM
 - RWA
 - Power
 - Structure
 - Metrology**
 - Avionics SW
 - Comms
 - Avionics HW
 - Control
 - Operations
- Systems

Concern	Mitigation
Timing is set in clock cycles but cycles do not correspond directly to time	Allocate time for calibration of metrology code
Reflective cone prototyping incomplete	Mimio cones used for testing until prototypes compete
Rate gyros can only be polled at 1 Hz	Low angular rates may not require higher polling freq

05 December 2002

EMFFORCE - CDR

98

<AA>

In code, timing is set in clock cycles, but the time for one clock cycle varies depending upon the processing requirements of the program. Someone will need to load the code on a tattletale and read the output with an oscilloscope, and alter the code until the timing is correct (i.e.. The master and slave vehicles will stay in synchronization)

Avionics Software



Oscar Murillo

05 December 2002

EMFFORCE - CDR

99



EMFFORCE

Overview and Requirements

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Avionics software coordinates vehicle computation processes, managing CPU time and computer memory
- Requirements flow from control:
 1. Run control loop at 2-10Hz
 2. Build vehicle “operating system”
 - Get metrology data (Primary Vehicle Array, PVA)
 - Pass data to/from communication software
 - Provide correct format for control input (Master State Array, MSA)
 - Process control output (Master Actuation Array, MAA) – send to power/actuators
 3. Monitor vehicle health/safety at 0.5-5Hz

05 December 2002

EMFFORCE - CDR

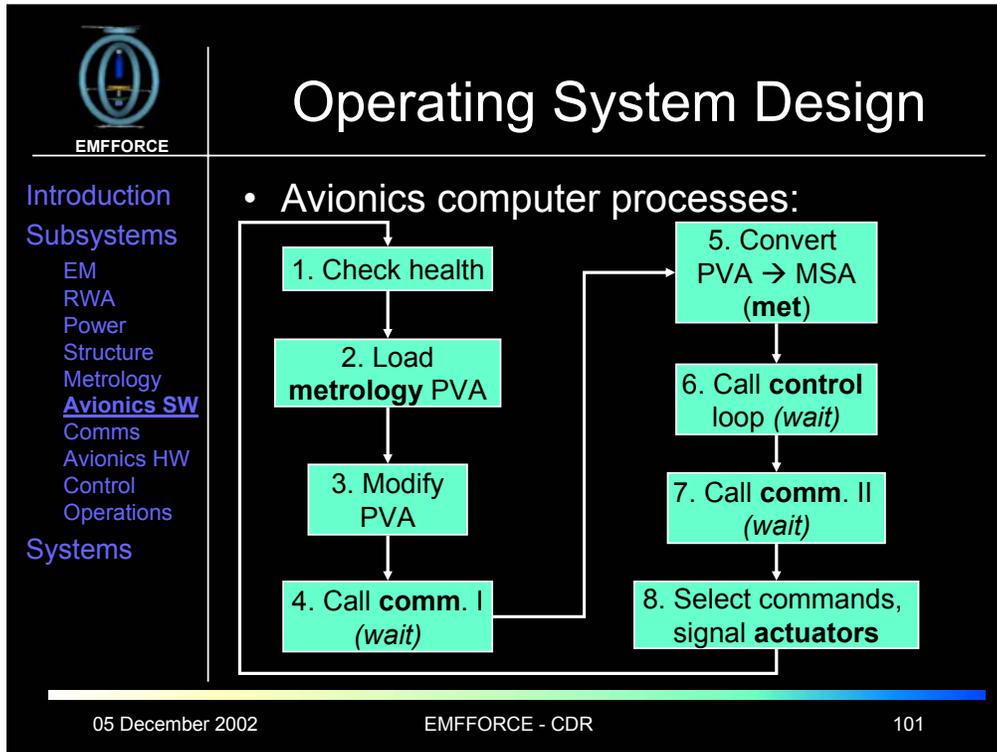
100

<MAS>

The avionics software is the brain of each EMFFORCE vehicle. The purpose of the avionics software is to manage all processes that occur on an individual vehicle, and distribute computational resources among those processes.

Avionics software requirements include the following considerations:

1. The control loop must run at a frequency of at least 2Hz, because the rotation rate prescribed by the system requirements is 1 RPM (1/60 Hz). To be accurate, the control law designed by the Control team needs feedback and input more frequently than one order of magnitude less than the rotation cycle length.
2. The operating system is basically a sequence of commands that both prioritizes and temporally orders the central computer processes. It is a short main program, but calls every other function used on board the vehicles (except the metrology code) in turn.
3. The software system must keep some processing time available for acknowledging safety feedback, e.g. current level from the magnets or speed of the reaction wheel, to help the team decide if the vehicle needs to be shut down or removed from the testing area.



<MAS>

The operating system design plans for a single thread of computation, running all processes sequentially. Because the control, communication, actuation and health modules all run on the same processor, only one action can be processed at a time. The “wait” noted in steps 4, 6, and 7 delineates when the processor runs subsystem-specific code (either control or comm.) and cannot process other information simultaneously.

1. Check health. The OS must call a function (written by Avionics) to obtain these health data at the beginning of every cycle; the levels are feedback required by the control loop.

2. Load metrology PVA. The avionics computer must receive the most recent local position and angle data from metrology (PVA). Intra-vehicle communication is done via a digital serial line.

3. Modify PVA. Before the PVA can be released to the other vehicles for further calculation, it must also include the local angular rate. The module to import the rate gyro reading and append it to the PVA is part of the avionics software; the vehicle OS must call this module in turn.

4. Call Communication I. After the PVA is complete, the OS calls the communication software to begin its cycle. The communication system updates the foreign PVAs on each vehicle.

5. Convert PVA to MSA. The Master State Array (MSA) contains all the information about the entire system at one time; it is the set of data used by the control loop as input. The Metrology team is actually responsible for writing the module to calculate the MSA from multiple vehicle PVAs.

6. Control loop. The control loop is the reason for the OS and is projected to be the most complicated calculation. The true control code will be implemented during January 2003.

7. Call Communication II. This comm sequence shares the MSA, which is sent to the ground station from all vehicles as a check against errors and discrepancy among the vehicle calculations.

8. Command Actuators. Processes the output from the control into a signal of the type accepted by the actuators.



EMFFORCE

Other Avionics Processes

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Communication with Metrology computer to transfer data
- Command signal to actuator power
 - Actuator controller accepts pulse-width modulated signal (PWM)
 - PWM available as embedded function of the Tattletale computer
- Integration of startup/shutdown and health maintenance code

05 December 2002

EMFFORCE - CDR

102

<MAS>

In addition to writing the vehicle operating system, the Avionics team is responsible for any software not under direct control by another subsystem. This includes several modules that link subsystems together, such as the communication process for the two Tattletale computers to talk with each other. (This is not a Communications team responsibility because it is contained within each individual vehicle; Comm team manages RF channel communication.) Other avionics modules are the control-actuation interface, the code that brings in the rate gyro data, and some interaction with health and warning signals provided by the Operations team.



EMFFORCE

Avionics SW Testing

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

Test		Objective
1	PWM function code	Command actuators
2	Metrology interaction	TT8-TT8 comm, gyro
3	Empty OS loop	Find max system speed
4	Begin comm sequence	Electronics integration
	Higher-level tests	System/ops integration

- Tests planned for Dec 2002 - Feb 2003

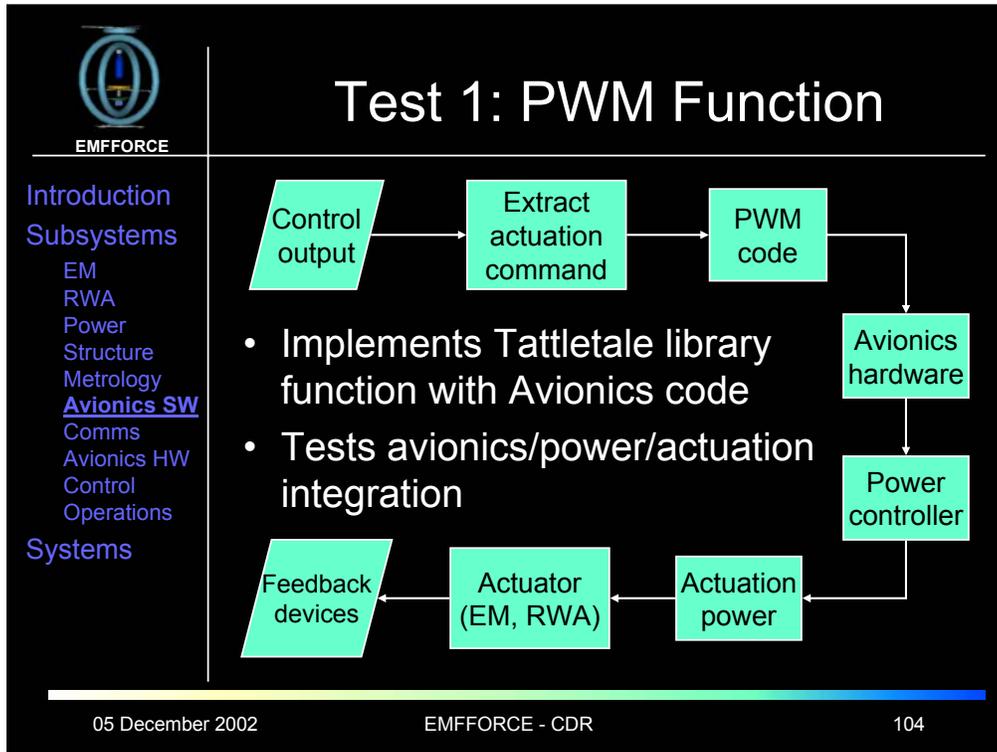
05 December 2002

EMFFORCE - CDR

103

<MAS>

There are four major SW integration tests planned by the Avionics team for completion in January 2003. Each module that the avionics team writes must interface successfully with any related hardware (e.g. the rate gyro) as well as with the operating system. The operating system itself must be tested for functionality and efficiency; as we will see in concerns, the Avionics team must be absolutely certain that each vehicle has enough memory to run the test sequences required!



<MAS>

1. Control output. The control module produces the Master Actuation Array (MAA), a two-dimensional array that contains commanded voltage levels for the two electromagnets and reaction wheel in all vehicles. This is stored in the avionics computer memory.
2. Extract actuation command. The local vehicle control-actuation software module must extract the commanded levels for itself from the MAA according to the vehicle ID (set at system startup). It then translates the commanded level into a percentage of maximum voltage supply in preparation for the PWM signal. To do this, the module incorporates feedback from the magnets monitoring the actual current induced by a voltage supply and expresses the new commanded voltage as a percent of the maximum safe voltage allowed.
3. PWM code. The control-actuation module uses embedded functions from the avionics computer to (a) set up a designated I/O pin to carry a digital signal out, and (b) produce the PWM signal. The percent voltage determined in the previous step becomes the percent high time of the PWM signal; the period of the signal will be fixed.
- 4-8. Avionics hardware, power controller, power, actuators and feedback. The digital signal then goes to the MOSFET controller for the actuation power, which regulates the voltage supplied to each actuator. The actuators respond to the voltage supply (albeit delayed in the electromagnets due to their large time constant) and the effectiveness of the batteries is reported back to the loop via health feedback gathered by the operating system.



EMFFORCE

Test 2: Tattletale Interaction

Introduction
Subsystems
EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations
Systems

- Tattletale communication over serial line uses packaged library functions – verify functionality
- Test data transmission rate
- Debug timing issues (inter-TT8)



05 December 2002

EMFFORCE - CDR

105

<MAS>

The metrology access module utilizes embedded computer functions to designate two I/O pins on the computer as serial transmit/receive lines; the two computers communicate and transfer data over those lines.

The module polling the rate gyro checks a designated pin for an incoming signal voltage; prior to that the gyro signal passes through an analog-to-digital (A/D) converter, which is embedded in the computer as well.



EMFFORCE

More Avionics Tests

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Test 3: Run operating system (OS) with “dummy” scripts
 - Model control, comm, metrology, actuation interaction
 - Determine maximum cycle frequency
- Test 4: Integrate OS with comm processes
- Higher level tests: continue replacing “dummy” scripts with true subsystem functions

05 December 2002

EMFFORCE - CDR

106

<MAS>

Remaining subsystem tests beyond the four noted have yet to be designed in detail; these will be finalized after CDR.



EMFFORCE

Avionics SW Concerns

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

Concern	Mitigation
System timing	Optimize code Cut out extra functions
Variable tracking	Naming standards Master list
Control code mapping	Work with Control team over IAP to integrate

- Budgets combined with Avionics hardware section (follows Communications)

05 December 2002

EMFFORCE - CDR

107

<MAS>

Concern: *Timing and Maximum Update Rate*

Possible mitigation:

1. Optimizing code (for timing).
2. Buying more RAM.
3. Adding a Tattletale.
4. Switching computers (to one more powerful) – not practical due to time constraints.
5. Reducing the system rotation rate. The characteristic of the system that dictates the 2-10Hz cycle update requirement is the system speed of rotation in a representative spin-up maneuver. (For more information on control and the representative system tests, see related EMFF progress reports by André Bosch and Leah Soffer.[\[1\]](#)) If the target system rotation rate is slowed to less than one revolution per minute, the control updates may occur less frequently and still effectively complete the maneuver. However, this option is not appealing because slowing the system rotation rate weakens the connection between the representative test maneuver and the real system upon which it is based.

Concern: *Space and Memory Allocation*

Mitigation: Like reducing run time, there are multiple options for streamlining module size to accommodate storage in Flash memory.

1. Optimizing code (for space).
2. Cutting out functions.
3. Expanding flash memory. As of 03 December 2002, this has not been researched; it is part of the software integration scheduled for early January 2003.

Communications



Jennifer Underwood

05 December 2002

EMFFORCE - CDR

108



Overview

- RF network links vehicles
 - 3 vehicle nodes
 - 1 Ground Station node
- Each node includes
 - DR2000 communications prototyping board
 - Software modules included in Avionics processor

05 December 2002 EMFFORCE - CDR 109

<ESS>

Essential to the successful performance of this testbed and indeed of any satellite cluster system is the ability to pass information between the member vehicles within the cluster and the controlling ground station. A radio frequency network in the 900 MHz band has been implemented to accomplish this function.

The communications subsystem is comprised of the RF Monolithics DR2000 communications system prototyping board and associated software located in the avionics processor.

 EMFFORCE	<h1>Requirements</h1>	
<ul style="list-style-type: none"> Introduction Subsystems <ul style="list-style-type: none"> EM RWA Power Structure Metrology Avionics SW Comms Avionics HW Control Operations Systems 	<ul style="list-style-type: none"> • Provide RF link between three vehicles and ground station <ul style="list-style-type: none"> – Effective range: > 8 meters • Transmit data required by other subsystems <ul style="list-style-type: none"> – Cycle time: < 150 ms @ 19.2 kbps <ul style="list-style-type: none"> • Control and Ops are end users • Metrology and Avionics provide data • Currently need 7 packets of 43 data bytes each (350 total bytes per cycle) • Archive data for later analysis 	
05 December 2002	EMFFORCE - CDR	110

<ESS>

The communications subsystem requirements flow down from the overall subsystem function: to pass all necessary information wirelessly among the three vehicles and the ground station.

The RF transmitters and receivers must have an effective range of greater than 8 meters in order to ensure they cover the entire test area, including the operations laptop.

The system nodes must send and receive information determined by other subsystem teams to be essential to or desirable for their assigned functions. This information was placed under configuration control by the Communications and Operations Team in November 2002 in order to solidify the requirement. The cycle time for the communication system must be less than 150ms in order to ensure the control lag is acceptable. The cycle time is a function of the packet length, number of packets, and the processing time to encode and decode the data.



EMFFORCE

Requirements

Introduction
Subsystems
EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations
Systems

- Autonomously transmit and receive required data
- Respond to commands from ground station
 - Test initiation
 - State changes
 - Emergency intervention
- System reliability of no fatal errors for 95% of 7-minute tests
- Ensure vehicle interchangeability

05 December 2002

EMFFORCE - CDR

111

<ESS>

There must be direct and automatic communications from vehicle to vehicle in order for the system to automatically maintain its formation. The required update rates are several hertz, much faster than a human controller could monitor or direct.

However, the system is not completely autonomous on a larger scale. The ground station must be able to send commands to the cluster in order to begin preprogrammed tests and, if necessary, shut the system down when failures occur.

It is unacceptable for the subsystem to fail with significant frequency during the course of normal operations. Fatal errors include timeouts and internal processor errors. The subsystem must have some degree of fault-tolerance built in, so that one incorrect bit in a transmission does not cause the entire system to fail. A failure rate of 5% for ten-minute tests will be considered acceptable.

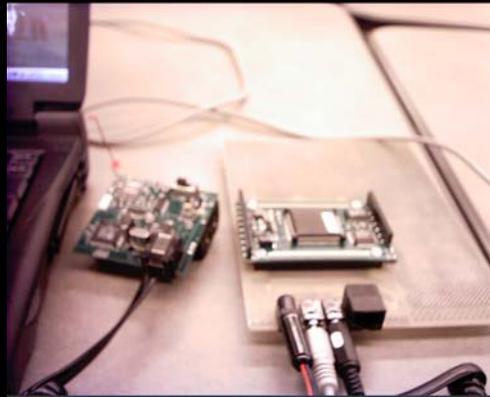


EMFFORCE

Current Design

Introduction
Subsystems
EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations
Systems

- Hardware
 - DR2000 ↔ TT8 interface



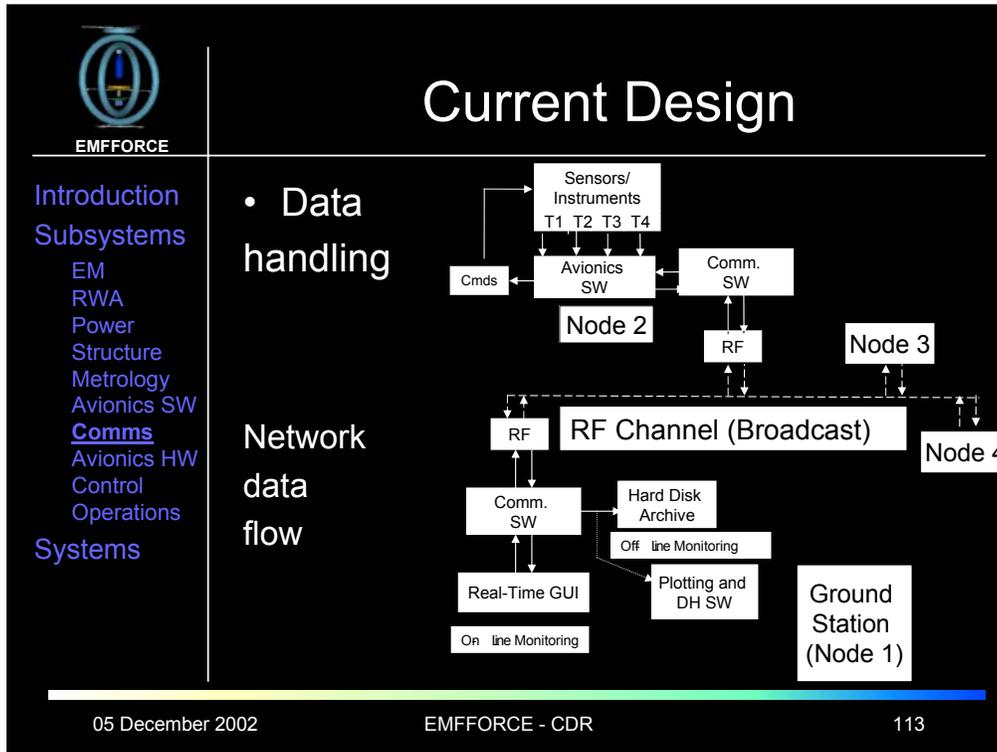
05 December 2002

EMFFORCE - CDR

112

<JEU>

As the design currently stands, the only hardware design involves the interface between the DR2000 and the TT8 processor. The current layout is shown in the picture above. To save weight, the black serial cable will likely be replaced with a handmade insulated wire cable that would run directly to the communication board on top of the vehicle (reference structure slides).



<JEU>

Another aspect of the communication subsystem design is data handling. Data handling involves how the data is passed through the system as well as any archiving system that may be installed at the ground station.

The diagram above illustrates the data flow through the network. Only one node schematic is shown since all three vehicles are designed to be interchangeable. Instruments and sensors send their information to the TT8 board which is interpreted by the avionics software. The information is packaged in various data arrays which are saved as global variables to be picked up by the communication software. The communications software then packages the data for transmission and ensures it is sent across the channel when the vehicle has the token.

On the ground station side, the communications software will be interfaced with the real-time operations GUI (Graphic User Interface). Additionally, the communications software will save all data packets sent across the broadcast channel to a hard disk archive, which could be accessed by an off-line mission monitor. With all the data stored, it is then possible to run plotting and data handling software to analyze the data from the various missions.



Current Design

Introduction

Subsystems

- EM
- RWA
- Power
- Structure
- Metrology
- Avionics SW
- Comms**
- Avionics HW
- Control
- Operations

Systems

- Data handling
 - Packet structure

To	From	Pkt #	Cmd	Length	Data	CRC 1	CRC 2
1 Byte	43 Bytes	1 Byte	1 Byte				

- Telemetry
 - Data that other subsystems need to transmit
 - Packets assigned Application ID #'s (APID)
 - Vehicles (transmit 2 types)
 - Ground Station (transmits 1 type)

05 December 2002
EMFFORCE - CDR
114

<JEU>

Besides network data flow, data handling also involves packet structure and telemetry. Since the DR2000 has built in data framing, most of the job has already been done. However, the data size (currently 43 bytes) and what is sent within the packets are left up to the discretion of the communication subsystem team members.

Telemetry involves what is being sent within the packets, or the data that the other subsystems need to transmit. Currently, all vehicles will transmit 2 packets when they have the token, while the ground station will only transmit 1. Since there are multiple kinds of packets (3 in total) and vehicles sending packets with information tailored to them (3), it was decided to use an Application ID numbering system to ID the packets.

Vehicle A (Node 2) has APID01 and APID02 assigned to it.

Vehicle B (Node 3) has APID03 and APID04 assigned to it.

Vehicle C (Node 4) has APID05 and APID06 assigned to it.

The ground station (Node 1) uses APID07 to send commands.

The next slide will detail what is contained within these APID's.



EMFFORCE

Current Design

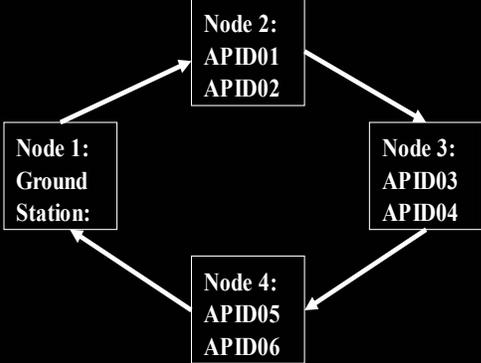
Introduction

Subsystems

- EM
- RWA
- Power
- Structure
- Metrology
- Avionics SW
- Comms
- Avionics HW
- Control
- Operations

Systems

- Token ring architecture
 - Odd APID except APID07
 - Primary Vehicle Array (PVA) + State Actuation Array (SAA) + Health array calculated by vehicle
 - Even APID
 - Master State Array (MSA) calculated by vehicle
 - APID07
 - Commands from ground station



```

graph TD
    Node1["Node 1:  
Ground Station"] --> Node2["Node 2:  
APID01  
APID02"]
    Node2 --> Node3["Node 3:  
APID03  
APID04"]
    Node3 --> Node4["Node 4:  
APID05  
APID06"]
    Node4 --> Node1
    
```

05 December 2002
EMFFORCE - CDR
115

<JEU>

Odd APID's contain: the Primary Vehicle Array (PVA) of the vehicle (which contains the position and rates of the vehicle as determined by the metrology subsystem), the State Actuation Array (SAA) of the vehicle (which contains the commanded actuation – currents and rates – of the entire system as calculated by the vehicle), and the Health array of the vehicle (information that the real-time operator needs in order to monitor the health of the system). These APID's also contain the token and APID flags, as well as a timestamp for when the packet was made, based on the real-time clock counter (in ms) on the TT8.

Even APID's contain: the Master State Array (MSA) of the vehicle (which contains the positions, rates, and other vital state information for ALL vehicles in the array). The MSA is compiled from the PVA's received over the channel plus the PVA of the vehicle

The current token ring architectures acts as follows:

The ground station transmits first, initializing the system. When operations is done initializing the system, an APID07 packet is sent telling node 2 it has the token. Node 2 transmits APID01 and APID02. APID02 contains the token flip telling node 3 it has the token. Node 3 transmits APID03 and APID04. APID04 contains the token flip telling node 4 it has the token. Node 4 transmits APID05 and APID06. APID06 has the token flip telling Node 1 (the ground station) that is free to send out commands. APID07 is sent out beginning the cycle again.



Verification

Introduction

Subsystems

- EM
- RWA
- Power
- Structure
- Metrology
- Avionics SW
- Comms
- Avionics HW
- Control
- Operations

Systems

- Step-by-step unidirectional testing successfully completed
 - Transmission over DR2000's
 - Laptop→DR2000→--→DR2000→WS
 - Transmission with TT8 in the loop
 - Laptop→DR2000→--→DR2000→TT8→WS
 - WS→TT8→DR2000→--→DR2000→Laptop

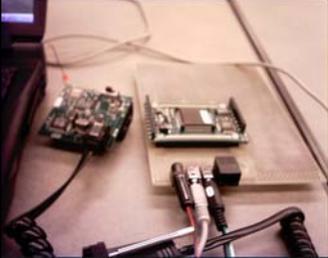
05 December 2002
EMFFORCE - CDR
116

<JEU>

Step-by-step unidirectional testing occurred in two phases: Transmission over just the DR2000's and transmission with the TT8 processor included in the loop.

After many hours of debugging, transmission over just the DR2000's was successfully implemented and repeated. At this point, the team learned how to write code to package the information in such a way that the DR2000's would recognize it and successfully transmit and receive data.

When the TT8 was added into the loop, it was discovered that there were interface issues between the TT8 and the DR2000. It took many hours to find ways around the problem. Once those issues were mitigated, one-way transmission was successful with the TT8 in the loop (receiving end as well as the transmission end). Now the team knew how to write code that would run on the TT8 to send and receive desired information.

 EMFFORCE	<h1>Verification</h1>	
<ul style="list-style-type: none"> Introduction Subsystems <ul style="list-style-type: none"> EM RWA Power Structure Metrology Avionics SW <u>Comms</u> Avionics HW Control Operations Systems 	<ul style="list-style-type: none"> • Node software testing <ul style="list-style-type: none"> – Tested major portions using Visual Studio C to ensure important functions worked correctly • Step-by-step bi-directional testing <ul style="list-style-type: none"> – Node 2 ↔ Node 3 	
		
05 December 2002	EMFFORCE - CDR	117

<JEU>

Once the communications team knew how to send and receive information with the TT8 processor in the loop, it was then possible to test software for a single network node. The software was written and major portions of it were tested using Visual Studio. Visual Studio allows one to easily see the results of functions without having to run the program on the TT8. This software included the functions that mapped between arrays and data packets. (Tested the Encode and Decode functions).

Once the single network node code was working, it was time to test the token ring architecture between two nodes. After several hours of debugging, the software worked! However, there were buffer overflow issues that were apparent (will discuss with concerns/mitigations).

The team now knew how to implement a token ring architecture between two nodes...



EMFFORCE

Results

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Overall results
 - Found methods to achieve desired results in network communication
 - Current working implementation a processor hog, may not achieve desired bit rate
- Conclusions
 - Streamlining of system required

05 December 2002

EMFFORCE - CDR

118

<JEU>

Overall, the testing to date of the communications subsystem has resulted in methods that achieve the desired results in network communication. However, the current implementation is a processor hog; it will be necessary to find ways to decrease the processing time necessary to achieve the desired results.

Now that it is known how to implement the communications subsystem, streamlining is required to ensure that the subsystem is able to achieve the desired bit rate.



EMFFORCE

Cost Budget

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

Development		Final Product (System)	
Item	Cost (\$)	Item	Cost (\$)
DR2000 (x2)	495	DR2000 (x4)	975
Misc. expense	50		
SUBTOTAL:	545	SUBTOTAL:	975
TOTAL SUBSYSTEM BUDGET:			1520

05 December 2002

EMFFORCE - CDR

119

<ESS>

The DR2000 purchasing process is complete. Two extra boards were purchased to have as spares because of the long (4-6 week) lead times associated with the boards. Other RDT&E costs are accounted for under the operations subsystem budget.



EMFFORCE

Mass and Power Budgets

- Introduction
- Subsystems
 - EM
 - RWA
 - Power
 - Structure
 - Metrology
 - Avionics SW
 - Comms**
 - Avionics HW
 - Control
 - Operations
- Systems

Item	Unit Mass	Per Vehicle
DR2000	0.05	0.05
Cabling	0.01	0.01
TOTAL Subsystem Mass:		0.06

Item	Per Unit		Vehicle	
	V	A	V	A
DR2000	3	0.05	3	0.05
TOTAL:	3	.05	3	0.05

All measurements in kg, volts and amps.

05 December 2002

EMFFORCE - CDR

120

<ESS>

DR2000 mass is negligible as a percentage of the rest of the system. Volume and placement are more urgent budget concerns.

The power required by the communications boards is negligible; the board will run on the same 3V circuit as other avionics components.

 EMFFORCE		Concerns/Mitigations	
Introduction Subsystems EM RWA Power Structure Metrology Avionics SW <u>Comms</u> Avionics HW Control Operations Systems	Concern	Mitigation	
	Current problem with buffer overflow (missed data) in 2 node network	–Add strategic delays → transport layer mitigation –More nodes may alleviate problem	
	Current code uses too much processing time	Optimize and simplify code	
	System may not achieve required data throughput	–Find ways to increase the effective bit rate –Streamline packets –Minimize processing time	
05 December 2002		EMFFORCE - CDR	
		121	

<JEU>

The communications subsystem has three major concerns.

First: It was found when testing the 2-node network that there appears to be a problem with buffer overflow since data would not show up on the receiving end on occasion. This is a transport layer problem, so one way to mitigate it is to add strategic delays in the software to give the buffers enough time to clear.

Furthermore, adding more nodes to the system may alleviate the problem by adding in more delay and allowing the buffers to clear.

Second: The current code eats up too much processing time. The obvious solution is to optimize and simplify the code.

Third: The throughput of the system is low. There data rate isn't sufficient currently to meet control requirements. There may be ways to increase the effective bit rate. The subsystem team will look into this. Also, streamlining the packets will help to reduce the problem. Finally, once the processing time is minimized, the throughput should increase considerably.

Avionics Hardware



Jennifer Underwood

05 December 2002

EMFFORCE - CDR

122



EMFFORCE

Hardware Overview

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

Avionics hardware entails the overall physical integration of the vehicles.

- Allocation of I/O channels and pins
- Design of avionics board
- Wiring of subsystems to board
- Ensuring signals are being sent and received as needed via testing

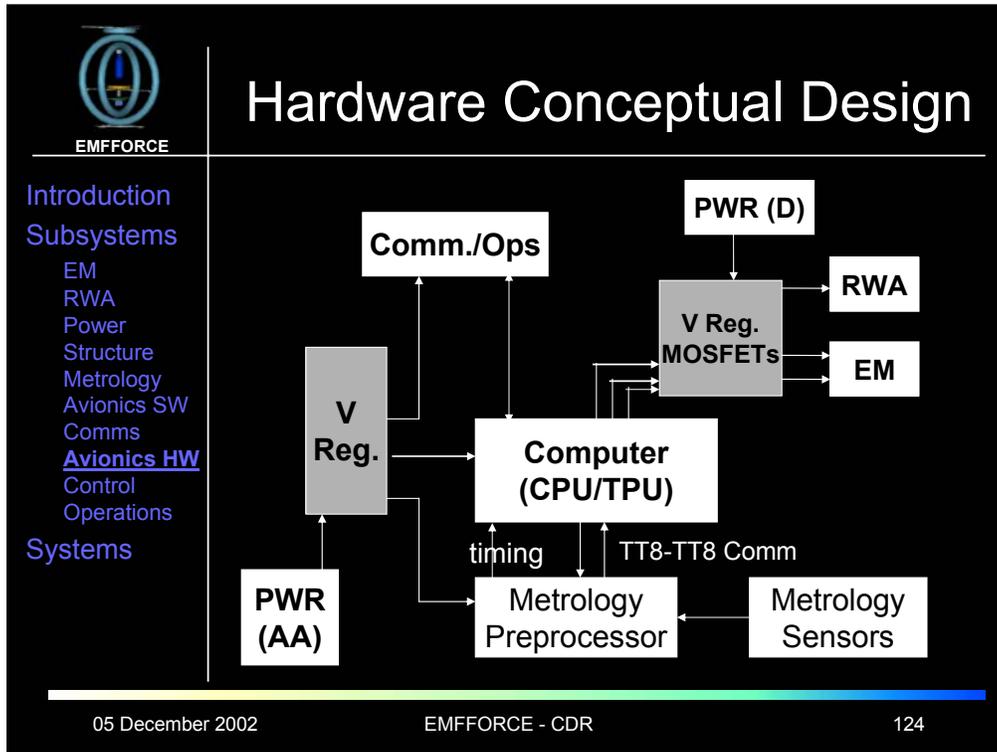
05 December 2002

EMFFORCE - CDR

123

<SJS>

The Avionics team is responsible for all hardware design integration in the EMFFORCE project. This includes but is not limited to the I/O channel and pin allocation, the design of the Avionics board, the creation of a prototype avionics board for use until finalized boards are procured, and all wiring and other hardware integration. The bulk of this hardware integration occurs after each subsystem is completed.



<SJS>

The Avionics hardware design layout is as follows:

- Central to the avionics subsystem is the computer – a Tattletale Model 8 (TT8) with Motorola CPU and TPU.
- The computer interfaces directly with four other pieces of hardware:
 - Voltage regulator – supplies 5V power to TT8 from AA batteries – Power Team
 - Metrology – supplies Primary Vehicle Array updates through signal channel (wire). The metrology computer is also a TT8 computer.
 - Comm./Ops – sends/receives all data going in/out of the immediate vehicle system from/to TT8.
 - Utilizes a serial cable connection (RS232).
 - MOSFETs – takes the actuation signal output from TT8 to implement needed current (using power from D cell batteries)



EMFFORCE

Electronics Board Design

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- 4-layer board (avionics board, ground plate, avionics power board)
- Avionics TT8
 - Inputs: SerialA1 (code loading), TT8-TT8 Rx, A/D Rate Gyro, EM Amperage (2), power, SerialA2 (comm. and code loading)
 - Outputs: EM (2), RW, TT8-TT8 Tx
- Metrology TT8
 - Inputs: IR, US (3), Serial 1&2 (code loading), TT8-TT8 Rx, power
 - Outputs: IR, US, TT8-TT8 Tx

05 December 2002

EMFFORCE - CDR

125

<SJS>

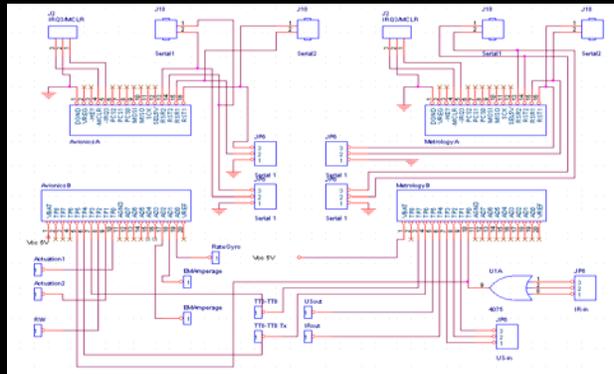
The overall electronics board design shall be a 4-layer board design. The top layer will be the main avionics board, the bottom side will house the electronics power board, and the two shall be separated by a ground plate. This design conserves both mass and volume for the vehicle.



EMFFORCE

Electronics Board Design

- Introduction
- Subsystems
 - EM
 - RWA
 - Power
 - Structure
 - Metrology
 - Avionics SW
 - Comms
 - Avionics HW**
 - Control
 - Operations
- Systems



05 December 2002

EMFFORCE - CDR

126

<SJS>

The following is the Avionics board design:

- The Metrology and Avionics TT8s shall be attached to the Avionics board via one TSW-116-07-SS connector and one TSW-120-07-SS connector per Tattletale computer.
- 4 RS232 jacks, (corresponding to the Serial1 and Serial2 lines for each computer) shall be placed on the board, in a manner such that code loading can easily occur.
- The Digital Ground (DGND), -MCLR, and -IRQ3 lines shall have male connectors such that a female connector can be used to load programs (DGND must be paired with either -MCLR and -IRQ3 to load either FLASH or ROM)
-
- The Comm. Board shall be connected to the main Avionics board via a RS232 cable (requiring from Avionics: Tx, Rx, and DGND).
- 3 US signals shall all be inputs to the Metrology TT8.
- The 3 IR signals shall converge through an OR gate before metrology computer processing. This single IR signal shall also be sent to the Avionics TT8 for time synchronization purposes.
- The 2 Tattletales communicate via one Tx line and one Rx line.



EMFFORCE

Prototype Testing

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- The board design theory shall be tested via prototype boards to:
 - Verify that board design is correct
 - Determine if software functions as desired
- Board design includes:
 - 2 PR-8 boards
 - 1 breadboard with OR gate
- Randomly generated transmission code shall be sent from TT8 to TT8.
- Actuation signals sent to EM/RW upon completion and actuation levels shall be measured.

05 December 2002

EMFFORCE - CDR

127

<SJS>

The board design theory shall be verified via prototype board design.

This prototype board shall be comprised of 2 Tattletale PR-8 boards and other breadboards.

Testing shall occur as software and EM and RW are completed.



EMFFORCE

Avionics Cost Budget

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

Development		Final Product (System)	
Item	Cost (\$)	Item	Cost (\$)
PR-8 Proto-board	190	Avionics board	1200
TT8 Repair/New	200	TT8 Repair/New	400
Cables etc.	35		
SUBTOTAL:	825	SUBTOTAL:	1200
TOTAL SUBSYSTEM BUDGET:			2025

05 December 2002

EMFFORCE - CDR

128

<MAS>

The avionics item of most significant cost is the circuit board holding the two Tattletales and other electronics. Other than that, the only significant expenditure for the Avionics team is the cost of repairing or replacing Tattletale computers. EMFFORCE does not have to pay for the Tattletale computers new because the SPHERES project has more extra Tattletales than we need for testing, operation and backup.



EMFFORCE

Avionics Mass and Power

- Introduction
- Subsystems
 - EM
 - RWA
 - Power
 - Structure
 - Metrology
 - Avionics SW
 - Comms
 - Avionics HW
 - Control
 - Operations
- Systems

Mass Item	Unit Mass (kg)	Qty.	Per Vehicle (kg)
Circuit board (no TT8)	0.05	1	0.05
Tattletale Model 8	0.03	2	0.03
Wires, etc.	N/A	N/A	0.03
TOTAL Subsystem Mass:			0.11

Power Item	V-supply	Amps
Tattletale Model 8 (x 2 per vehicle)	5.0	0.30

05 December 2002

EMFFORCE - CDR

129

<MAS>

There are two Tattletale computers per vehicle: one for metrology and one for avionics/comm./control. Both are mounted on the avionics board; therefore, both are part of the Avionics team mass budget.



EMFFORCE

Avionics HW Concerns

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

Concern	Mitigation
Board design does not satisfy all integration needs	Prototype boards used for integration testing until arrival of avionics board
Improper board layout	Review OrCAD plans with experienced faculty prior to board fabrication
Learning Curve	Begin final wiring end of IAP (as soon as boards arrive)
Board fabrication problems	Order boards by beginning of January, so that they can be tested and reordered in time for second term if necessary

05 December 2002

EMFFORCE - CDR

130

<SJS>

The hardware concerns mainly involve the learning curve. OrCAD layout has taken a great deal longer than originally anticipated, and this is due to the learning process involved with both the software and with circuit design. Therefore, the Avionics team intends to address the team's concerns by designing a prototype board to ensure that the board is complete in theory, and will send in the boards by the end of the Fall 2002 term to be fabricated. This way, if there are any problems in the board design/fabrication, problems can be fixed by the beginning of the Spring 2003 term.

Control



Leah Soffer



EMFFORCE

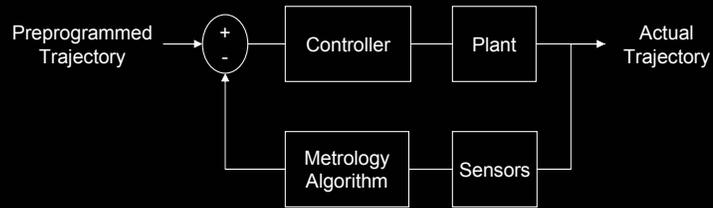
Control Overview

Introduction

Subsystems

- EM
- RWA
- Power
- Structure
- Metrology
- Avionics SW
- Comms
- Avionics HW
- Control**
- Operations

Systems



The purpose of the control system is to send commands to the actuators (electromagnets and reaction wheel) based on preprogrammed inputs and metrology sensor data.

<LS>



EMFFORCE

Requirements

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

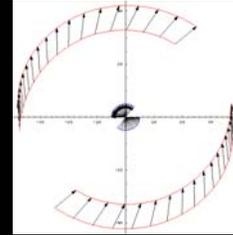
Avionics HW

Control

Operations

Systems

- Must exhibit control in two modes
 - Steady state
 - Spin-up/de-spin
- Robust controller
 - Disturbance rejection
 - Trajectory following
- Rotation rate in steady state of system to be 1 RPM
- Displacement error 15 cm
- Maximum relative angle error 5 degrees



05 December 2002

EMFFORCE - CDR

133

<LS>

These requirements are derived from the requirements document. A maneuver is stated in the requirements document that the vehicles must begin at rest, spin-up to steady state, and de-spin to rest in a total of seven minutes. The steady state rotation must be 1 RPM. These numbers were chosen to limit testing time to allow for limited resources such as gas supply and battery life. The requirement of 1RPM may be relaxed due to a slow time constant of the magnets.

The maximum displacement error is determined from examination of the linear model. A 15 cm error in displacement creates a 10% change from the non-linear to linear model. Also, this requirement is derived from the metrology sensing which is accurate to 1 cm. The controller can not be more accurate than the sensors. The angle error was determined in a similar fashion. Examining the linear model showed that an error in 5 degrees produced a 10% change. Also, metrology is accurate to 3 degrees at a 2 meter separation distance, so our control error is again outside of the metrology error.



EMFFORCE

Test Cases

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

1. One vehicle (only RW control)
 - a. Disturbance rejection
 - b. Trajectory following
2. Two vehicles (RW and EM control)
 - a. One vehicle fixed – disturbance rejection
 - b. One vehicle fixed – slewing, trajectory following
 - c. Both vehicles free – disturbance rejection
 - d. Both vehicles free – slewing, trajectory following
 - e. Spin-up
3. Three vehicles (RW and EM control)
 - a. Middle vehicle fixed – disturbance rejection
 - b. Middle vehicle fixed – slewing, trajectory following
 - c. All vehicle free – disturbance rejection
 - d. All vehicles free – slewing, trajectory following
 - e. Spin-up

05 December 2002

EMFFORCE - CDR

134

<LS>

Because the final goal of spin up is quite advanced and complicated, a series of test cases have been developed to step slowly through the learning process from simple to more complicated problems. Test case one with one vehicle has already been performed on a mock-up vehicle. Test case two will be performed next term at MIT. These two tests are the nominal test cases. Test case three is extra and may be performed on the Denver flat floor where there is room for three vehicles.



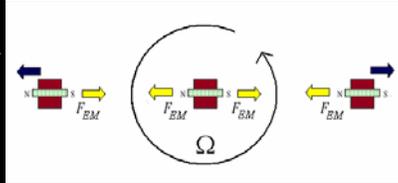
Steady State Spin Modeling (3 Vehicles)

- Introduction
- Subsystems
 - EM
 - RWA
 - Power
 - Structure
 - Metrology
 - Avionics SW
 - Comms
 - Avionics HW
 - Control**
 - Operations
- Systems

• Force Balance

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

$$F_{EM} = \frac{c_0 \mu_{avg}}{s^4} + \frac{c_0 \mu_{avg}^2}{(2s)^4}$$



• Perturbation Analysis

$$m\ddot{s} = \frac{c_0 \mu_{avg}^2}{s^4} + \frac{c_0 \mu_{avg}^2}{(2s)^4} - m\Omega^2 s$$

Yields
unstable poles at $\pm \frac{h}{s_0^2} = \pm \Omega$

$$c_0 = \frac{3\mu_0}{2\pi}$$

$$\mu_A = \mu_B = \mu_C = \mu_{avg}$$

05 December 2002

EMFFORCE - CDR

135

<BAB>

This slide demonstrates the modeling done for the electromagnetic forces. We looked at the forces in the steady state spin mode first because we noticed that the system is unstable. Modeling the system confirmed our initial thoughts. We decided to tackle this unstable system first.

This slide shows the electromagnetic forces acting as the system's centripetal force, accelerating the vehicles into steady state orbit. These forces define the equation of motion for the system along the axis of the vehicles of the array. Performing a perturbation analysis and dropping off the higher order terms, on the assumption that they are small, we were able to calculate the poles of the system. As suspected, one of the poles lies in the right half plane indicating an unstable system.

We also noticed that the poles of the system are the array rotation rate. This means that the system's time constant is the inverse of Ω or about 10 second, assuming the rotation rate is 1 RPM. This becomes important when analyzing the time elapsed before the B field of the magnet changes with a commanded voltage change. As long the latter time constant is faster than the former the system is controllable.



EMFFORCE

EM Control for Disturbance Rejection

Introduction

Subsystems

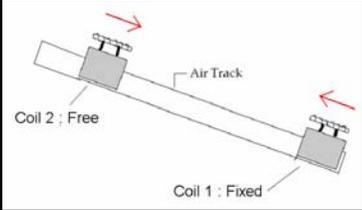
- EM
- RWA
- Power
- Structure
- Metrology
- Avionics SW
- Comms
- Avionics HW
- Control**
- Operations

Systems

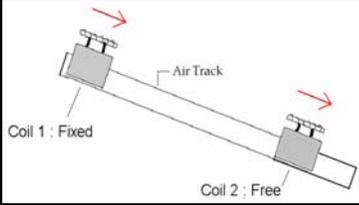
- Last term EM control on airtrack
- Unstable setup like steady state spin
 - Two approaches
 - Classic Control
 - Phase Lead
 - State Space
 - LQR to minimize cost:

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

- R_{xx} weights state
- R_{uu} weights control



Stable Setup



Unstable Setup

05 December 2002

EMFFORCE - CDR

136

<LS>

An air track was built by two students, Richard Cross and Farmey Joseph, in the 16.62x class last term to be used to demonstrate electromagnetic control. There are two setups on the air track, a stable and unstable configuration. In modeling the system, it was found that there are two poles on the imaginary axis at $\pm 1.5i$ in the stable configuration where the fixed magnet is on the bottom. The poles in the unstable case, where the fixed magnet is on the top of the air track, are at ± 1.5 on the real axis. Controlling the electromagnets in the unstable configuration is very similar to controlling our vehicles during steady state rotation. For this reason, controllers were explored for this case.

First, a phase lead controller was designed using SISOTOOL. The results were successful with small steady state error and small overshoot. However, state space design is more practical for the final system due to its complexity. A state space model was developed and a linear quadratic regulator (LQR) was implemented assigning high cost to state, and more specifically the position. This as well provided a successful controller as shown in the following video.



EMFFORCE

Magnet Test Video

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems



05 December 2002

EMFFORCE - CDR

137

<BAB>

This video is a demonstration of the controller built by Ms. Laila Elias for the linear air track testbed.



EMFFORCE

RW Control for Disturbance Rejection

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

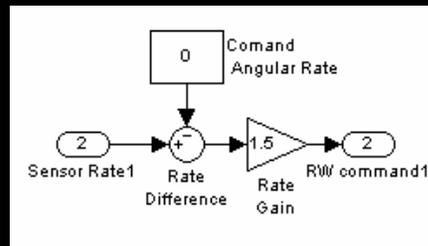
Control

Operations

Systems

Disturbance rejection controller:

Feedback gyro rate data to drive vehicle angular rotation rate to commanded input through LQR gains.



05 December 2002

EMFFORCE - CDR

138

<LS>

This term we modeled and designed controllers for test case one. We built a model vehicle consisting of an gas carriage, reaction wheel, motor, CO2 supply, and rate gyro. We built controllers finding optimal gains using LQR.

For the disturbance rejection controller, we weighted the angular rate greater than position to find the gains, and weighted the states more than the control. The simplified version of the simulink model shows that an angular rate can be commanded and the controller drives the difference between the command and sensor data to zero.



EMFFORCE

Reaction Wheel Video 1

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems



05 December 2002

EMFFORCE - CDR

139

<BAB>

This video is a demonstration of the controller built by the Control team for test 1a. It shows the vehicle rejecting disturbances to keep the rotation rate at zero.



EMFFORCE

Reaction Wheel Video II

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems



05 December 2002

EMFFORCE - CDR

140

<BAB>

This video is a demonstration of the controller built by the Control team for test 1a. It shows the vehicle rejecting disturbances to keep the rotation rate constant.



EMFFORCE

RW Control for Tracking

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

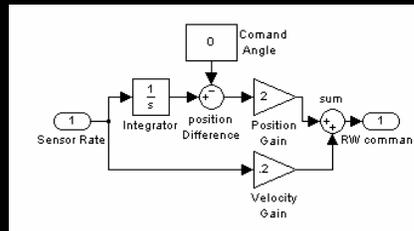
Operations

Systems

Tracking controller:

Problem! Need angle data for full state feedback!

Attempts at using an estimator were unsuccessful, so an integrator was used.



05 December 2002

EMFFORCE - CDR

141

<LS>

To control position, we needed position information. The sensors only provided rate data. First, we tried implementing an estimator that would predict the position based on past data. There were problems with the implementation and due to time, we moved to using an integrator. Originally, we were cautious to use an integrator because integrating sensor data integrates noise, but we were able to adjust a constant to minimize the error that is integrated. We again used LQR to find optimal gains, this time weighting position greater than rate. This controller successfully commanded inputted angles.



EMFFORCE

Reaction Wheel Video III

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

05 December 2002

EMFFORCE - CDR

142

<BAB>

This video is a demonstration of the controller for test 1b. This controller moves the vehicle from its initial angular position to a commanded one.



EMFFORCE

Modeling for RW and EM

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

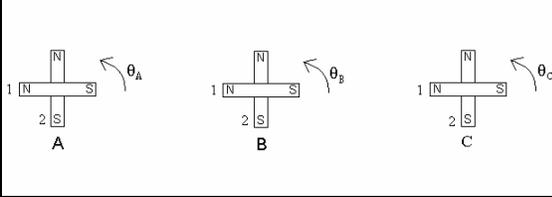
Comms

Avionics HW

Control

Operations

Systems



•Force Balance (with coordinate system fixed on vehicle B)

$$m\ddot{x}_A = F_{A1/B1} + F_{A1/B2} + F_{A1/C1} + F_{A1/C2} + F_{A2/B1} + F_{A2/B2} + F_{A2/C1} + F_{A2/C2}$$

•Similar for $\ddot{x}_C, \ddot{y}_A, \ddot{y}_C, \ddot{\theta}_A, \ddot{\theta}_B, \text{ and } \ddot{\theta}_C$

•Linearize with respect to magnetic moments, separation distances, and rotation angles, dropping the higher order terms

•This process gives the A and B matrices for a state space analysis where $\dot{x} = Ax + Bu$

05 December 2002

EMFFORCE - CDR

143

<BAB>

To model the system we start with force balancing equations. To accomplish this, the electromagnetic forces for each dipole pair must be calculated and summed. Using these equations of motions we can do a perturbation analysis and linearize with respect to the magnetic moments, the separation distances, and the rotation angles. This was done using Mathematica. Dropping the higher order terms, the A and B matrices can easily be found. These equations are then used to design the controller using a Linear Quadratic Regulator (See XXX slide).



EMFFORCE

Control Design for Test Cases 2 and 3

- Introduction
- Subsystems
 - EM
 - RWA
 - Power
 - Structure
 - Metrology
 - Avionics SW
 - Comms
 - Avionics HW
 - Control**
 - Operations
- Systems

- LQR used (2a optimal gains shown below)

x_A	y_A	θ_A	\dot{x}_A	\dot{y}_A	$\dot{\theta}_A$	
-0.006	0.001	0	24	2	0	μ_{A1}
0.001	0.006	0	2	34	-0.001	μ_{A2}
0	0	0.009	0.001	0.006	3	$\tau_{RW,1}$

- For disturbance rejection, rates are weighted more. For tracking, positions are weighted more
- In all cases, EM is weighted more than RW
- Input trajectories for spin-up being calculated.

05 December 2002

EMFFORCE - CDR

144

<LS>

LQR produces gains for every state and actuator combination. EM is more expensive control, so its weight is greater than that of RW. For disturbance rejection, the gains associated with rates are greater. For tracking the gains associated with position are greater. Limits will be built into the controller so that commands will never be sent to the actuators which are outside of the operating range.

Several approaches to spin-up are being considered. In one, a constant input will be given to EM and a torque profile is generated as the input to the reaction wheel. In another approach, both an EM and torque profile are created to spin-up in one minute. Other ideas will be explored to meet the requirements and optimize spin-up.

Preliminary learning about coding the controllers has been done, but the majority of the coding will be done over IAP.



EMFFORCE

Control Concerns

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

Concern	Mitigation
Near field effects of the magnets	Use far field approximation and try to fix
Slow time constant of the EM	Slow down array rotation rate or model inductive delay in controller
Designing a working controller for spin-up	Design multiple possible controllers using different spin-up approaches
Learning to code on the TT8	Focus on this task for IAP

05 December 2002

EMFFORCE - CDR

145

<BAB>

Our first concern is the near field effect of the magnets. In our models we used the far field equations to model the forces and torques supplied by the magnets. The far field assumption does not exactly hold that the separation distances we intend to operate. We have the equations that supply the forces and torques at the separation distance we intend to operate but they involve elliptical integrals. Have the TT8 compute these integrals repeatedly would introduce significant time lag into our system. To mitigate this risk we will continue to use the far field assumption and we will later modify the controller once empirical data exists until the controller is functional. If this approach does not work then we will attempt to construct a "look-up" table for the elliptical integrals. This way the TT8 would know what to output given the inputs without having to compute the elliptical integral.

Our second concern comes from the fact that the time constant of the electromagnet is what drives the array rotation rate. This time constant is, by preliminary calculations, very slow. To ensure that the system has sufficient control authority to complete its mission we might need to loosen the requirement of one array rotation per minute. By loosening this requirement, the mission will be more easy to achieve.

Another concern is that designing a working controller for spin-up may prove to difficult. There is so much that can go wrong in spin-up, and there are so many different ways to design a controller that accomplishes this mission. To mitigate this concern we intend to analyze and design controllers for different spin-up scenarios.

Our last is that we have yet to learn to code on the TT8. Software often times is the Achilles heel of any project and we have had to push the task of learning and experimenting with the TT8 until IAP. This tasks need to be accomplished by the end of IAP in order for the project schedule to be met.

Operations



Leah Soffer

05 December 2002

EMFFORCE - CDR

146



EMFFORCE

Operations Overview

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- The “O” in CDIO
 - Operate the system at MIT during various stages of development
 - Operate the completed system at the Denver Flat Floor Facility
- Demonstrate the feasibility of EMFF outside the development labs
- Guide development toward these ends

05 December 2002

EMFFORCE - CDR

147

<ESS>

The ultimate goal of the CDIO program is to operate the completed testbed at Lockheed Martin’s Flat Floor Testing Facility in Denver. All subsystems must not only work as designed, but must come together into a complete operational system that can perform useful research in a bare-lab location.

The EMFFORCE mission is to demonstrate the feasibility of EMFF, and this can only be done through planned experimentation with coordinated data collection and analysis.

Everyone must know exactly what is going on, and be able to perform the mission and overcome whatever setbacks may occur in real-time while EMFFORCE is deployed to Denver.



EMFFORCE

Ops Requirements

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- **Maintain safety**
 - Personnel – no mishaps
 - Protect test facilities and equipment
- **Validate mission completion**
 - Demonstrate all operational requirements of integrated system
 - Record relevant data to validate functionality
- **Optimize operations for efficiency**

05 December 2002

EMFFORCE - CDR

148

<ESS>

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

1. The well-being of our team members is vital. We must also safeguard the testing facility and associated equipment against damage from system malfunction. Personal injury or severe infrastructure damage will negate any mission successes that may have been achieved.
2. Mission completion, which includes the satisfaction of all operational requirements listed for the system (given in the introduction) and is evaluated under the framework of the Test Program Plan. A demonstration of full system performance is required.
3. Efficiently planning and conducting operations will save time and money. We should do as little work and spend as little money as possible without jeopardizing the above priorities.



EMFFORCE

Required Capabilities

- Operations-oriented development
- User interface with physical system
- System interface with test environment
- System health monitoring
- Telemetry recording
- Real-time teamwork and coordination

Introduction
Subsystems
EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations
Systems

05 December 2002 EMFFORCE - CDR 149

<ESS>

In order to meet the requirements of safety, operational validation, and efficiency, the Operations Section must implement the following subsystems, documentation and capabilities.

1. Guide the development of the EMFFORCE project while looking out for operational considerations. We should not build a vehicle that is too complicated or fragile to operate in the field or that does not meet operational requirements.
2. Develop the user interface with the physical system that will guide how it is operated. This includes the hardware and software by which the user will control the system and the System Operator Manual, that directs the user in how to use these interfaces and troubleshoot components.
3. Consider the system interface with the test environment that will be the means by which performance is demonstrated and validated. Constraints posed by the various testing environments at MIT and the Lockheed Martin facility must be addressed in the Test Program Plan.
4. The system must provide some feedback to the operator and to the decisionmaking components of the autonomous control system. These are interfaces between Operations and other subsystems.
5. In order to accomplish the validation mission, data from the sensor systems and inter internal processes of the computers must be transmitted and recorded for analysis
6. Finally, the class team must be sufficiently prepared with a knowledge of the system and of its operational characteristics to effectively operate it in real-time outside the lab after system integration.



Current Design Deliverables

- Introduction
- Subsystems
 - EM
 - RWA
 - Power
 - Structure
 - Metrology
 - Avionics SW
 - Comms
 - Avionics HW
 - Control
 - Operations
- Systems

- Ground Station
 - Telemetry software and data logging
 - Command and Control capability
- Vehicle Ops
 - System health monitoring
- Documentation
 - System Operations Manual
 - Test Program Plan
 - Field Operations Plan

05 December 2002 EMFFORCE - CDR 150

<ESS>

From the desired capabilities of the subsystem, the following deliverables were extracted. The operations subsystem is unique in that it has physical and procedural components external to the individual test vehicles

The ground station is the link between users and the vehicles. It participates in the RF network along with the vehicles. Its primary functions are C2 and data logging.

Operations team will monitor the health of the vehicles through several sensors that are now in procurement.

Several documents also needed to be created in order to guide operations at MIT and in the field. The System Operations Manual is the user's manual for the system, including all assembly instructions standard functions, and troubleshooting assistance.

The Test Program Plan is the means by which tests are tracked against the requirement to validate all the operational requirements of the integrated system.

The Field Operations Plan describes in detail the method for moving all necessary equipment and personnel to the Denver lab and back again.



EMFFORCE

Ground Station Design

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Occupies node 4 on Comm Network, transmits APID07
 - Command vehicles to begin test
 - Change vehicle identities
 - Despin or shut down system
- LabView GUI runs embedded C Code that decodes all RF data packets passing over the network
- Processes these data to provide description of system functionality
- Displays NRT health data
- Logs all data for system performance analysis

05 December 2002

EMFFORCE - CDR

151

<ESS>

The Ground Station occupies node 4 on the cluster communications network token ring architecture. Every comm cycle, it will have an opportunity to pass commands to the vehicles. These commands are necessary to tell the system to start spin-up and spin-down, to change vehicle identities in software and to command a controlled halt to a test.

The Ground Station consists of a laptop running LabView with a DR2000 attached to its serial port. It will receive and decode all RF traffic that passes over the RF network

This data is then analyzed and catalogued by the LabView program to provide near real-time information on the state of the system, and should identify many problems several seconds before they cause system failure, thus providing the safety monitors with an opportunity to manually arrest the vehicles.

Eventually the data that is saved will be needed to analyze the performance of the control system and validate the system as a whole.



EMFFORCE

Vehicle Ops Design

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Monitor health variables and provide control feedback from actuators
 - Current measurement in each coil
 - Reaction Wheel driving current
 - Battery voltages in actuation and avionics circuits
- Operations hardware
 - LED bank indicates health data
 - Switches break actuation and avionics circuits

05 December 2002

EMFFORCE - CDR

152

<ESS>

The power and actuation subsystems provide hardware monitoring through the avionics processor. In the case of the actuation subsystems, the data from the actuators of their actual state can be compared against their commanded state to provide feedback for the controller.

An inductive ammeter near the coils will measure their current flow. A sudden uncommanded drop in coil current would likely signal a failure of the cryogenics subsystem and would require immediate shutdown to protect the system.

Similarly, should the reaction wheel approach saturation speed, the operator needs to know in case the system needs to be shut down.

Battery voltages for both power circuits are monitored to provide the operator warning of impending power failure.

When any of these items approach failure, a red LED will light on the ops board, prompting the controller to either despin or shut down. Switches in the circuits of power and actuation may also be used as a means to influence system state.



System Operations Manual

- Assembly
- Safety
- Troubleshooting
- Subsystem operations descriptions with ORM summary
- System Operational States
 - Software and user actions

05 December 2002 EMFFORCE - CDR 153

<ESS>

The Operating Manual is a reference source used by the operators in the field when the engineer who built the system is not available. As such, it needs to be as nearly a complete description of the behavior of the system as possible in order to maximize the probability of a successful mission.

Standard operating procedures (SOP) are implemented to hold constant those variables that might cause unforeseen reactions from the system. These procedures also reflect lessons learned in the development cycle for how to prevent problems. Once the system has reached operational status, it is no longer appropriate to just guess about how to do things.

Operational Risk Management (ORM) is the practice of minimizing the likelihood and consequences of mishaps and accidents by understanding their causes and functional mechanisms. The various subsystem teams will identify risks and work with the Operations Section to implement countermeasures as part of the system SOP.

Chapters include the following: General Considerations, Assembly/Disassembly, Batteries, Cryogenics, Avionics, Test Operations and Monitoring, Troubleshooting, Components List



EMFFORCE

System Operational States

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Initialization
 - Turn on: Avionics, Comm, Metrology
 - Off: Electromagnet, RW, Gas Carriage
 - Run diagnostics and report status
- Deployment
 - Manually place on floor
 - Turn on: Gas Carriage
 - Manually place vehicles in initial position
 - Metrology assists placement
 - Turn on: Control

05 December 2002

EMFFORCE - CDR

154

<ESS>

Initialization powers up the electronics and checks for faults before placing the vehicle on the floor.

Deployment activates the Gas Carriage and guides the vehicles to their initial positions. EMFFORCE personnel will be able to place the vehicles manually on the floor. Metrology will take data and guide the vehicles to the commanded starting position by providing cues to the operators



EMFFORCE

System Operational States

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Spin-up (Series IT-2E and IT-3E)
 - Run Control diagnostics
 - Turn on: Electromagnet, RW
 - Control algorithm in Spin-up mode
- Steady State Rotation
 - Control algorithm in Steady State mode
- De-spin
 - Control algorithm in De-spin mode

05 December 2002

EMFFORCE - CDR

155

<ESS>

Spin-up confirms that the Control system is talking to the Actuation devices, and then powers on the devices. The Control system commands Actuation to steer the system towards the steady state goal by using the Spin-up algorithm.

For tests other than IT-2E and IT-3E, other control modes are activated in order to fulfill control testing requirements.

In Steady State, the system maintains the desired rotational velocity and monitors variables.

De-spin switches the Control algorithm again to attempt to bring the vehicles to rest. This is the stopping state that is used while control is still possible.



EMFFORCE

System Operational States

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

- Shut down
 - Turn off: Electromagnet, RW, Control
 - Vehicles may be manually arrested by safety team
- Recovery
 - Manually move the devices to the edge of the floor
 - Turn off: Gas Carriage, Comm, Metrology, Avionics

05 December 2002

EMFFORCE - CDR

156

<ESS>

Shut down turns off the magnet, reaction wheel, and Control system, leaving the vehicles “dead in the water.” Hopefully the vehicles will be close to rest, having completed the De-spin actions. If not, an emergency shutdown will allow operators to secure the vehicles manually without further damage.



EMFFORCE

Ops Cost Budget

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

Development		Final Product (System)	
Item	Cost (\$)	Item	Cost (\$)
Liquid N2	300	Ops Electronic	120
Plate Glass	397	Ops Laptop	1843
TT8 Repair	357		
Ops Random	100		
SUBTOTAL:	1154	SUBTOTAL:	1963
TOTAL SUBSYSTEM BUDGET:			3117

05 December 2002

EMFFORCE - CDR

157

<ESS>

Development costs.

Operations is responsible for testing facility support and resource procurement activities during development.

Liquid N2 is an expendable resource that must be purchased. Plate glass provides a flat and smooth surface for testing of gas-carriage-supported vehicles. As Tattletales break during routine development, they can be cheaply repaired by the manufacturer.

System Costs.

Operations requires a small number of electronic components for the user interface on the vehicles. Most of the operations system cost come from the laptop used for the ground station. However, this laptop is being utilized during development by several teams and the amount of money allocated to this category is misleading; the Laptop is a valuable development resource not accounted for in any development budget.



EMFFORCE

Ops Mass and Power Budget

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

Item	Unit Mass (kg)	Per Vehicle (kg)
Ops Board	0.05	0.05
TOTAL Subsystem Mass:		0.05

Item	Per Unit		Vehicle	
	V	A	V	A
Ops Board	3	0.01	3	0.01
TOTAL:	3	.01	3	0.01

* All measurements in kg.

05 December 2002

EMFFORCE - CDR

158

<ESS>

Operations requires very little mass and power resources. The Ops board contains switches, some solid state electronics to perform comparisons, and LED's to display error indicators.



Concerns/Mitigations

	Concern	Mitigation
Introduction Subsystems EM RWA Power Structure Metrology Avionics SW Comms Avionics HW Control <u>Operations</u> Systems	Inadequate testing of spin-up algorithm before Denver tests	research Lobby 7 as possible test site for IT-2E
	Loss of control failure may occur during tests	Plan for non-catastrophic control failure Detect instabilities early through health monitoring
	Superconductor or reaction wheel may become unusable during tests leading to safety issue	Practice arresting vehicles after planned actuation system shutdown

05 December 2002
EMFFORCE - CDR
159

<ESS>

The control program for the spin-up state needed for Integrated Test 2E cannot be tested on the tabletop facilities available at MIT. Due to the likelihood that this will not function properly the first time it is attempted, we want to find some other way to test it at MIT. The floor of Lobby 7 is locally smooth enough to float a vehicle, but further research is needed to determine if the gaps between marble tiles, slope deviations of the floor, or cryogenic safety considerations might prohibit testing there.

Since the control system is experimental for any given series of tests, it is likely that the system will exit the region of control stability and become uncontrollable. This will lead to the vehicles either coming together or floating off in a random direction. This failure mode will be addressed by manually stopping the vehicles after departure from stability and by trying to provide warning of impending departure from system health monitoring

Similarly, a temperature increase or other disturbance may cause a failure of the actuation system. Safety requires that the actuation system be shut down once the vehicles become uncontrollable. The safety personnel tasked to arrest the free moving vehicles need to practice this in a planned test so they can do it when the loss of control happens unexpectedly.



EMFFORCE

Concerns/Mitigations

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

Concern	Mitigation
Denver Test Site may not be available or cost effective	Evaluate alternative sites at Lobby 7, Lockheed Palo Alto, NASA MSFC and NASA JSC
Ferromagnetic material in Flat Floor prohibits testing	Test in Lobby 7 or alternative site
Field Operations planning errors	Ensure materiel accountability Comprehensive plan for actions on site

05 December 2002

EMFFORCE - CDR

160

<ESS>

If for some reason the trip to Denver does not happen, another site will have to be found for Integrated Test 2E and all of Test Phase 3.

The floor in any of the flat floor facilities has yet to be evaluated for magnetic properties. If this is an issue, we will have to move testing to an alternative site.

Errors and oversights in the Field Operations Plan can make any field test trip worthless. This concern will be addressed by providing a comprehensive field operations plan, carefully reviewed to ensure all necessary spare parts, test equipment, and maintenance equipment is included.

Systems



Will Fournier

05 December 2002

EMFFORCE - CDR

161



System Budget: Mass

Subsystem	Mass per vehicle (kg)
Electromagnet	8.70
RWA	1.51
Power	3.54
Structure	4.52
Metrology	0.45
Comm.	0.05
Avionics	0.11
Operations	0.05
TOTAL:	18.93

05 December 2002 EMFFORCE - CDR 162

<MAS>

- Control subsystem is not represented on this slide because Control team has mass budget of zero (no physical subsystem)
- Because the slide addresses vehicle mass only, additional Operations budget is not included (e.g. laptop computer)
- System is approaching the budgeted limit due to changes in subsystem reports as follows:
 - EM: + 2.1 kg (increase in coil size)
 - Str: + 1.0 kg (new items: base plate, hardware)
 - Pwr: - 0.9 kg (reduced need for D cell batteries)
 - Met: + 0.25 kg (included frame, reflective cones)
 - C-O: - 0.1 kg (originally overestimated board mass)
 - Avi: -0.08 kg (also originally overestimated board mass)
 - Total, this increases our mass by approximately 2.8 kg from where it was (just above 16 kg).



EMFFORCE

System Budget: Power

Introduction Subsystems

EM
RWA
Power
Structure
Metrology
Avionics SW
Comms
Avionics HW
Control
Operations

Systems

Powered Subsystem	Volts per vehicle	Amps per vehicle
EM (2 coils) (D cells)	0.00	200.00
RW (D cells)	3.01	10.20
Metrology (AA cells)	5.00	1.36
Comm. (AA cells)	3.00	0.05
Avionics (AA cells)	5.00	0.15
Operations (AA cells)	3.00	0.01
Electronics TOTAL:	N/A	1.57

05 December 2002

EMFFORCE - CDR

163

<MAS>



EMFFORCE

System Budget: Code

[Introduction](#)

[Subsystems](#)

[EM](#)

[RWA](#)

[Power](#)

[Structure](#)

[Metrology](#)

[Avionics SW](#)

[Comms](#)

[Avionics HW](#)

[Control](#)

[Operations](#)

[Systems](#)

RAM (Data)		Flash (program)		
Variable Pkg.	Size	Module	LOC	Size (kB)
PVA (x3 vehicles)	0.5 kbits	OS	1000	4
MSA	0.5 kbits	Control	2000	8
MAA	0.5 kbits	Met access	1000	4
Comm. transfer	5.0 kbits	Comm.	2000	8
Control work	5.0 kbits	Ops/startup	1000	4
Other processes	20.0 kB	Tests	1000	4
TOTAL:	20+ kB	TOTAL:	8000	32
Available:	256 kB	Available:	64000	256 kB

05 December 2002

EMFFORCE - CDR

164

<MAS>



EMFFORCE

System Budget: Cost

[Introduction](#)

[Subsystems](#)

[EM](#)

[RWA](#)

[Power](#)

[Structure](#)

[Metrology](#)

[Avionics SW](#)

[Comms](#)

[Avionics HW](#)

[Control](#)

[Operations](#)

[Systems](#)

Subsystem	Spent (\$)	Allocated (\$)	Remaining (\$)
EM	8,450	25,060	16,610
RWA	1,020	1,020	0
Power	370	2,500	2,130
Structure	600	2,080	1,480
Metrology	10	460	450
Comm	1,470	1,520	50
Avionics	370	2,030	1,660
Operations	2,270	5,690	3,420
TOTAL:	14,560	40,360	25,770

- EMFFORCE budget cap: \$50,000
- With margin at CDR: \$45,000

05 December 2002

EMFFORCE - CDR

165

<MAS>

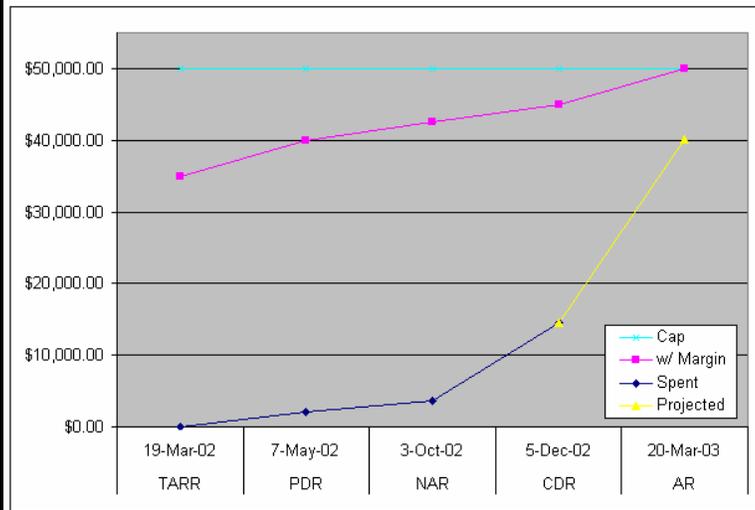


EMFFORCE

System Budget: Cost

- Introduction
- Subsystems
 - EM
 - RWA
 - Power
 - Structure
 - Metrology
 - Avionics SW
 - Comms
 - Avionics HW
 - Control
 - Operations

Systems



05 December 2002

EMFFORCE - CDR

166

<MAS>



EMFFORCE

Field Test Travel Budget

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

Personnel		Materiel	
Item	Cost (\$)	Item	Cost (\$)
Travel (12)	4500	FedEx	2000
Lodging (12)	1200	Packaging	500
Food (12)	480	Van (Cargo)	300
		Van (12 Pax)	500
		Spare Parts	300
SUBTOTAL:	6180	SUBTOTAL:	3600
TOTAL COST PER TRIP (3 nights):		9780	

05 December 2002

EMFFORCE - CDR

167

<ESS>

This is an estimate of the cost of a trip from Boston to Denver for 4 days and 3 nights, including two days of testing at the Lockheed Facility.

Travel and Lodging plans for 12 personnel (8 students and 4 faculty) at the prevailing available rate on Expedia.com. The food budget is a subsidy of \$10 per day for each team member.

Most of the system will be shipped via commercial freight carrier rather than carried by the EMFFORCE team on the commercial airline. The \$2000 estimate is based on the cost of shipping the SPHERES system to the NASA microgravity facility in Texas. The materiel will also have to be packaged securely to protect fragile systems from damage en route.

Once in Denver, two vans will be needed to transport personnel and materiel to and from the test site. A small amount is also allocated for spare parts purchase on site; this should also cover the necessary liquid nitrogen expenses.

The total cost of a trip to Denver with half the project personnel and the entire system is thus \$10000. A significant portion of this might be saved by either reducing personnel in attendance or using the MIT travel office to buy cheaper tickets. Currently two field test missions are in the high level schedule. The utility of the trips must be weighed against their high cost before the final decision to go can be made.



EMFFORCE

System-Wide Concerns

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

Avionics HW

Control

Operations

Systems

Concern

Mitigation

Inefficient allocation of labor resources

- Systems plans and allocates schedule by the hour
- Restructure teams next semester
- Systems members have no other program responsibilities

Schedule Overrun

- Student work during IAP
- Optimize labor allocation
- Descop tests to only two vehicles

05 December 2002

EMFFORCE - CDR

168

<WDF>

There are several concerns of the current system's team which if left unchecked may cause the failure of the project. The greatest concern is that student resources are being poorly allocated and thus some students are being overworked far beyond a level that is acceptable in this academic setting. Because next spring students are only allocated 6 hours per work for this class the problem is likely to become exacerbated. This problem can be alleviated with greater authority and flexibility given to the system's team. The root cause of the current problem is the limitation of students to a particular sub-system. However, not all sub-systems require an equivalent amount of resources. Detailed planning of individuals and the task they need to accomplish set from the top instead of schedules created from below can help alleviate this problem. In order for this reallocation to be done effectively those responsible for setting the system resources should not be responsible for other elements of the program.

The second critical concern for the project is that the current schedule design leaves little margin for schedule delays. Because the end date of the project is fixed by the graduation of the work force it is not possible to create more margin in the tasks that must be accomplished. The best solution to this problem is the same as the solution to the previous concern. Better allocation of program resources from a dedicated management authority can help to bring the system back ahead of schedule and reestablish margin in the schedule. If the system falls further behind schedule the program will be forced to evaluate the necessity of two system tests on the flat floor facilities in Denver. It may be possible to conduct more extensive testing at MIT that can be arranged within a more flexible scheduling environment.



System-Wide Concerns

	Concern	Mitigation
<p>Introduction</p> <p>Subsystems</p> <ul style="list-style-type: none"> EM RWA Power Structure Metrology Avionics SW Comms Avionics HW Control Operations <p><u>Systems</u></p>	Control – Code mapping	Dedicate heavy resources during IAP
	Software timing	<ul style="list-style-type: none"> •Optimize Code •Slow down control update rate and system spin rate
	Coil Containment Manufacture	<ul style="list-style-type: none"> •Student Hours during IAP •Hire out machining

05 December 2002
EMFFORCE - CDR
169

<WDF>

There are also several program elements that may cause unaffordable delays in the project schedule. Most of these delays revolve around software concerns. First, there is no student experience on the project with writing control algorithms in C. Therefore, mapping the control laws from D-Space to C code capable of running on the vehicles' processors maybe difficult. Our hope for managing this problem is to provide the control team with extra people to help alleviate the coding burden and have this work performed during IAP (when time is more abundant).

Avionics and Communications are finding their codes are running to slowly. This will in effect delay the update rate for the control inputs. The groups are hoping to optimize their codes in order to speed them up. However, it remains unclear at the moment if it will be possible to function at a rate that is acceptable to the control group. All teams need to examine more closely the requirements of the system in order to clarify the full extent of the problem. If necessary the vehicles can be spun at a slower rate and this would alleviate some of the burden. This however, does place an added burden on the vehicles consumables (gas supply, and batteries). This issue will be examined in greater detail.

The final component that has the potential to cause serious delays in the schedule is the manufacture of the coil containment system. Current estimates note that approximately 80 hours of machine time is needed to manufacture the containers for three vehicles without spares. It will be very difficult to complete all of this manufacturing using the currently available student resources during the semester. Depending on student availability, we hope to have the containment all manufactured during the Independent Activities Period in January either with students of the class or undergraduate research assistants.



EMFFORCE

Integration

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

Comms

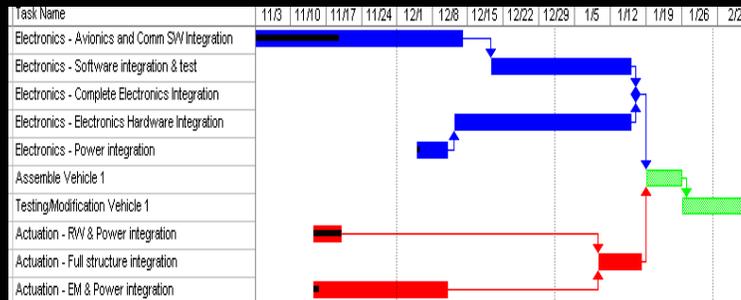
Avionics HW

Control

Operations

Systems

- Three Components
 - Electronics
 - Actuation
 - Vehicle Assembly



05 December 2002

EMFFORCE - CDR

170

<WDF>

The culmination of this semester's work occurs with the final integration of the various sub-systems into one complete vehicle. There are three major elements to the integration process. Integration will occur in an incremental process with two parallel branches. The electronics sub-systems, which include Avionics, Metrology, Communications, and Power, will perform their own integration bridging the interfaces in both software and hardware. The first stage of the software integration has already begun and full electronics integration will be completed by Friday Jan. 17, 2003 during Independent Activities Period (IAP). The second branch includes all of the actuation sub-systems; Reaction Wheel Assembly, Electromagnets, Power, and Structure. The integration with Power and the Reaction wheel is already complete and the integration with the electromagnet will be completed by the end of the semester. The integration of the actuation system with the vehicle structure will occur during the first weeks of IAP. When both the electronics and actuation systems are complete they will integrate together to complete the final vehicle assembly. Finally, the class will test the completed vehicle and verify that it performs as required. Any necessary modifications will be noted and incorporated into the manufacture of the next vehicle to start at the beginning of the spring semester.



EMFFORCE

Test Program

[Introduction](#)

[Subsystems](#)

[EM](#)

[RWA](#)

[Power](#)

[Structure](#)

[Metrology](#)

[Avionics SW](#)

[Comms](#)

[Avionics HW](#)

[Control](#)

[Operations](#)

[Systems](#)

- Will validate the integrated system against operational requirements
- Scheduled Tests
 - MIT Tests through Integrated Test 2E
 - Denver Tests 3A-3E schedule TBD
- Testing operations support
 - Procured plate glass for Integrated Tests 1A through 2D.
 - Researching utility of MIT lobby 7 as alternative test site for Integrated Test-2E

05 December 2002

EMFFORCE - CDR

171

<ESS>

The test program must be completely specified well before deployment to ensure that it will accomplish the mission objectives, which are laid out in the requirements document.

We are going to Denver because the flat floor facility there is the only one in the country that will let us adequately evaluate the complete system w.r.t. its operational requirements.

The IT-3X will be the first time the full system has been evaluated, and will be the first true check on all the models simultaneously. While most concepts should have been demonstrated in lab, the combination of all systems brings new complexities to the planning process.

Similarly, IT-3X will be the first time the planning and craftsmanship of the full system have been evaluated, and the results, if positive, will be a good indicator that EMFF is indeed feasible.



EMFFORCE

Schedule Spring 2003

Introduction

Subsystems

EM

RWA

Power

Structure

Metrology

Avionics SW

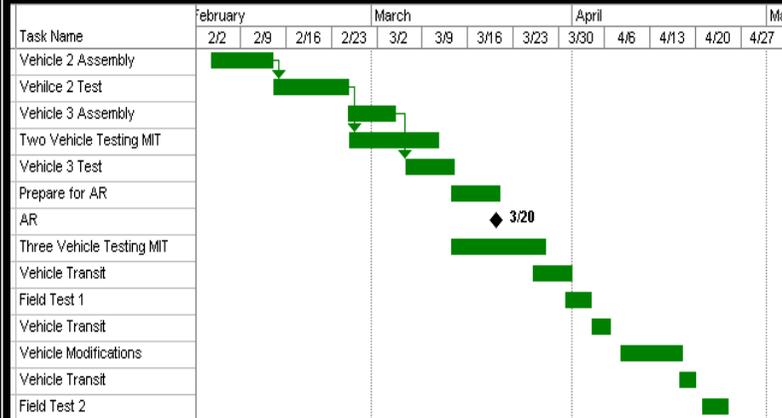
Comms

Avionics HW

Control

Operations

Systems



05 December 2002

EMFFORCE - CDR

172

<WDF>

With the start of the spring semester in February 2003, the class will need to shift focus. The current sub-system teams will no longer be relevant, as all sub-system design and manufacture should be completed. The Control team will continue to work parallel to this schedule, working to develop accurate control algorithms and coding them into the vehicle processors. The rest of the class will focus on vehicle assembly and testing. Each student is limited to six working hours per week for this project, therefore the necessary work must be divided up evenly among the available resources. This will require a detailed testing and operations plan that will be created during IAP. The important no slip milestones are the Acceptance Review on March 20, 2003 and the field tests in Denver Colorado Scheduled for the weeks of March 31 –April 4 2003, and April 13-20 2003.

The field tests will demonstrate the feasibility of electromagnetic control for formation flying satellites. With the completion of the proof of concept for electromagnetic control the system can then be evolved to work in a 3-D plane, and finally upgraded to an actual satellite formation of vehicles. We are confident that the hard work and determination of the class will allow us to accomplish our mission.

Questions?



05 December 2002

EMFFORCE - CDR

173

BACKUP SLIDES



05 December 2002

EMFFORCE - CDR

174

Structures Backups



05 December 2002

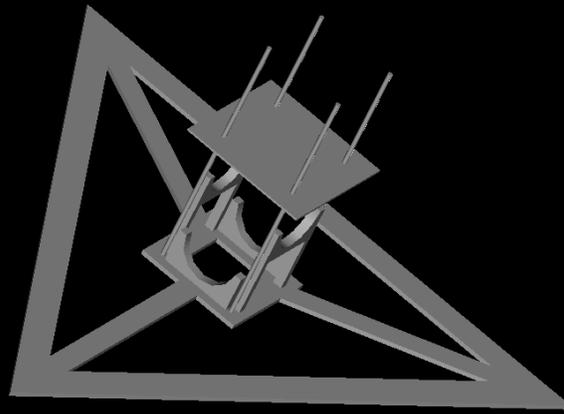
EMFFORCE - CDR

175



EMFFORCE

Backup Design



05 December 2002

EMFFORCE - CDR

176

<GG>



Liquid Nitrogen Gas Supply

- Motivation: Determine if usage of LN₂ as Gas supply is feasible
- Proof of concept, 17 September 2002:
 - Uninsulated tank filled with LN₂
 - At “steady state,” boil off sufficient to float a 4.5 kg carriage on glass for 18 minutes
- Results sufficient for design development
 - Heating element for increased boil off
- LN₂ gas supply design deemed infeasible under schedule and manpower constraints

05 December 2002

EMFFORCE - CDR

177

<ALS>

When the cryogenic system was introduced to the project, it was proposed that the gas from the LN₂ boil off be used as the gas supply to power the pucks. A proof of concept test was designed and conducted to determine whether or not it was feasible.

To conduct the test, an uninsulated tank of the same size as the CO₂ tanks was cooled to “steady state” and then filled with LN₂. This tank was then capped and hooked up to an gas carriage. The pressure indicator used was later found to be broken, so there is no pressure data from the test. However, the gas produced was sufficient to float approximately 4.5 kg across three pucks on glass for 18 minutes. The favorable results of this test induced the structures team to pursue the design of an gas supply system using the nitrogen gas. Included in such a design was the idea that a heating element could be used to increase the boil off rate, and therefore, the pressure, should the insulated steady-state boil off not be sufficient for the desired mass or test time.

After some design iterations and consultation with the electromagnet team, this design was deemed infeasible for the project due to schedule and manpower constraints.

Metrology Backups



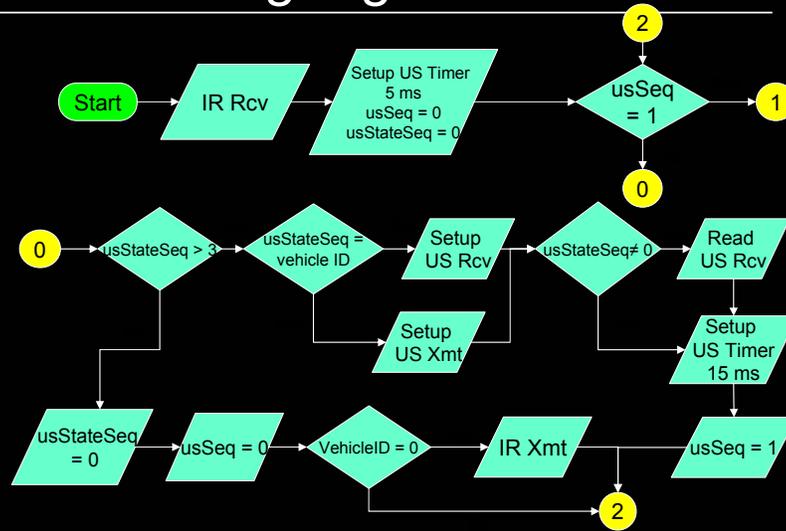
05 December 2002

EMFFORCE - CDR

178



Metrology Software Design: Timing Algorithm



05 December 2002

EMFFORCE - CDR

179

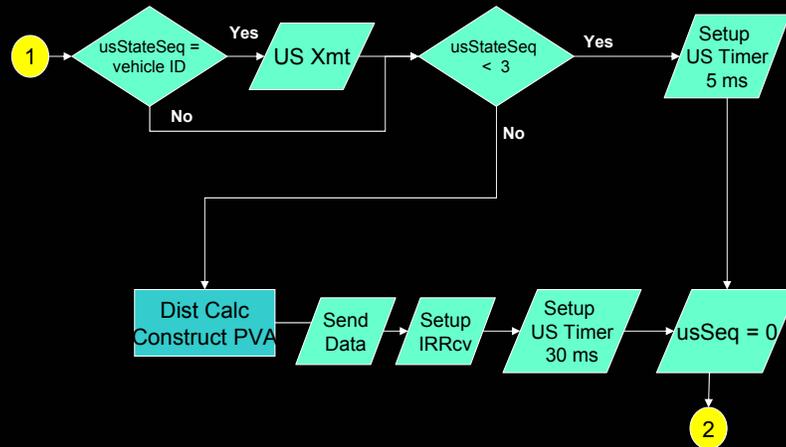
<OM>

As mentioned, the IR signal triggers an interrupt. The interrupt begins the timer, `usTimer`, which periodically triggers another interrupt. The following sequence is followed each time the timer triggers the `usTimerRcv` interrupt.

The code does one of two things based off `usSeq` counter. When `usSeq = 0` the system prepares to transmit or receive (depending on vehicle ID and location in timing sequence). It next reads in the time the US receiver read a signal from the previous US transmission. Last it resets the timer to trigger the next timed interrupt. These events occur each time except the last state (`usStateSeq = 4`). In this case, both counters are reset to zero and if the vehicle is the master vehicle, an IR pulse is sent out.



Metrology Software Design: Timing Algorithm(cont)



05 December 2002

EMFFORCE - CDR

180

<OM>

When usSeq = 1 the vehicle transmits a US signal if the vehicle ID matches the usStateSeq timer. It then resets the US timer to trigger the next interrupt. If all three vehicles have transmitted (corresponding to usStateSeq > 3), the program begins the distance calculation to provide the information needed to construct the PVA. If the avionics TT8 is ready to receive the PVA, the data is transmitted over a serial line. Next, the program resets the IR interrupt and allows the IR receiver to trigger that interrupt. Lastly, the US Timer is again reset to trigger the last timer interrupt of the sequence.

Communications Backups



05 December 2002

EMFFORCE - CDR

181



EMFFORCE

Comm: What's next

- Future design implementation
 - Data Handling
 - Archive system on ground station
 - Integrate with Ops
 - Software
 - Optimization
 - Test full interchangeability
 - Network
 - 3- and 4-node network

05 December 2002

EMFFORCE - CDR

182

<JEU>

Communications has the following tasks remaining:

Data Handling: The archiving system needs to be developed and tested on the ground station. Once that is done, it needs to be integrated with the operations GUI and tested. Finally, it everything will be tested as a whole to ensure the entire subsystem works as designed and meets all the requirements.

Software: The ground station software needs to be written. ALL code needs to be optimized to minimize processor time and hard drive space. Finally, the software needs to be tested for interchangeability.

Network: The 3- and 4- node network structures still need to be tested. The 3-node network is expected to be tested and debugged before the end of the term. The 4-node network can't be tested until the ground station software is written and debugged.



Comm Tests

- Test motivations
 - Need to phase in knowledge of communication and network implementation
 - Hardware/software interface between DR2000 and TT8 demanded it
- Test sequence
 - Test software to transmit and receive data
 - Step-by-step unidirectional testing
 - Test software functions written for a single network node
 - Test software to transmit and receive data both ways
 - Step-by-step bi-directional testing
 - Test network implementation
 - Step-by-step addition of network nodes

05 December 2002

EMFFORCE - CDR

183

<JEU>

The communications subsystem has implemented many tests. Most of the tests have been done to aid in learning how the hardware works and how the hardware and software can be interfaced. In this sense, testing must occur to phase in knowledge of the communication and network implementation. Furthermore, early issues with the interface between the DR2000 and the TT8 demanded that careful testing occur.

To implement testing phase in, the following sequence was devised:

Write and test software to transmit and receive data

Write and test software functions for a single network node

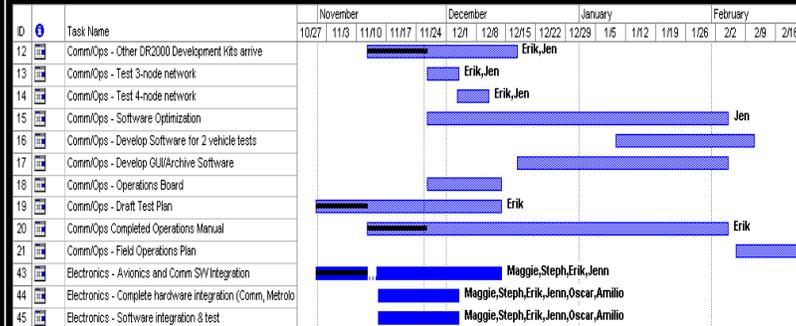
Write and test software to transmit and receive data both ways (need two nodes to accomplish this)

Test network implementation by carefully adding network nodes



EMFFORCE

Comm Schedule



- Schedule for completion of the communications subsystem.
- Software completion currently the greatest risk.

05 December 2002

EMFFORCE - CDR

184

<JEU>

The communications subsystem team has laid out a scheduling plan to catch up on some of the software development that needs to occur. The remaining DR2000 development kits are currently in SPHERES hands. The company assumed that these DR2000s were to be built according to the SPHERES specifications. However, those specifications do not meet EMFFORCE needs. Thus, the SPHERES team is being very generous in making the necessary adjustments before handing them over. The communications team expects the last few DR2000 boards to arrive before the end of the semester.

The communications team hopes to finish testing the 3-node network by the beginning of December. However, recent complications will most likely push this schedule back another week or two to coincide with the testing of the 4-node network. Either way, the team plans to have a working 4-node system by the end of the semester.

Software optimization will be an ongoing project, most likely lasting until the beginning of spring semester. Some optimization work has been accomplished, but the results of the changes will not be known until the end of the semester at the earliest.

In order to facilitate full testing of a two vehicle system, specific software will be written to enable the necessary 3-node network prior to the start of said test.

The Operations lead, Erik Stockham, will be developing the GUI interface and archiving software over IAP in time for full system testing in February. Likewise, Erik will complete the necessary operations electronics board (Vehicle health LED's) by the end of this week. Erik will also be completing the Test Plan and Operations Manual before the end of the semester and the beginning of second term respectively. The Field Operations Plan will be developed after the Test Plan and the Operations Manual are complete.

Avionics and communications software integration has been ongoing. Full integration will not be complete until more of the individual subsystem software has been developed and tested.

Since the communications hardware is more or less complete, hardware integration should occur as soon as the other participating subsystems are ready.



EMFFORCE

Comm Software

- Functions map between arrays (12 bit data) and packets (need bytes)
- Modularity
 - Software functions apply for any vehicle
 - Will enable full interchangeability of vehicles
 - Each vehicle defaults to a node
 - Command packet can assign any node to any vehicle
- Token ring implementation
 - Token = 1 → “I have token”
 - Token = 0 → “I’m passing token”
 - Combined with APID of packet tells vehicle when it should send or listen

05 December 2002

EMFFORCE - CDR

185

<JEU>

The communications software does several things.

First, it contains functions that are capable of “mapping” between the data arrays that avionics is storing to global variables (PVA, MSA, SAA) which are 16 bit element arrays containing 12 bit data, and the data bytes the communications board transmits, which must all be 8 bits.

Second, the software functions will be written such that the software for all the vehicles are virtually identical. Thus, software functions will be as general as possible. Keeping the functions general will help to enable the full interchangeability of the vehicles. The software will be written such that each vehicle defaults as a certain node. The initialization commands can then assign any node to any vehicle, effectively swapping nodes. This can be done by writing sections of the software within loops that will only be tripped by a certain flag.

Third, the software enables the token ring implementation. The token switch (1 for “I have token” and 0 for “I am passing token”) combined with the APID of an incoming packet should be able to tell the vehicle that it has the token. When a vehicle does not have the token, it listens and stores the incoming packets to a buffer. When it has the token, the vehicle decodes the stored packets, saves as data arrays and passes the processor to avionics which does its thing. Once avionics is done, the communications code encodes its packets and transmits them.



EMFFORCE

Comm History

- Hardware
 - Metrics
 - EM rejection (frequency)
 - Bandwidth/data rate
 - Size, weight, power, range
 - Ease of interface
 - Cost
 - Trades
 - LAN vs. RF
 - AC5124C-10 vs RFM DR3000-1
 - Selection
 - RF: DR3000-1
 - Later changed to DR2000
 - Built in data framing and error correction

05 December 2002

EMFFORCE - CDR

186

<JEU>

During the preliminary design phase, the communications team considered 8 metrics to down-select to an appropriate communications board. They were: EM rejection, bandwidth/data rate, size, weight, ease of interface, cost, power consumption, and range. After researching the various high-level options (LAN and RF), it was determined that LAN was less favorable for our system than RF (reference PDR).

The next step was to choose an RF board. The two boards that were originally considered were the AC5124C-10 and the RFM DR3000-1. The AC5124C-10 meets all requirements and even comes with a development kit. However, it's on the expensive side and the company resides in Europe, which may add to shipment time. The power consumption is quite a bit more than that of the DR 3000-1 (which also meets all requirements and comes with a development kit). Finally, the DR3000-1 is familiar to many of the staff as it was used in SPHERES. One possible downside to the DR3000-1 is that some EMFFORCE operations may occur outside of its operating range (but this is unlikely). The brief trades analysis used above determined that the better option was the DR3000-1.

Near the beginning of Fall semester 2002, a better option was found: the RFM DR2000. The DR2000 has built in data framing and error correction and still meets EM rejection, interface, range, bandwidth/data rate, size, weight, and power consumption requirements. It also comes with it's own development kit. Built-in error correction has significantly decreased the amount of development and test time of the communications system. One downside is that it costs more per board than the DR3000-1.



Comm History

- Architecture (assumed 2 RF channels)
 - Trades
 - Sequential
 - Pass token to determine who talks and to whom
 - Hub makes calculation
 - Simultaneous
 - Pass token to determine who talks to everyone
 - All vehicles make calculations
 - Hybrid
 - Combination of Sequential and Simultaneous
 - Selection
 - Hybrid with 2 RF channels
 - Later changed to simultaneous with 1 RF channel
 - Control decision
 - Need only 1 channel

05 December 2002

EMFFORCE - CDR

187

<JEU>

There were originally two communication lines since it was thought that in order to maintain autonomous formation the hub and the ground station had to communicate independently.

Sequential: The vehicle that has the token communicates to the hub vehicle on the second communication line while the remaining vehicle is silent and awaits its turn. Once the vehicle with the token completes its communication, the hub takes the token and passes it to the other vehicle. Once the states have been collected, the hub makes control calculations and broadcasts the state updates.

Simultaneous: The vehicle with the token communicates to the hub and the third vehicle simultaneously (broadcast) on the second channel while they remain silent (channels are half duplex). The token is then passed to third vehicle, which broadcasts its information over the second channel. Then the token is passed to the hub which communicates its information to the other vehicles. Finally, all vehicles make control calculations independently and move accordingly.

Hybrid: The token is passed exactly as described for the simultaneous architecture. All vehicles make independent control calculations. The hub is the only vehicle to transmit the new state vector. If there is a disagreement between any vehicles on the new state, steps can be taken to determine the correct new state.

Originally, the decision was to use the hybrid architecture with 2 RF channels because it met the control subsystems requirements as they were known at that point. It was later determined that only 1 RF channel was necessary. The control subsystem team then decided that the vehicles would be fine operating independently. At that point, the architecture moved more toward a simultaneous network design with 1 RF channel, with the ground station as a member of the token ring

Control Backups



05 December 2002

EMFFORCE - CDR

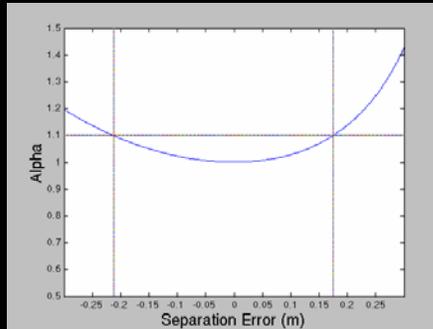
188



Separation Error Requirement

- Create a performance measure α where:

$$\alpha = \frac{\text{non-linear}}{\text{linearized}} = \frac{1/\left(1 + \frac{\delta r}{r}\right)^4}{1 - 4\frac{\delta r}{r}}$$



05 December 2002

EMFFORCE - CDR

189

<BAB>

This slide shows our mathematical derivation of the maximum separation distance at which our modeling assumptions, mainly that the higher order terms are small, still hold. To accomplish this we create a performance measure, α , such that it calculates the ratio of the non-linear force to our linearized model. When this ratio is 1.1 the non-linear force is 10% greater than the modeled force. It is at this point where we say that the assumption does not hold and draw the requirement. We chose 15 cm, a separation error smaller than the graph indicates, as the requirement. The Control team feels while the requirement is generous yet valid since it indicates less than 10% error in our model.



EMFFORCE

Lessons Learned from Modeling

- For all test cases, except for spin-up, one vehicle had to have a constant field on both magnets
- The number of state variables and control variables increases when a vehicle is added or when a fixed vehicle is freed

05 December 2002

EMFFORCE - CDR

190

<BAB>

The first lesson we quickly learned is that without holding a constant field on one of the magnets the system is not controllable. In this case the vehicles would be placed on the testbed without any initial field in the magnets. As the system is disturbed, the magnets have no field on which to push or pull and thus have no means by which to hold their position. Both dipoles must be energized because one cannot achieve motion in two dimensions with only one dipole energized. For the purposes of modeling, we made the horizontal magnet's magnitude ten times that of the vertical magnet.

The next lessons we learned is that the further we got into modeling the test cases the larger the state and control vectors got. This growth was caused by either of two reasons: increasing the number of vehicles on the testbed or freeing up a formerly fixed vehicle. Increasing the number of vehicles naturally leads to more states because the state of the new vehicle – x , y , and θ – have to be accounted. In addition, it also leads to more control variables since now there are two more magnets and an extra reaction wheel the controller can use to control the system. Freeing up a fixed vehicle allows that vehicle to move making the x , y and θ states important. It also allows that vehicle's reaction wheel to have an effect on the vehicle's motion adding a new control variable.



EMFFORCE

Increase in states demonstrated

- For test cases 2a and 2b

$$\dot{\underline{x}} = A \begin{bmatrix} x_A \\ y_A \\ \theta_A \\ \dot{x}_A \\ \dot{y}_A \\ \dot{\theta}_A \end{bmatrix} + B \begin{bmatrix} \mu_{A1} \\ \mu_{A2} \\ \alpha_A \end{bmatrix}$$

- For test cases 2c and 2d

– Increase in states and control variables

$$\dot{\underline{x}} = A \begin{bmatrix} x_A \\ y_A \\ \theta_A \\ \theta_B \\ \dot{x}_A \\ \dot{y}_A \\ \dot{\theta}_A \\ \dot{\theta}_B \end{bmatrix} + B \begin{bmatrix} \mu_{A1} \\ \mu_{A2} \\ \alpha_A \\ \alpha_B \end{bmatrix}$$

05 December 2002

EMFFORCE - CDR

191

<BAB>

This slide shows the state and control vectors for test 2a and 2b and contrasts them against the vectors for test 2c, 2d, and 2e.