Electromagnetic Formation Flight

Progress Report

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DESCRIPTION OF THE EFFORT

The Massachusetts Institute of Technology Space Systems Lab (SSL) and the Lockheed Martin Advanced Technology Center (ATC) are collaborating to explore the potential for a Electro-Magnetic Formation Flight (EMFF) system applicable to Earth-orbiting satellites flying in close formation.

PROGRESS OVERVIEW

Work at the MIT SSL is continuing on two fronts: the CDIO class, and the MIT SSL graduate research group. The CDIO class is currently in the process of designing an electromagnetic test bed called EMFFORCE. One requirement of this testbed is the ability to determine each satellites relative position to one another. This month's report will discuss the analysis and trades used to determine the preliminary design of the EMFFORCE test bed metrology subsystem.

Metrology

1. Subsystem Overview
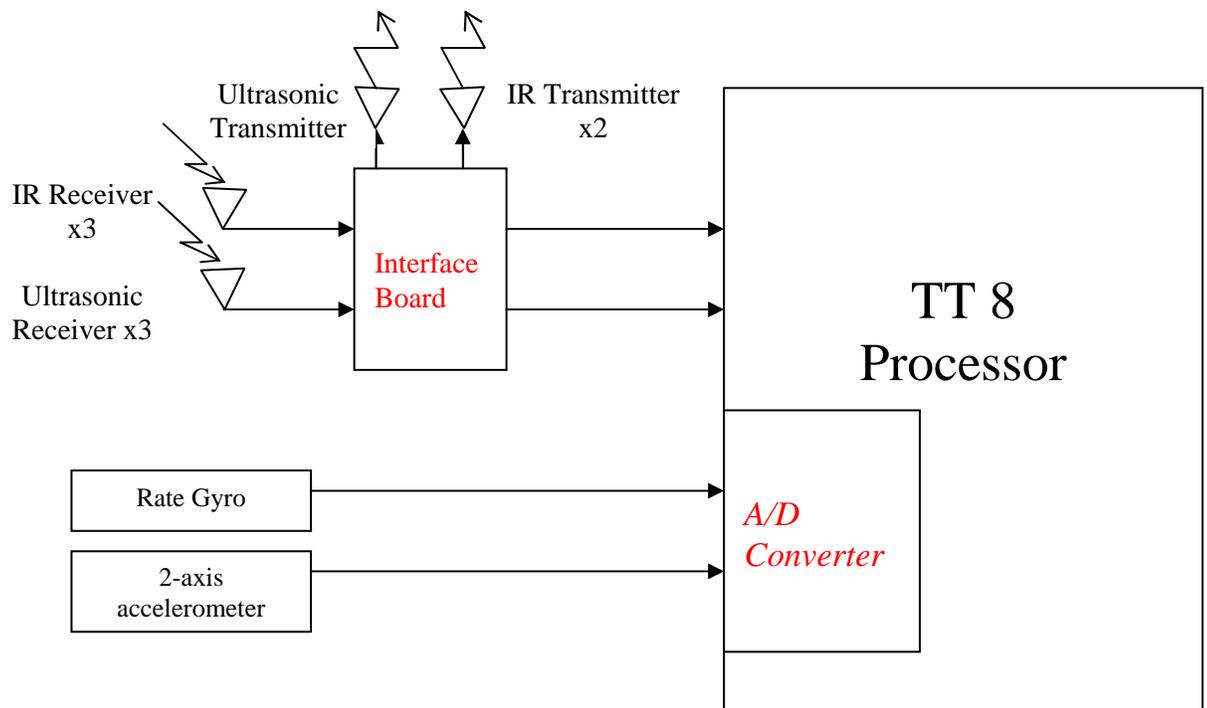
Fig. 1: Metrology Block Diagram

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

2. *System Trade Analysis*

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

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

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

3. Design Overview

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

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

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

3.1. Algorithm

The algorithm of the system uses the distance readings from the sensors. Because it knows the distance, it knows an infinite number of points the signal can be coming from, all lying on a circle. Using the information from the three sensors, one can overlay these three circles to determine the exact location (within a tolerance) of the vehicle. Using the following three equations, one can determine the two unknowns. It is possible to use only two sensor readings, however, there are times when there will be two solutions. The third equation removes this second solution. However, if a sensor fails, previously know information can be used with the two solutions to determine which is the correct solution.
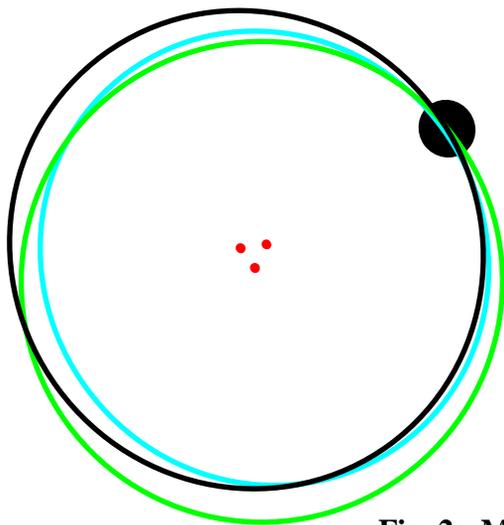
$$(x_{sat} + x_1)^2 + (y_{sat} + y_1)^2 = d_1^{\,2}$$

$$(x_{sat} + x_2)^2 + (y_{sat} + y_2)^2 = d_2^{\,2}$$

$$(x_{sat} + x_3)^2 + (y_{sat} + y_3)^2 = d_3^{\,2}$$

Fig. 2: Metrology Algorithm Overview

4. Ultrasonic Transmitter

4.1. Purpose of Part

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

4.2. Discussion of Trade Analysis

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

5. Ultrasonic Receiver

5.1. Purpose of Part

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

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

5.2. Discussion of Trade Analysis

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

6. Infrared Transmitter

6.1. Purpose of Part

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

6.2. Discussion of Trade Analysis

The current options for infrared emitters are either to use one omni directional emitter (similar to the ultrasonic system), or to array several directional emitters. The infrared

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

7. *Infrared Receiver*

7.1. *Purpose of Part*

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

7.2. Discussion of Trade Analysis

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

8. *Rate Gyro*

8.1. *Purpose of Part*

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

8.2. *Discussion of Trade Analysis*

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

9. Accelerometer

9.1. Purpose of Part

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

9.2. Discussion of Trade Analysis

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

10. Metrology Design Issues

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

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

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

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

11. External Interfacing Needs

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

11.1.   Avionics Interfaces

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

Table 1: Avionics Input/Output

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

11.2.   Communications Interface

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

11.3.   Control Interface

The metrology system will interface with the control subsystem via the avionics system. The metrology software will take all inputs from sensors. The metrology software will then calculate the separation distance between each vehicle as well as the relative angular orientation of each vehicle. This information will be provided in polar coordinates with the origin at the center of each vehicle. Specifically, the metrology software will return values for s_{AB}, s_{BC}, s_{AC}, α_B , α_C, β_A, β_C, γ_A, and, γ_B. (see figure 4 below) The metrology software will also return linear velocity data (by taking the derivate of the data from the accelerometers) and angular velocity data from the rate gyros. The form of this data and the refresh rate will be determined by the control team and has not yet been determined.
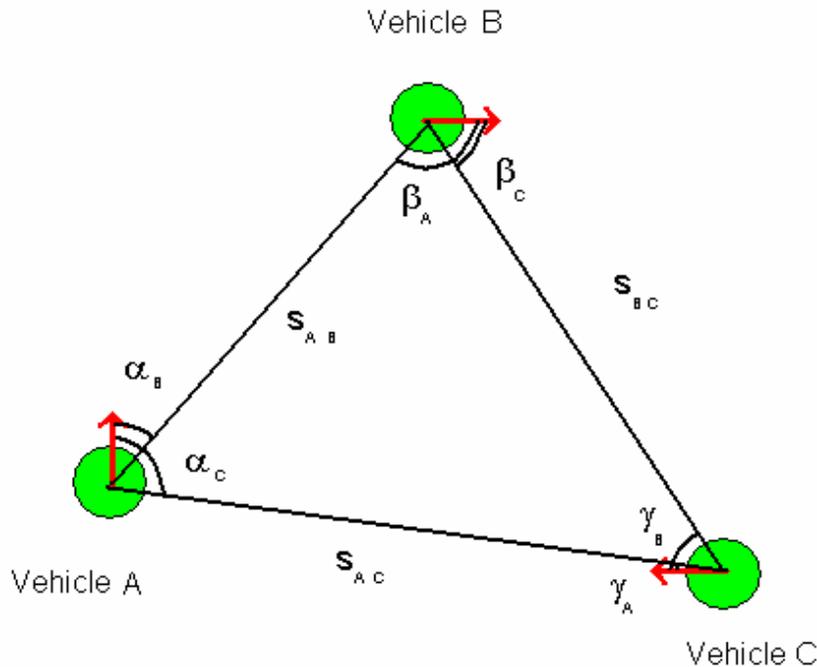
Fig. 4: Distances and Angles Determined

11.4.   Power Interface

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

11.5.   Structural Interface

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

12. Estimated Budgets

Table 2: Budget Estimates

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

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

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

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

13. Conclusion

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