Non-Advocate Review

October 3, 2002
Space System Product Development Class
Department of Aeronautics & Astronautics, MIT
Electro Magnetic Formation Flight Of Rotating Clustered Entities

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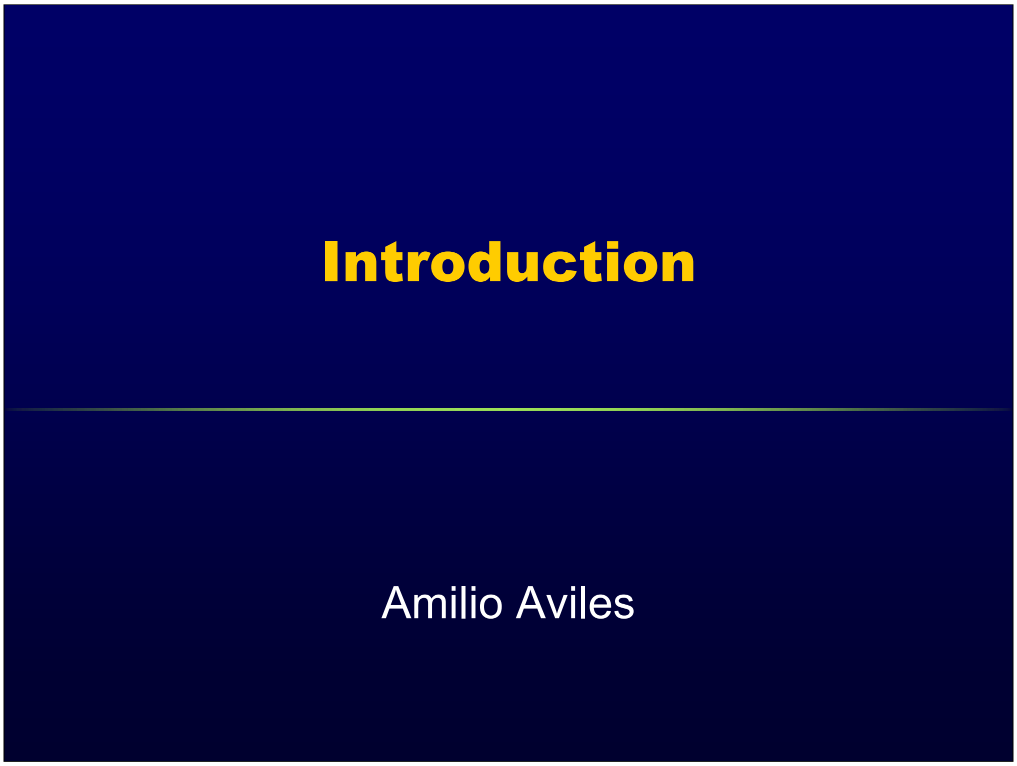
Welcome to the Non-Advocate Review for project EMFFORCE (Electro Magnetic Formation Flight of Rotating Clustered Entities).



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<NAME> will be giving an introduction for the presentation. She will address the mission statement as well as background and motivation for the project, provide a brief requirements summary, and then give an overview for the rest of the presentation.

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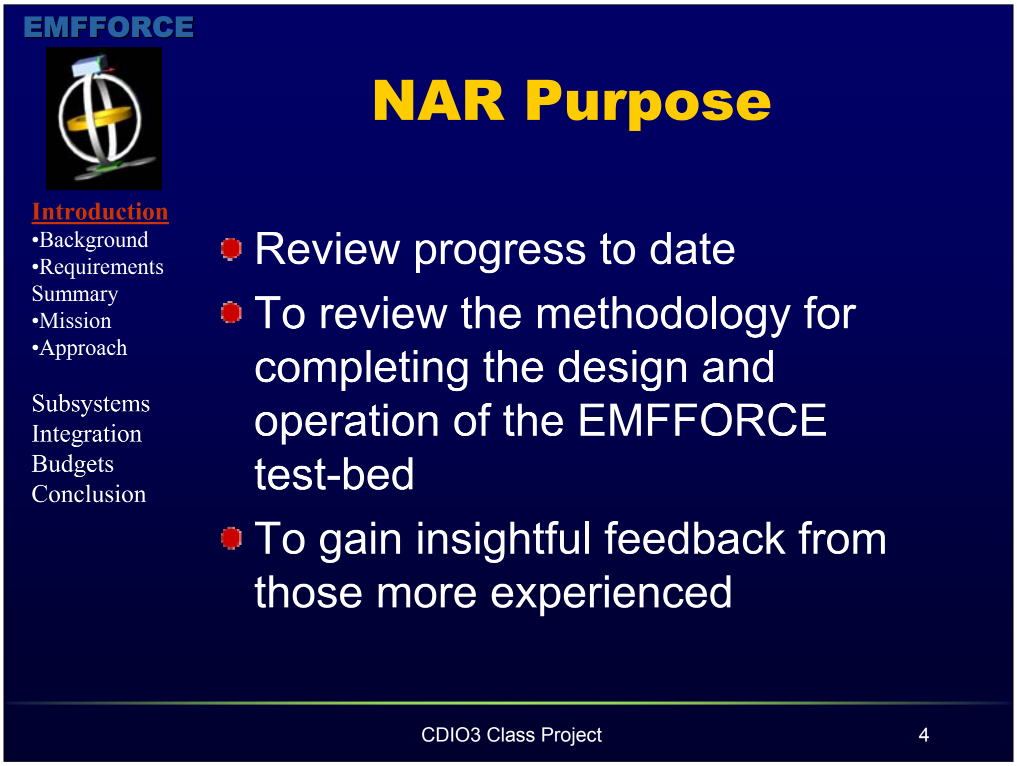
After the Trade Analysis and Requirements Review in March, 2002, the Space System Product Development Class split itself into four groups before embarking on the design process. These groups, as listed above, were further split into smaller teams responsible for the following; (actuation) electromagnet, reaction wheel, (formation flight) metrology, control, (electronics) avionics, communications, (structure/power) structure, and power design. The three-member systems group is comprised of one member from three of the four groups at any given time. The members of this group are on a seven and a half week rotation. The governing team, therefore always has two experienced members. All groups also have a liaison to the rest of the class and sub-system groups. This sub-system/systems group structure will remain for the rest of the EMFFORCE project.



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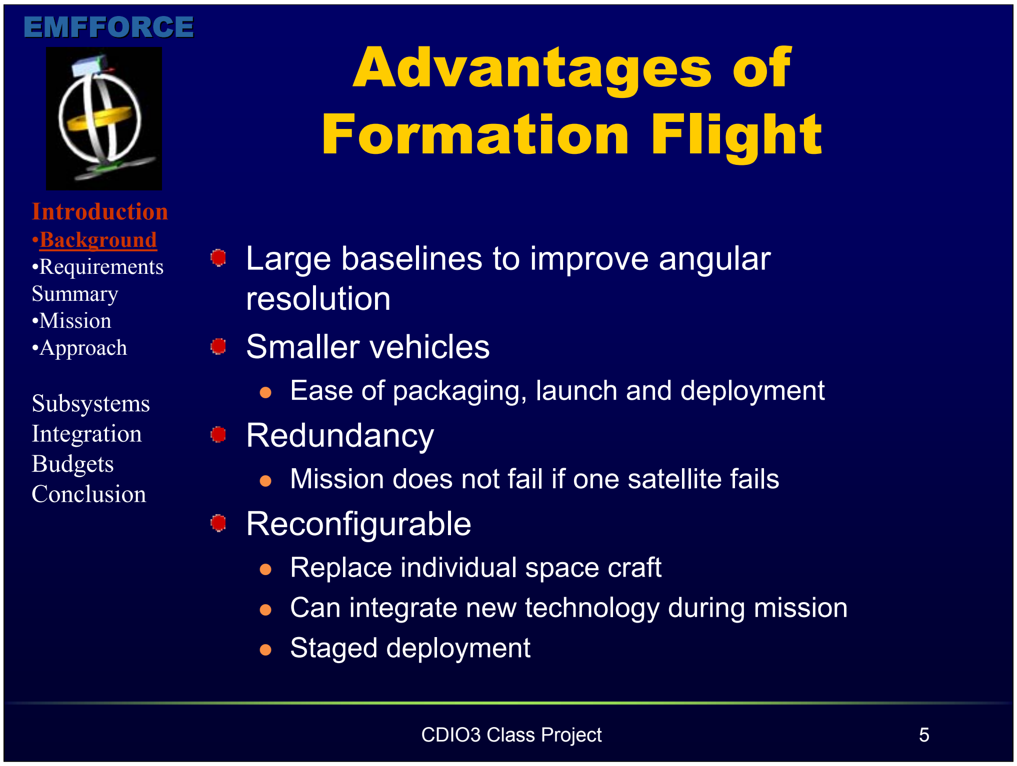
The purpose of the NAR presentation is



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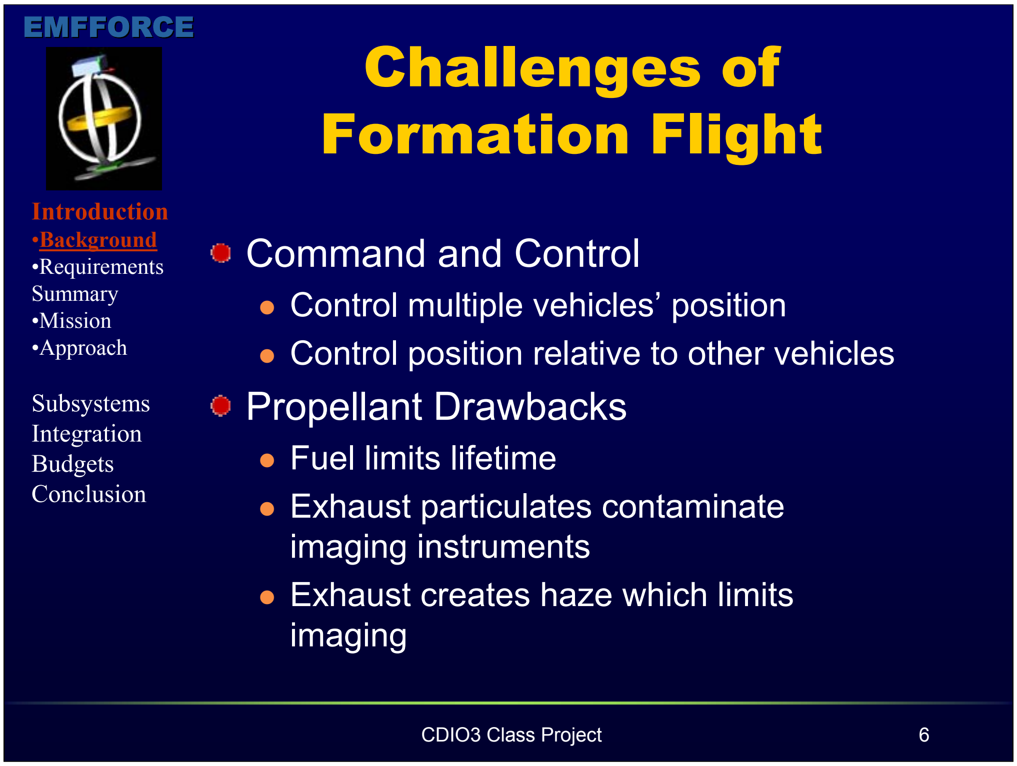
Advantages of formation flight include higher resolution with smaller vehicles. To achieve similar resolution would be much more costly with one large vehicle rather than with more than one formation flight vehicles. The smaller vehicles also prove easier to pack launch and deploy. Not only do formation flight satellites allow for failure, continuing the mission with few satellites when one breaks down; these systems also allow for new technologies to be integrated in to occurring missions.



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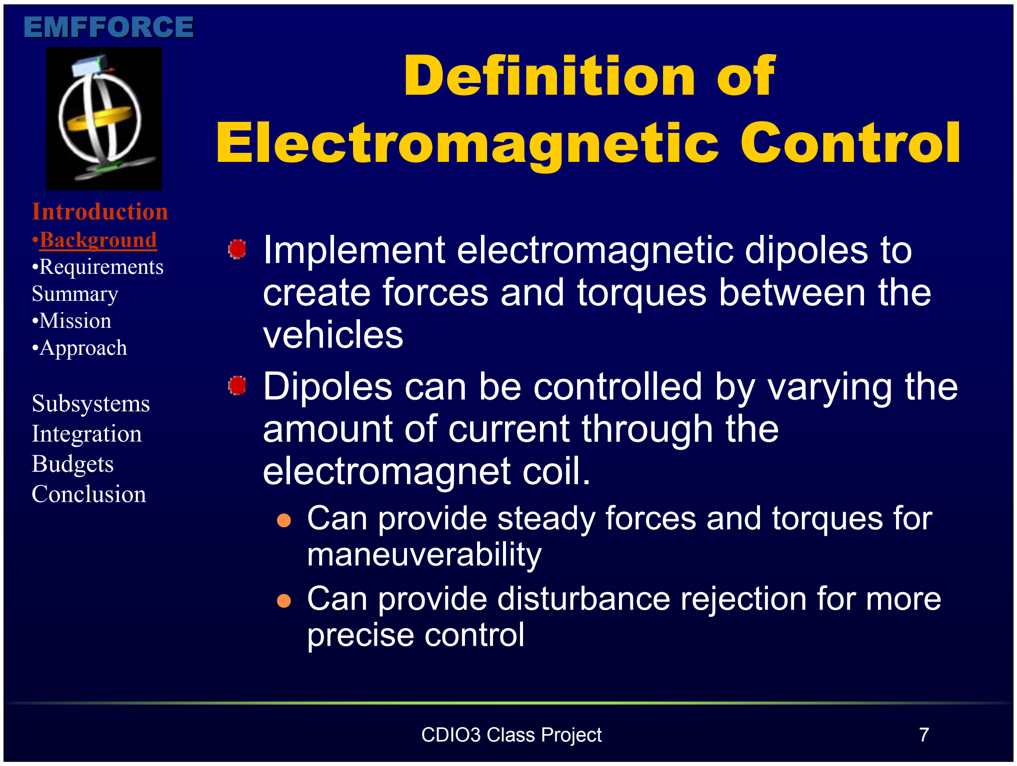
In current formation flight done with thrusters, the propulsion system actuates each vehicle with inertial degrees of freedom, however for formation flying satellites, in order to remain in formation the satellites should also be able to actuate their relative position/motion to other satellites.

There are also many drawbacks to the use of propellants. Not only does the amount of fuel limit the lifetime of the mission, but exhaust particles can contaminate and damage imaging equipment (contact contamination) as well as create a haze of pollution that the telescope must look through (radiative contamination).



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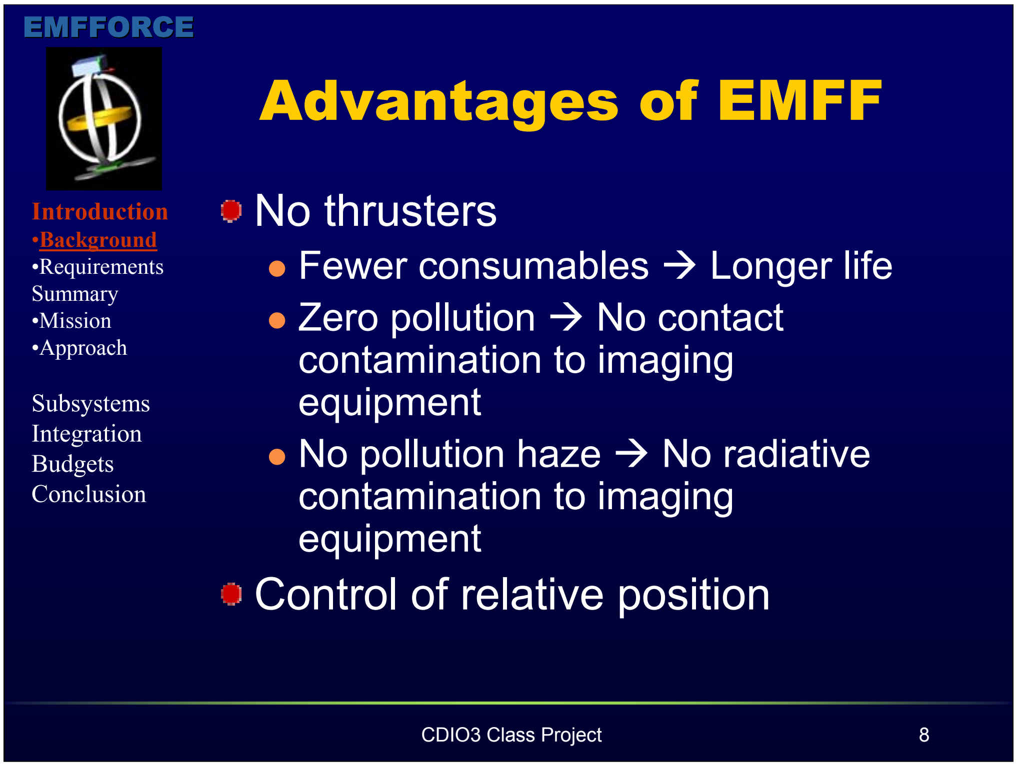
Electromagnets will create dipoles that will provide the "thrusting" forces and torques between vehicles. The strength of dipoles can be controlled by varying the amount of current through the electromagnet coil. Control of the dipole strength as well as direction (rotation of magnet) can provide large forces for maneuvering as well as small disturbance rejection for more precise control.



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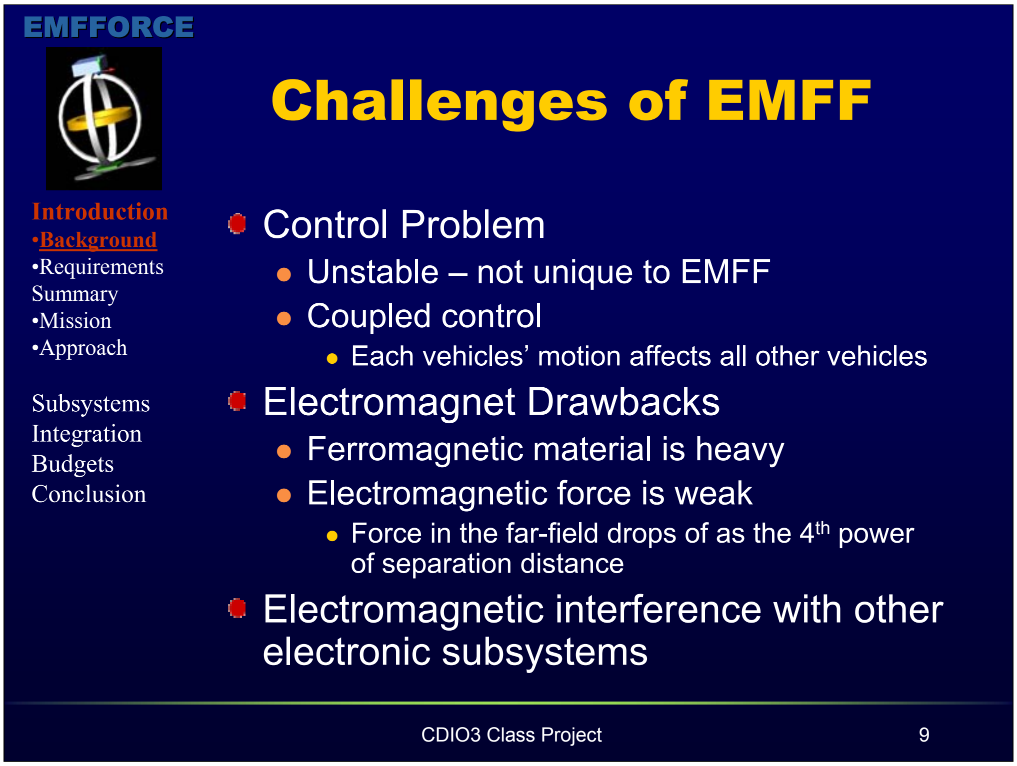
In order to overcome the challenges of formation flight as described before, the MIT Space Systems Laboratory (SSL) has begun the investigation of elector-magnetic formation flight.

Thrusters and their propellants impose many of the undesirable aspects of current formation flight. EMFF, because it does not use propellants, will not have a lifetime limited by the amount of fuel on board, nor will contact contamination or radiative contamination be a problem. Since formation flight requires precise relative control EMFF leads to better control because EMFF controls the relative position instead of the absolute position.



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One of the current challenges faced with EMFF is the control problem. Due to the rotation of formation flight systems the control problem becomes unstable and complex. Although this is not unique to EMFF, when paired with the coupled control problem of relative motion the control system of EMFF becomes increasingly complex.

There are also many drawbacks to the electro-magnet itself. The magnetic material is very heavy, and the magnetic force is weak. The force drops off as the 4^{th} power of the separation distance in the far-field. The electro-magnet also potentially interferes with other subsystems on board the system.

EMFFORCE

Customer Requirements

Introduction
- Background
- **Requirements Summary**
- Mission
- Approach

Subsystems
Integration
Budgets
Conclusion

- Three vehicles
- Representative Formation Flying Vehicles
- Control to replace thrusters
- Control four DOF
- Robust controller
  - Disturbance rejection
  - Reposition vehicles

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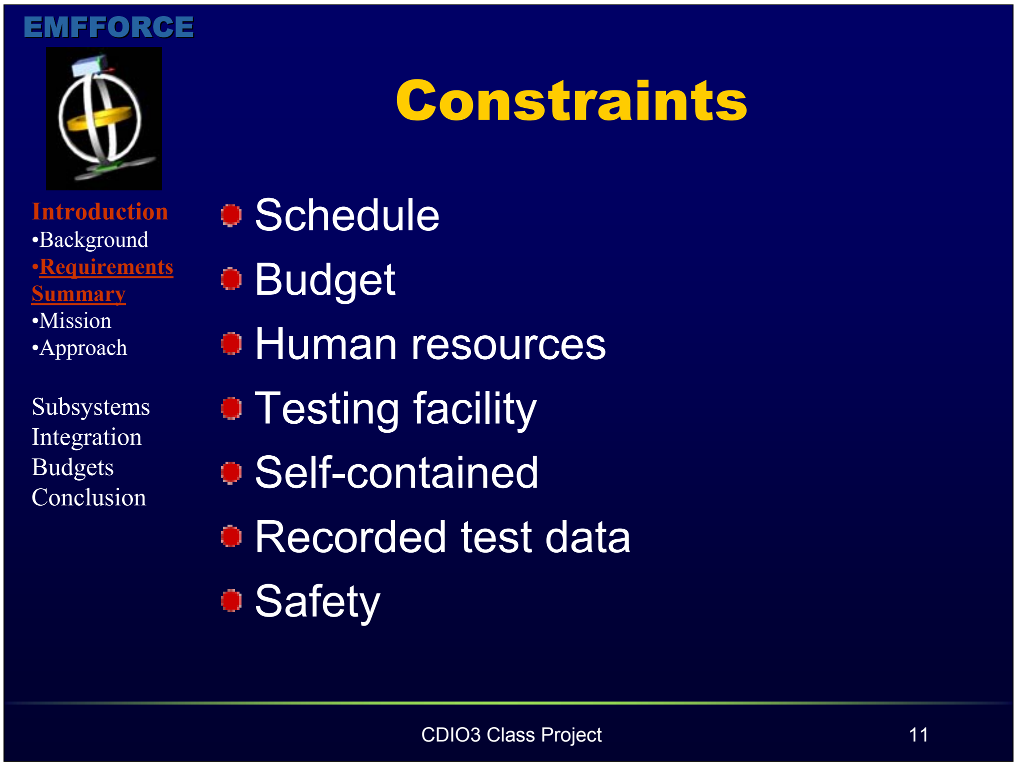
The Customer Requirements are derived from the Executive Summary EMFF Proposal by MIT SSL, and the Technical-Management Proposal by MIT SSL and Lockheed-Martin ATC. This project must show representative formation flying maneuvers to demonstrate the feasibility of using electromagnetic control for actual space missions. More specifically, this includes showing dynamically changing formation geometries and replacing failed formation elements. Because this project is to demonstrate an alternative to thruster control, no thrusters may be used. The vehicles must control in four degrees of freedom. Finally, the controller must counteract any disturbance force, be able to reposition satellites within the formation, and generate restoring forces necessary to maintain stability.



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•The system must be designed, built, and tested by May 2003.

•There is a financial cap of $50,000.

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

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

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

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

•Safety must be preserved at all levels of work throughout the project timeline. This includes safety of the people, the system, and the test facility.

EMFFORCE

System Functional Requirements

Introduction
- Background
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Musts:

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

Shoulds:

- Representative 5 rotation maneuver
  - One rotation spin-up, 3 rotations steady state, and one rotation spin-down
- Operate in the far field

CDIO3 Class Project 12

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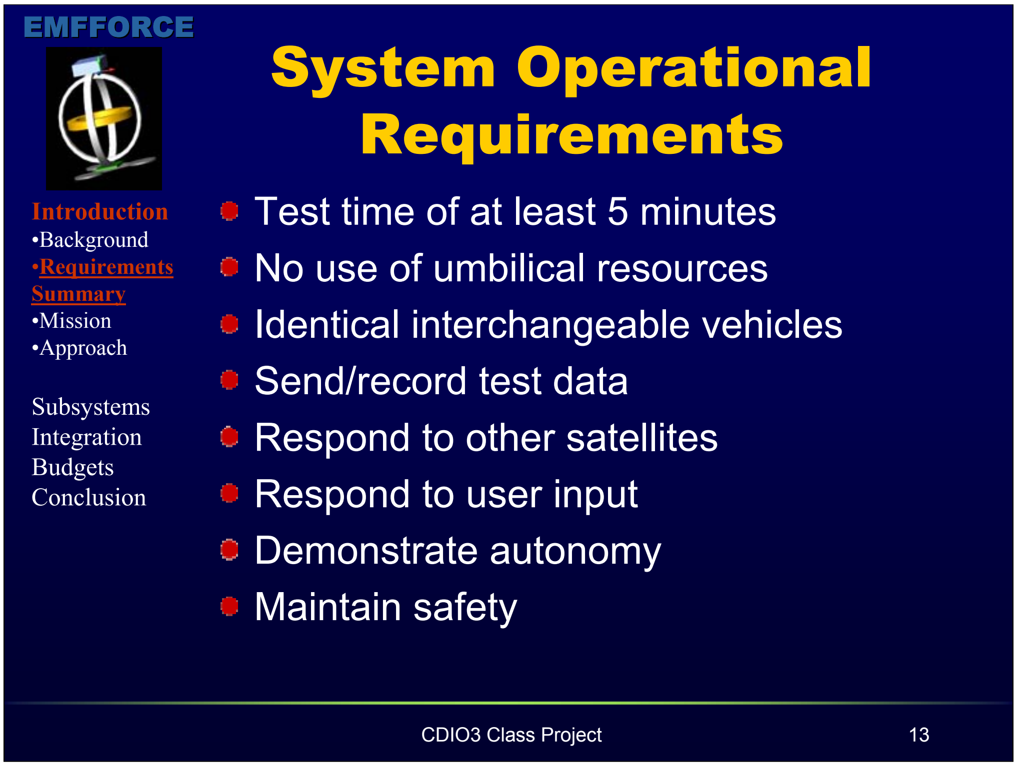
•The system must demonstrate stable maneuverability using at least three vehicles. This will facilitate translation to more vehicles. Control each relative system degree of freedom implies the system must be demonstrated in 2 dimensions with identifiable transition to 3 dimensions. Also, it cannot control absolute motion of center of mass.

• The system should complete a representative five-rotation system maneuver. This maneuver will include one rotation for spin-up from rest to a separation distance of at least 2 meters. Then, it will complete three rotations at a constant angular rate of 6 degrees of arc per second for a 2 meter separation distance. This comes from a desired angular rotation rate of 1 rpm. Finally, it will have one rotation to de-spin to rest. The system should operate in the far field of EM control, which currently implies a separation distance of at least 10 times electromagnet length.



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•The system shall operate without needing recharged batteries or gas resupply for a period of time useful to perform several tests.

•Operate with no external umbilicals means the power supply must be on-board, wireless communication must be used, and all other resources (such as gas supply) must be self-contained.

•Each vehicle must be identical to the others in the system. This allows mission flexibility in that each vehicle can perform any task. Also, the vehicles must be able to be replaced. Identical vehicles allows for easy replacement, as well as cost efficiency through standardized parts.

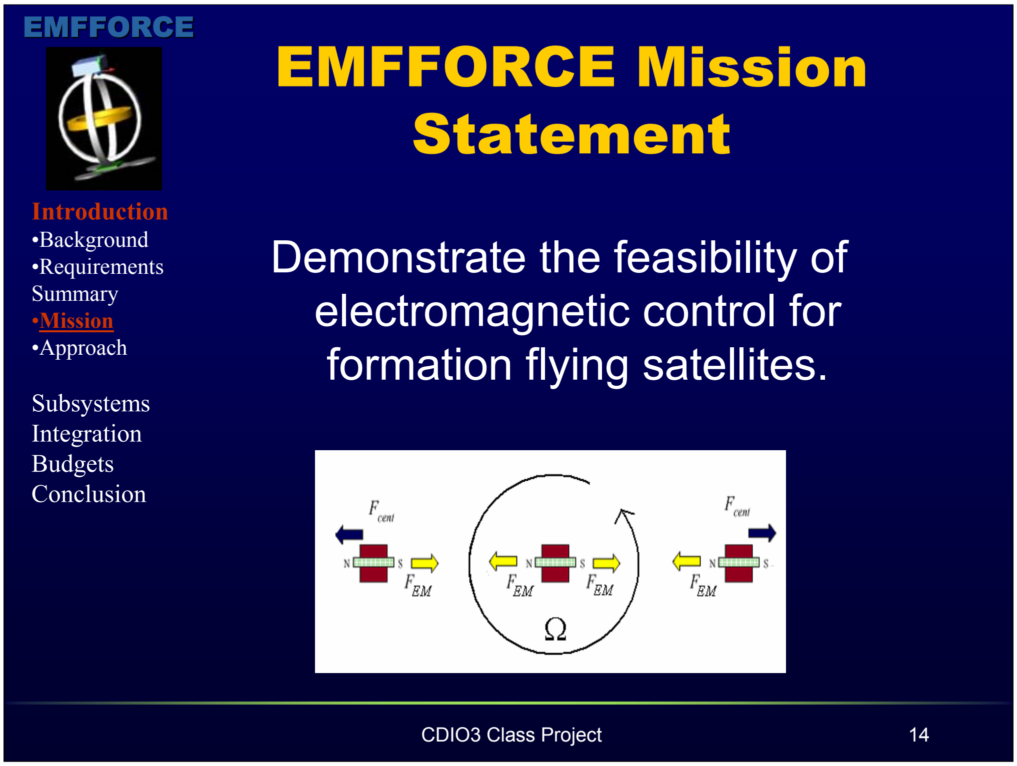
•Each vehicle shall record flight data including position and health. The data will be sent to a ground station for inflight analysis, as well as recorded for later download and analysis.

•The system shall respond to other satellites in formation in real time at a distance of at least 2 meters to demonstrate far field, but no greater than 8 meters due to size of testing facility.

•The system shall respond to user input from a ground station within 0.1 seconds.

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

•The system must not be damaged during testing, nor damage the testing facility.



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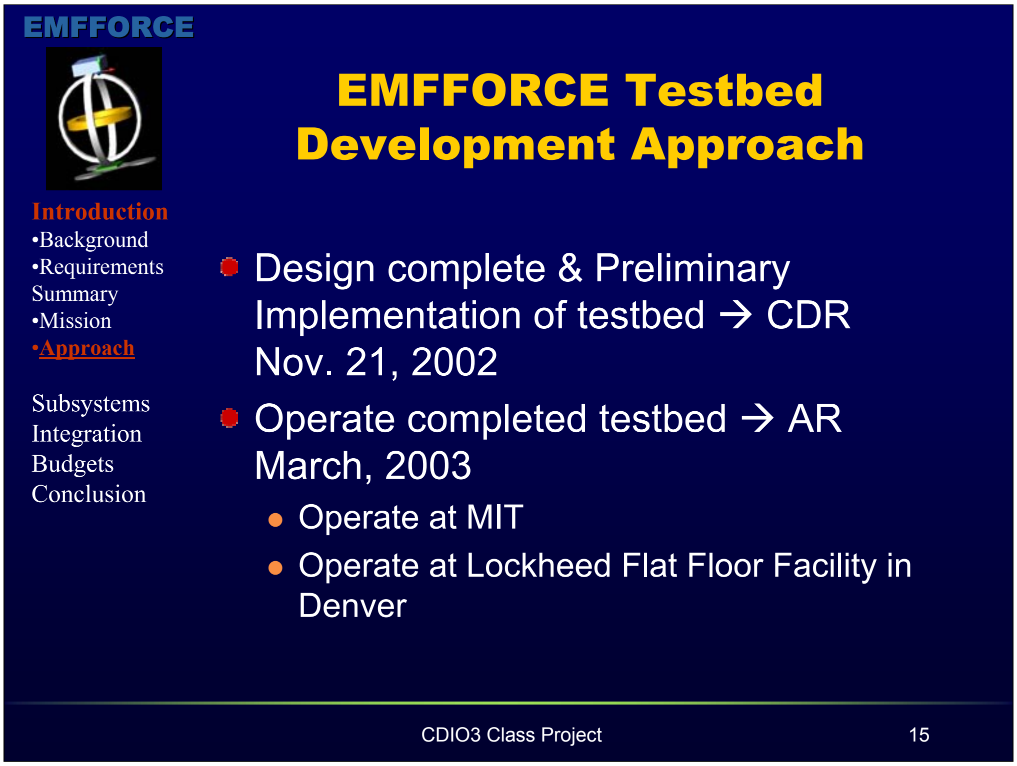
The mission statement as stated above implies that Project EMFFORCE aims to operate a formation flying testbed which represents real world applications. Therefore a 2-D operational testbed must be translatable to a 3-D operational testbed. Electromagnetic control implies the design and implementation of a controller using no thrusters but instead coupled electromagnetic forces as well as angular momentum storage.



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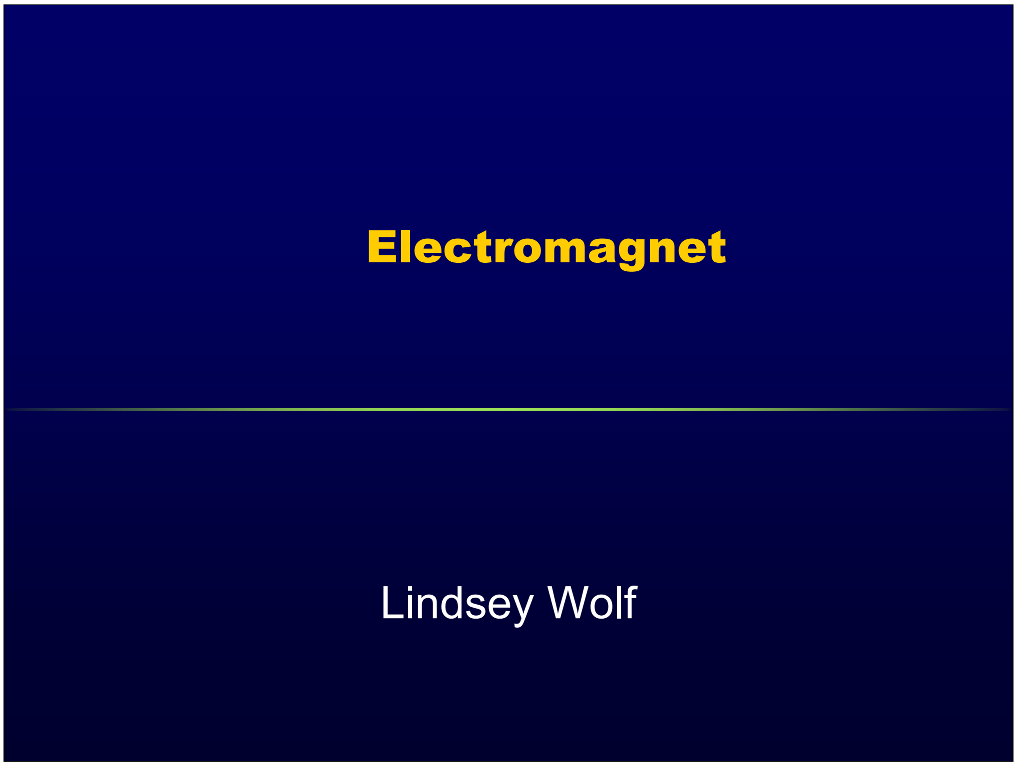
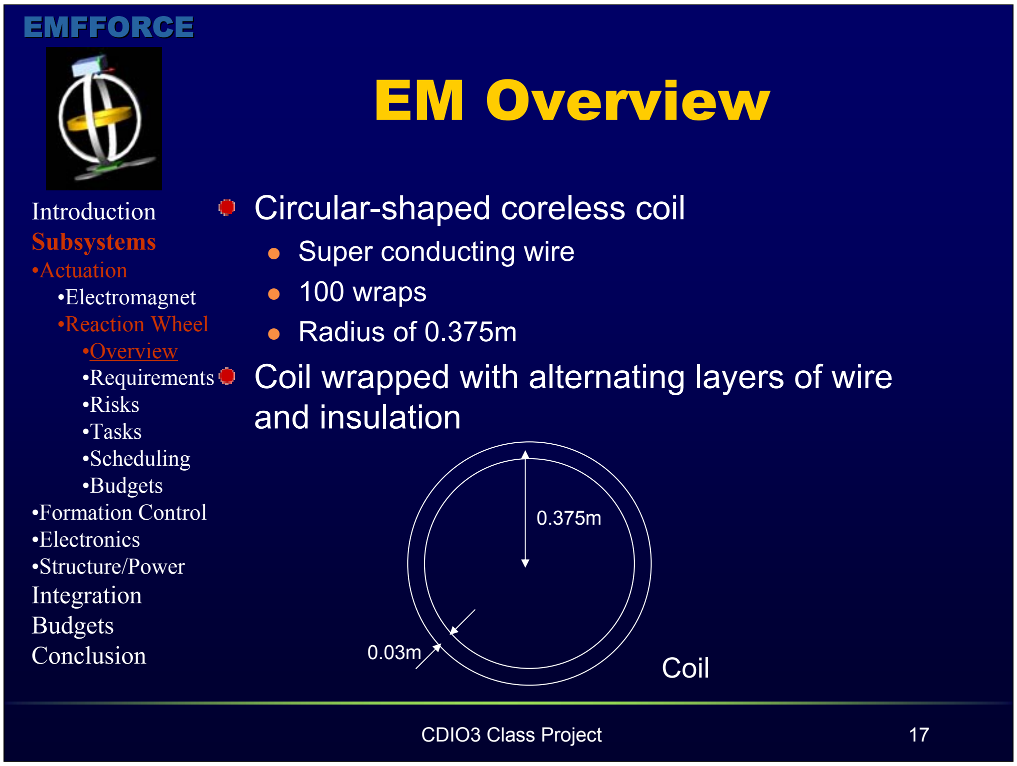
To complete the implementation and the operation of the test bed, the design class hopes to follow the above approach. Today Project EMFFORCE presents a Non Advocate Review of their progress thus far. In November 2002 they hope to have built a prototype and will present their Critical Design Review, and after the Acceptance Review in March 2003, the class will operate the accepted test bed at the Lockheed Flat Floor Facility in Denver, Colorado.



<JEU>

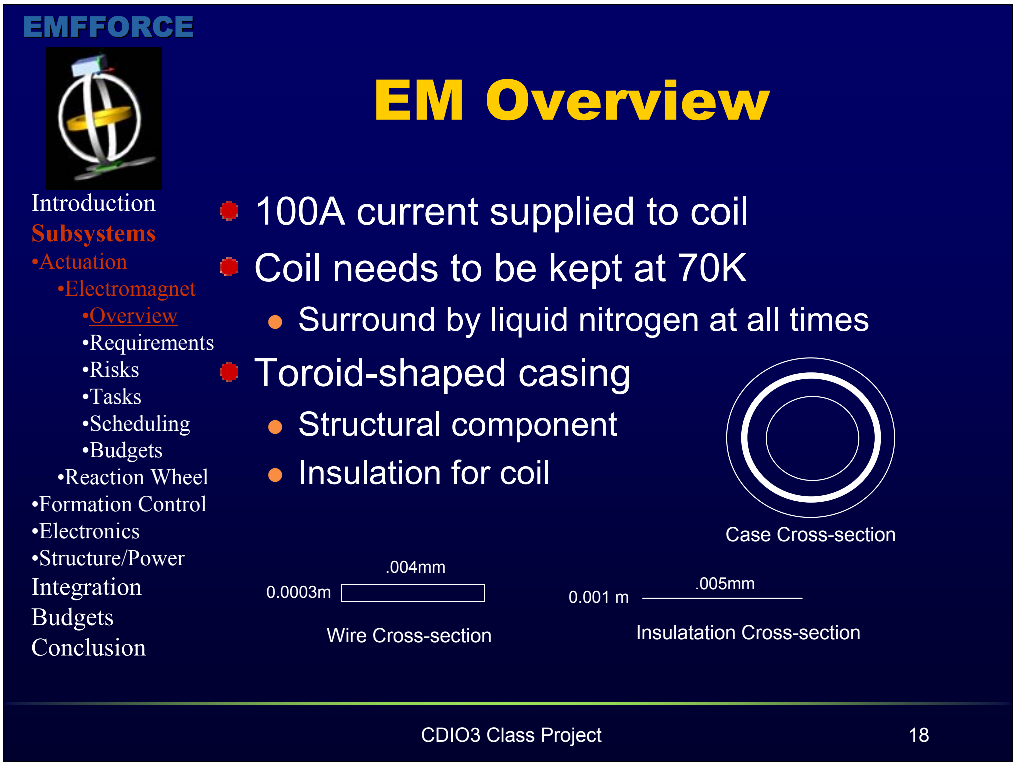
Welcome to the Actuation Subsystem section of the NAR presentation. Lindsey Wolf will present.



<JAB, MSW, LLW>

The geometry of the coreless electromagnets is shown above. Because two magnets will be placed perpendicular to each other with their centers about the same point, the radii of both coils cannot be the same. One coil will have a radius of 0.375m, while the other will have a radius of 0.345m (the maximum allowable radius to fit inside the larger coil).

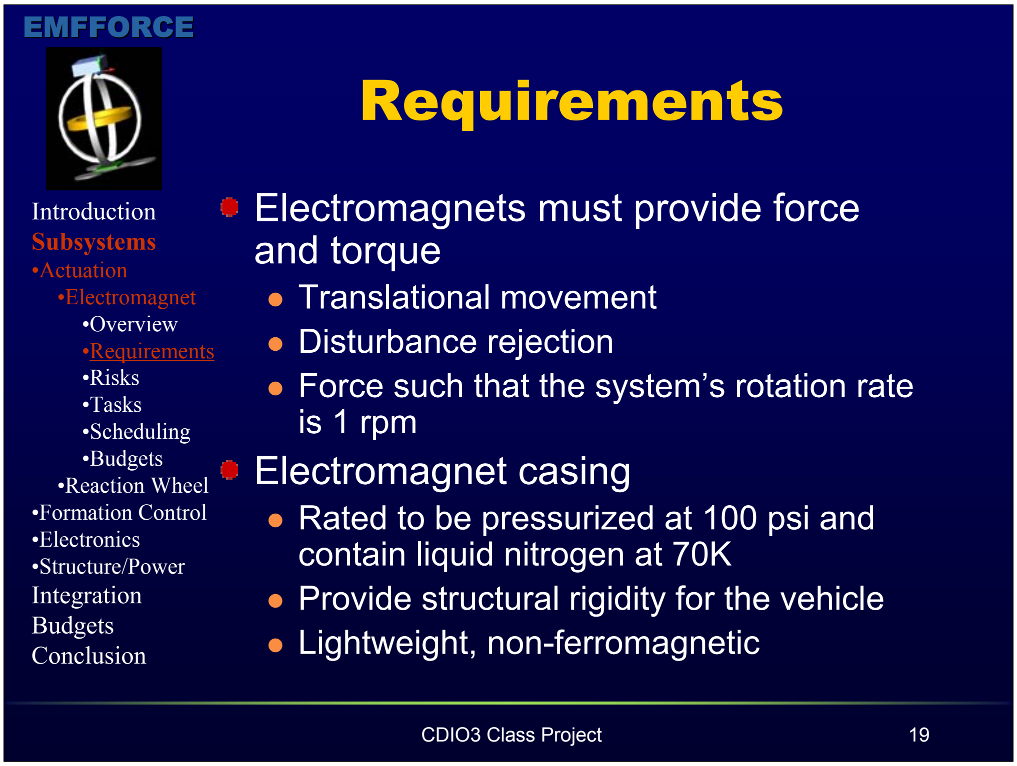
The super conducting wire does not come already insulated. Therefore, insulation must be provided so the magnet doesn't short circuit. Insulation for the wire will be provided by thin layers of Kapton between each wrap of super conducting wire.



<JAB, MSW, LLW>

The super conducting wire is capable of handling large currents. 100 Amps is the amount of current required produce the force necessary to keep the vehicles spinning in steady-state, at 2 rpm.

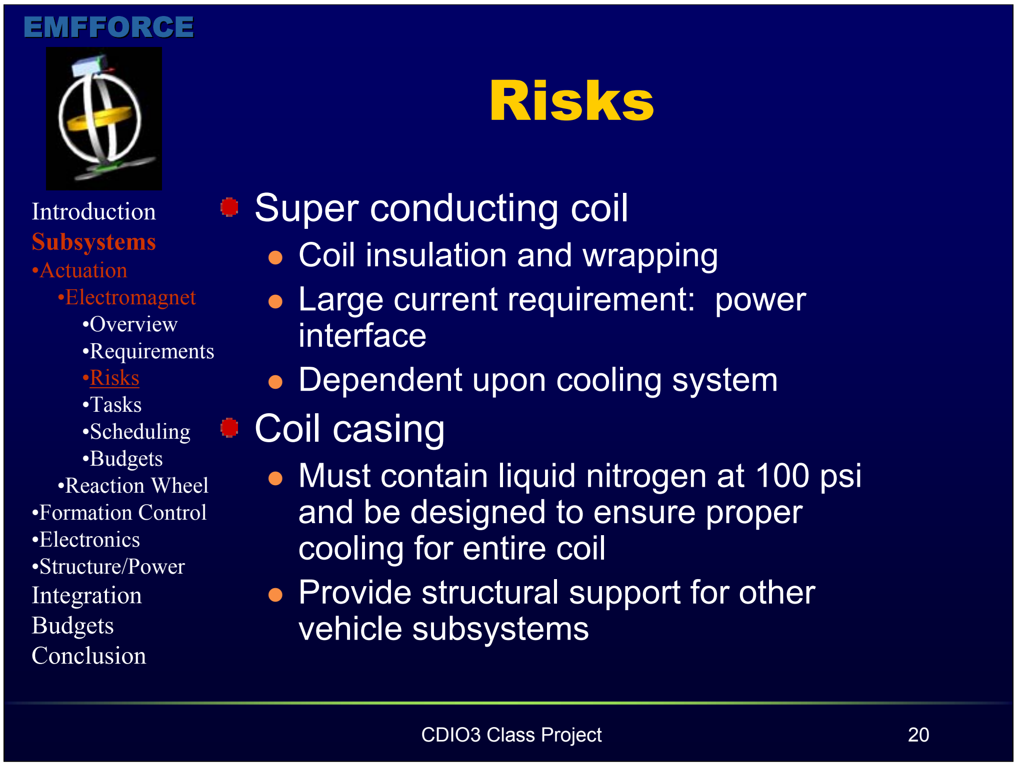
To keep the coil at an operable temperature, it must be continuously cooled. The magnet casing essentially provides a constant liquid nitrogen bath for the magnet. The magnet casing is also the method by which the magnets are attached to the structural frame of the vehicles.



<MSW, JAB>

The electromagnet should provide force and torque for disturbance rejection as well as translational movement such that the system can maintain a rotation rate of 1 rotation per minute.

Since the electromagnet coils will be made of superconducting material that will only superconduct below 77K, the superconductor must have a cooling system. The electromagnet casing must be designed to encase the superconducting coils in liquid nitrogen (70K) at 100psi. Additionally, the casing must provide structural rigidity for other subsystems to mount to. It should be designed to minimize mass and also must be non-ferromagnetic so as not to interfere with the field created by the superconducting coils.

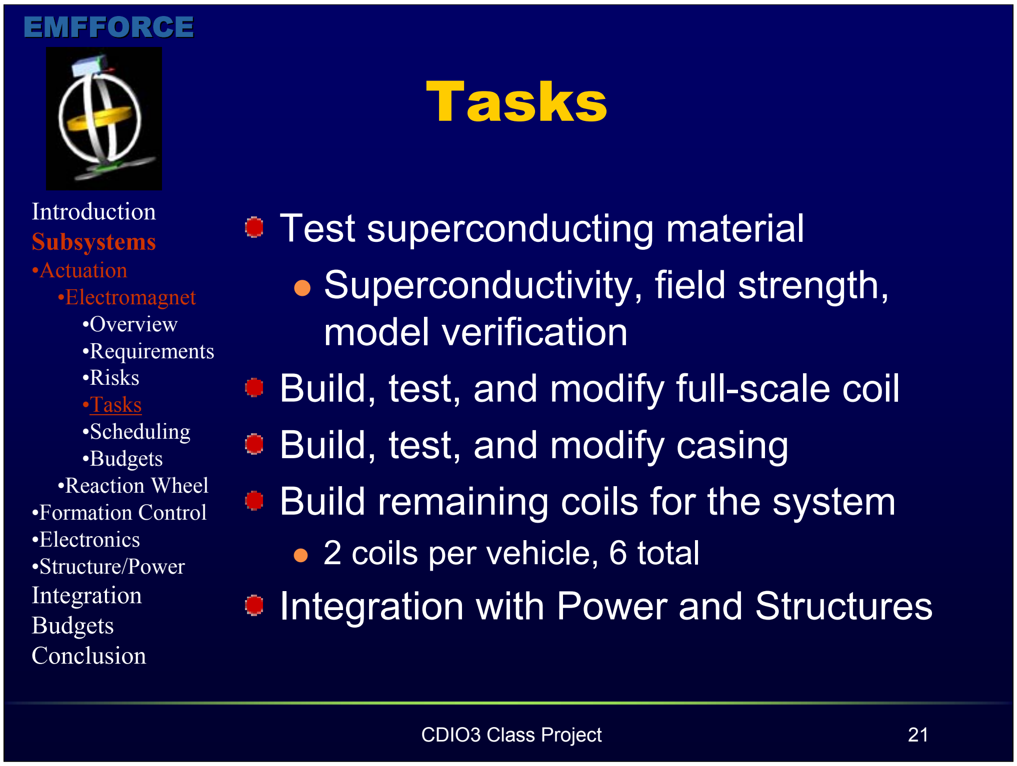


<MSW, JAB>

Using superconductor material for the electromagnet poses several risks:

The superconductor does not come from the manufacturer with insulation. The EM Team has tested Kapton as an insulator with the test sample of superconductor, and it currently seems like the most viable option. The specific type of Kapton as well as adhesive options for Kapton needs to be investigated to determine what will be used for the final design. Additionally, the EM Team needs to consider how it will safely and efficiently wrap the coils. The superconducting material cannot be bent beyond a turn diameter of 100 mm and must be handled carefully. The method of wrapping (i.e. using a spindle, by hand, etc.) as well as the configuration (single stack, multiple stacks) must be considered. Since the superconductor can handle and will be designed to run high levels of current, the EM Team must carefully discuss interfacing with the Power Team to ensure that the current requirement can be met safely.

The casing must be designed such that the coil can be kept below 77K or else there will be resistance within the wire (no longer superconducting). The casing should be designed to enclose the coil in liquid nitrogen at 100psi and should allow for the liquid nitrogen to cover a large enough surface area of the coil to ensure proper cooling. Since the coil casing may be used as the vehicle structure, it must provide structural support for the mounting of other vehicle subsystems while meeting requirements.



<MSW, JAB>

The tasks for the EM team include:

1. Testing the superconducting material to see that it behaves as a superconductor with zero resistance in the liquid nitrogen bath. Additionally, current must be run through the coil to provide data for field strength to verify models for the coils. **Note: This experimentation has already been conducted; the superconductor had zero resistance in the liquid nitrogen bath, and the field strength measurements corresponded to our model.

2. After testing the sample material, the EM team will build one full-scale coil to test wrapping techniques, configuration, and field strength. If necessary, modifications will be made and tested.

3. The casing for the superconducting coil will be built and tested then integrated with the full-scale coil. Modification and testing will be conducted.

4. The remaining coils and casing will be built based on the first coil. Currently, each vehicle will contain 2 coils for a total of 6 coils. Since the first coil has already been built, only 5 additional coils need to be built, encased, and tested.

5. The coils will be integrated with the power team to provide the current for the coils. The casing will be used as the vehicle structure.

EMFFORCE

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•Formation Control
•Electronics
•Structure/Power
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START	END	TASK
26SEP	8OCT	Test superconductor material, determine sizing for coil
10OCT	17OCT	Build and test 1 full-scale coil
10OCT	24OCT	Build and test electromagnet casing
17OCT	17OCT	Order superconductor for system (5 additional coils)
24OCT	7NOV	Build and test casing for additional coils
24OCT	7NOV	Build and test system coils
7NOV	14NOV	Coil, casing integration
14NOV	21NOV	Power integration
21NOV	13DEC	Structures integration
4FEB	13MAR	System testing, integration, modification
13MAR	31MAR	Preparation for field testing
31MAR	3APR	Field Testing 1
3APR	21APR	Modification
21APR	24APR	Field Testing 2

CDIO3 Class Project 22

<JAB, MSW, LLW>

This table tracks the work schedule of the EM team from the present to the projected end of the project.

The first priority is to make a full-scale coil using the super conducting wire. The testing of the first full-scale coil will be conducted in a liquid nitrogen bath, as the casing for the magnet will not yet be made.

The schedule plans to have the EM system ready for integration with other systems by CDR on November 21.

EMFFORCE

EM Budgets

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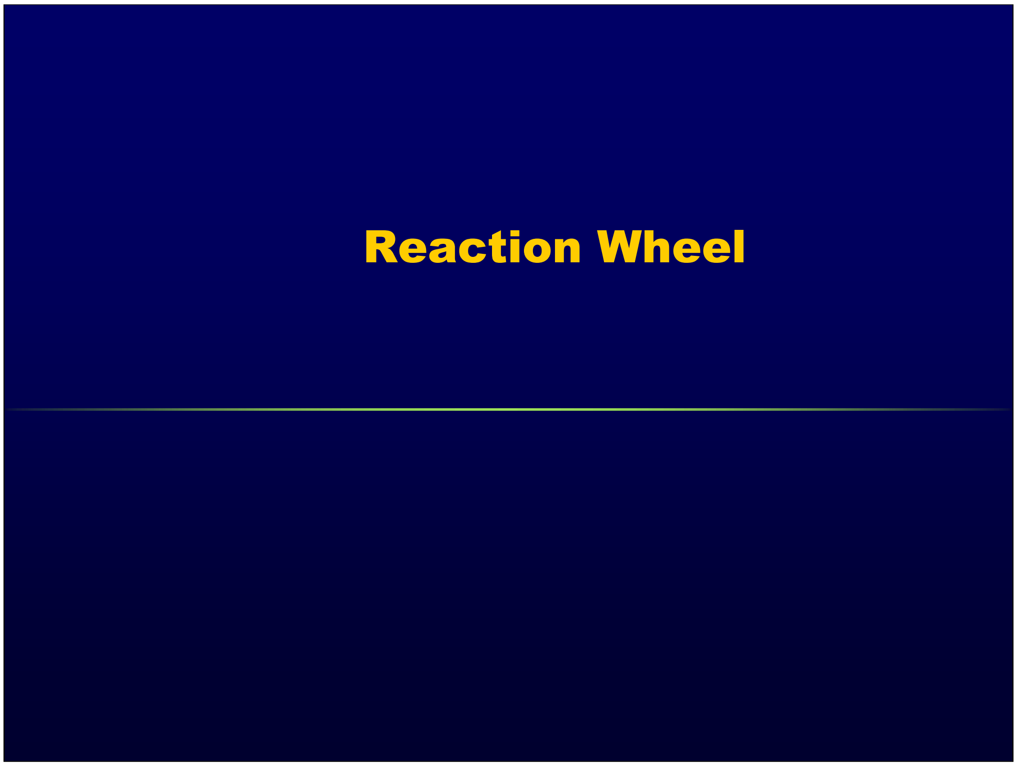
Part	Qty	Cost ($)	Mass (kg)	Power (W / V)
Super Conducting Wire	2	5860	4.6	N/A
Coil support and N_2 container	2	400	2	N/A
Total (per vehicle)		6260	6.6	N/A
Misc.				
Total (per system)	6	18780	19.8	N/A

CDIO3 Class Project 23

<JAB, MSW, LLW>

Cost, mass, and power budgets are given in the table above. Each vehicle has two super conducting wire coils at a cost of $2930 and 2.3 kg each. Each coil requires its own casing at a cost of $200 and 1 kg each. These components give the total system budget values given above.



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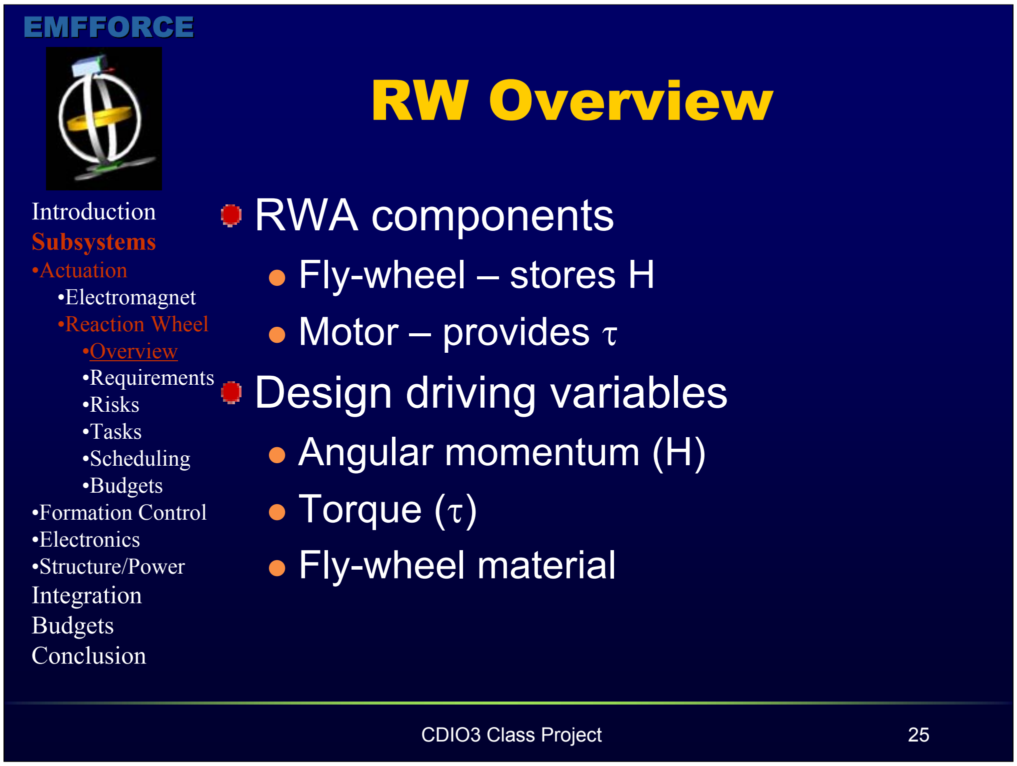
Welcome to the Actuation Subsystem section of the NAR presentation. Lindsey Wolf will present.

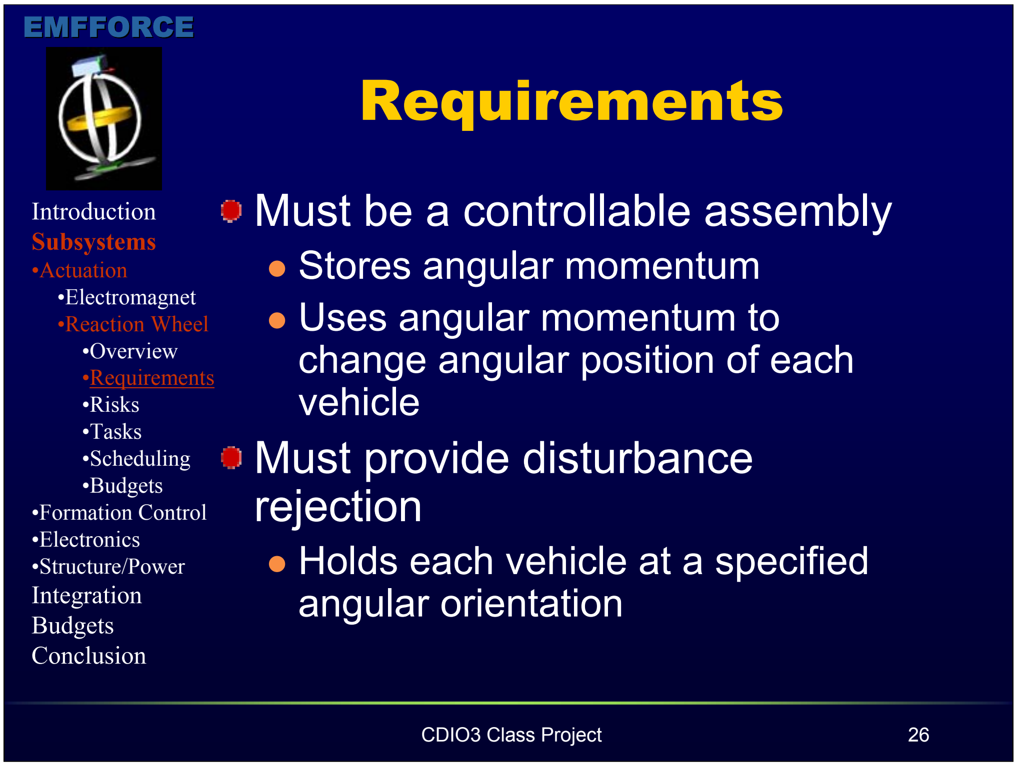


<WDF, LLW>

The Reaction Wheel Assembly consists of two major components. First, a fly-wheel which will be spun to serve as an angular momentum storage device. Second, the assembly has a motor which spins the fly-wheel and also provides the torque on each individual vehicle necessary to control the vehicles angular position.

There are two main design-driving variables: angular momentum and torque. Angular momentum stored in the fly-wheel must balance the angular momentum present in the system due to the spin-up of the electromagnets. The motor must provide the required torque to balance the moments induced by the electromagnets. The amount of torque required by the motor increases as the magnets move closer together.

A third variable that drives design is the fly-wheel material. Throughout the design process a range of different materials have been considered for this purpose, each with its own advantages.

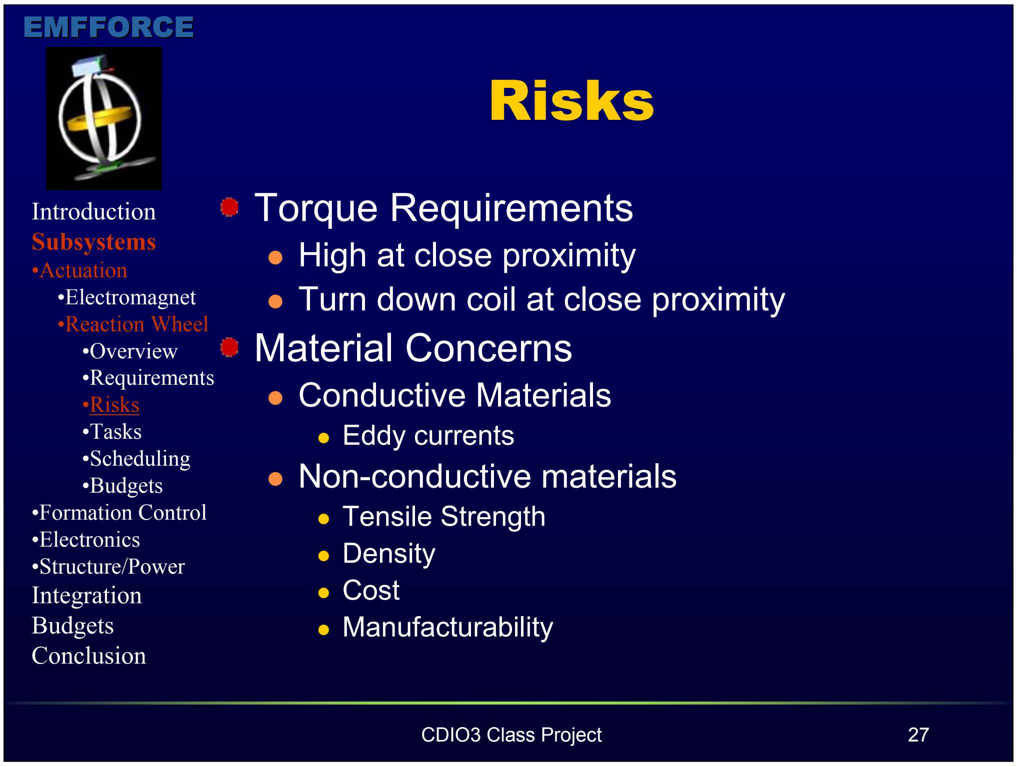


<WDF>

Requirements expanded from requirements 7.3.1.1.2 and 7.3.1.5 in version 5.1 of requirements document.

7.3.1.1.2 Angle tolerance based on angular rotation rate.

7.3.1.5 A method of angular momentum storage other than traditional thrusters.

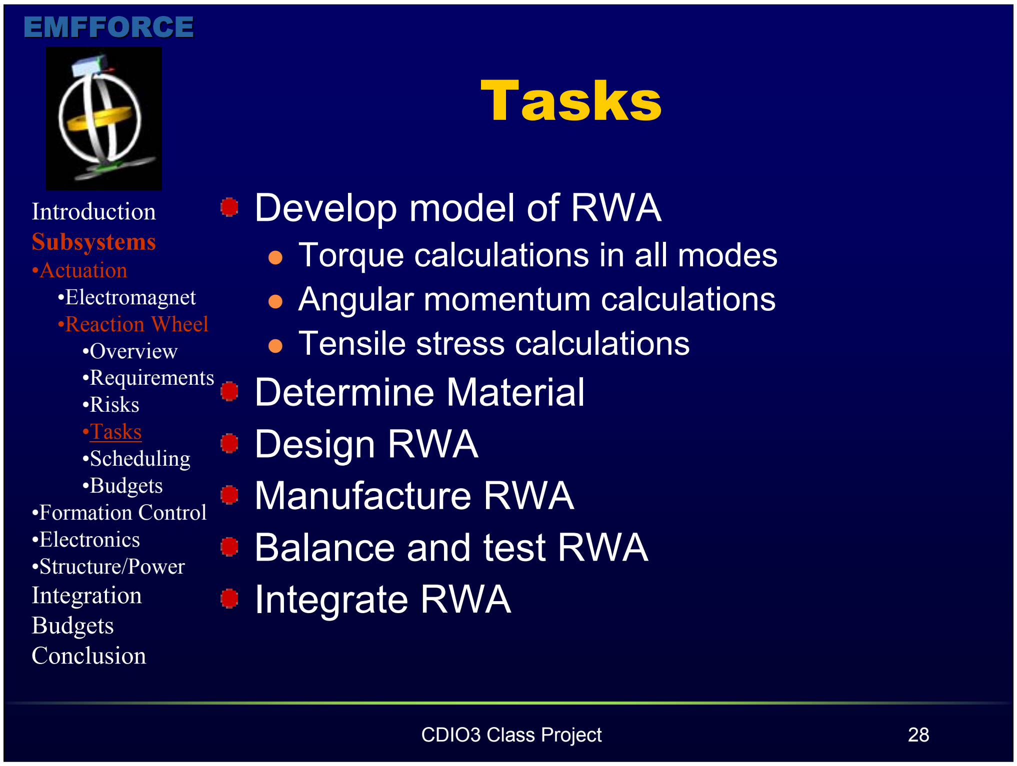


<WDF, LLW>

Due to mass and size restrictions it is not possible to use a motor capable of handling all possible torque scenarios. When both coils are extremely close (separation 0.02m), turned on at full power (100 Amps), and at right angles to each other, the torque that the motor would need to generate is in excess of 6Nm. However, for all of the scenarios in which the system is intended to be tested the torque requirements are far more reasonable and the reaction wheel motor will be designed to handle these more reasonable loads. The approximation for required torque at 1m separation is 0.8Nm.

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." Due to this constraint, the original material choice – aluminum – cannot be used. Investigation into other material options is being done. Currently, the most promising option appears to be high-density urethane material.

Preliminary concerns were raised about using non-conductive materials. These included a lack of tensile strength (needed for high reaction wheel rotation rates), low densities (a minimum mass is needed to provide the necessary angular momentum storage), and cost or manufacturability since many non-conductive materials would have to be custom ordered and could not be machined on campus. Research into high-density urethanes and plastics have eased some of these concerns. For the current estimates of the vehicle size and mass these materials do have the necessary strength and material properties. Also certain manufacturers have been found which can provide custom wheels at very reasonable costs.



<WDF, LLW>

A model for the design of the RW must be finalized. This model incorporates calculations that consider: balance of angular momentum, balance of torques, tensile stress on the RW. The model will take total system mass and vehicle moment of inertia as inputs and provide mass and size for the RW. A preliminary model is complete at this time. However, the RW team awaits the final values for system mass and vehicle moment of inertia before the RW design can be finalized.

Material selection must be completed. Current material possibilities include a variety of plastics and composites.

RW design will be completed in CAD. Design follows directly from model described above.

RW will be professionally machined, but balanced and tested in lab facilities at MIT. Testing includes defining a series of test protocol to ensure that the RW will function properly in both the spin-up and steady-state modes.

The first step of integration is within the RWA – the motor and the wheel. Next, the RWA will be integrated with the Power and EM groups, and finally the Structure group will assemble the entire system.

EMFFORCE

Scheduling

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- Actuation
  - Electromagnet
  - Reaction Wheel
    - Overview
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    - Scheduling
    - Budgets
- Formation Control
- Electronics
- Structure/Power

Integration
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Conclusion

START	END	TASK
17SEP	26SEP	Develop Reaction Wheel Model
26SEP	8OCT	Assist EM Team Finalize vehicle variables
8OCT	17 OCT	Design Reaction Wheel Order components
17OCT	14NOV	Assist EM Team
14NOV	21NOV	Balance Test RWA begin integration with Power

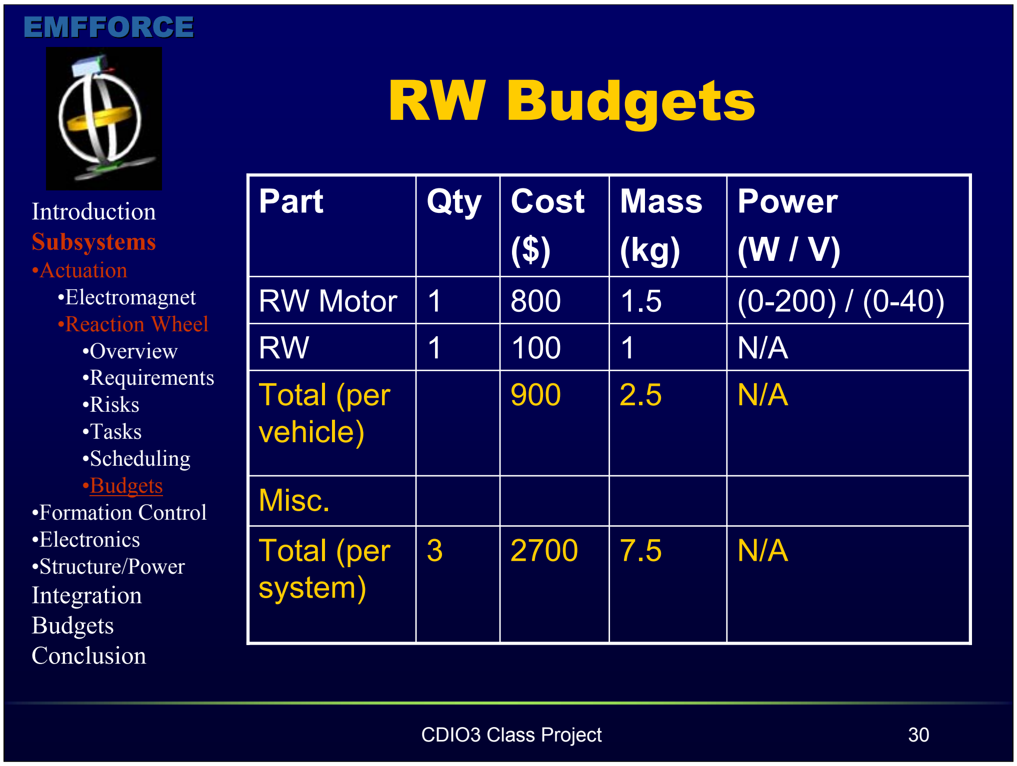
CDIO3 Class Project 29

<WDF>

The reaction wheel assembly must be complete, tested, and integrated with the power sub-system by Nov. 21, 2002. The RW Team will need one week from the arrival of the reaction wheels to integrate with the motor assembly, balance the wheels and perform validation tests on the wheels. Since the reaction wheels have a lead time of 4 weeks the order must be placed no later than Oct. 17, 2002. While the wheels are being manufactured the RW Team will assist the EM Team in the design and construction of the electro-magnet and cooling system.

In order to complete the reaction wheel assembly design and place an order by Oct. 17, 2002, the RW team will need final values for the mass of the vehicle and moment of inertia of the vehicle by Oct. 8, 2002. This requirement should be noted by other sub-systems.

Until the vehicle parameters are finalized, the RW Team will assist the EM Team in the design of the electro-magnets.



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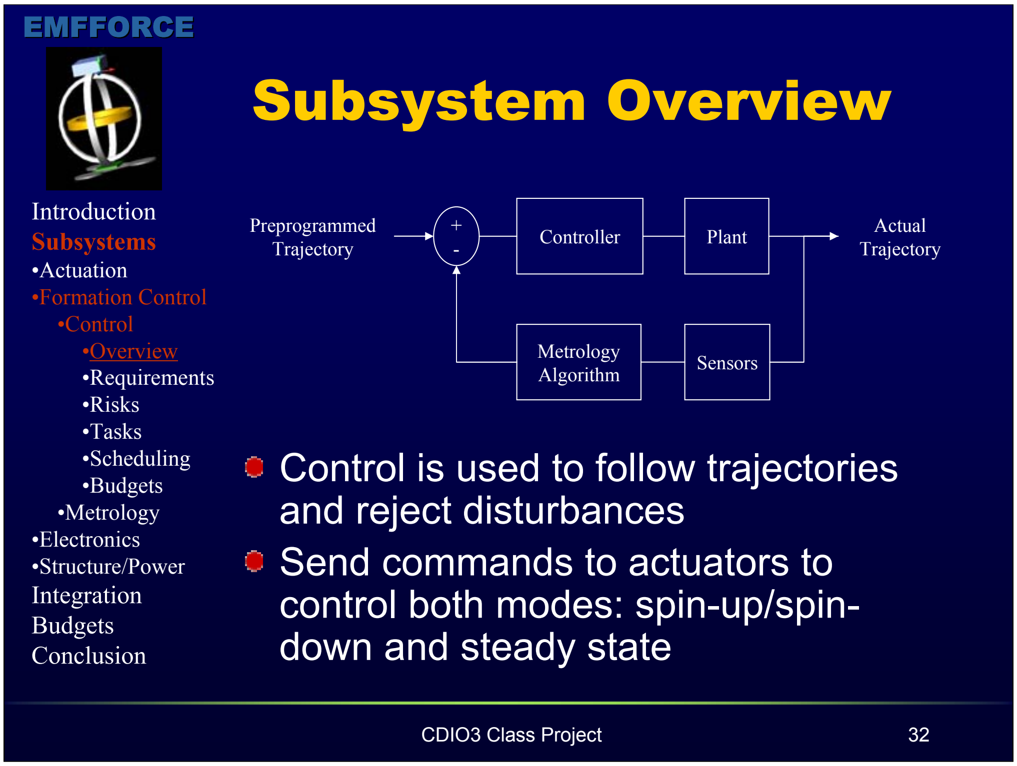
The current numbers are accurate estimates of the reaction wheel assembly. Specific motor selection and reaction wheel material selection are not yet complete, and will be completed as noted on the schedule. However, these estimates will not vary significantly from the actual costs and mass of the sub-system.

The power budgets are given in a range because the current motor choice is capable of operating with varying levels of voltage. Thus, using a current of 5A, a wide range of power requirements emerges.

<BAB, LS>

Welcome to the Control Subsystem section of the NAR presentation. Erik Stockham will present on behalf of Leah Soffer and Andre’ Bosch.



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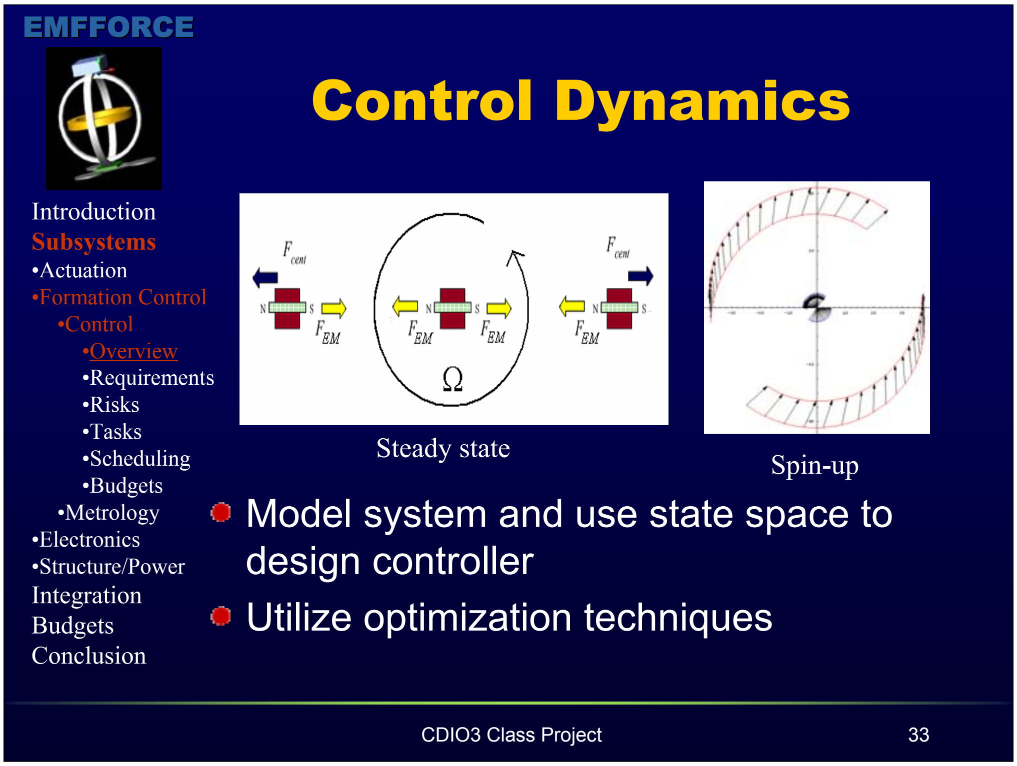
The control subsystem sends commands to the actuators in order to maneuver the vehicles. The actuators that are commanded are the reaction wheels and the electromagnets, controlling torque and force. The commands are sent in the form of an output voltage.

The tasks of the control team are to follow predetermined trajectories and reject disturbances. To do this, the controller will use metrology sensor data as feedback.

In this mission, there are two modes that must be controlled: spin-up/de-spin and steady state. In spin-up, the vehicles are taken from rest and accelerated until they reach the desired rotation rate in steady state mode. De-spin is similar to spin-up, but brings the vehicles from steady state rotation to rest through deceleration. These modes are further described in the next slide.



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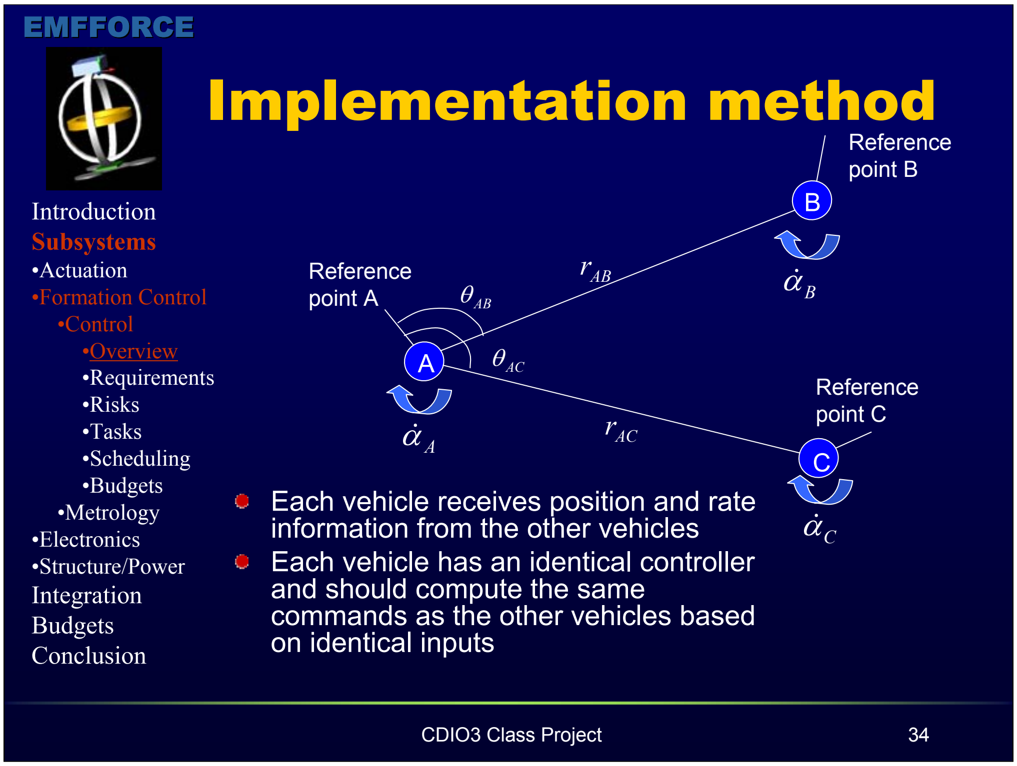
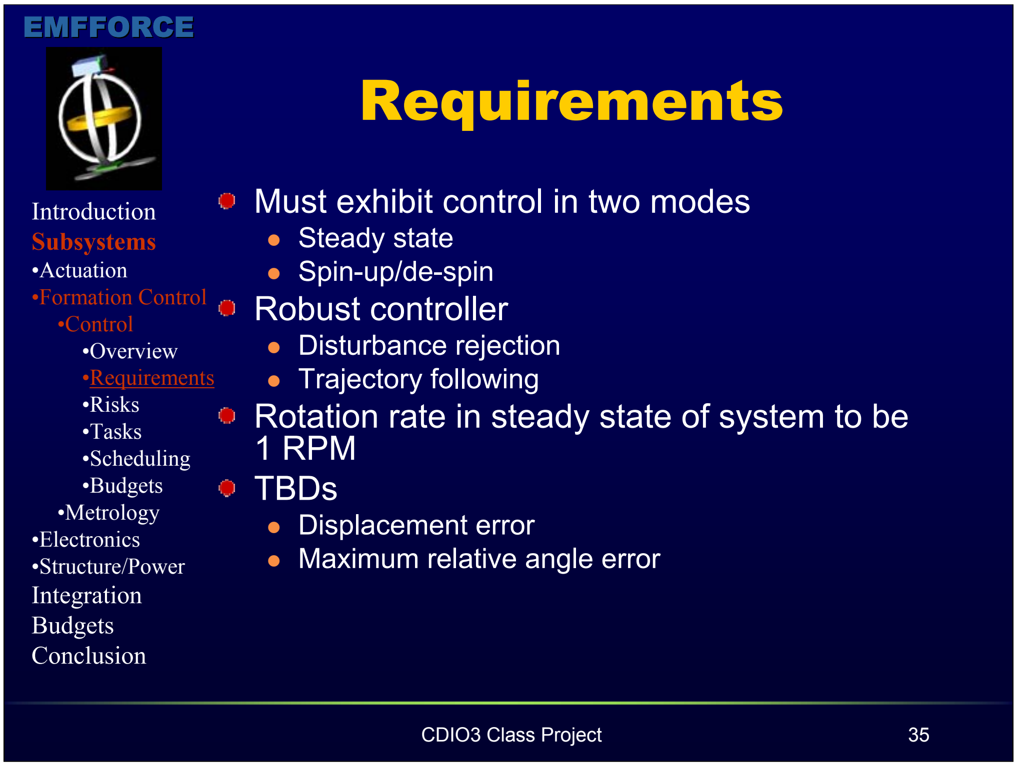
In steady state, the electromagnets of all three vehicles are aligned. The forces acting on the system are centripetal and electromagnetic forces. Through force balance equations, the system can be modeled in state space form. By assigning value to the electromagnet actuators versus the reaction wheels, an optimal controller can be built.

In spin-up, the three dipoles begin aligned with adjacent dipoles perpendicular to each other. When the electromagnets are turned on, the forces cause the vehicles to torque and move. A controller will be built that determines the required torques and forces to follow the shown path until the electromagnets are aligned in parallel.



<LS>

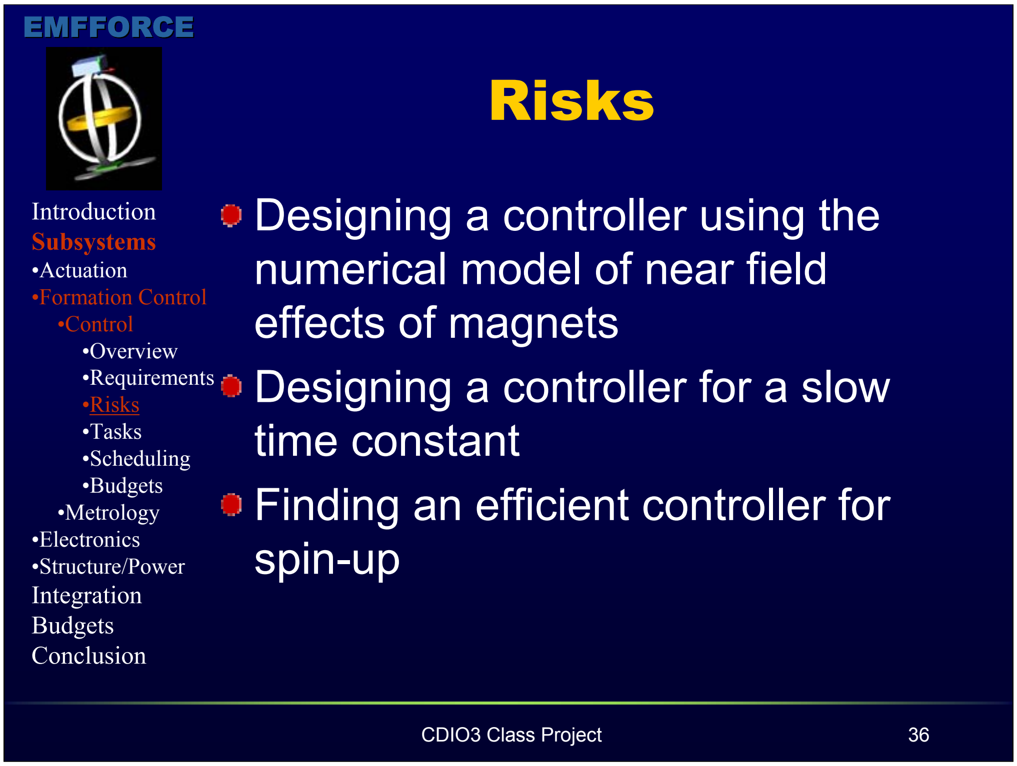
Each vehicle will determine its separation distance to the other vehicles (r_{AB} and r_{AC}). Also, they will determine the angle to the other vehicles from some reference point on the body of the vehicle. (θ_{AB} and θ_{AC}). The vehicle will also know its inertial rotation rate alpha dot from rate gyros. These five pieces of information will be sent to the other two vehicles and the ground station. Then each vehicle will have the same three sets of data. This information will be resolved in a coordinate system fixed on one body (the designated hub) and the control will be calculated by each vehicle. However, because each vehicle will have received the same information and contains the same control law, all three calculations should be identical. In case of an error, the control matrix from the hub vehicle will be transmitted and employed.



<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 five minutes. The steady state rotation must be 1 RPM. This requirement may be relaxed due to the time constant of the new magnets.

The displacement error was initially limited to one tenth the separation distance between the two vehicles. This comes from the limit on the accuracy of the metrology inputs. However, this requirement might be changed when a better understanding of the system is gained. Currently, the maximum relative angle error is only know to be a fraction of ninety degrees. When the physics of the system is better understood, this requirement will be refined.

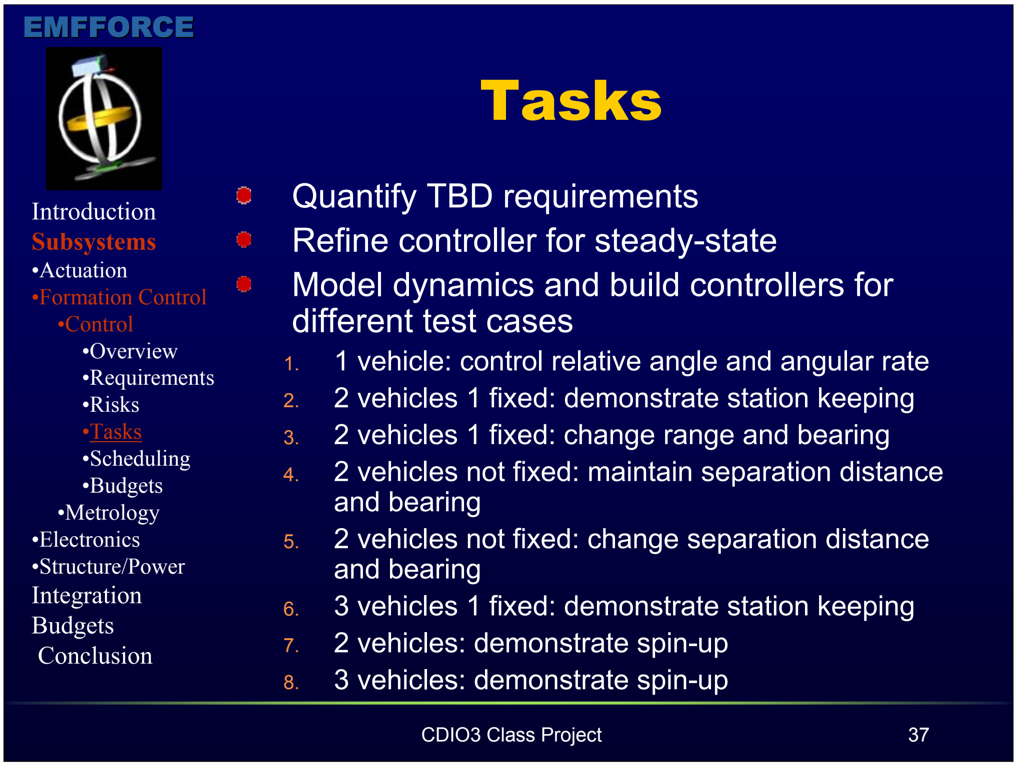


<BAB>

Our first risk is that it is difficult to evaluate the analytical model of the near field effects of the electromagnets. Initially the project was going to use electromagnets made of iron cores wrapped with copper wire. These electromagnets were found to be too weak for our application. Therefore the Electromagnet team decided to use large coils of super-conducting wire. These electromagnets behave differently from the ones before. Also, since we increased the radius of the coil without proportionally increasing the separation distance, the vehicles now fall in the near field. In the near field, the B field is different than in the far field. The equations that govern the B field are no longer analytical but numerical. This makes it more difficult to evaluate the analytical model of the near field. To mitigate this risk we will use a combination of computer simulations and empirical data to more accurately (and quickly) evaluate the near field effects.

The second risk is that the new magnets also behave differently given a step increase in current. Although the final magnet design has not yet been chosen, the final design should be chosen with the magnet's time constant in mind. This means that the magnet should respond quickly enough to changes in input current to be controllable. To mitigate this risk we have shown that, in theory, even if this magnet's time constant is too slow (slower than the poles of the system) the system is still controllable. By this we mean that if the controller were to take into account the behavior of the magnet and cancel out its effect then the system is controllable. The problem here is exactly canceling out the effect of the electromagnet. If we find that this method is not possible, then we will simply have to slow down the rotation rate of the system in steady-state until the electromagnet's time constant is fast enough.

Our third risk lies in coming up with a plan for the Spin-up/de-spin controller. There are an infinite number of trajectories to accomplish spin-up/de-spin. The risk here is that our lack of understanding may not lead us to the most efficient controller. To mitigate this risk we will use computer simulations and more accurate models to find the most efficient controller.



<BAB>

First we must develop a model for spin-up/de-spin. From this model, we will gain sufficient understanding to be able to design a spin-up/de-spin controller. We already have a model and a controller for the Steady State mode. We wish to refine these. Most of our tasks are test driven. We will use an incremental approach to our control construction. Each of the tests above guides the controls team towards a controller ultimately capable of the three vehicle system the project wishes to build.

EMFFORCE

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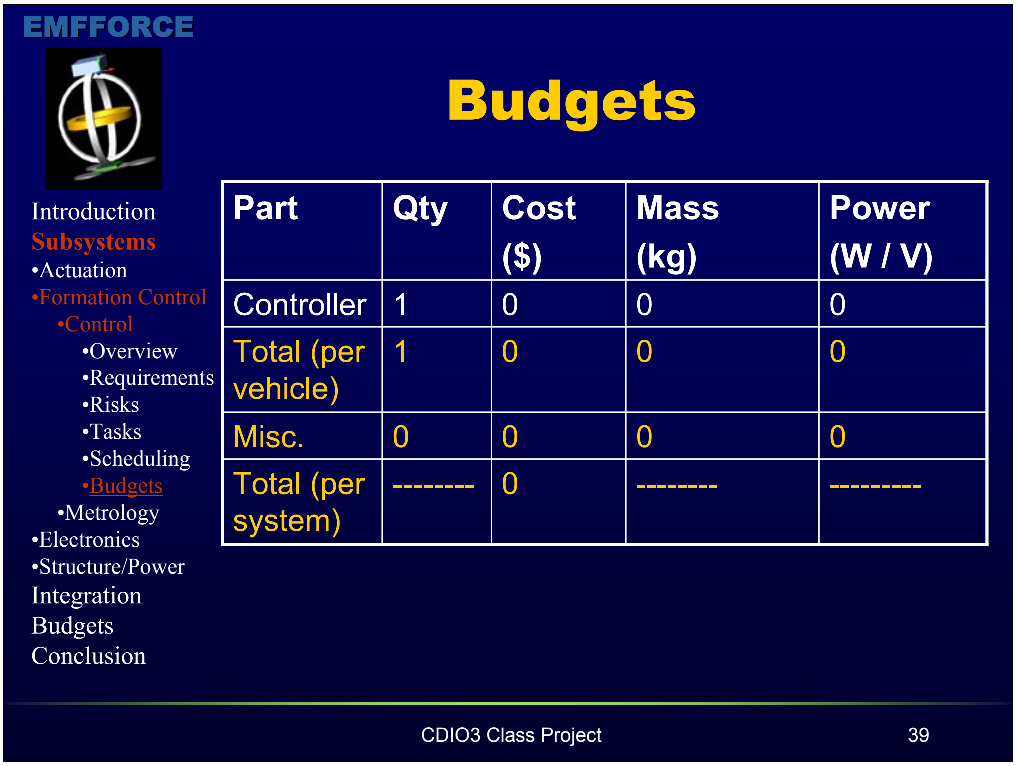
START	END	TASK
1OCT	31OCT	Quantify TBD requirements
8OCT	8OCT	Perform test case 1
10OCT	17OCT	Model/design for test cases 2 and 3
22OCT	29OCT	Model/design for test cases 4 and 5
31OCT	5NOV	Model/design for test case 6
7NOV	14NOV	Model/design for test case 7
19NOV	3DEC	Model/design for test case 8
21NOV	21NOV	Critical Design Review
5DEC	10DEC	Refine steady state controller
IAP	IAP	Assist in integration testing
February	March	Test cases 1-8 on vehicles

CDIO3 Class Project 38

<BAB>

This slide shows the Control teams milestones for the remainder of the project. A more complete schedule for testing depends on the functionality of the vehicles next semester. The schedule also depends on the tests other teams wish to perform.



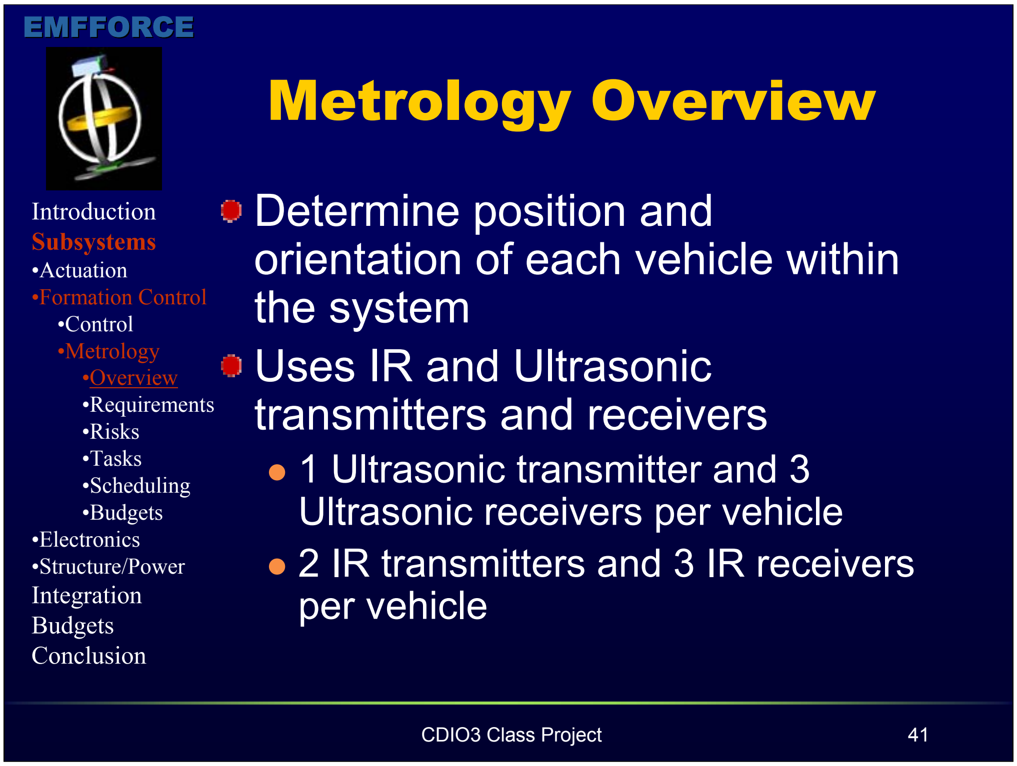
<BAB>

Since we are not a physical system our mass and power. Our monetary budget is also zero since we have all the software and computers we need to carry model the system and design the controllers.

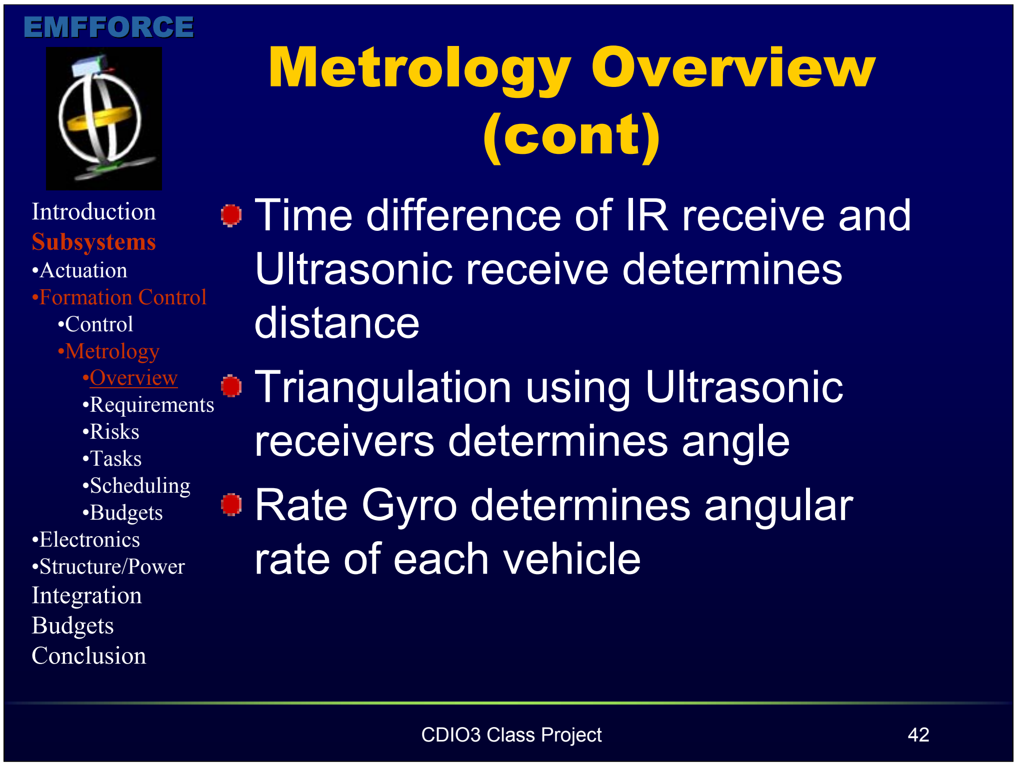
Metrology

<JEU>

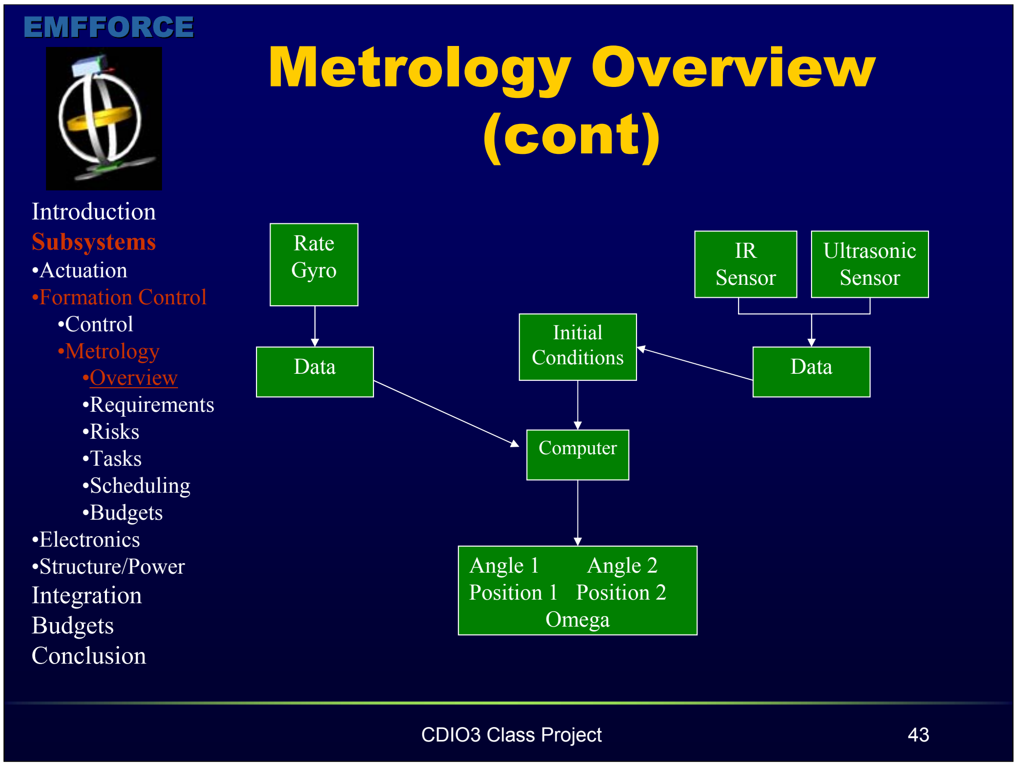
Welcome to the Communications and Operations Subsystem section of the NAR presentation. Erik Stockham will present.



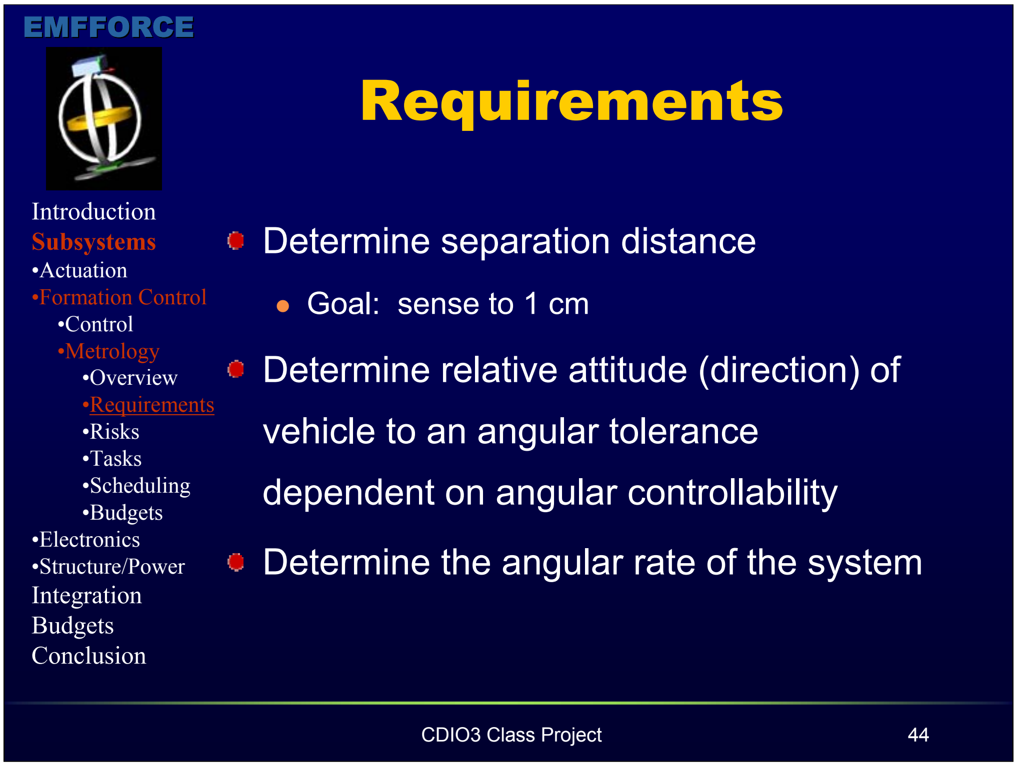
<om> The basic goal of the Metrology system is to determine the position and orientation of each vehicle in the system. The system design uses IR and Ultrasonic transmitters to do these estimations.



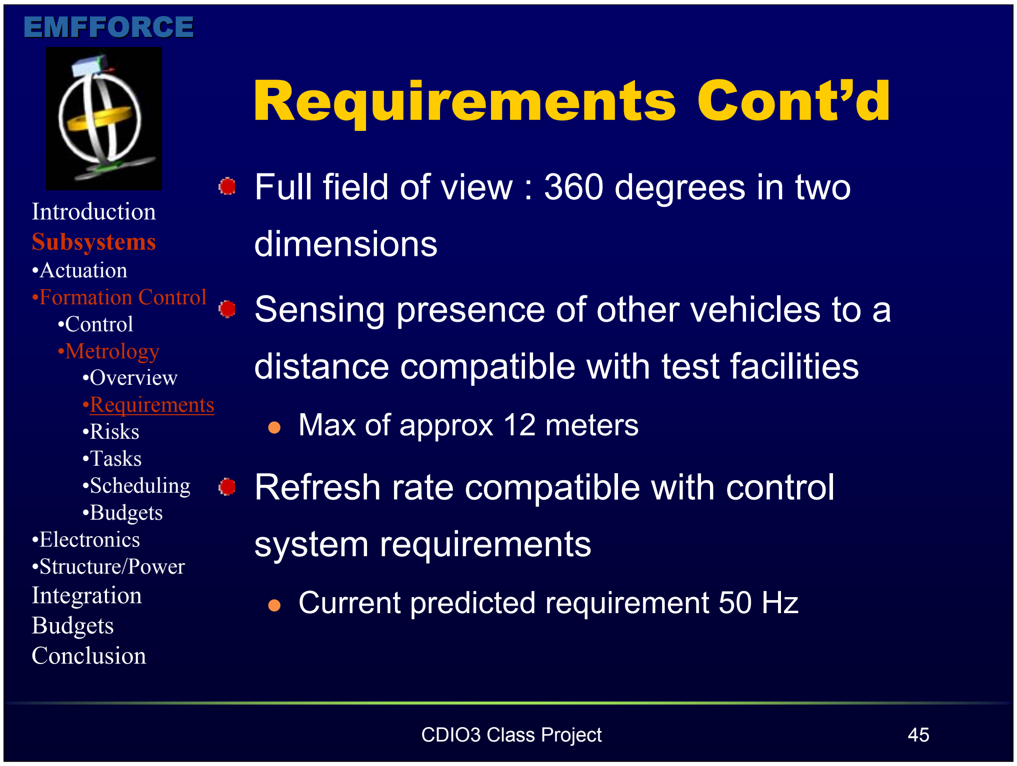
<om>The basic algorithm for the system uses the time difference of the IR and Ultrasonic signals to determine the distance of the other vehicles. In addition, the orientation of the 3 receivers help determine the angle from which the signal came. The system currently takes longer than the required refresh rate, so a rate gyro gives us data to update the change in angle to the required refresh rate.



<om> The angle and is determined from the rate gyro, using the initial conditions set by the IR and Ultrasonic sensors. The rate gyro has a drift rate that prevents it from being accurate when integrated. The rate gyro can be configured to the refresh rate desired by the control system. The position data will be solely determined by the IR and Ultrasonic sensors. In order to get position data at the required refresh rate a velocity calculation will need to be done from distance and time data provide by previous readings. The estimated velocity will then be used to calculate the position of the vehicle to increase the refresh rate of the overall system.



<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 360º 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 to 60 Hz.



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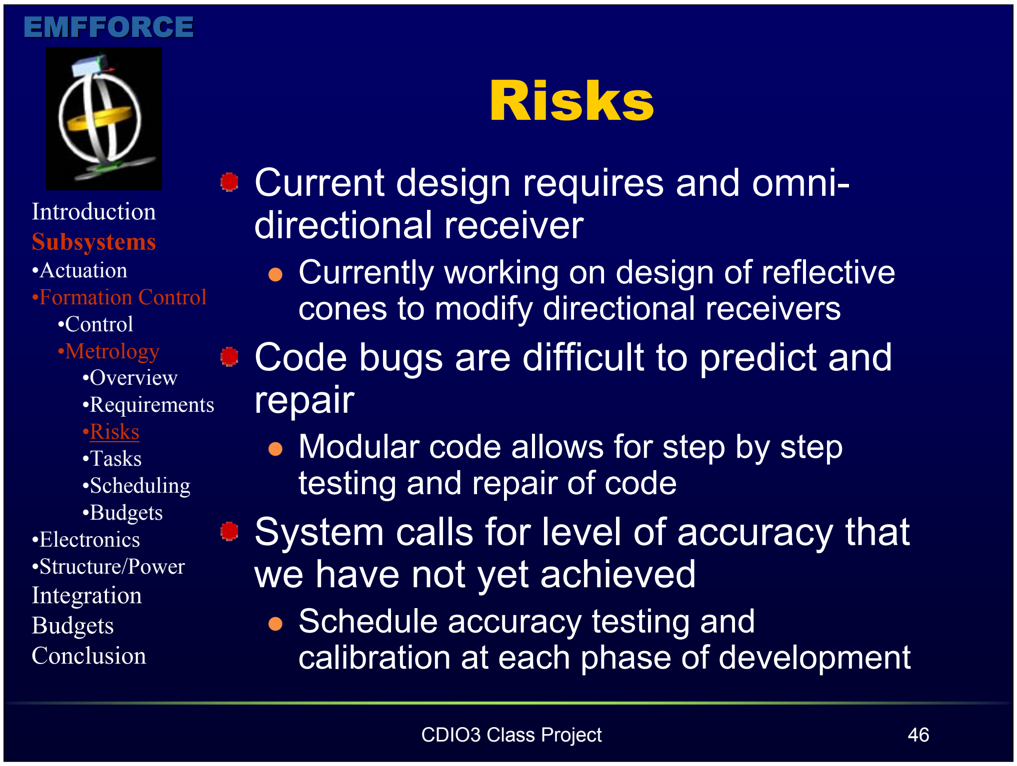
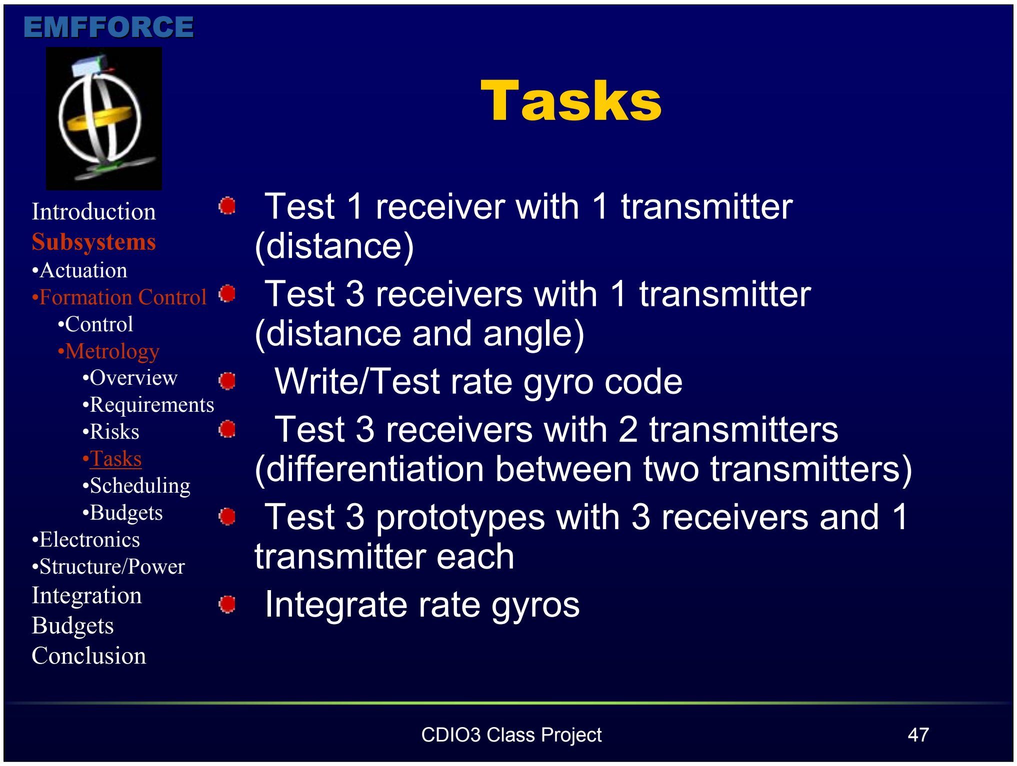


We do not yet know the effect of the directional cones on the accuracy of distance measurement. We have not yet decided on a final configuration for the cones.

Use of modular software design SHOULD help to catch bugs, however coding is never that easy.

We are still learning how to use the TT8 this will slow progress for some time.

Accuracy is of great importance but experience from SPHERES seems to indicate that sonic systems are very hard to calibrate. Testing has demonstrated high sensitive.

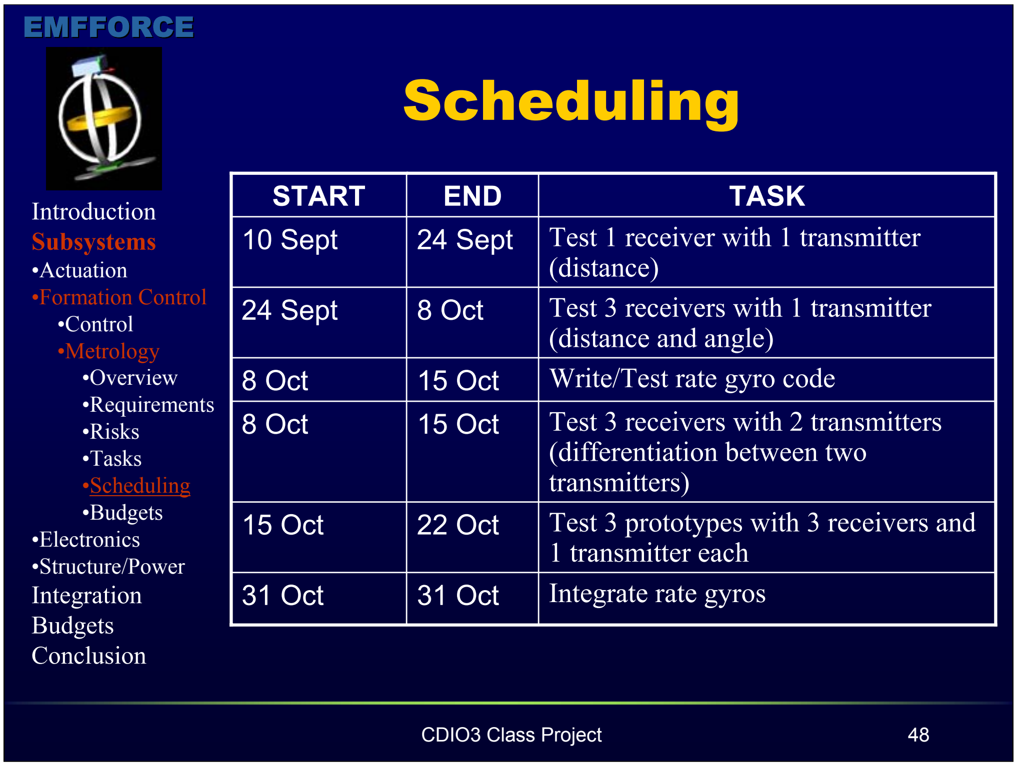


Currently scheduling shop time with Don to discuss fabrication of reflective cones based on the samples provided by the electronic ink corporation.

-Linear distance measurement code was created over the summer by Maggie Sullivan.

-Oscar Murillio has created a Matlab script that calculate the distance and orientation given three linear distance measurements

-Currently working on combining the two pieces of code into an algorithm for 2D distance and orientation measurement with sonic inputs.



START	END	TASK
10 Sept	24 Sept	Test 1 receiver with 1 transmitter (distance)
24 Sept	8 Oct	Test 3 receivers with 1 transmitter (distance and angle)
8 Oct	15 Oct	Write/Test rate gyro code
8 Oct	15 Oct	Test 3 receivers with 2 transmitters (differentiation between two transmitters)
15 Oct	22 Oct	Test 3 prototypes with 3 receivers and 1 transmitter each
31 Oct	31 Oct	Integrate rate gyros

We've broken the task down into steps to better track our progress.

Preliminary testing was inconclusive. Testing was delayed since reflective cones were not readily available. Instead we proceeded to work on the 3 receiver system. We will continue testing as soon as the hardware is ready.

We are planning to work on the rate gyro code using the gyros left over from SPHERES. We will order our own gyros at a later date, based on results from code tests.

EMFFORCE

Budgets

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Part	Cost ($)	Mass (kg)	Power (W at V)	
Sonic (1+3)	70	0.05	0.3	5
IR (2+3)	30	0.04	0.25	5
Gyros	1200	0.06	0.16 to 1.2	8 to 24
Total (per vehicle)	1300	0.15	0.71 to 1.75	
Miscellaneous	300	N/A	N/A	N/A
Total (system)	4200	0.45	2.13 to 5.25	

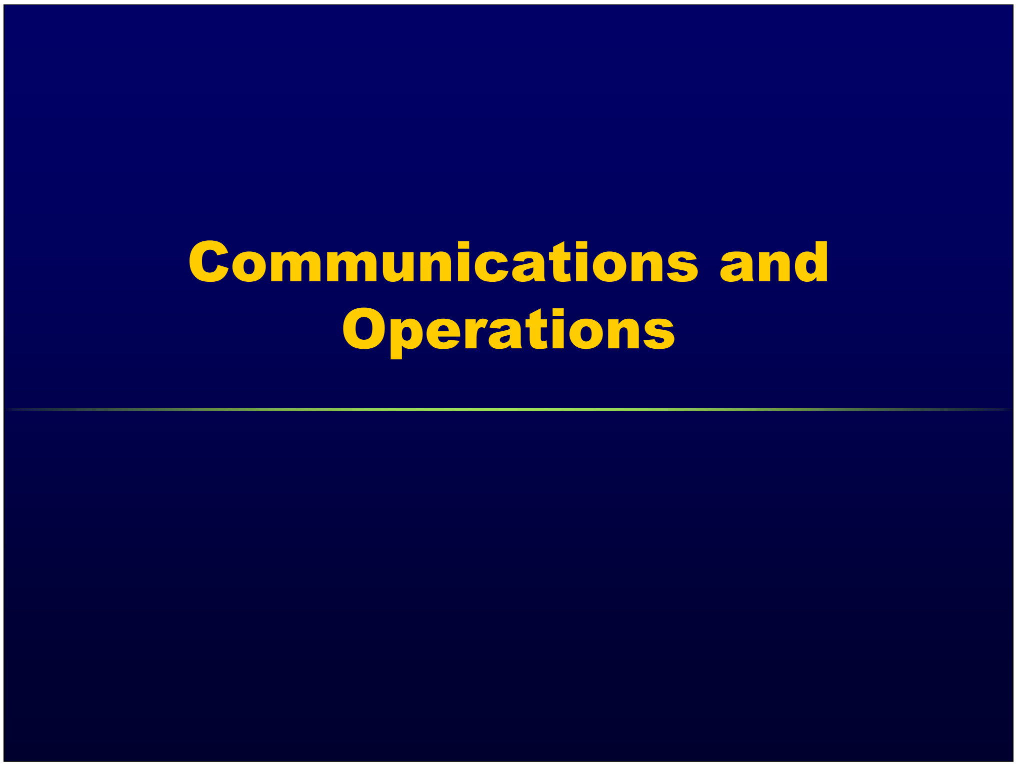
CDIO3 Class Project 49

Though we already have most of the IR and Sonic units that we need (thanks to a generous donation from the Electronic Ink Corp.) We may still need to purchase some of the components, namely IR receivers and circuit boards to interface with the sensors.

We have included a miscellaneous category to our budget because we are afraid of unknown added cost associated with design and production of circuit boards.

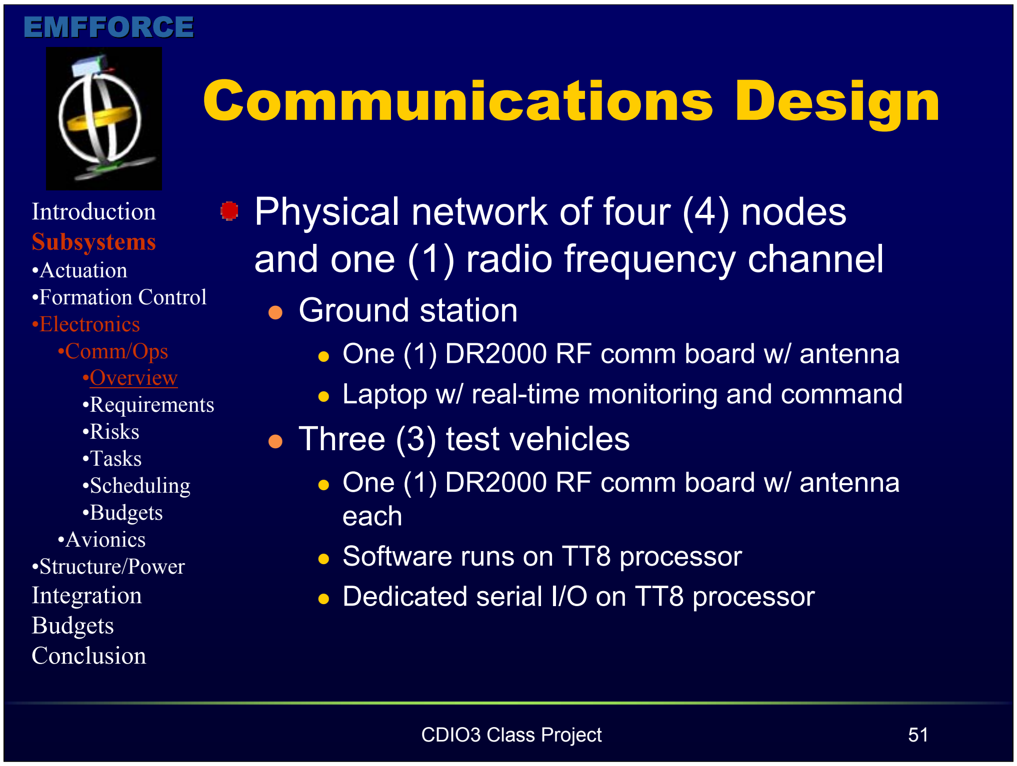
It was determined that accelerometers were not well suited to our application and would exceed our budget.

Rate gyros are still required to return angular rate data.



<JEU>

Welcome to the Communications and Operations Subsystem section of the NAR presentation. Erik Stockham will present.

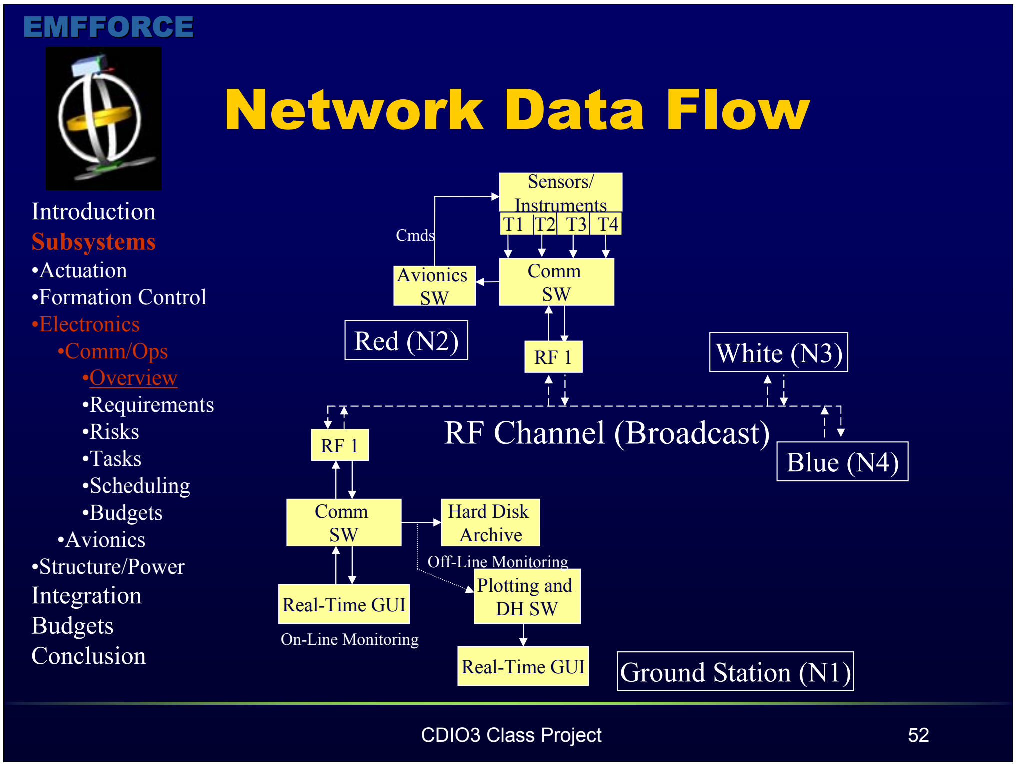


<JEU>

The communications design consists of a physical network of four nodes. The ground station (laptop) and the three test vehicles comprise this network. Each node has one DR2000 communications board with an antenna that operates on the system frequency (>900MHz for EM interference rejection). The DR2000 has many desirable features including: hard-coded error-detection and correction, built-in packet transmission, small size and weight, and low voltage draw.

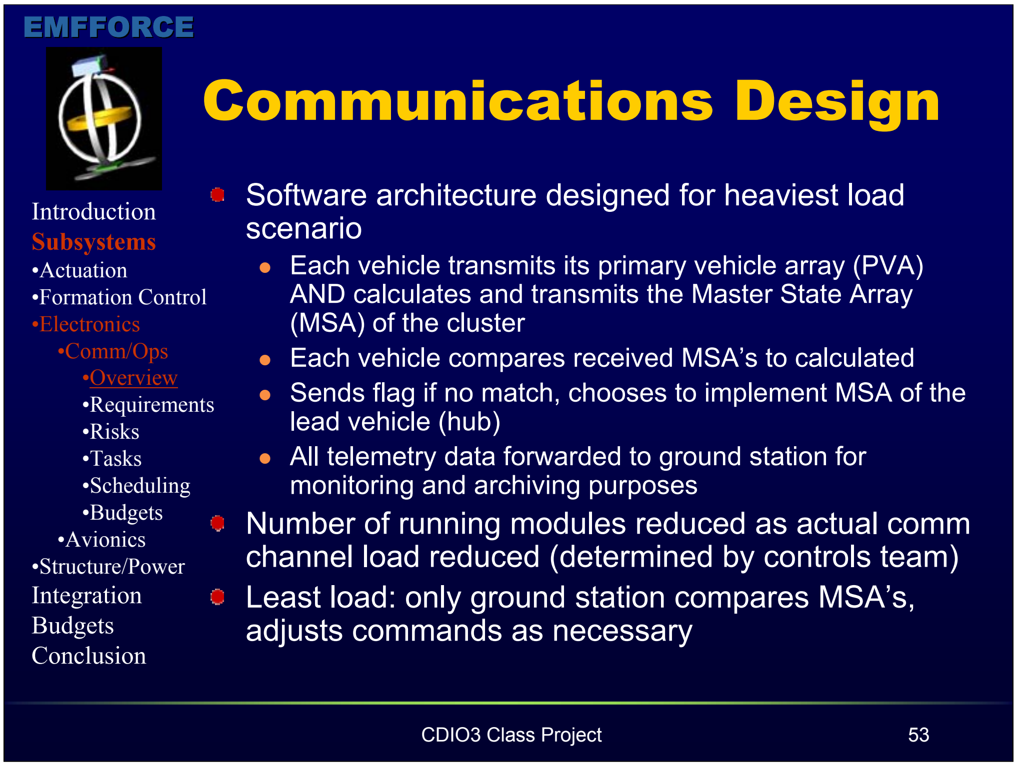
The ground station node consists of a laptop running real-time monitoring and command software. The ground station node only uses its antenna actively if it issues a command. Otherwise, the ground station passively observes the system and archives the telemetry data sent through the communication channel. It will only issue commands for corrective or emergency maneuvers, or to set the mission.

Each test vehicle also maintains communications software space with the onboard avionics TT8 processor. The avionics subsystem will also assign hardware pins to the communications subsystem for use with the DR2000 communications board.



<JEU> modified 10/1

This slide visually demonstrates the network design by describing the flow of data through the system. The three test vehicles (Red, White, and Blue) are completely interchangeable and the ground station has the option of using off-line monitoring if deemed necessary. This slide also indicates some of the major interfaces between communications and operations and the other subsystems.



<JEU>

Until the control team makes a decision concerning which network architecture best meets its needs, the communications team plans to implement a software architecture designed to meet the heaviest load scenario. This scenario follows:

1. Each vehicle calculates & transmits its own primary vehicle array (PVA)

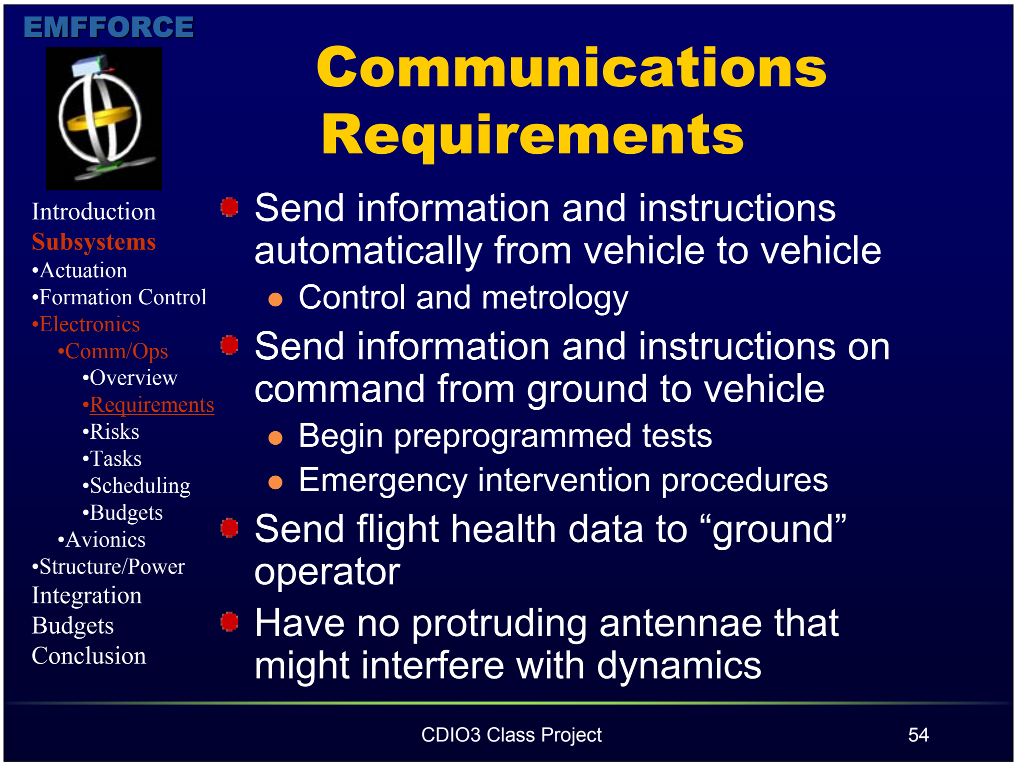
2. Each vehicle receives all PVA's, then calculates & transmits the Master State Array (MSA) of the system

2. Each vehicle compares the received MSA's to its calculated MSA

3. If the comparison fails, the vehicle sends a flag to the ground station, then it chooses to implement the MSA of the lead vehicle (hub)

4. The ground station receives all telemetry data (including health) for monitoring and archiving purposes. If a flag is raised, the operator makes a decision on whether to switch hubs, to initiate a controlled shutdown of the system, or to take no action

As it becomes more clear which architecture best suits the needs of the control team, unnecessary modules will be commented out. Should the desired implementation fail to work, reverting to a higher load scenario will be trivial.



<JEU>

The subsystem requirements are taken nearly verbatim from the Requirements document created during the first half of Spring term 2002.

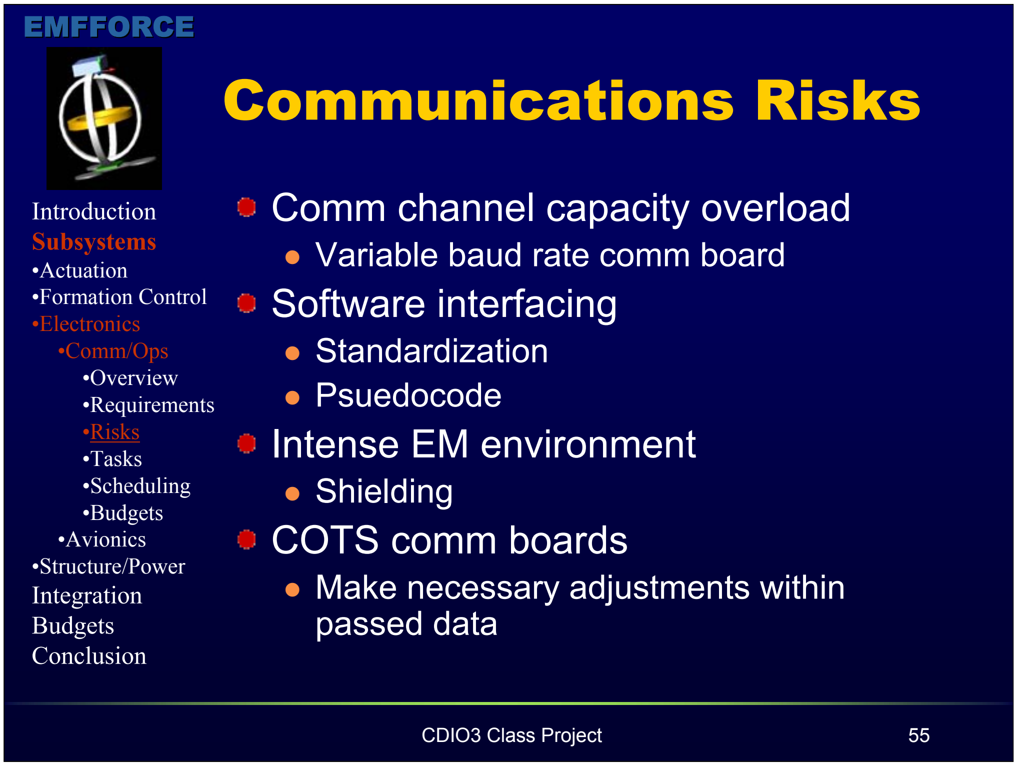
The Communications subsystem should be able to send information and instructions automatically from vehicle to vehicle. This implies that during normal operational states, the subsystem must rely on software developed for the particular operational state. This further implies the need for robust communications software.

The subsystem should also be able to send information and instructions on command from ground to vehicle. This implies that the software should be flexible enough to handle commands outside of normal operating states, including emergency interrupts and overrides.

Furthermore, these requirements imply that the subsystem hardware should have sufficient range to operate between all vehicles and the ground station.

The communications subsystem should be able to send flight health data to the “ground” operator. This implies that the subsystem should supply sufficient bandwidth (and hence have sufficient data rates) to process telemetry (and other test data), health, and commands. This also suggests either a full duplex system or multiple communication channels to handle forward-path (user to Hub) communications and reverse-path communications (Hub to user).

The communications subsystem shall have no protruding antennae that might interfere with dynamics. This implies that the system will NOT be tethered, hence a wireless form of communication. Furthermore, this implies that antennae are acceptable as long as they do not interfere with the dynamics of the vehicle.



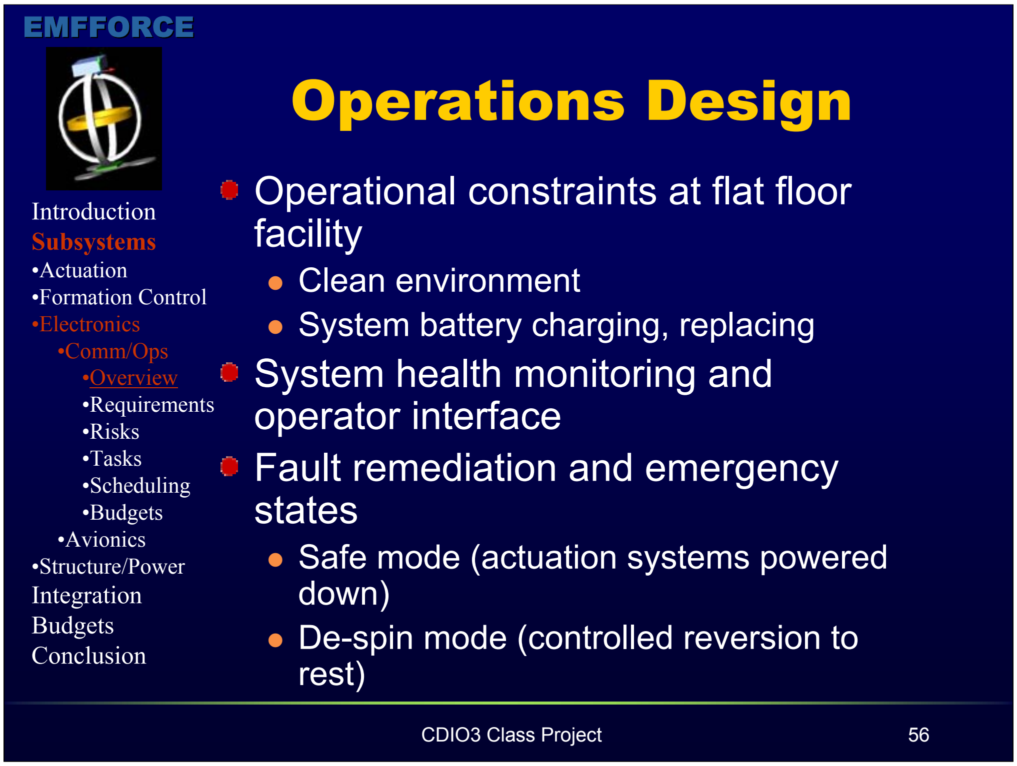
<ESS,JEU>

Specific demands of control and metrology systems may evolve beyond capability of Comm system to support all task loads. While the interface has already been defined, unforeseen problems may arise that require additional wireless data transfer capability. One way to mitigate this risk is to implement a communications board with a variable Baud rate. The number of baud's per second is directly related to the number of bits per second that are passed through the system.

Software interfaces between the two Groups tasked with software development will pose a challenge. The Groups must constantly keep each other aware of any changes made to the interfaces so the integration does not run over schedule. This risk may be mitigated by standardization of software functions as well as comparison of psuedocode among the two Groups prior to coding.

Intense EM environment may cause adverse interactions with electronics. Similarly, the liquid nitrogen may damage sensitive electronic components if not properly handled. These risks may be minimized using shielding.

COTS communications boards may not be completely adaptable to network architecture requirements. The DR-2000 boards are very capable and include a significant on-board data-processing capability. However, the communications system as currently designed may require additional versatility. Adding a secondary header within the packet framing standard pre-coded into the DR2000 should create the necessary versatility.



<JEU>

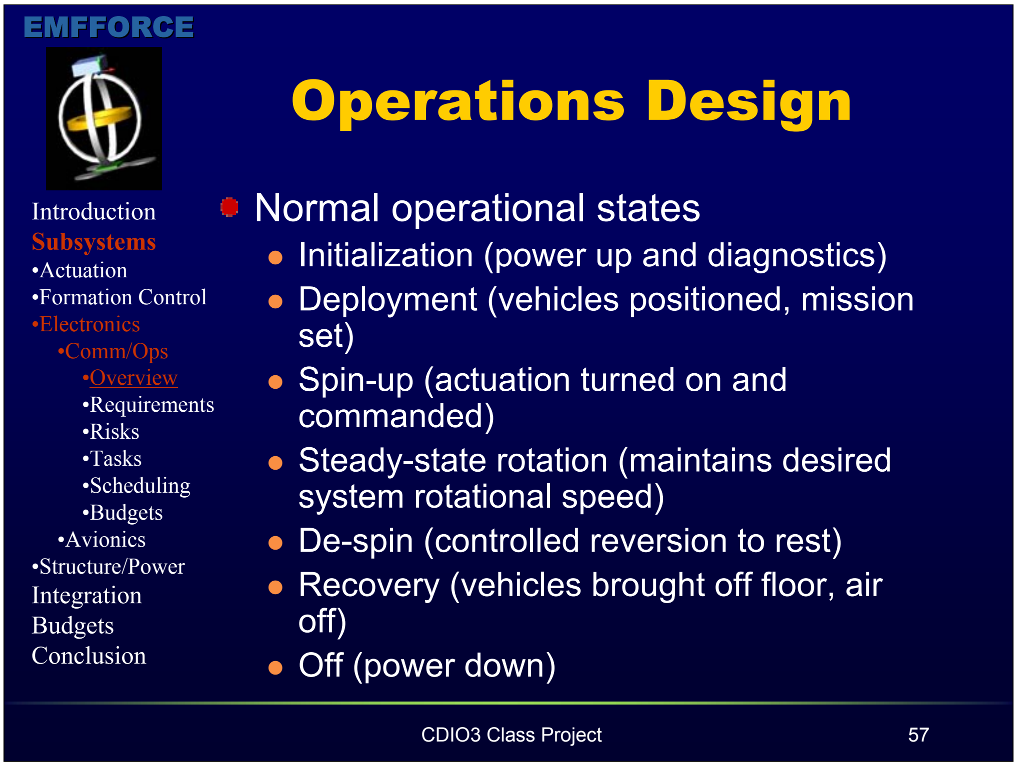
There exist several constraints brought about by operating outside of MIT: As dictated by the Lockheed Martin Flat Floor Facility in Denver, personnel may not walk out on the floor without protective footwear. The floor is protected as a clean environment, thus personnel must undergo decontamination procedures prior to entering the test area. This will add time to test preparation.

Constraints that exist whether at MIT or abroad: The laptop used must support the communications needs (as a node in the network) in addition to sustaining operational needs. The laptop must process the received data as fast as it arrives for real-time (and off-line) monitoring. The archived data will allow data analysis at a later time.

The batteries used by the vehicles will need to recharge. Once recharged, the batteries will replace those currently in the vehicles.

It will be necessary to monitor the health of the system at all time. Critical health telemetry points will be given green, yellow, and red limits and will be plotted against time to measure rates. These will be observable on the operator interface (most likely labview).

Should an emergency occur, the operator will have the option to remediate the fault (if possible) or to call on emergency states to prevent catastrophic failure or injury. Remediation of the failure can only occur if the failure can be detected and corrected before the failure becomes critical. Emergency states include safe mode, where ONLY the actuation systems are powered down so the personnel on the floor may recover the vehicles safely. De-spin mode allows the operator to initiate a controlled reversion to rest whereby the personnel on the floor may recover the vehicles. Both states keep the electronics systems up so that telemetry data may still be collected for failure analysis.



<JEU>

The operations design also includes normal operation states. They are as follows:

Initialization. In this state, the vehicle powers up the electronics and checks for faults before the operators place the vehicle on the floor. The ground station designates a vehicle as the hub, illuminating an LED on the selected vehicle.

Deployment. Deployment activates the metrology and air carriage subsystems and guides the vehicles to their initial positions. The ground station transmits the planned mission to the vehicles, including initial position, desired steady state flight parameters, and other variables.

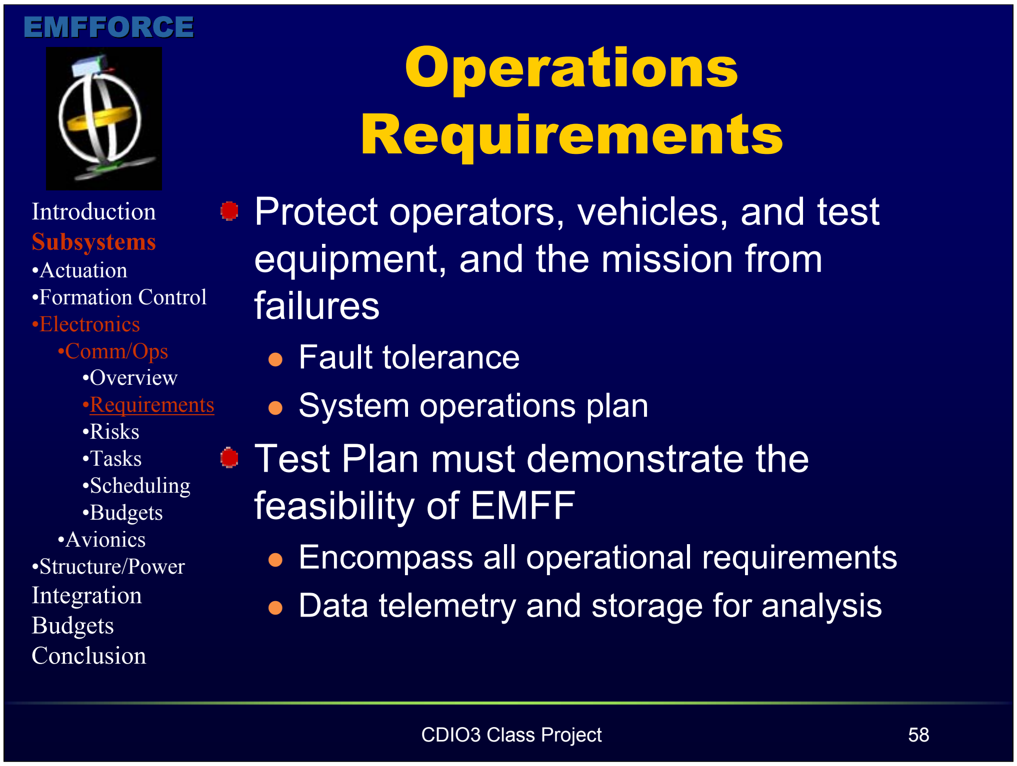
Spin-up. At the command to initiate spin-up, the actuation devices leave standby mode and act upon commands from the control subsystem.

Steady-state Rotation. When metrology indicates that the system is within the desired steady-state parameters, the system automatically enters steady-state rotation mode without operator input. In this mode, the control algorithm changes to maintain the desired rotational velocity.

De-spin. De-spin switches the control algorithm again to bring the vehicles to rest from the Steady-state Rotation Mode. After the vehicles have completed De-spin, they are placed in Safe Mode for recovery by operator command.

Recovery. Upon entering Safe Mode, the operators will attempt to first bring the vehicles to rest and then move them off the floor. Once the vehicles are off the floor, the air carriage is powered down.

Off. The state where none of the electronics systems are drawing current and the air carriage is inactive.

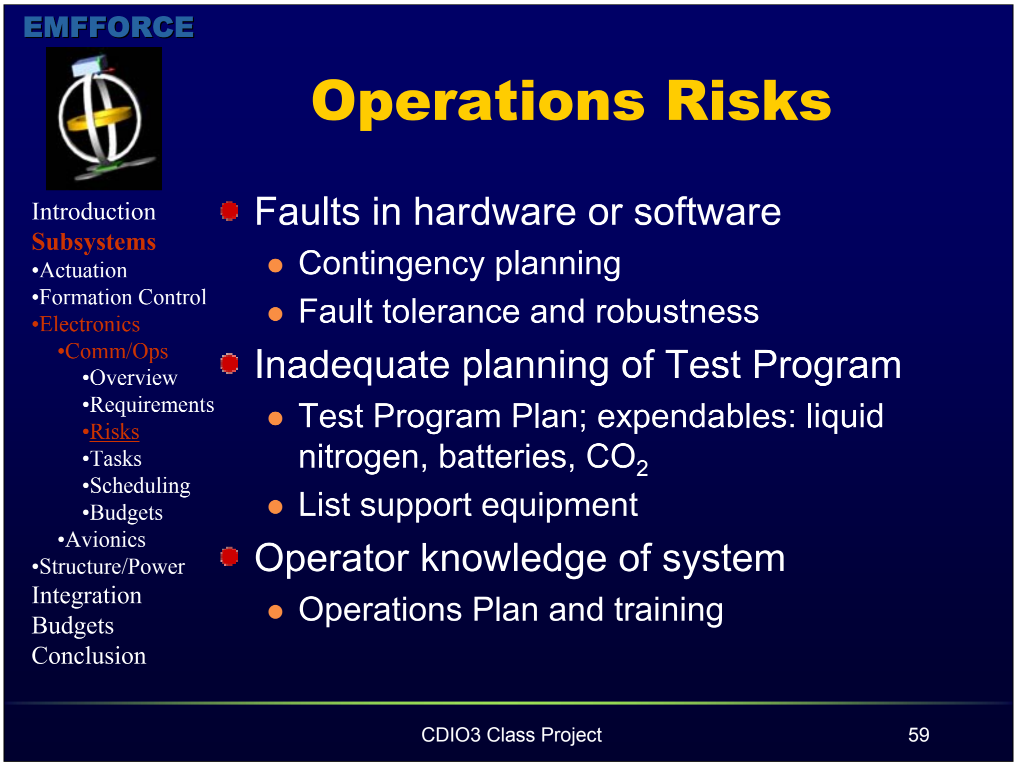


<ESS>

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 more important than completing the project. 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 and is determined by the system test program. 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. Equipment longevity must be promoted at all levels, as our two most valuable resources of time and money both suffer from broken parts that need to be either repaired or replaced. Conservative stewardship of materiel will pay off in the long run.

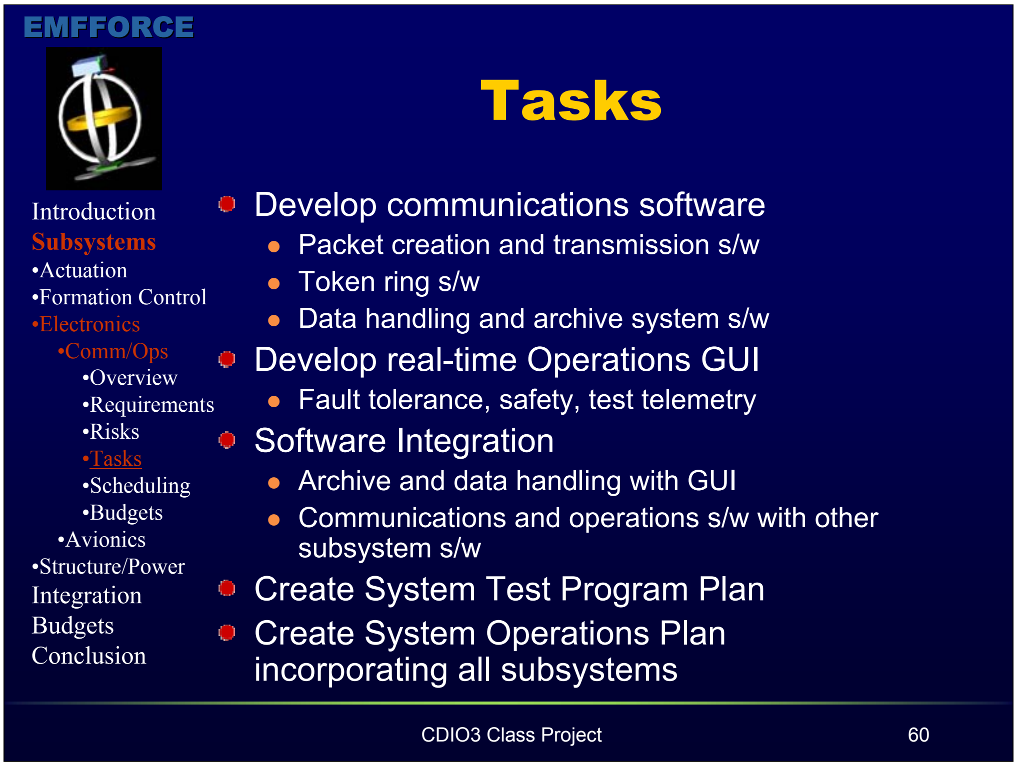


<ESS>

Faults in hardware or software may cause equipment failure and/or safety hazards. When things go wrong, the consequences are sometimes not predictable. We could injure a crewmember, damage the system, or fail to complete a test if the team does not plan for as many failure modes as possible. The goal here is to minimize the consequences of misdesign or malfunction

A poorly planned test program may fail to accomplish the objective of the entire mission: to demonstrate the feasibility of EMFF. All factors must be accounted for, and performance margins should be included. As things will always go wrong, there must be sufficient room to still finish the required tests.

Operators may lack essential knowledge of system functions for efficiency and troubleshooting. When setbacks occur in the field, the operators assigned to that test mission must be able to solve problems quickly as they occur. The division of the EMFFORCE team into two traveling groups necessitates good documentation and training for those who are selected to go.



<ESS>

The Communications task is to build a system that can accomplish the communications mission of transmitting data from one vehicle to another as required by the other systems. This will involve the integration of communications software and hardware and carefully tracking electronic interfaces with the other subsystems, especially Avionics Team and the Formation Flight Group.

The Operations tasks are to manage everything not physically included on the vehicles and to prepare the system for real-time testing and evaluation. The EMFFORCE vehicles will be controlled by the laptop ground station, which will provide the commands necessary for beginning and ending the tests. It will also monitor the status of the test vehicles and collect data for analysis. In addition to these mission-critical functions, the operations equipment will serve to reduce the consequences of system failures or inaccuracies by intervening in the autonomous control system and either bypassing the error or commanding an emergency shutdown.

The Comm/Ops Team also must develop two documents: the System Test Plan and the System Operations Plan. The Test Plan is the testing schedule for the field tests. It will describe what objectives need to be met and how they will be measured, and will take into account the operational constraints of limited expendable resources. The Operations Plan will standardize how the EMFFORCE Team operates the vehicles, and will include checklists for various functions as well as operator-oriented systems descriptions. These will serve to counter the risk of lack of operator knowledge of the system.

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Schedule

START	END	TASK
17SEP	26SEP	Software interfaces and module plan, select and buy hardware
24SEP	14OCT	Comm modules ready for testing
24SEP	17OCT	Ops GUI ready for testing
17OCT	31OCT	Draft System Test Plan
14OCT	31OCT	Communications integration
31OCT	14NOV	All EMFFORCE software integrated
04DEC	13DEC	Integrate software with vehicles
04DEC	13DEC	System Test Plan
13DEC	04FEB	Operations Plan
February		Integration Testing
31Mar	24Apr	Field Tests

CDIO3 Class Project 61

<ESS>

17SEP-26SEP Software interfaces: Set required software interfaces with Avionics, Control, and Metrology to solidify requirements for data transmission rates and processing. Define discrete modules according to these interfaces. (ESS) Comm Hardware:Select and buy necessary CommOps Hardware (JEU)

24SEP-03OCT NAR: Set task and integration plan for remainder of project.(JEU)

24SEP-14OCT Comm Software:Write and debug all necessary Comm software(JEU)

24SEP-17OCT Primary Ops System: Implement core Ops system to occupy node on system communications network and to track interfacing test data. (ESS)

14OCT-31OCT Comm System:Integrate Comm hardware and software into a system containing the required modules.(JEU)

17OCT-31OCT Draft Test Plan: Create draft system Test Plan that will be included in CDR. The Test Plan must show that the system satisfies all operational requirements.(ESS)

31OCT-06DEC Ops System: Add functionality to Ops system to include realtime data display and decisionmaking aids designed to increase system reliability and fault tolerance.(ESS)

31OCT-14NOV Electronics, Formation Intergration: Combine all software modules and associated hardware from the Electronics and Formation Flight Groups and solve any interfacing problems.(JEU)

14NOV-21NOV CDR: Preparation and Presentation of current design and test results to date.(ESS,JEU)

04DEC-13DEC System Integration: Combine integrated Electronics and Formation Flight package with Structure and Actuation hardware to ready vehicles for full system test. Solve any software issues discovered at CDR.(JEU,ESS)

04DEC-13DEC Test Plan: Finalize the Test Plan that will guide the system testing in the Spring (ESS)

13DEC-04FEB Operations Plan: Create system operations plan based on CDR design that will detail how the system will be operated during the field-testing.(ESS)

04FEB-27FEB Integration Testing: Test the interfaces between all subsystems and make necessary modifications to system.(JEU,ESS)

27FEB-13MAR MIT Testing: Operate system in accordance with the Test Plan and modify system and/or Ops Plan as required.(ESS,JEU)

06MAR-13MAR Field Prep: Finalize all preparations for Field-testing(ESS)

13MAR-20MAR AR: Prepare and conduct AR(JEU,ESS)

31MAR-04APR Field Test:First Field Test

07APR-17APR Final mods:Fix anything that doesn't work. Probably too late.

21APR-24APR Field Test: Last Chance.

EMFFORCE

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Part	Cost ($)	Mass (kg)	Power (W at V)	
Ops Laptop	1843	N/A	A/C outlet	110 V
DR2000 kits	450	0.2	.25 W	3 V
Total (per vehicle)	225	0.2	.25 W	3 V
Total (ground)	2068	N/A	A/C outlet, .25 W (RF)	110 V, 3V (RF)
Total (per system)	3193	0.6	1W	3 V

CDIO3 Class Project 62

<ESS>

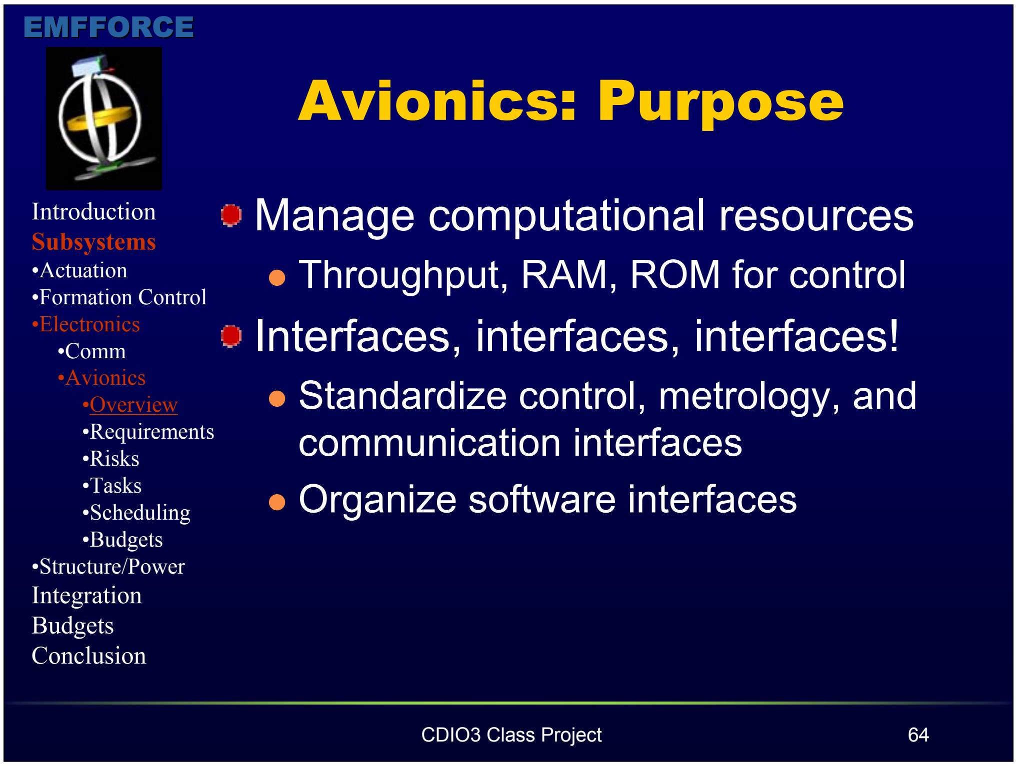
Comm Ops owns only the RF boards and antennae on the vehicles, which weigh less than 0.2 kg (per vehicle). Similarly, the power is needed only to drive the RF boards.

The system cost includes the Operations Laptop at $1843 and six new RF boards (RF Monolithics DR2000) at $225 each. Each development kit comes with two RF boards, at a cost of $450 per kit.

So long as nothing breaks, the only cost during prototyping and testing is labor, which is free.

Avionics

Amy Schonsheck

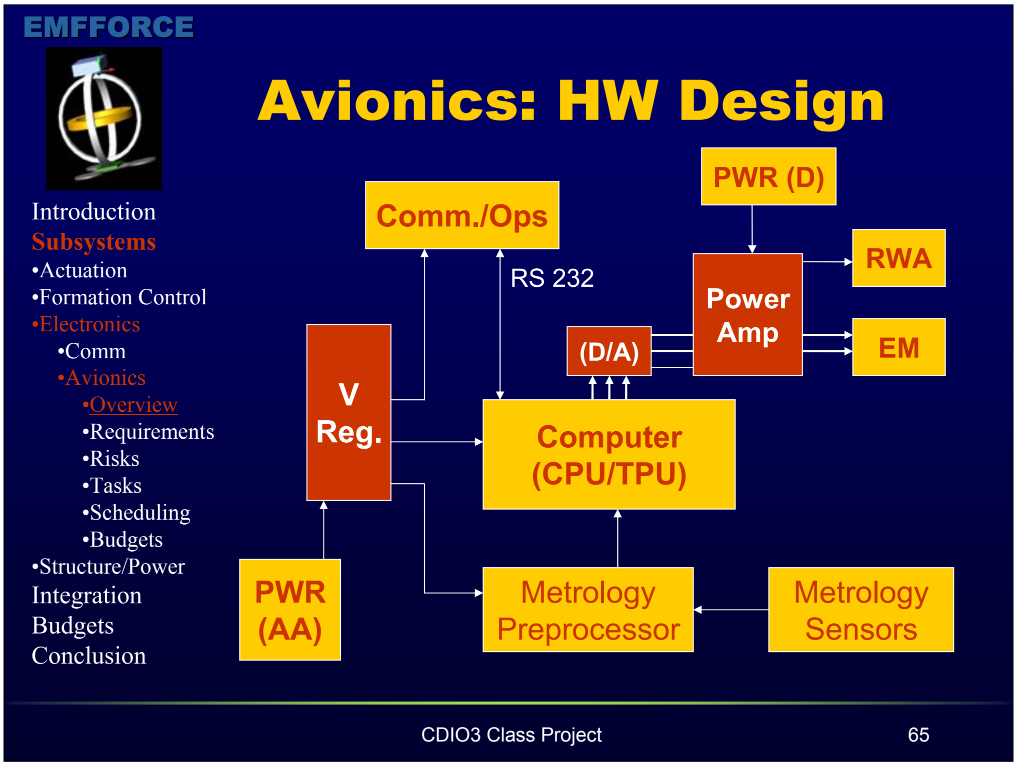


<MAS>

The purpose of the Avionics subsystem is twofold: (1) to manage computational resources on board the vehicles, and (2) to ensure all hardware and software interfacing with the central computer is standardized, including checking other electronics board interfaces.

1. The primary purpose of avionics subsystem is to make sure the all communication, operation and metrology processing is done such that the control loop has the resources it needs to complete its calculations. This includes:
   - Throughput: computer processes enough MIPS (million instructions per second) to calculate control loop in real time
   - ROM (EEPROM for TT8): semi-permanent FlashMemory for loading code
   - RAM: temporary memory for storing vehicle and master arrays (variable matrices)

2. The secondary purpose of the avionics subsystem is to ensure all electronic connections around the computer are safe, both for the system and for the operators, as well as at optimal operational levels.



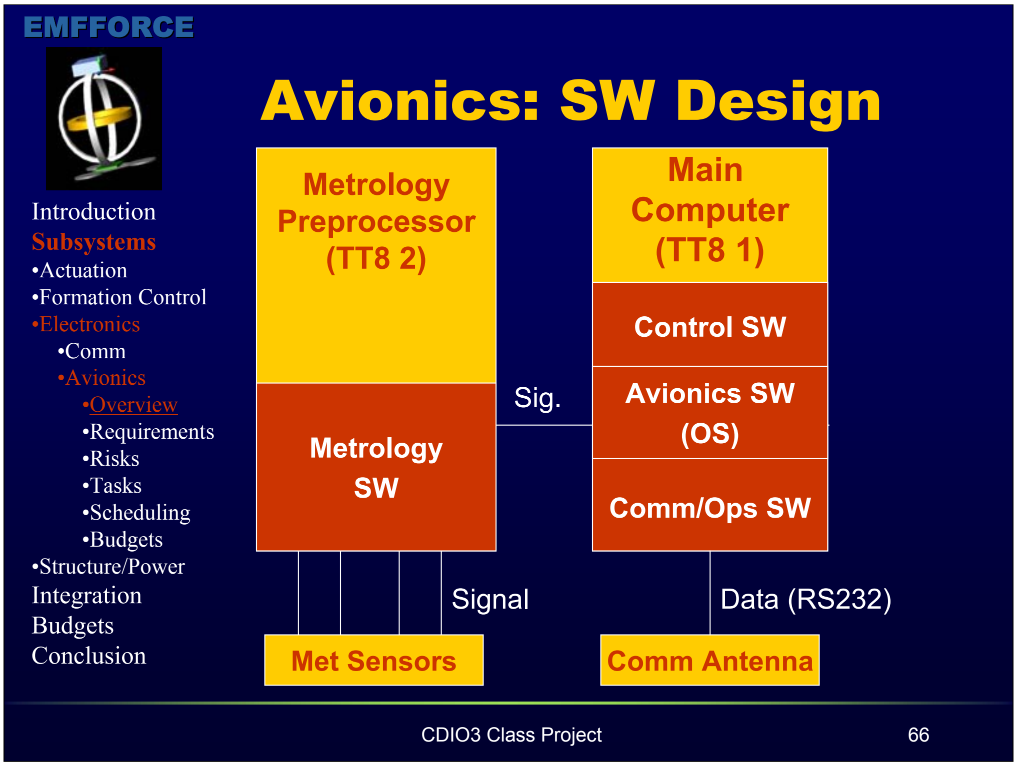
<MAS>

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)
- •Comm/Ops – sends/receives all data going in/out of the immediate vehicle system from/to TT8.
  - •Utilizes a serial cable connection (RS232).
- •Power amplifier – takes the actuation signal output from TT8 to implement (using power from D cell batteries)
  - •Possible intermediate step of D/A converter, depending on the type of power amp used (switch-mode or not)



<MAS>

The Avionics hardware design layout is as follows:

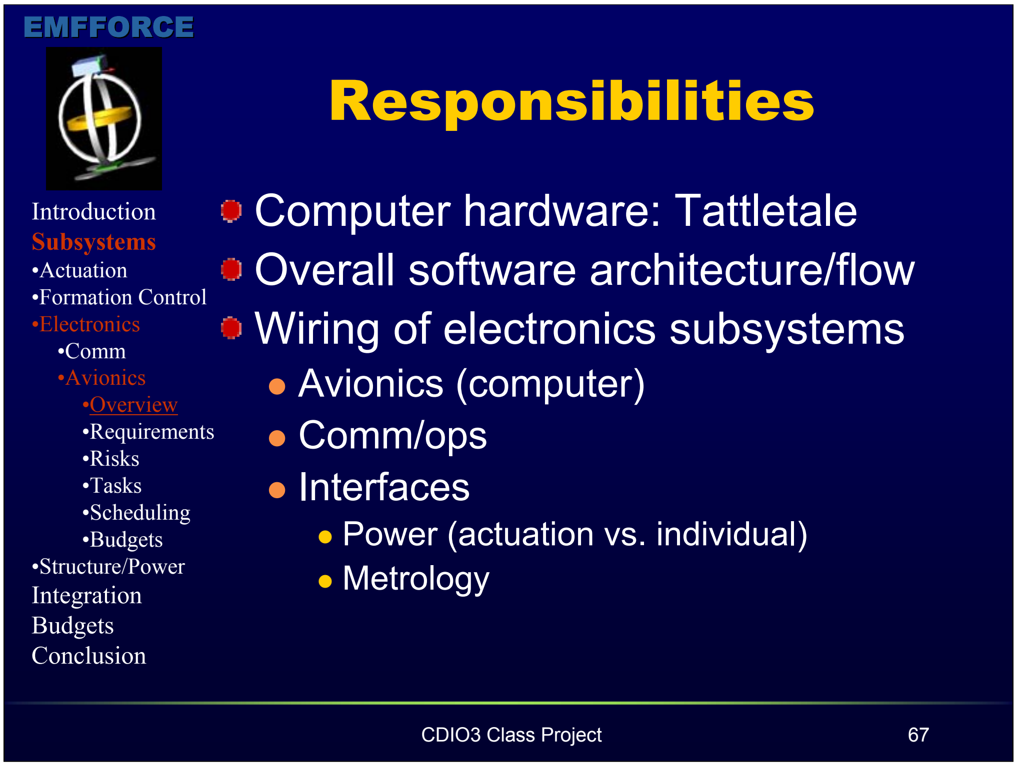
•The main computer (TT8 1) holds software for three subsystems.

•Avionics software directs and manages all computational resources through a main function, or operating system (OS).

•Control software is the system control algorithm, implemented in C to run on the TT8. Its module is called by the OS.

•Comm/Ops software controls all vehicle-vehicle and vehicle-ground data passing and communication. It interfaces with the OS when gathering data to pack and send, and when distributing recently received and unpacked data.

•The second computer (TT8 2) holds the "Metrology Preprocessing System." The Metrology team is responsible for implementing their systems of transmitters, receivers and preliminary calculations. The Avionics OS polls the Metrology TT8 for updated Primary Vehicle Arrays (PVA).



<MAS>

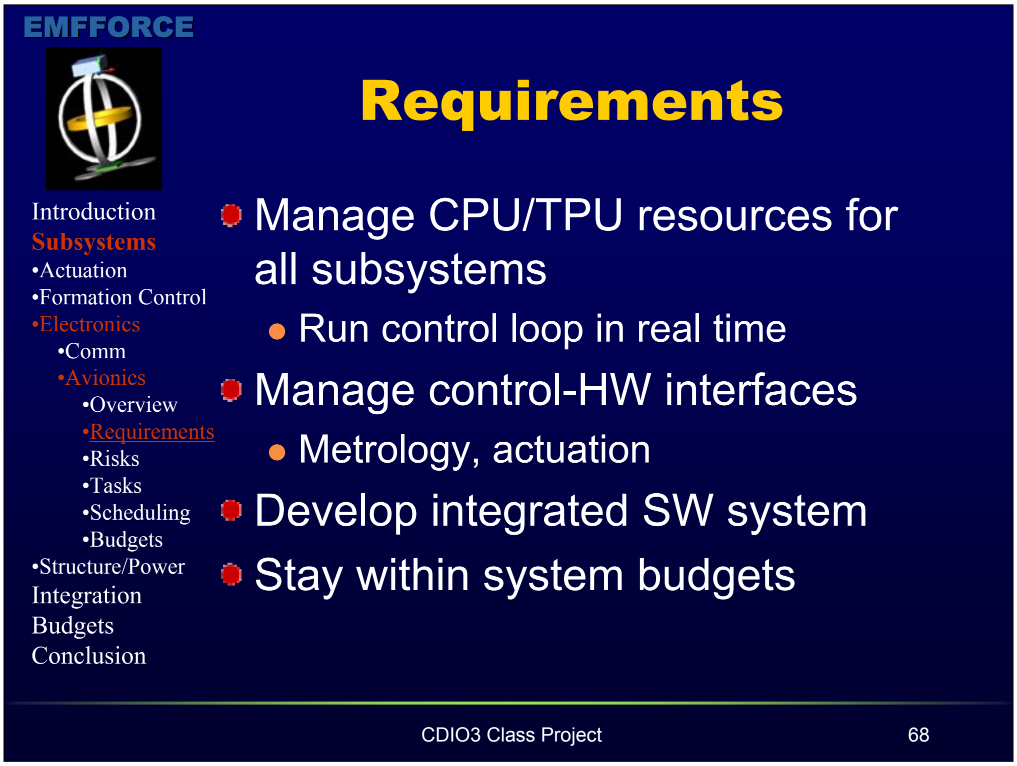
The final output of the Avionics includes the following:

•All items dealing with the Tattletale

•Overarching software plan and “operating system”

•Wiring together the electronics subsystems, including interfaces with power supply (AA for electronics boards) and power amps (connected to D cells for actuation).

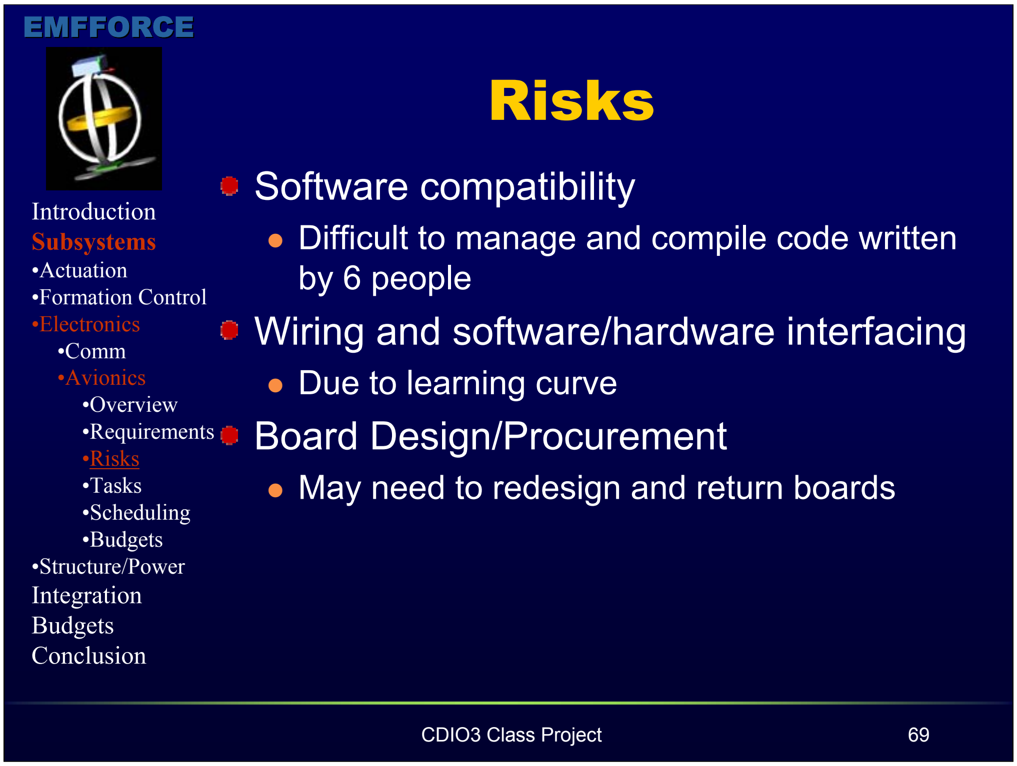
- Note: There will be a significant amount of collaboration with the Structures team on the wiring design and with the Power team for the actuation and power supply.



<MAS>

Avionics Subsystem Requirements.
The Avionics subsystem shall:

1. Manage Central Processing and Time Processing Unit resources for all subsystems. The central computer is the "brain" of each individual vehicle, and the focus of the avionics subsystem. It must regulate processing power and memory among the subsystems that require calculations, particularly communications and control. Specifically, the avionics must run the control loop [as written by Control Team] in real time. This includes:
   - Holding state matrices in memory that contain position, orientation, velocity, and rate data for the system
   - Updating the input matrices with Metrology data [after preprocessing in the Metrology subsystem]
   - Performing multiple degrees of matrix operations to run the loop
   - Sending the loop output to the amplifier for the actuation subsystems [EM, RWA], which sets the current flow.
2. Manage control-HW interfaces. The Avionics Team must ensure that all signals entering and leaving the CPU are of appropriate voltage and strength. This includes data input from the metrology preprocessing system in the form of the Primary Vehicle Array (PVA, explained in Communication section), and commanded output to the actuation elements. Between the actuators and the computer stands a power amplifier (primarily the responsibility of the Power team) which must be supplied with the correct signals to amplify.
3. Develop integrated SW system. Although each subsystem team who requires computer programs will be writing its own code, the Avionics team is responsible for organizing all scripts into a single "operating system" on the central computer. This includes writing a master program as well as standardizing style for continuity purposes.
4. Stay within system budgets. The system as a whole has strict budgets on mass, power draw, size, and cost. To meet its requirements, the Avionics subsystem must abide by these budgets while still achieving the functional objectives.

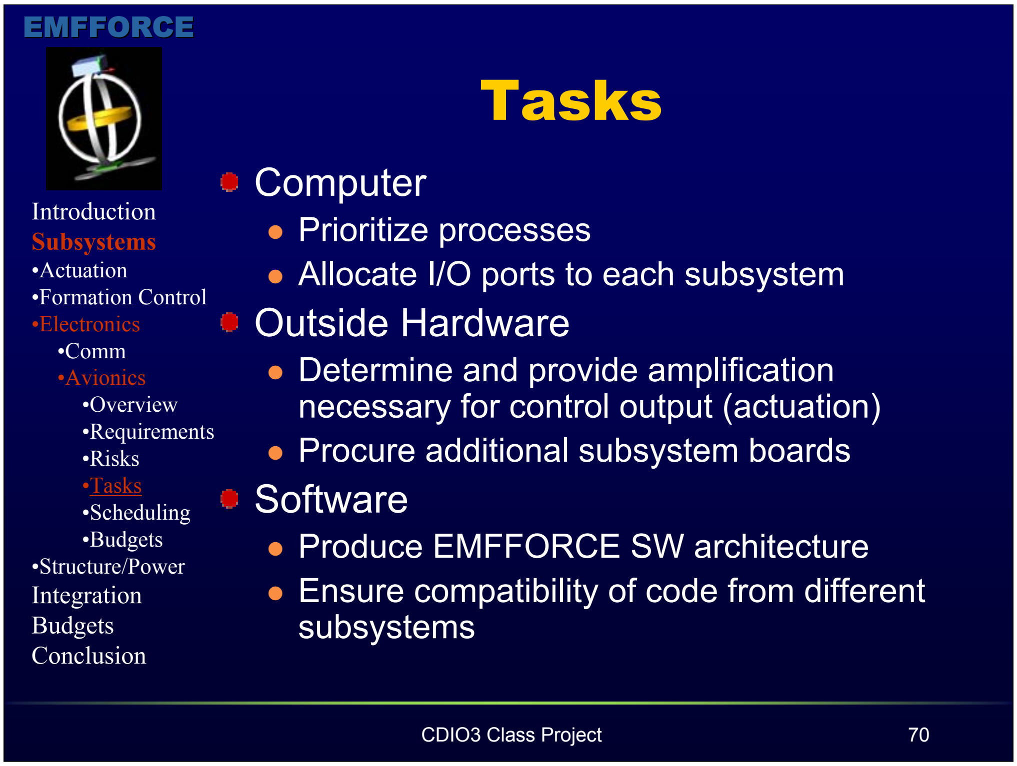


<SJS>

Avionics can be broken down into two sections (1) software and (2) hardware.

(1) Software compatibility may be the Avionics team's biggest concern. It is quite difficult for six people to write code that will function as one large composite code. Actions must be taken to ensure code compatibility early on in the code writing process, so that problems can be fixed as they arise.

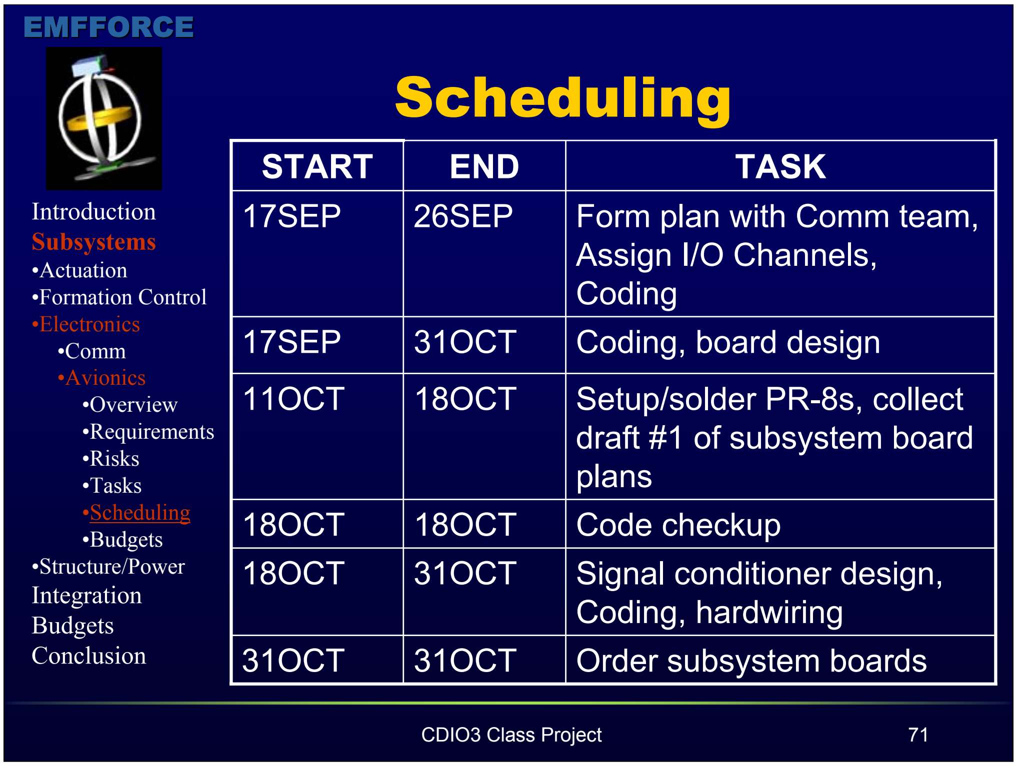
(2)Hardwiring and integration is another risk in that it is difficult to judge how long this will take the Avionics team. The team is unexperienced in this field, and therefore a learning curve must be taken into consideration. The subsystem boards may need to be redesigned and returned, so ample time in designing and receivng the boards must be allocated.



<SJS>

Avionics Subsystem Requirements.
The Avionics subsystem shall:

1. Prioritize processes (That is, memory must be allocated to the comm., controls, and metrology accordingly).
2. Allocate channels and input/output pins to each subsystem. (This is to ensure early on that the Tattletale has a sufficient amount of pins and channels for our vehicle to function and will ensure that no two subsystems plan on utilizing the same channel number).
3. Be responsible for any necessary signal conditioning for actuation.
4. Decide upon a single code template in order to ensure software compatibility and write the software "shell" code to integrate the various subsystems's code.



<SJS>

The avionics team intends to follow this schedule (most recently updated: 01 October 2002) from the beginning of the Fall 2002 semester through CDR. This schedule is subject to changes. The avionics team first determined the necessary tasks pertaining to avionics (see section "RISKS"), then determined a logical order in which to complete these tasks. Lead time of hardware, learning curves of avionics design, integration deadlines and goals (CDR deadline), and schedule compatibility with other subsystems are the driving forces of this schedule.

Because the largest risk is that of software incompatibility, one of the first tasks of the avionics team was to create a software template for all other subsystems to utilize. Also, the Avionics team schedule includes many "software checkups" throughout the term. These software checkups help to ensure that software is being designed by the various subsystems in such a manner that it can be easily integrated into the system near the end of the term.

Hardware integration will also be a major task of the Avionics team. Therefore, the team plans on collecting various revisions of the individual subsystem boards from the other subsystem teams so that the Avionics team can monitor the board design progression. The Avionics team also shall order the boards so that they can be integrated into the system by 22 Nov 2002.

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Part	Qty	Cost ($)	Mass (kg)	Power (W at V)
Boards	2	550	0.06kg	TBD
Total (per vehicle)	----	1100	0.12kg	TBD
PR-8	2	95	N/A	N/A
TT8 Repair.	N/A	200	N/A	N/A
Total (per system)	------	3595	--------	---------

CDIO3 Class Project 72

<SJS>

NOTE: The cost estimates were originally calculated for the entire system.

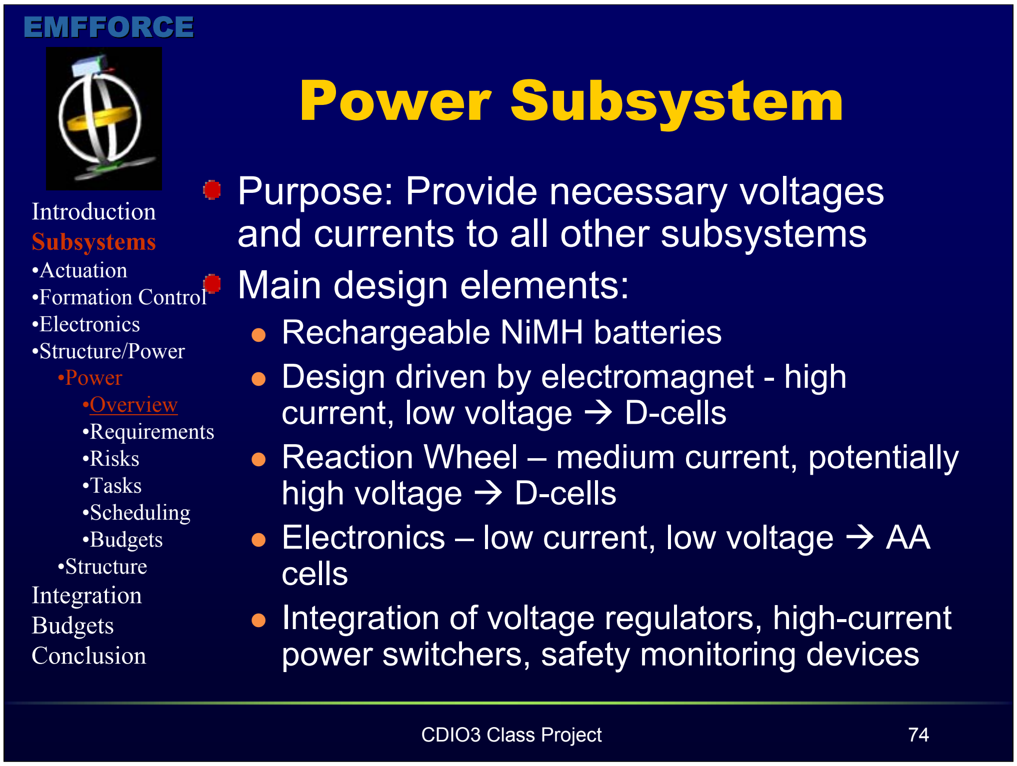
•The cost-per-vehicle show in the table assumes two boards per vehicle. TT8 cost budget is for Tattletale repair.

•An extended budget for each item should cover any repairs or replacements during the project; this is factored into the “system” calculation.

•PR-8 boards are for prototyping usage only, therefore, their mass does not factor into the vehicle or system mass.

•4PCB (custom board vendor/manufacturer) cannot give EMFFORCE accurate cost/mass estimates of the individual subsystem boards until the individual subsystems design the boards in detail. This subsystem board design shall occur between now and 31Oct. Power estimates shall also be determined at that time.

Power



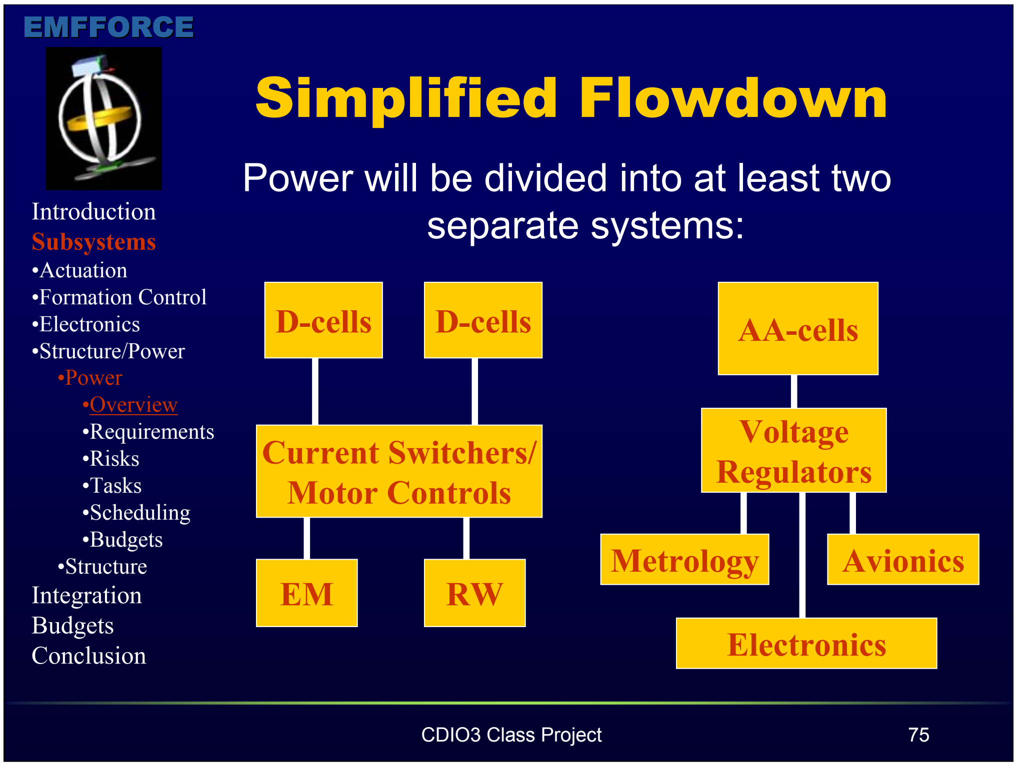
<TAS>

The function of the power subsystem is straightforward – to provide electrical power to the rest of the system. The subsystems requesting power are the electromagnet, reaction wheel, metrology, avionics, and comm/ops. Each has a different set of voltage and current requirements that must be met by the power subsystem.

The present design calls for using rechargeable nickel metal hydride (NiMH) D-cells to provide the power for the electromagnet and reaction wheel. The remaining subsystems will be powered by rechargeable NiMH AA-cells. The decision to use these types of batteries will be discussed in the requirements section. Currently, most of the effort is focused on the design of the electromagnet batteries. The electromagnet requires extremely high voltages (up to 100 Amps) at a low voltage, a combination rarely seen for high-power systems. Designing this portion of the subsystem is quite a challenge, since most commercial products are not tailored for this type of application.

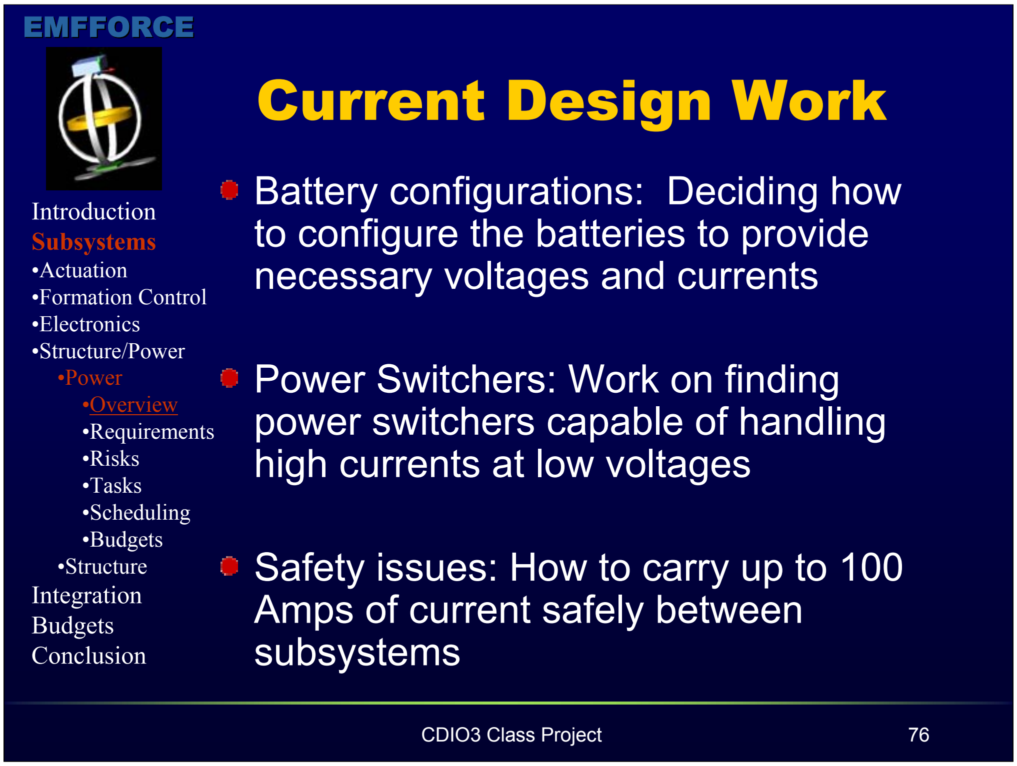
The reaction wheel will require a modest current at potentially high voltages, so D-cells will likely be used. The electronic subsystems will operate at low voltages and low currents, so standard AA cells will be sufficient.

When completed, the final power subsystem will be an integration of the main batteries, voltage regulators, power switchers, and possible safety monitoring devices.



<TAS>

Here is the simplified flowdown of power from the main batteries to the individual subsystem components. The power subsystem will be composed of two separate systems: D-cells and AA-cells. The reasoning behind this is discussed in the requirements section. The D-cell batteries will be linked to one or more current switchers and/or motor controls. These will take inputs from the on-board computers and control the amount of current going through the electromagnet and reaction wheel. The current switchers and motor controls will be similar to those found on modern electrical vehicles, which are designed to operate at very high currents. The AA-cells will feed to a system of voltage regulators tailored to the specifications of the electronic subsystems. The metrology, avionics, and communications subsystems can easily plug into the power subsystem.



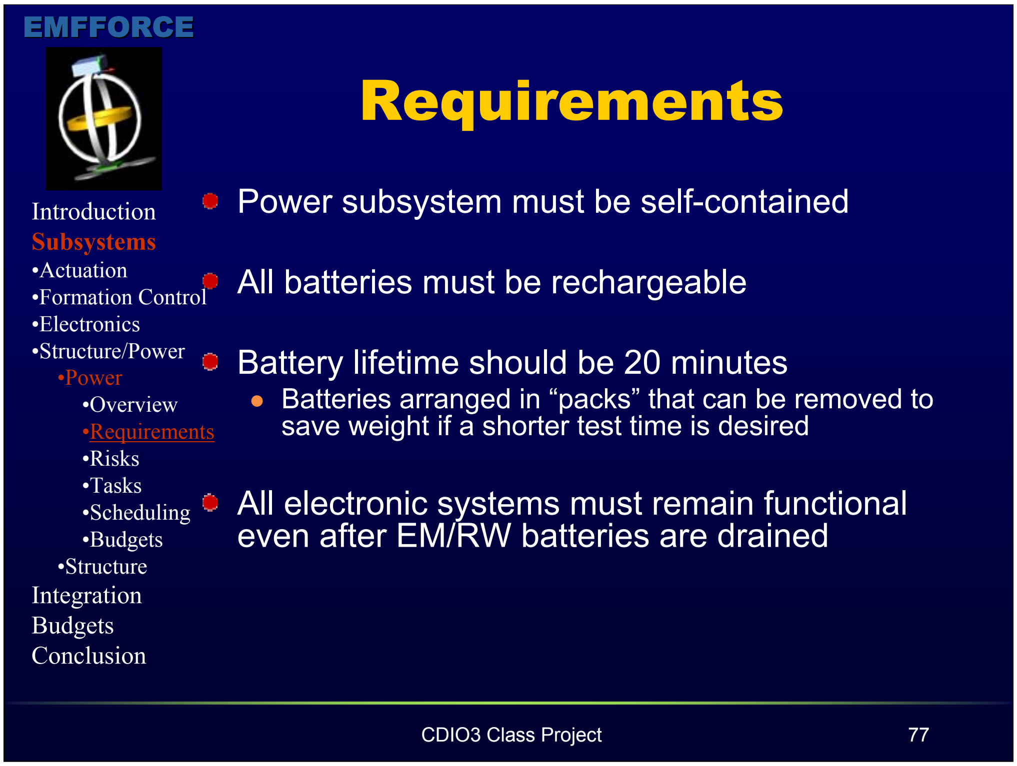
<TAS>

The current design work is focused on a few major areas. First is figuring out the primary battery configurations. The electromagnet will require the D-cell batteries to be wired in such a way as to provide high currents at relatively low voltages. The reaction wheel will require much higher voltages and lower currents and will have a different D-cell battery configuration. Likewise, the AA-cells must be wired in such a way as to provide adequate voltages to each of the other subsystems.

Part of the difficulty in the power design for the electromagnet is finding a current controller that is powerful enough to handle up to 100 Amps yet operates at a low voltage. The D-cells are capable of providing very high currents, but since each cell is only 1.2 Volts, large voltage requirement means adding many more batteries in series. This substantially increases the overall mass and cost. Work is currently being done to find a controller that will meet the unique power needs of the system.

The third pressing issue is figuring out the logistics of how to safely carry up to 100 Amps of current throughout the EMFFORCE system. Such high currents can cause many problems – among them are the batteries heating up to dangerous levels, risk of electric shock to the operators, and finding wires that can efficiently handle such high levels of current. These issues must be dealt simultaneously with the rest of the subsystem design work.

Part of the safety design may also include health monitoring systems. These would generally be small indicators (possibly LEDs) which would alert the operators of any problems with the batteries. These could also be used to indicate when the batteries must be replaced. Since these indicators are not considered to be of primary importance, their design will be saved until after the rest of the power subsystem is completed.



<TAS>

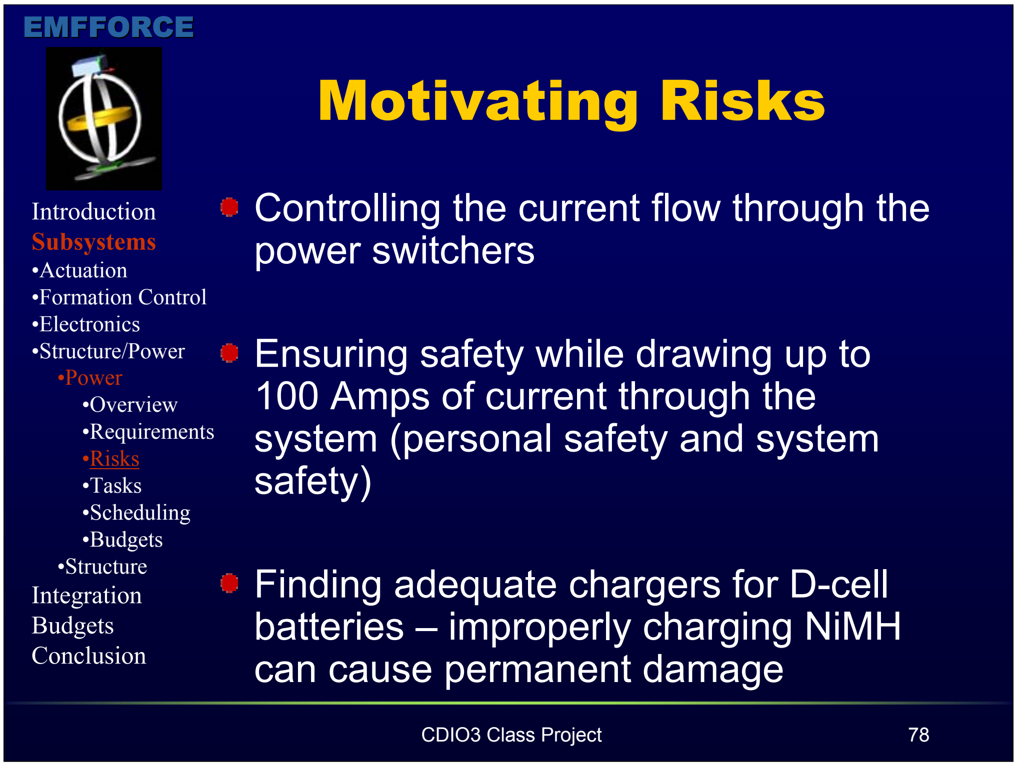
The power subsystem is being designed to meet a basic set of requirements. These have developed over the course of the EMFFORCE project, and the most current requirements are the following:

The power subsystem must be self-contained – this requirement is actually true for all subsystems. The nature of the project dictates that there be no wires or connections from the vehicles to the outside world. Each vehicle must be free-floating, meaning that everything must be contained on board, including the power.

All batteries must be rechargeable – Both cost and environmental concerns factor into this requirement. Due to the high number of batteries on board each vehicle, purchasing new batteries for every test would be infeasible. Also, using rechargeable batteries prevents the need for disposable of hundreds of batteries over the course of the project.

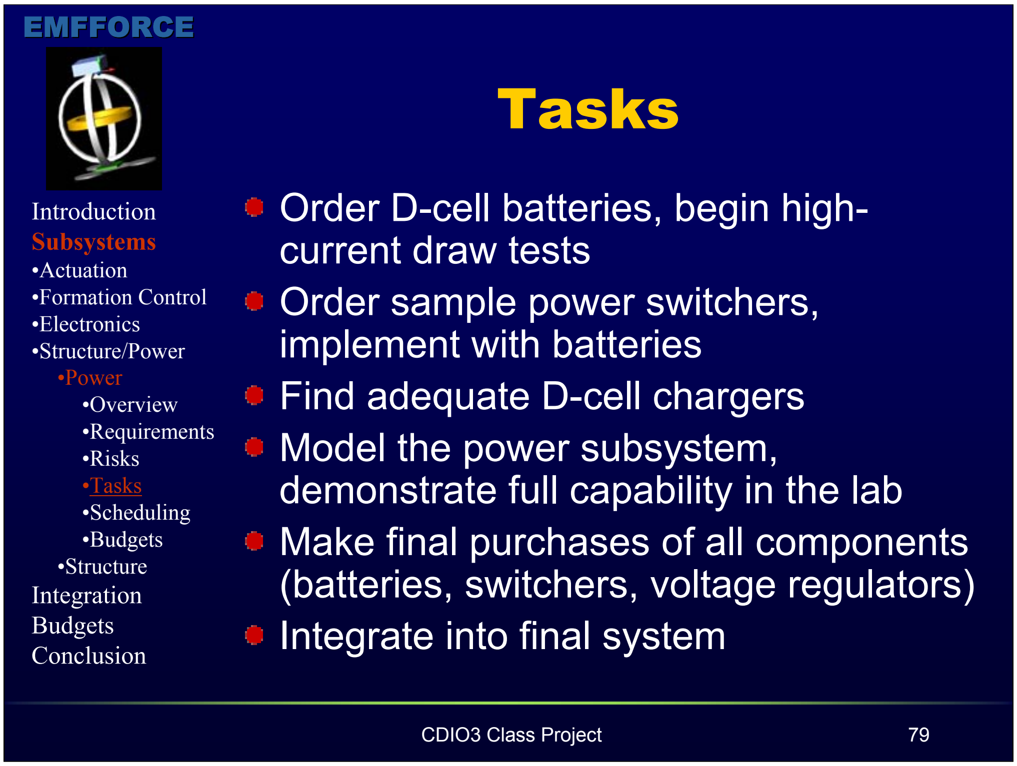
Battery lifetime should be around twenty minutes – Originally, the lifetime requirement was thirty minutes, but in some cases it has been easier to design for a slightly shorter duration. For example, battery weight can be reduced substantially if the requirement is reduced from thirty to twenty minutes. The final goal is to have battery duration as close to thirty minutes as possible, but not less than twenty.

All electronic systems must remain functional even after the main batteries have been drained – This is the most recently added requirement. The EMFFORCE team realized that it would be necessary to have communications, metrology, and avionics capabilities even if the batteries for the electromagnet and reaction wheel were drained. For this reason, there will be at least two separate power systems on board. One will be exclusively for the EM and RW (and will be composed of D-cells), and the other will be for electronic purposes (and will be composed of AA-cells).



<TAS>

There are a few associated risks that are guiding the design process. As mentioned earlier, controlling the flow of current through the power switchers is a difficult task. Time must be spent finding an adequate controller and learning how to properly implement it in the system. Also, the safety of drawing up to 100 Amps of current is a big risk factor. The system must be carefully designed to minimize the risk of danger to the operators and to the other system components. Finally, finding adequate chargers for D-cell batteries can be difficult. Most chargers hold up to four batteries at a time, but the EMFFORCE project may need 50 or more batteries for each test. Charging times also tend to be quite long (around 16 hours), and so this must also be taken into account. These risks are the motivation for several of the tasks mentioned next.



<TAS>

This is a list of tasks that must be completed by the end of the semester. Completing these tasks will help ensure a fully- designed and operational subsystem that can be easily integrated with the other subsystems. The schedule for completion of these is given next.

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START	END	TASK
26 SEP		Order sample switchers, batteries
26 SEP	10 OCT	Find, order D-cell battery chargers
1 OCT	24 OCT	Design overall system using lab models
17 OCT		Make final purchases of components
24 OCT	7 NOV	Test the final design, determine integration with Structure
12 NOV		Ready for integration with all subsystems

CDIO3 Class Project 80

<TAS>

This is the tentative schedule for work on the power subsystem. The schedule calls for full system integration to be ready by 11/12. This is actually somewhat earlier than the planned integration for the rest of the subsystems. Since the power subsystem should be ready before the other subsystems are complete, human resources can be re-allotted to help out other subsystems in need.

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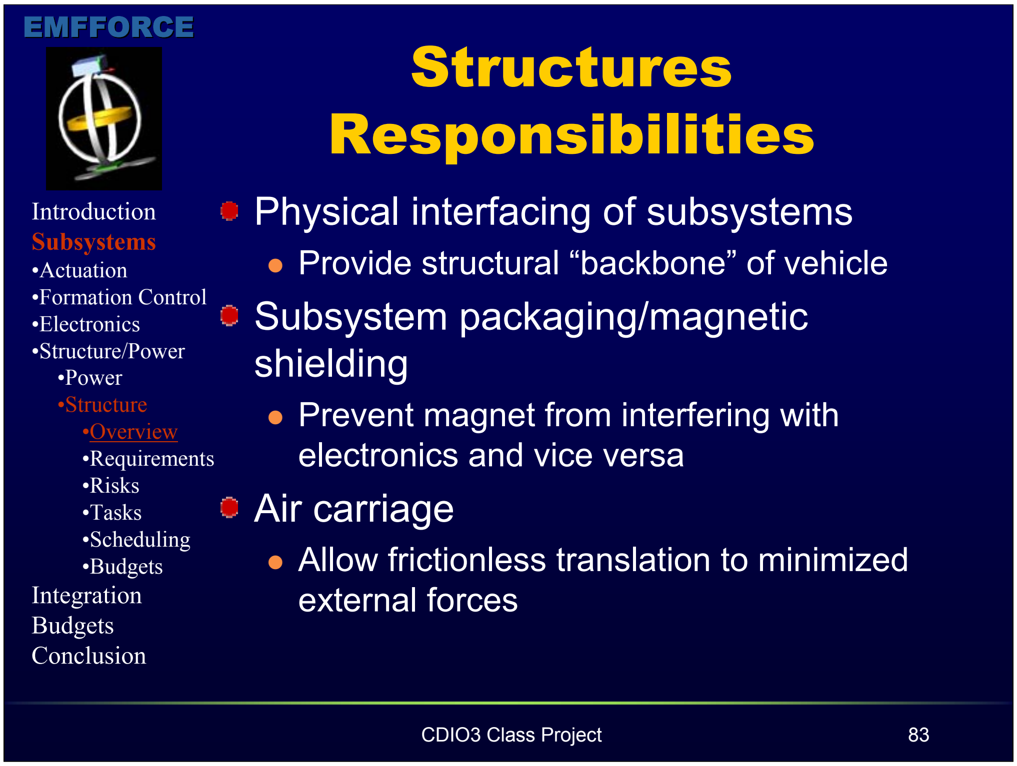
Part	Qty	Cost ($)	Mass (kg)
D-cells	20 X 2	400	3.5
AA-cells	10 X 2	100	0.3
Chargers	5	100	N/A
Power Switchers	2	150	0.05
Voltage Regulators	3	150	0.05
Misc. Electronics	-	100	0.1
Total (per vehicle)		**1000**	**4.0**
Total (per system)		**3000**	**12.0**

CDIO3 Class Project 81

<TAS>

Here is the proposed budget for the power subsystem. It includes all the necessary components of the system with the most recent estimates for cost. It is much higher than previously presented, but represents a more accurate estimate of the actual cost of each component.

Structure

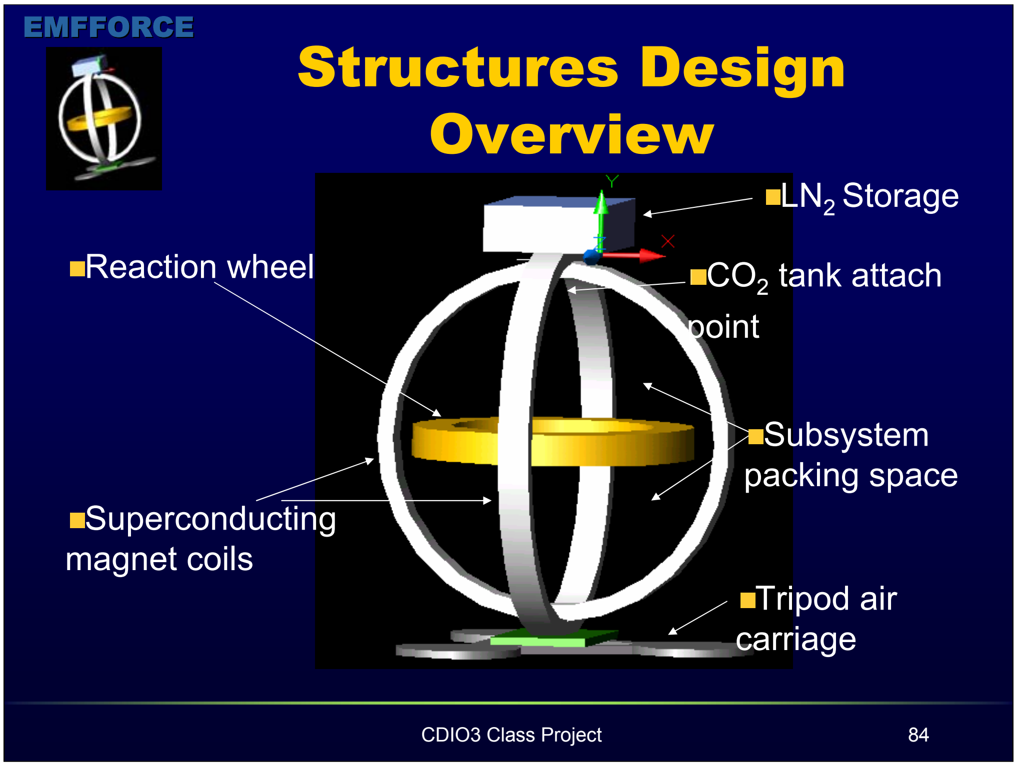


<ALS>

The structures team is responsible for three main items. First, the subsystems must be integrated and oriented to allow their other interfaces to be in place. This requires that the structures team manage the “real estate” inside of the vehicle, always keeping in mind issues such as minimizing mass, vehicle stability, and rotational symmetry.

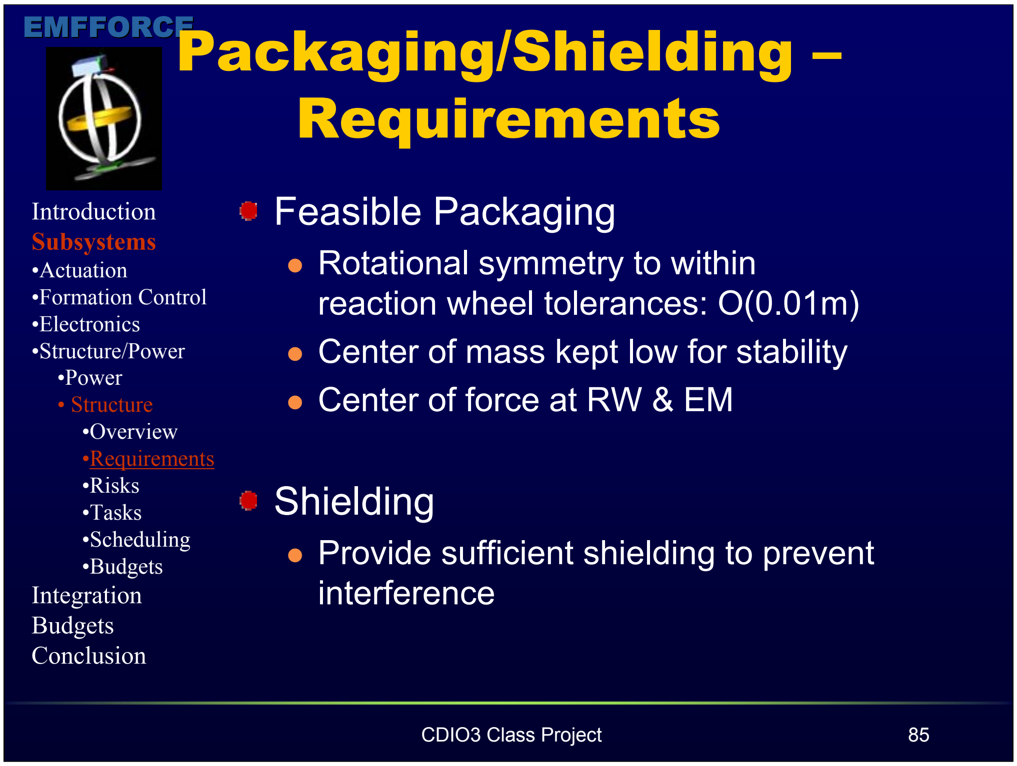
Along with the physical architecture of the system, the structures team is responsible for development and testing shielding to prevent interference of the magnet with the electronics and vice versa.

Finally, the structures team must develop the air carriage system to allow the vehicles to translate frictionlessly. This system includes a gas supply and storage system and a delivery system, commonly referred to as a “puck” because of its shape and function.



<ALS>

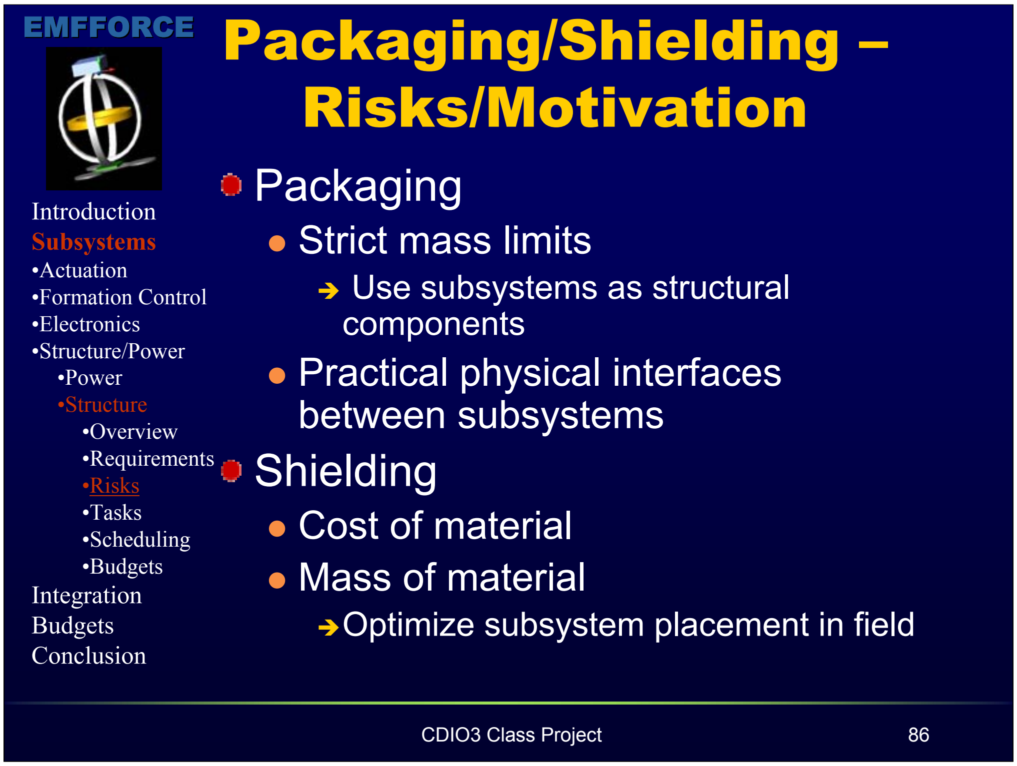
This diagram shows a rough sketch of what the vehicles will look like with the superconducting magnets. This is a drastic deviation from the previous core magnet design. The reaction wheel will be mounted in the vertical center of the vehicle with the other subsystems packed around it. The battery packs will stay underneath the reaction wheel to keep the CG low. The container for the magnet will be designed to hold liquid nitrogen and to hold the vapor at a pressure to power the air carriage pucks. This design has not been tested, so the CO2 tank attach point will be included so that the vehicle could use a tank instead. The use of a tank will add 1kg of mass to the vehicle.



<GG>

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.

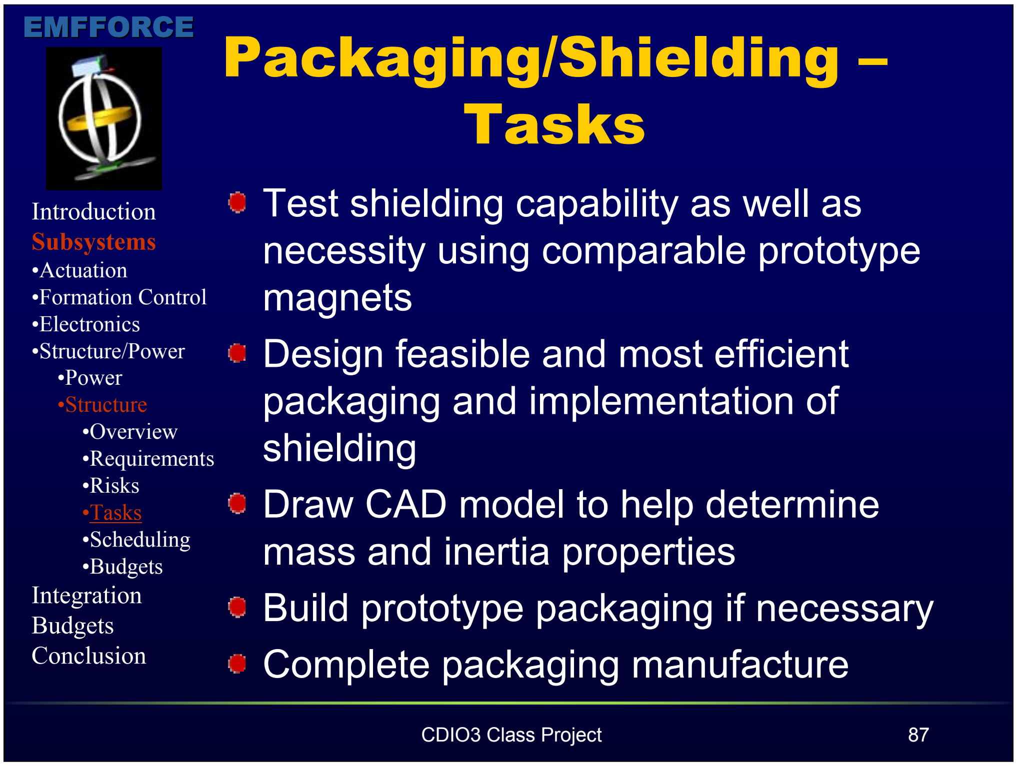


<GG>

The ultimate design of the packaging must not only maintain feasibility but it must also weigh as little as possible. Although there is no hard requirement on the mass of the packaging, the structures team aims to build zero mass packaging hopefully resulting in minimal mass possible.

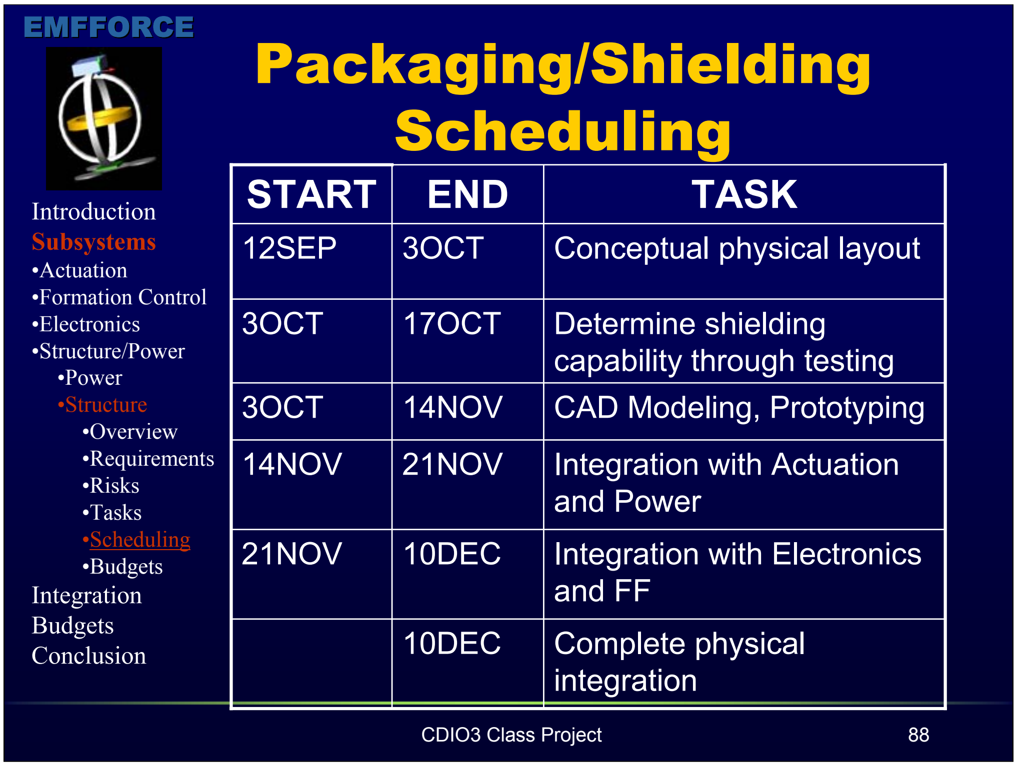
The next main obstacle the structures team must overcome is the physical interfacing between subsystems. The structures team must not only negotiate volume and space in the total packaging but must make sure all subsystem interfaces work smoothly and efficiently.

Again it is imperative that the structures team studies, tests, and shields if necessary the magnetic interference with the electronic subsystems.



<GG>

The structures team must design the most efficient packaging configuration. The entire EMFFORCE team has helped with the initial layout, but the structures team must now refine that layout and work out the details. A CAD model of the EMFFORCE vehicles will be helpful in calculating parameters such as the moment of inertia and mass of the vehicles, parameters useful to other subsystem teams.



<GG>

In order to meet the EMFFORCE milestones the structures team will follow this schedule.

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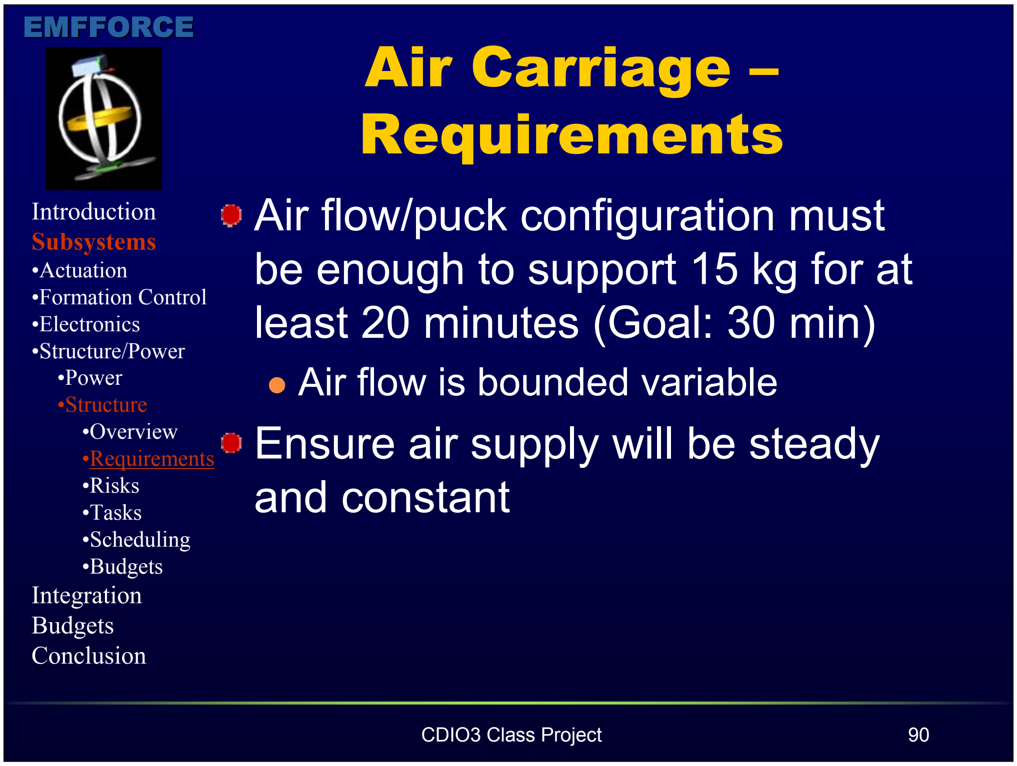
Part	Qty	Cost ($)	Mass (kg)	Power (W / V)
Packaging	3	100	1.25	0
Shielding Sample	1	189	--	0
Shielding	3	85	0.25	0
Total (per vehicle)		185	1.5	0
Misc.		189	--	0
Total (per system)		774	4.5	0

CDIO3 Class Project 89

<GG>

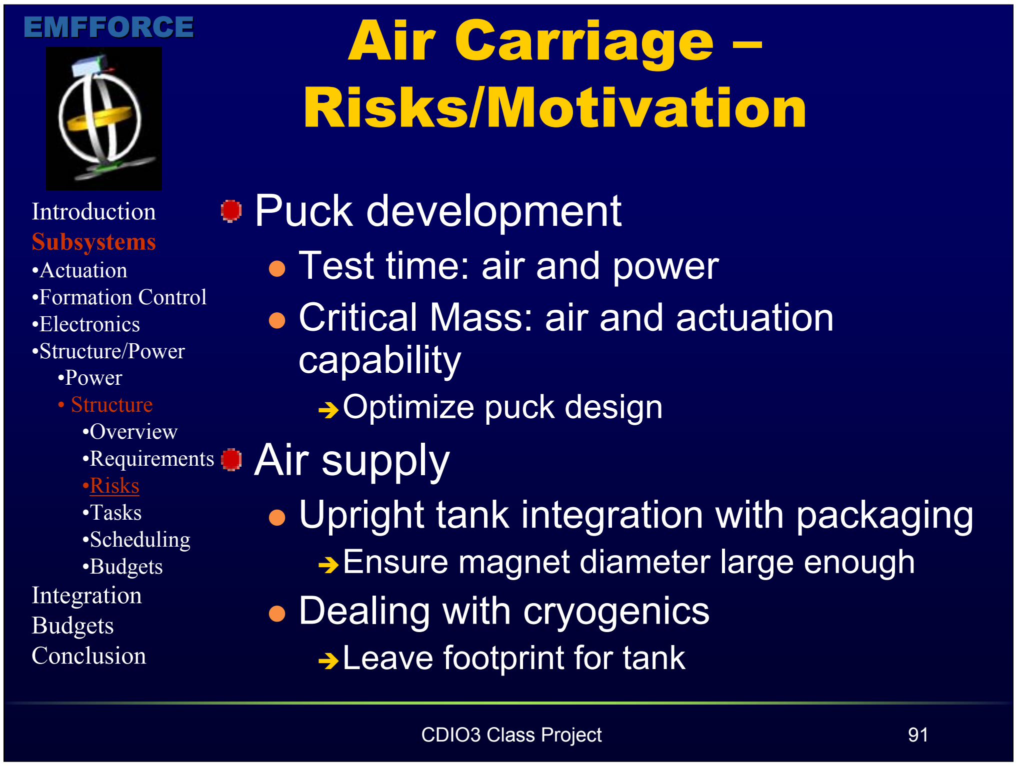
Although the structures team aims for a zero-mass packaging, a more realistic estimate is 1.5kg. This includes all structural components such as nuts, bolts, and frame components.

The shielding kit is a one time purchase used only for testing and does not contribute to cost per vehicle. <ALS>



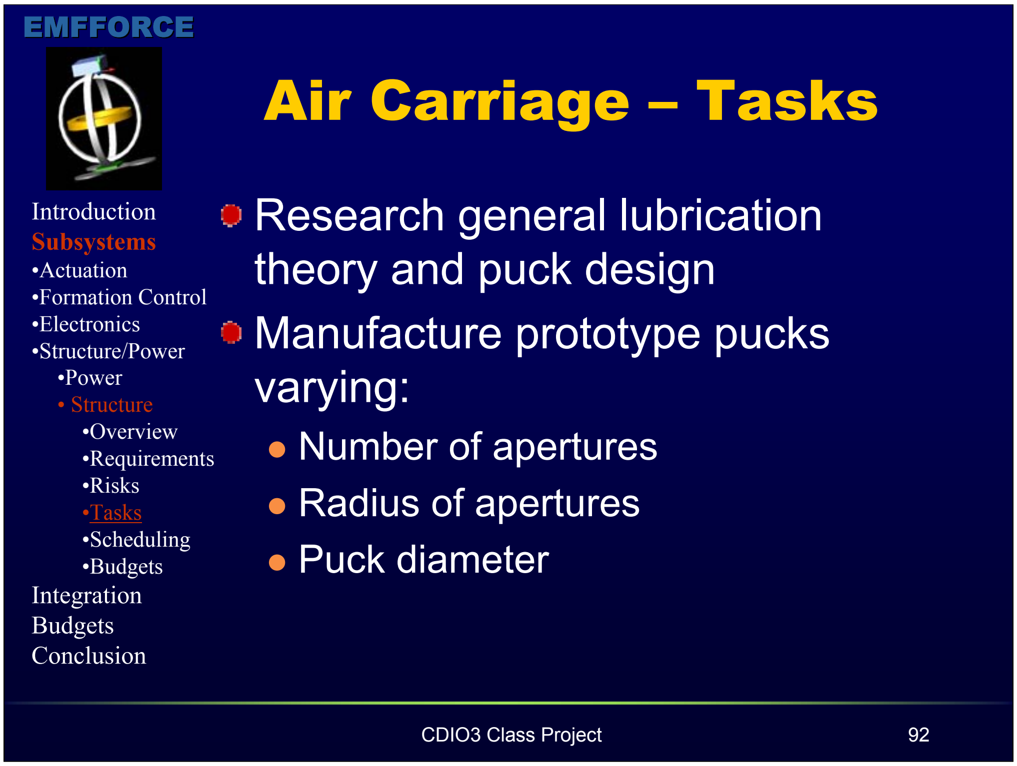
<ALS>

The air carriage must be able to support the mass of the vehicle for the entire test duration (defined in the requirements document as 30 minutes). This makes airflow the bounded design variable: it must be sufficient for the mass, but low enough to enable the air supply to last the test duration. It follows, then, that the air supply must be steady and constant to ensure that the pucks float continuously.



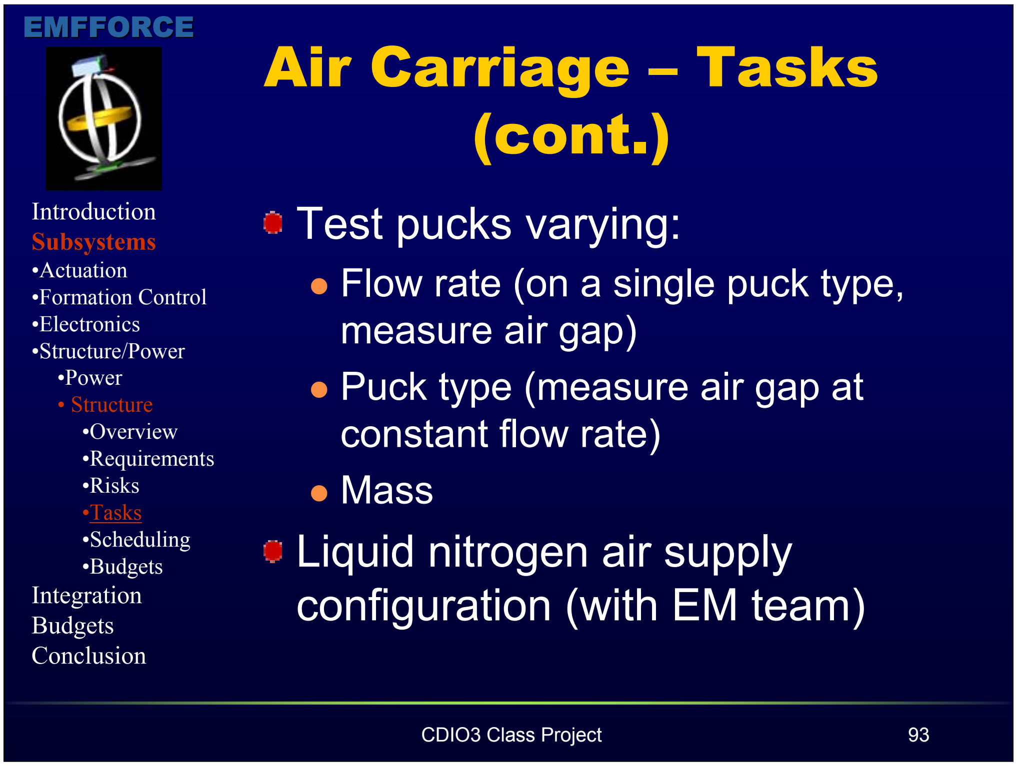
The difficulties that the structures subsystem will face when dealing with the air carriage are not numerous. First, by optimizing the puck design, the mass of the system will become less of a dominating factor in determining test duration.

By far, the most difficult hurdle in the air carriage design will be integrating the air supply into the packaging, especially if the gas from the cryogenics system is used to power the pucks. In this case, the structural nature of the magnet must be enhanced to allow it to be pressurized by the gas. It is also a possibility to include a heating element to increase the rate of gas production. This requires more complicated control and feedback and would introduce a software interface into the structures subsystem. <ALS>



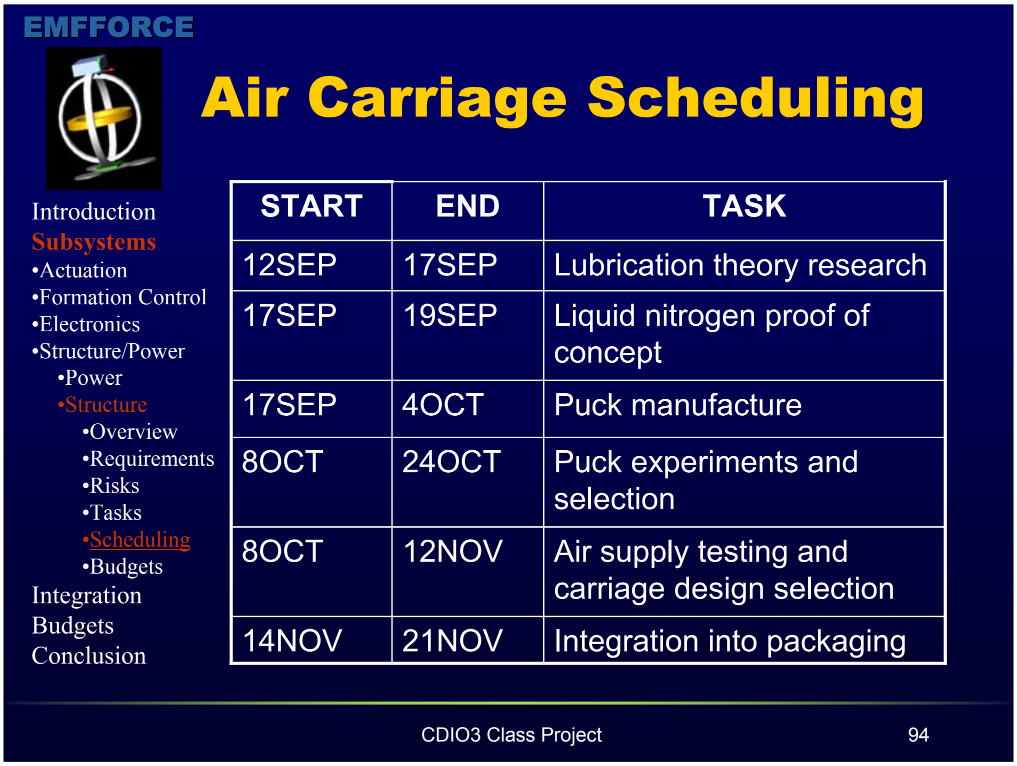
The structures team plans to develop the air carriage system architecture by the following progression:

First, structures will conduct general library research on lubrication theory and hydrostatic gas bearings. This research will involve no mathematical modeling of the complex flow problem. Rather, it is focused on a solid conceptual understanding of the principles behind gas bearings and common design strategies. Next, the structures team will manufacture a set of prototype pucks to empirically test proposed puck design varying the design variables: number of apertures, radius of apertures, and puck diameter. <ALS>



Using the prototype pucks, the structures team will determine each configuration's sensitivities to flow rate and mass as they relate to gap height. Trends in these observations will enable the structures team to choose a locally optimum puck design. <ALS>

Due to recent developments, the use of nitrogen gas (produced by the cryogenic system) might be a feasible option. As the design of the electromagnet and cryo system develops, so too will the design for nitrogen use in the air carriage. <ALS>



Lubrication theory research is ongoing, but the preliminary research was completed on 17 September. The prototype pucks shall be manufactured and ready to test by 4 October. The puck testing in turn will be completed and a final puck design downselect made by 24 October. The air carriage will be ready for structural integration coinciding with the actuation group on 14 November. <ALS>

Proof of concept testing of a nitrogen-boil-off air supply was completed on 19 September. Further testing will be ongoing as the physical architecture of the cryogenic system takes place. <ALS>

EMFFORCE

Air Carriage Budgets

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- Electronics
- Structure/Power
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  - Structure
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    - Requirements
    - Risks
    - Tasks
    - Scheduling
    - Budgets

Integration
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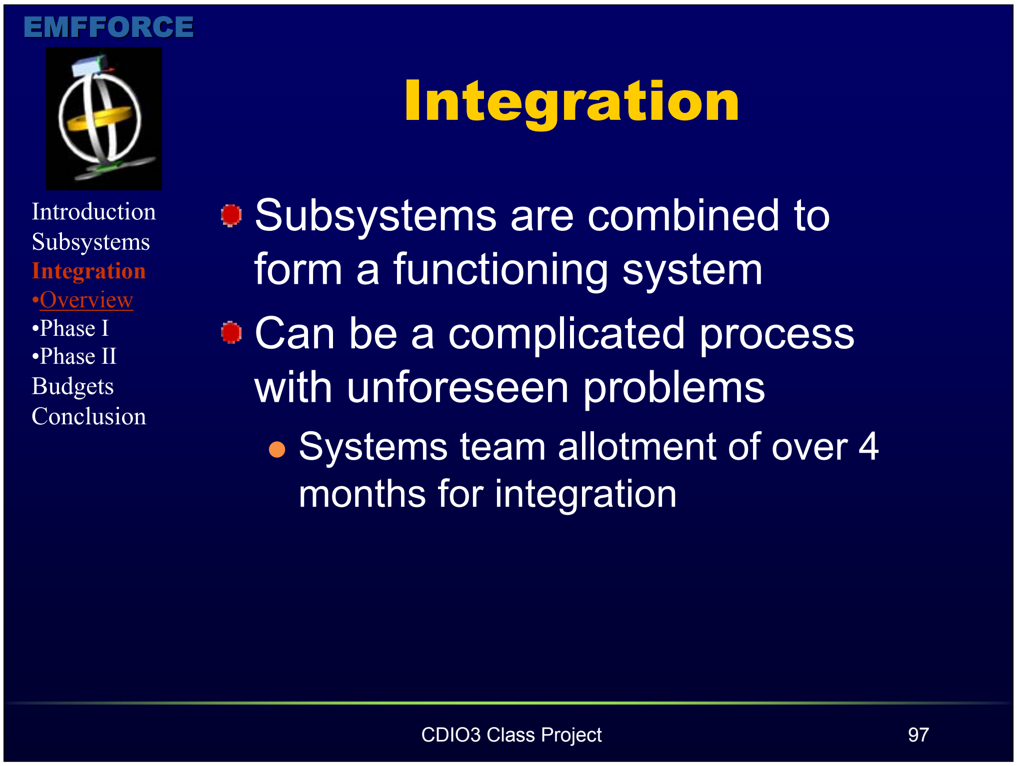
Part	Qty	Cost ($)	Mass (kg)	Power(W / V)
Sheet Al	1	200	1	0
Plumbing	3	30	.5	0
Tanks	1	250	1	0
Heating element (LN_2)	3	TBD	TBD	TBD
Total (per vehicle)		95	2.5	TBD
Misc.		250	--	--
Total (per system)		540	7.5	TBD

CDIO3 Class Project 95

To prototype, test, and build the air carriage, the structures team requires ¼ inch aluminum sheet for the pucks and plumbing fittings. Rechargeable CO_2 tanks have already been purchased for a total of $250. If the nitrogen from the cryogenic system is used to supply gas to the pucks, the tanks are not needed. The air carriage currently requires a mass budget of 2 kg, but this could be traded with other structural mass in the event that the nitrogen system is implemented. <ALS>

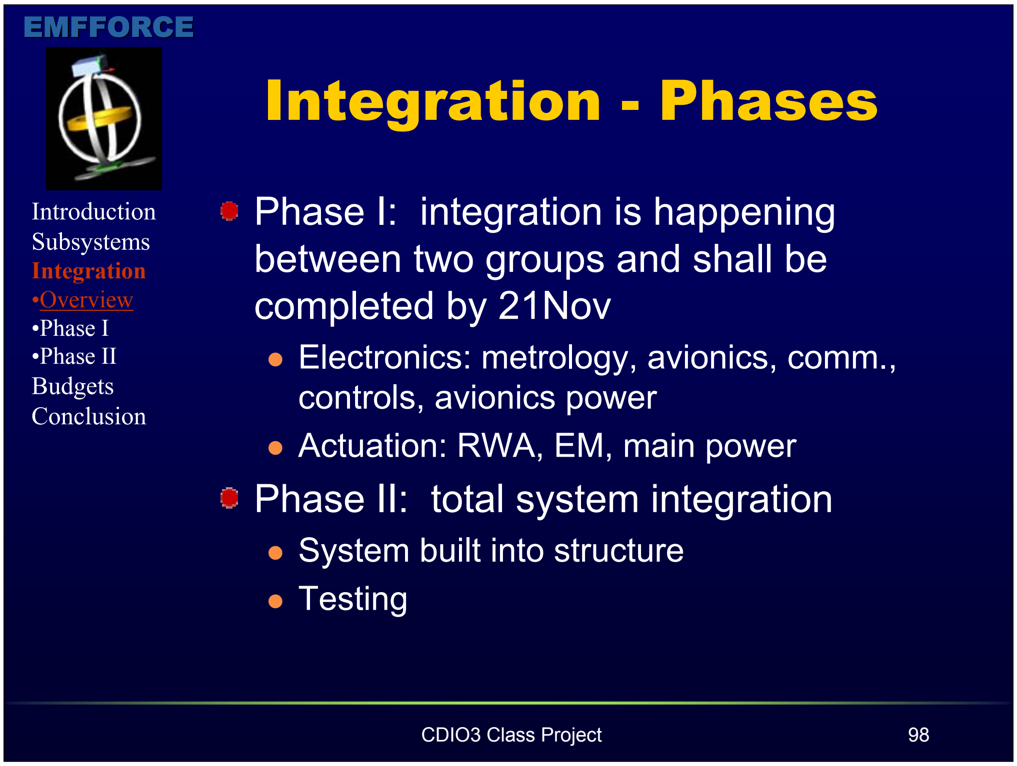
<SJS>

Stephanie Slowik and Melanie Woo, both current members of the EMFFORCE systems engineering team, shall present the project plan on integration.



<SJS>

Integration is the process by which the individual EMFFORCE subsystems are combined to form a functioning system. It is critical to have and follow a plan initiated in the design phase to address any integration concerns early on. It is the duty of the systems team to ensure this ease of integration through subsystem plan analysis.



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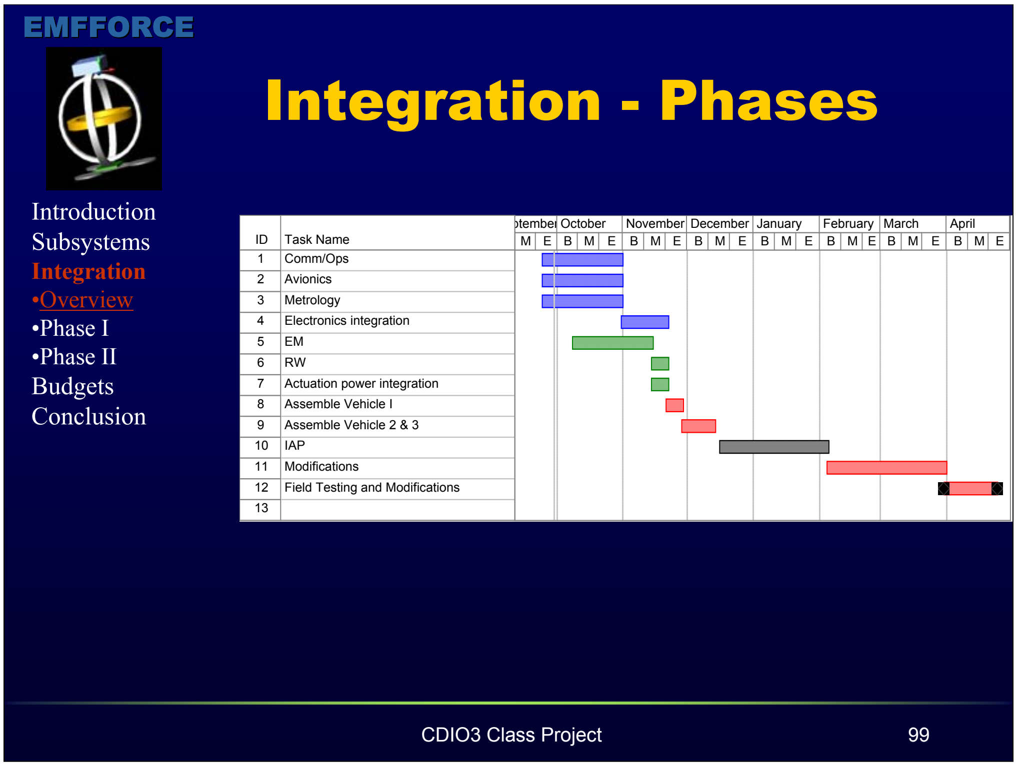
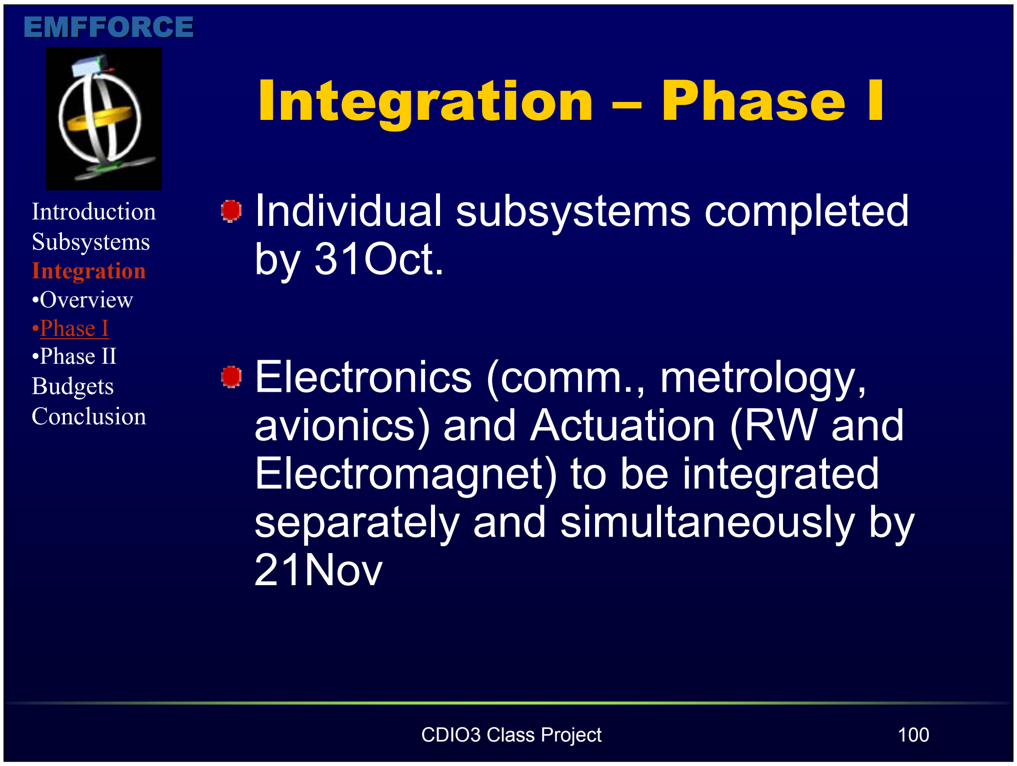


<SJS>

The overall integration shall occur in two phases:

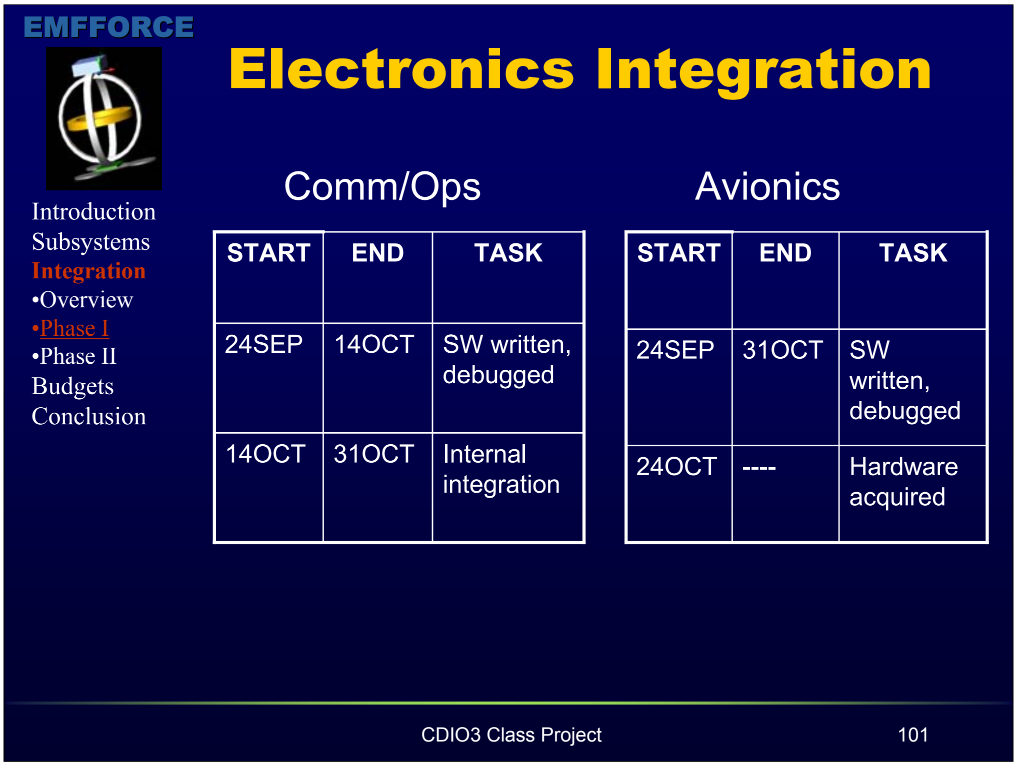
Phase I: In phase one, integration is happening between two groups and shall be completed by 31Oct. The electronics group shall be integrated with each other, yet still separate from the actuation group.

Phase II: In phase two, integration shall occur between the Phase I Electronics and Actuation integration groups. Phase II includes assembling one vehicle, the test of this vehicle, modifications, the assembly of the two remaining vehicles, and the two field tests.



<SJS>

Comm./Ops, Avionics, Metrology, and much of the Controls subsystems shall be fully integrated by 14Nov. Individual subsystems shall be integrated with themselves by 31Oct so that Phase I integration can be completed during the period from 31Oct – 14Nov.



<SJS>

Much of the error correction software has already been written. Communications and Operations aims to have their software written and debugged by 14Oct so that complete Comm/Ops integration and subsystem level testing can occur until 31Oct.

The avionics subsystem shall consist of the overall software shell (the master program) that can call all other program procedures as well as the TT8 computers and the wiring between the computers and the various subsystems. While most of the software shall be written by 31Oct, the majority of the hardware interfacing shall occur between 31Oct and 21Nov.

EMFFORCE

Electronics Integration

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Metrology

START	END	TASK
24SEP	24OCT	SW written, debugged
24OCT	31OCT	Internal integration (rate gyros, sensors
31OCT	14NOV	MSA SW written, debugged

Controls

START	END	TASK
31OCT	14NOV	MSA SW written, debugged

- Control algorithm cannot be finalized w/out vehicle testing
- Metrology to help Controls with code

CDIO3 Class Project 102

<SJS>

Metrology must design the sensors as well as write the software to determine vehicle location. Integration between the metrology software and the hardware (transmitters and receivers) shall occur on an on-going basis.

The Controls team is developing its control algorithm in a series of 8 different stages. Stages 1-5 can be completed without the vehicles; however, stages 6, 7, and 8 must make use of the built vehicles to fine tune the algorithm. Therefore, the final stages of the Control subsystem can only be completed once the rest of the vehicles are designed and built (The Controls subsystem shall finish the subsystem design during Phase II scheduling).

EMFFORCE

Electronics Integration

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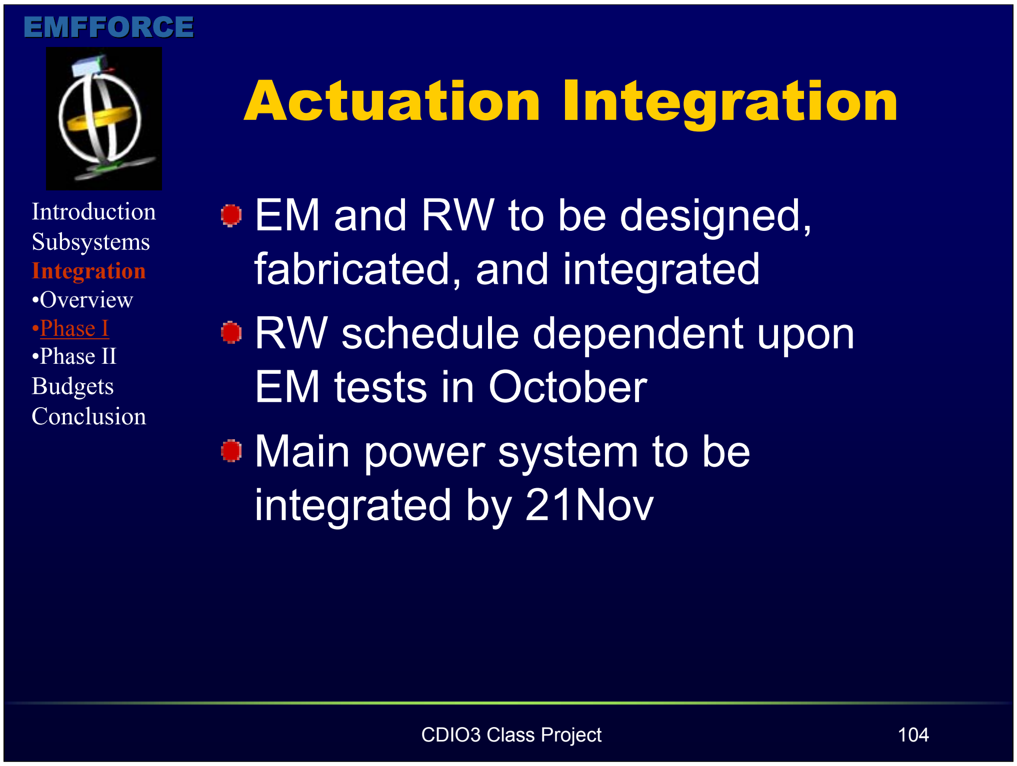
START	END	TASK
31OCT	14NOV	Complete SW integration
31OCT	07NOV	Procure circuit boards
07NOV	14NOV	Complete HW integration
14NOV	21NOV	SW/HW integration
07NOV	21NOV	Power integration

CDIO3 Class Project 103

<SJS>

The total electronics integration schedule is as shown above.



<SJS>

Phase I integration for the Actuation section shall be completed by 21Nov. It shall occur as the schedule following shows.

EMFFORCE

Actuation Integration

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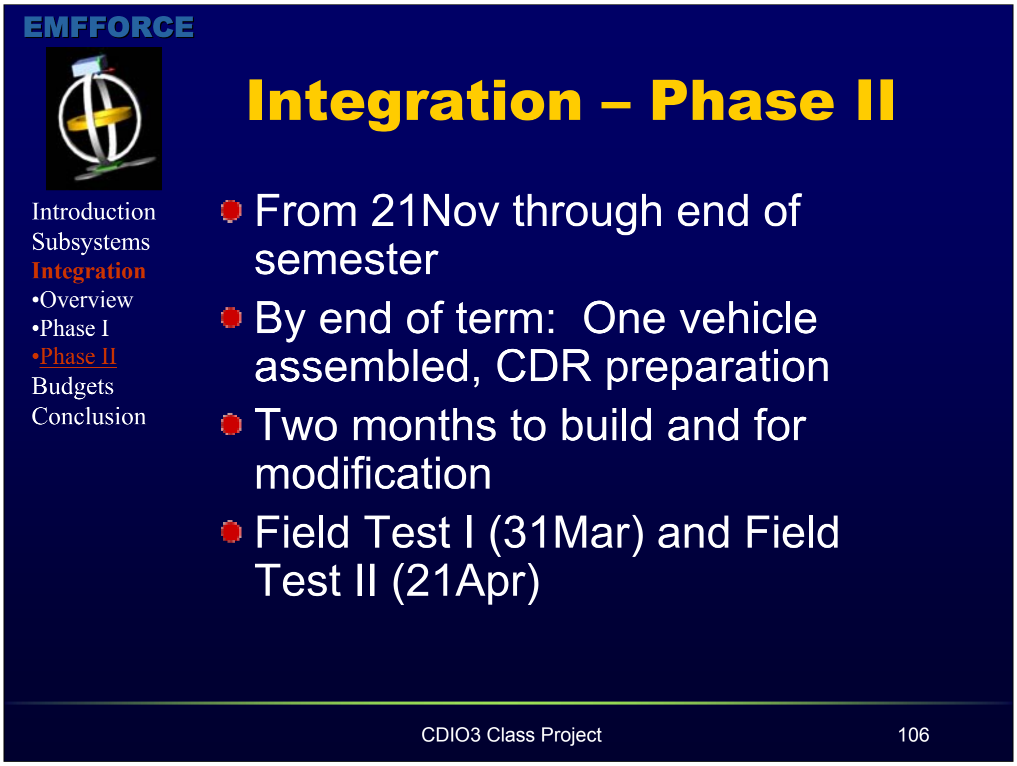
START	END	TASK
08OCT	----	Coil dimensions finalized, RWA variables finalized
10OCT	17OCT	Full size coil built/tested, Design RWA
17OCT	----	Superconductor and RWA ordered
24OCT	14NOV	Coils and casing built and tested, test and balance RWA
14NOV	21NOV	Power integration

CDIO3 Class Project 105

<SJS>

Above is the Phase I schedule for the electromagnet and the reaction wheel assembly. Dates are subject to change because they are based on estimates on material arrival and procurement time.



<SJS>

Phase II consists of the integration of the two sections (electronics and actuation) developed in Phase I as well as the building, modification, and testing of the system.

EMFFORCE

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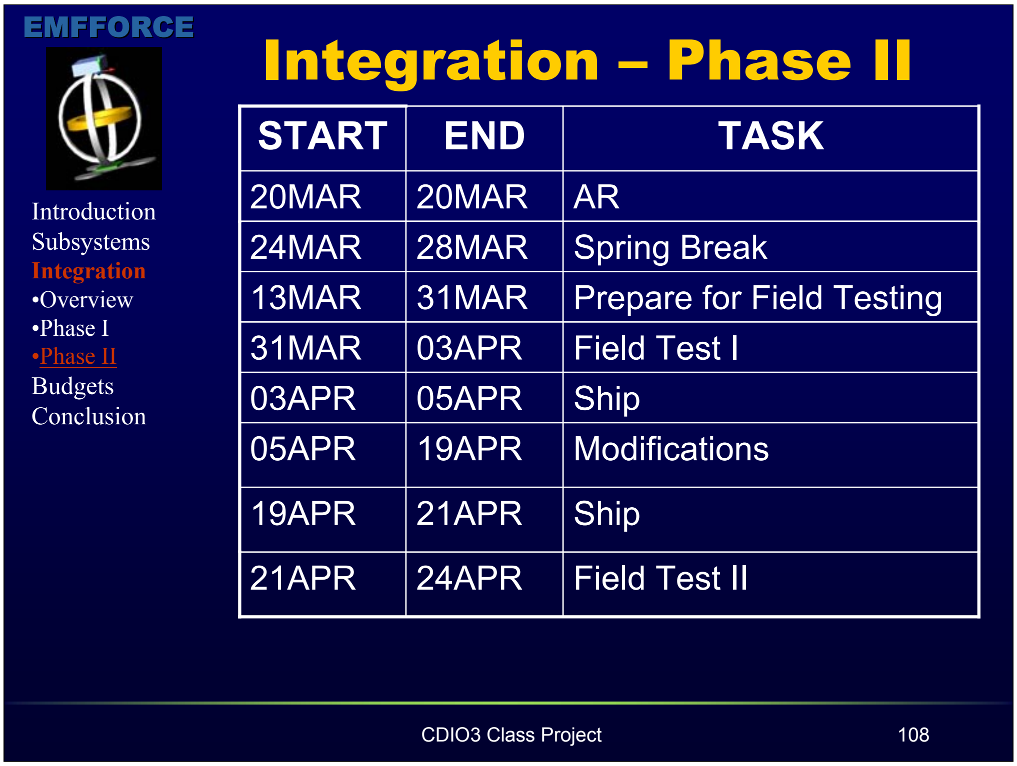
Integration – Phase II

START	END	TASK
21NOV	13DEC	Vehicle 1 Assembled
28NOV	05DEC	Prepare for CDR
05DEC	05DEC	CDR
13DEC	04FEB	Part Procurement, Vehicles 2 & 3
04FEB	18FEB	Testing/Modification, Vehicle 1
04FEB	13MAR	Build/Test Vehicles 2 & 3
13MAR	20MAR	Prepare for AR

CDIO3 Class Project 107

<SJS>

The following schedule is for the I&T of EMFFORCE.



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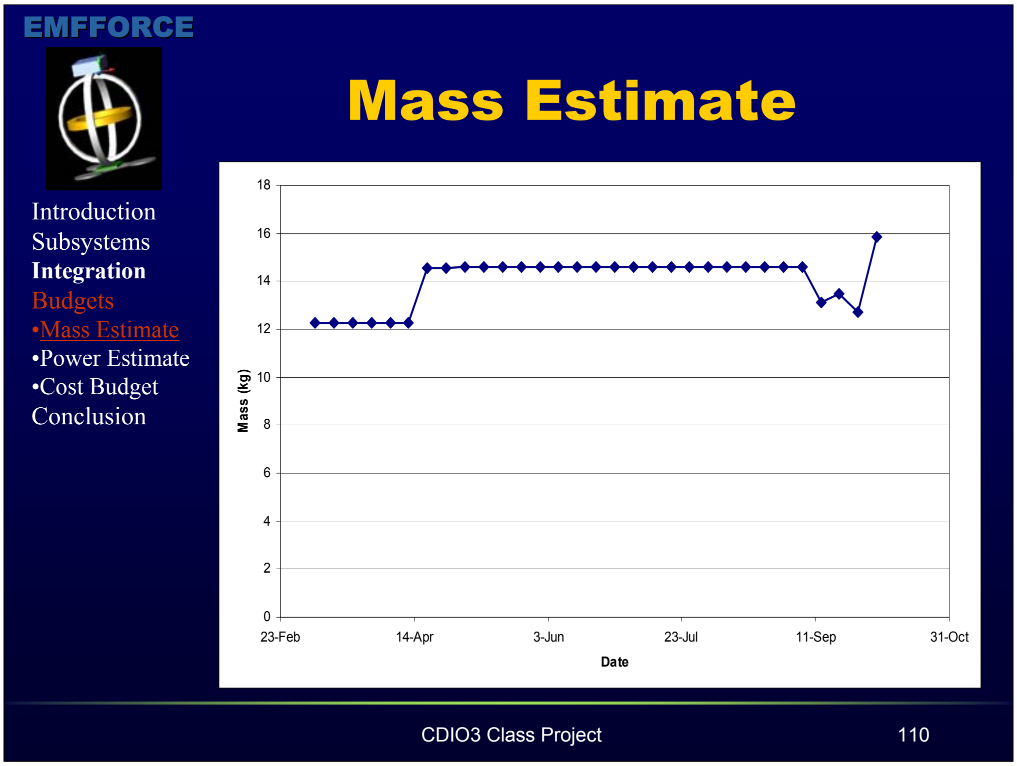
The following schedule is for the I&T of EMFFORCE.

Budgets



<MSW>

This is the mass estimate. The first increase in mass corresponds to a resizing of the electromagnet core in April and the resulting increase in power and structures. The decrease in mass at the beginning of September corresponds to the use of a coreless, superconducting coil. The most recent increase in mass was due to the increase in size of the coil and an increase in mass of the structure and power.

EMFFORCE

Power Estimate

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•Power Estimate
•Cost Budget
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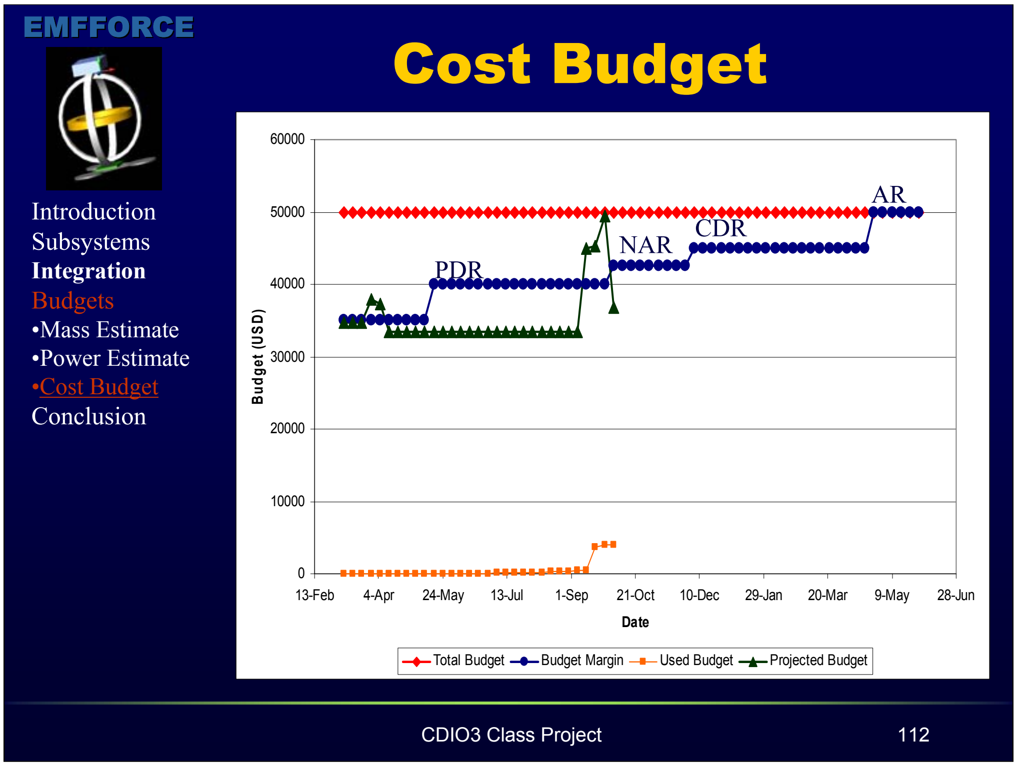
Subsystem	Part	Watts	Voltage
RW	Reaction Wheel	0-200	0-40
Metrology	Sonic	.3	5
	IR	.25	5
	Gyros	.16 – 1.2	8 – 24
Avionics	Boards	TBD	TBD
Structures	Heater	TBD	TBD

CDIO3 Class Project 111

<MSW>

Currently, systems is tracking the required power at a certain voltage. We are still waiting for estimates on the power requirement for the avionics boards, possible heater for the liquid nitrogen system, and the power supply for the coil.



<MSW>

This is the cost budget for the EMFFORCE Project. The total budget is $50,000. The budget margin is 30% before PDR, 20% between PDR and NAR, 15% between NAR and CDR, 10% between CDR and AR, and 0 after AR.

The large peak in the projected budget in September corresponds to a rise in cost due to the design change to superconducting coils. The drop at the beginning of October corresponds to a significant decrease in the projected cost of the superconducting wire.

The peak in the used budget may be attributed to the laptop and to the communication boards purchased.

Conclusion

EMFFORCE

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Conclusion

- Design altered to utilize superconducting electromagnets
- By end of semester, one vehicle to be assembled
- Within 15% budget margin

Questions
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