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THE ORION MICROSATELLITE : A DEMONSTRATION OF FORMATION FLYING IN ORBIT

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Abstract

The Orion microsatellite project is funded by NASA Goddard Space Flight Center. The goals of the project are to demonstrate determination of position and attitude of spacecraft in a formation using carrier phase differential GPS, and closed loop autonomous control of the formation. The mission is designed so it can be performed with a constellation of three or more Orion spacecraft, or a constellation of one Orion spacecraft and the Emerald spacecraft. The spacecraft are designed and built by the Formation Flying Laboratory and the Space Systems Development Laboratory, both at Stanford. The Orion spacecraft will build on the heritage of prior Stanford satellites: Sapphire and Opal. The bus will be cube shaped, 0.5 meters on the side. The command and data handler is the SpaceQuest CPU, based on the NEC V-53 microprocessor. In addition there will be another StrongARM based CPU performing mission specific, CPU intensive calculations. This second CPU could be combined with the GPS computer. The Orion spacecraft will use a cold-gas propulsion system, using Nitrogen gas. The on-board propellant will provide 40 m/s delta V. Magnetic torquer coils will be used for detumbling after deployment. The subsystems will be connected using an I2C serial data bus. The GPS receiver and computer is in development at Stanford. A single Orion spacecraft is slated to fly with the University Nanosatellite mission.

Introduction

There is a growing need for small, inexpensive spacecraft capable of performing scientific or government missions requiring autonomous operations in a precise formation. The goal of the Orion project, supported by the NASA Goddard Space Flight Center, is to demonstrate some of the techniques that could be employed by these future missions.

An Engineering Prototype was constructed by the Formation Flying Laboratory and Space Systems Development Laboratory (SSDL). This prototype consists of flight equivalent versions of the major subsystems, and is used to develop the satellite data bus, flight software, and fine tune the operations plan. A detailed look at the tradeoffs and descriptions of each subsystem is presented.

The original Orion mission calls for flying three identical satellites in a variety of formations. Since then, the opportunity of flying an Orion satellite alongside the University Nanosatellites was presented, so a new mission was developed that allows us to achieve all goals of the original Orion mission in this new scenario.

Orion Mission Design

The near-term desire is to identify technologies that will be required for formation flying missions. It is crucial to understand what types of subsystems will be needed, and what spacecraft resources are critical for this particular class of multi-satellite missions. In conjunction with this effort, some basic proof-of-concept missions will then need to be executed in order to build a knowledge base of experience from which future, more sophisticated missions can benefit.[1]

Mission Planning

The Orion mission aims to serve these purposes by identifying low-cost components that can be used and modified for space flight. These components will then be integrated to develop a complete satellite system that demonstrates the performance benefits of formation flying. More precisely, the Orion project is considered to be a high-risk research and development venture whose primary concerns are twofold: (1) To demonstrate the use and operation of a low-cost, low-power, multi-channel GPS receiver for real-time determination of the attitude and position of a small satellite. (2) Demonstrate the ability to organize a group of small vehicles into a pre-determined formation on orbit.[2] The statement of high-risk reflects the nature of the components to be used: off-the-shelf, non-space-rated, and integrated by students with significant, but still narrow, spacecraft building experience.

In order to achieve the goals mentioned above, the set of spacecraft developed will need to exchange GPS data between satellites. They will then need to use that data to execute pre-planned, organized maneuvers. The maneuvering process will be governed by real-time autonomous control software that will be directed at a high level from the ground. A careful operations plan will need to be created so that mission resources are adequately conserved.

Mission Success and Goals

The Orion mission's criteria for success are posed on two levels. The first level is a set of minimum requirements, while the second tier is a set of mission goals. Each are described briefly below. The minimum requirements define the mission activities that must occur for the mission to be considered successful and/or useful. The mission goals define the expected performance of the final system. The design team agreed upon each of these concepts and criteria at the project's outset.

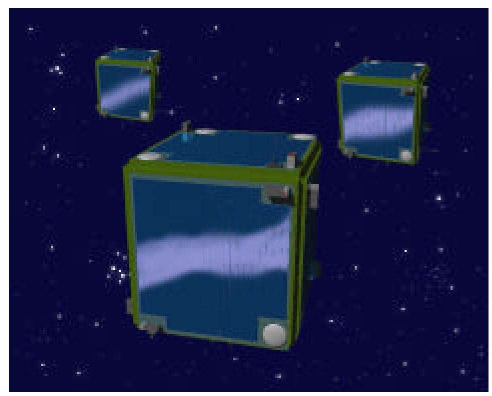

Figure 1. Three Orion satellites flying in formation.

The minimum success criteria for the Orion mission are as follows:

1. The GPS receiver payload must be able to calculate absolute orbital position in real time to within 50 meters. Attitude determination must be calculated to within 2°.
2. The attitude of each spacecraft in the formation must be controlled to within 10°.
3. At least two satellites must be arranged on command in an in-track formation. The satellite spacing must be even over a range of 1 kilometer, and the formation must be held for at least 30 minutes. Relative position between satellites must be known to within 5 meters so that a 20-meter precision of control may be enforced. The process must be repeatable two times over the period of one week.

The mission goals for the Orion project include the minimum success criteria, except that the formation flying experiment goals are advanced. The upgrade in performance includes the mandate that three satellites must be arranged in-track for 30 minutes and spaced evenly over only 100 meters. Relative position knowledge is tightened to only one meter, while relative position control is reduced to 5 meters. The process must be repeatable 5 times over a period of two weeks. In addition to these flight criteria, another goal of the mission is to demonstrate on-orbit autonomy using various control architectures. This includes switching from a parking mode to the formation-flying mode using different assembly schemes. The project team feels that these performance criteria will be sufficient to contribute significantly to the formation flying knowledge base.

Operations Plan

Although constructing a set of spacecraft capable of meeting the above requirements would appear challenging enough, it is clear that developing a set of complete and coherent operations plans adds to the challenge. Since this type of mission involves a number of small satellites that must remain in close proximity to one another, it is important to make sure the vehicle design and the manner in which the vehicles are operated are complimentary. Otherwise, there are increased odds that a design flaw may be created for which no operational contingency plan may be formed. It is therefore crucial to include some forethought about system operations at design time.

The initial concept for Orion mission operations occurs in four main stages. These stages are (1) Shakedown phase, (2) Dispersed constellation phase, (3) Compact constellation phase, and (4) Experiment phase. Each stage will have its own set of specific operations plans, as well as a defined set of plans for transitions between phases. Currently, the details for each phase exist as a high level outline. A brief description of each phase is given below.

The Shakedown phase is probably the most crucial of the operation segments. This set of on-orbit checkout routines is critical to ensuring that the system has survived launch and will function properly once deployed. The plan is to launch three Orion vehicles in a connected, stacked formation. Once deployed from the launch vehicle, a switch will be triggered so that power may be supplied to each spacecraft. The CPUs will come online and will activate the auxiliary control system. This control system will serve only to slow the tumble rate of the vehicles until the GPS payload can obtain a signal lock. Once a GPS lock is established, each vehicle can determine its orbit position autonomously. Position and system telemetry data will be stored in CPU memory until the first ground contact can take place. During that first contact, a more rigorous check of the onboard systems will take place. The propulsion control system and cross-link communications systems will be checked for readiness, and the start-up routine will be concluded. Upon successful completion of this checkout, autonomous control will be given to the satellites, and the command to separate the vehicles will be given.

The next two phases of operations are very similar. In the Dispersed Constellation phase, the vehicles will fly autonomously within a "parking box". In other words, each spacecraft will attempt to remain within a box whose center is a specific orbital reference point. Collision avoidance algorithms will be employed to help ensure that the spacecraft will not crash into one another. During this phase, relative position data will be collected and downloaded to the ground. The data will be studied to verify that system control is working as expected. In addition, insights into some of the on-orbit perturbing forces may be gained. At the end of this phase, a command will be up-linked to the system to transition into the Compact Constellation phase. The operations for this phase are identical to the previous one, except that the size of the parking box will be reduced. Again, data will be collected and returned to the ground to verify that the system has been compacted, and that all necessary control and collision avoidance algorithms are still working properly.

When the operations team is satisfied that all systems are functioning properly, a formation flying experiment will be scheduled on the spacecraft. Since the experiment lasts at least 30 minutes, it is highly likely that such an experiment would be scheduled between two consecutive ground station passes. The first pass will be used to start the experiment, while the second pass will be used to download the experiment data. During the experiment, each spacecraft will autonomously transfer from its position in the Compact phase parking box to the appropriate position in the formation. After the allotted time has expired, the formation control will stop, and the system will return to the Compact phase. This process can and will be repeated until the mission goals have been achieved.

Mission and Design Requirements

Now that some of the mission details have been described, a discussion about the resulting design requirements is presented. It is clear that the minimum mission success requirements define the key tasks to be performed by the complete satellite system. These tasks have direct bearing on the system design requirements. The system requirements in turn flow down to the subsystem and, ultimately, the component level.

Key Design Requirements

The mission requirements and goals demand that the final integrated system achieve several key functions. First, the GPS payload must function properly at all times. Without precise knowledge of relative position and attitude, none of the delicate orbit adjustments required may take place. Second and equally important, the communications system must allow data to be exchanged between satellites during all phases. Without a data cross-link, three individual satellites are in orbit instead of a three-vehicle system. This is an important distinction, and one of the main points to formation flying. The third key requirement is that the flight control software must be able to control the satellites to the required degree of accuracy. While the accuracy of control may not be as important, it is nonetheless required by the design team to meet minimum success for this project. Lastly, the design must incorporate adequate system resources to perform the experiments. The Orion design team has assembled a complete mission requirements document that outlines these key criteria and the subsequent subsystem requirements. To reconstruct such a document here is unnecessary to say the least; instead, a highlight of some of the more important requirements will be described.

GPS Payload Requirements

The primary requirements for the GPS payload are similar to those for a ground-based GPS unit. To obtain an initial position lock, at least one antenna must view four GPS satellites simultaneously for a few minutes. At least 3 antennas must then track a minimum of 4 common GPS satellites to maintain the position and spacecraft attitude solutions. The accompanying electronics must be able to calculate the appropriate position and attitude solutions from the acquired signals, store that data, and share it with the control software. The GPS payload is in a unique position for the system design. While it must adhere to the key mission requirements, it in turn dictates extra requirements to the other subsystems. For instance, since it must be active all the time, extra demands are placed on the power system to provide a particular, constant amount of energy. In order to maintain a lock on the GPS signal, the spin rate and pointing accuracy of each satellite must be kept below a particular threshold. Finally, the size and rate of accumulation of GPS position data influences the memory capacity and data bus speed for the command and data handling (CDH) subsystem.

Subsystem Requirements

There are six distinct subsystems that comprise the spacecraft bus for each vehicle in the Orion system. They are power, CDH, communications, structure, propulsion, and auxiliary control. Each subsystem has common requirements, such as those pertaining to mass, volume, and power budgets, as well as resistance to launch, radiation, and thermal loading. But some requirements are more specialized, and occur in direct response to the demands of the payload, or the formation flying mission in general.

For instance, great care must be taken with the structural layout. Since each space vehicle must be in constant contact with several GPS satellites at once, the receiver antennas must be placed so as to allow continuous coverage. This becomes difficult when also trying to choose a location for the downlink antenna. In addition, mass-changing components (such as fuel tanks) must be carefully placed so as not to affect the inertial properties of the vehicle.

The communication subsystem is a critical element that imposes several unique demands. First and foremost, the data link to the other spacecraft needs to be extremely reliable. Since other satellites in the constellation could be just about anywhere, the antenna beam pattern should be as homogeneous as possible over the entire sky, given the expected separations between spacecraft. In order to have enough link margin, the size and transmission rate of the exchanged data must be carefully considered as well. Similarly, the amount of memory in the CDH system must be chosen so that this data does not overflow its capacity between ground contacts. The CDH must also have a reliable, autonomous start-up mode that enables an individual satellite to obtain a GPS lock and signal other satellites in case the satellite in question shuts down temporarily.

In order to achieve the desired formation flying goals, the accuracy provided by a GPS system is necessary. Such a system is also beneficial since the power and size requirements are conducive to small spacecraft. But, as mentioned earlier, this choice greatly influences the overall design. For example, the main influence is on the attitude control system. The GPS payload essentially serves as the sensor in a feedback loop that controls each satellite's position. Since the attitude control system serves as the actuator in this loop, there is an obvious dependency between the two. For the most part, this dependency is mainly manifested in the maximum allowed tumble rate. Beyond this limit, the GPS payload will not be able to maintain its signal lock. The attitude control system (including the control software) must ensure that the vehicle is stable within this limit.

Subsystem Trade Studies

To this point, the mission plan and subsequent mission requirements for Orion have been noted. Now comes the task of describing some of the design choices made by the Orion team to satisfy these demands. Again, it should be noted that the Orion design team has constructed a detailed design document that describes the design trades and component research.[3] The intent here is not to reiterate this document word-for-word, but rather to highlight some of the key choices and trade studies performed for each subsystem.

Power

The power system design is relatively straightforward. Given the design requirements and the mission operations plan, a total of four basic flight modes were identified as described in the design document. These modes include the initial start-up mode, a "cruise" mode (corresponding to parking conditions), the experiment mode, and a data downlink mode. The start-up and cruise modes require less than 10 Watts, and correspond to the vast majority (>95%) of the operational life. The downlink and experiment mode power draws are about 25 Watts each; however, each mode is active for 30 minutes or less at a time. The design for the power system includes a system of batteries, solar cells, battery charger, and voltage regulators that are designed to provide an estimated average power input of 15-20 Watts. This easily provides enough power for the critical start-up and cruise modes, and allows the batteries to be charged up for use during the more power-intensive experiment and downlink modes. The initial choices for the batteries are Sanyo NiCd batteries. An Interpoint voltage regulator was selected for the power management duties. Both of these components were chosen mainly due to their design/flight heritage on other SSDL spacecraft. However, the design team is currently looking into the possibility of flying some Lithium ion batteries, which may prove to be more cost-effective and reduce mission risk.

Communications

The communications subsystem is definitely one of the most critical elements of the overall system. While other subsystems are necessary to make each space vehicle function properly, only a reliable cross-link and downlink can ensure that the ultimate formation flying mission can take place successfully. The in-house development of this subsystem was weighed against the choice of purchasing a complete, flight tested unit. Such units tend to cost a great deal more money, but purchacing one off the shelf significantly reduce the required manpower and system development time. We ultimately decided that given the project schedule and time constraints, that it would be advantageous to purchase a flight-tested communications unit that would perform to our specifications. However, the formidable task of integrating the unit remains. A description of the subsystem appears later.

CDH

The CDH system is the proverbial central nervous system to each vehicle. It handles the flow of information and commands to all portions of the spacecraft. In order to satisfy the given requirements, it is desirable to have a CPU with a large processing capacity and low power consumption. The main CPU must also be able to handle normal spacecraft housekeeping and command routing. A variety of other computing must be done aboard the spacecraft, which includes calculating the GPS position solution and meeting the computational demands of the control software. For these reasons, three CDH architectures were considered.

There are two CPUs that were considered for the above computing chores. First, there is the Motoraola 68332 microcontroller based Vesta single board computer.[4] This CPU has design and flight heritage with other SSDL satellite projects, and offers a fair amount of computing capability in a low-power package. However, this CPU is in no way able to handle the intensive computations required for calculating GPS solutions and complex control algorithms. For this reason, a StrongARM (SA) processor was chosen. These CPUs offer up to 200 MIPS of calculating power for less than one Watt.[5] Although still in development and never flown in space, this type of processor seemed ideal for the more intensive operations.

The first of the three architectures involved connecting two SA processors together. One processor would appear on the bus side, and would be used for housekeeping and calculating control algorithms. The other processor would reside on the payload and would be used to calculate GPS position and attitude solutions based on the incoming signals. A second architecture uses 3 CPUs: a Vesta CPU on the bus side that handles housekeeping chores, a SA processor that calculates the necessary controls, and a SA payload CPU which takes care of GPS signals. The problem with these setups is that exchanging data between the SA CPUs needs to be done smoothly. During an experiment, a problem in transferring position data to the control calculator could be disastrous. It would be much more desirable to have the GPS and control calculations done on the same processor. Thus, a third architecture was proposed. In this case, a single Vesta board resides on the bus, while the SA processor on the payload handles both the GPS solution and the control calculations. The Vesta handles housekeeping chores and routes the propulsion commands that comes from the SA processor. The main concern with this architecture is whether or not a single SA processor can handle all of the processing required. An initial analysis indicated that the available throughput was great enough, and so this option was chosen.

Attitude Control

The demands on the attitude control system are very stringent for such a small satellite. The design team decided early on that the only way to handle such requirements would be to incorporate some form of three-axis control. Momentum wheels and control gyros were considered. These methods were analyzed and even demonstrated to be feasible, however the power consumption was just too large. Other passive methods were investigated, but none of them had the required control authority. The final solution was to design a cold-gas propulsion system. Initial analyses have shown that the control authority is more than adequate to adjust the space vehicles' position and attitude. In addition, the amount of fuel required to complete the mission can be stored on board. The difficulty remained when considering the start-up mode. It was considered too risky to use propulsive control when no GPS lock exists. As such, a less-risky auxiliary system is needed. A magnetometer-torquer coil combination was chosen for this chore.[6] This active system provides enough authority to gently de-tumble a satellite so that the GPS lock can be attained. Ground operators then have the option of carefully testing the propulsion system before activating it.

Structure

The main influences on the space vehicle structure have generally been discussed. The main impact is that antennas must be carefully placed so as to provide reliable communications links, while fuel components must be located so that the dynamic properties of the vehicles change a minimal amount over time. Finally, it is desirable to minimize the moments of inertia for the spacecraft in order to make maneuvering and rotation easier. An alternate view is that this would allow the on-board fuel to be used more effectively.

Development to Date

Development of the Orion satellite is currently at the Engineering Prototype stage. This Prototype was assembled in June 1999, and includes CDH, Power, Auxillary Control and Propulsion subsystems connected to the spacecraft power bus and an Inter-Integrated Circuit (I^2C) data bus, as well as a full featured spacecraft operating system. Because the design still evolved when the Prototype was constructed, many components are "flight equivalent", i.e. their functionality is equivalent to the functionality of the actual flight component. The size of this prototype is repersentative of the flight vehicle: 0.5m x 0.5m x 0.5m cube. The weight of the prototype is many times that of the flight vehicle due to structural differences.

GPS payload

The Orion GPS payload consists of a single 6-antenna attitude and relative navigation receiver using carrier-differential GPS. The GPS receiver design is based on the Mitel Plessey GPS chipset, using the GP2015 RF front end and the GP2021 12-channel correlator.

Engineering Prototype unit

At the present moment, the GPS payload is comprised of two receivers. The first is a 4-antenna attitude capable receiver. The second receiver is a 2-antenna relative navigation receiver. These receivers both are based on a modified version of the Mitel-Plessey Orion receiver design. (Note: the receiver name should not be confused with the project name, it is purely coincidental). The modifications include a second RF front end and an external clock input. This Orion receiver has two RF front ends, a correlator (with six channels assigned to each RF front end), an ARM60 processor, and the required EPROM and RAM memory. Another board provides the 5V regulated power input and RS232 serial input and output. The attitude receiver uses two of these modified Orion cards with a common clock. Integrated Carrier Phase data is shared between the two cards over the serial ports. The ARM60 closes the low level code and carrier tracking loops on both cards. Furthermore, on one ARM60 the absolute position solution is determined (using standard pseudo-ranging), and the other determines the attitude. This process is currently run at 5 Hz. The relative navigation receiver uses just a single Orion receiver card, with the Integrated Carrier Phase data being sent from a second receiver though the serial port. The processor computes both the absolute position solution and the relative position solution. Because of the greater computational load, the solution is performed at only 1 Hz. Current tests show relative position accuracy on the order of 2 cm.

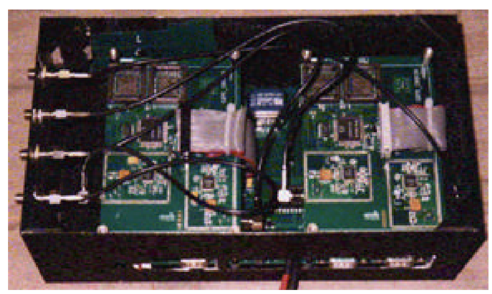

Figure 2. Early prototype Orion GPS receiver.

Future development

The next steps include both hardware and software changes. Hardware changes must be made to tie together a single six-antenna receiver with the computational power capable of performing the absolute position solution, the attitude solution, and the relative navigation solution. There are also planned improvements in the software algorithms. The planned improvements include: improved bias initialization algorithm, orbit estimator, non-aligned antenna compensation, and low power mode. Carrier differential GPS techniques require first the determination of the integer cycles between antennas. Initializing this bias in the measurements is the greatest challenge in using carrier techniques, and improved motion based initialization techniques must still be incorporated in the software. The second major addition is an orbit estimator. In the orbital environment, the relative velocities between the user and the GPS spacecraft is mush larger than terrestrial applications, and therefore presents a much higher Doppler space to be searched for the GPS signal. Without estimating the expected relative velocity and thereby narrowing the Doppler search space, it is possible that signal lock is never acquired. The third improvement is to account for phase differences between non-aligned antenna bore-sights that will certainly occur between the multiple spacecraft. Finally, changes will be made to allow switching from a full capability operational mode requiring approximately 8W of power to a low power mode only tracking with a single a antenna just to maintain signal lock but requiring only 2W of power.

Structure

The Orion spacecraft structure consists of 5 shelves, and four side panels. The top and bottom shelves are also the top and bottom sides of the spacecraft, respectively. The shelves and the panels will be made of vented Al-Al honeycomb for flight, but the prototype is wood, with aluminum face sheets. The edges of the shelves are surrounded by a so called aluminum picture frame. Threaded inserts are placed around the edge in this picture frame, and this is what the side-panels are fastened to. This structure was developed for ease of frequent assembly and disassembly during the development cycle. The shelves have cutouts to accommodate the torquer coils, the power and data bus cables, and the Propulsion system plumbing.

Power subsystem

The power subsystem must provide 5V and 12V regulated, and 12V – 14V unregulated power to the other subsystems of the satellite at 4A peak current. To achieve this, the power subsystem consists of solar cells, batteries, a regulator, and a battery charger unit.

The Engineering Prototype is lacking solar cells, but has all the other components of the power subsystem. The battery system consists of 12 Sanyo KR-5000DEL 1.2 V 5000mAh NiCd rechargeable batteries in series. They are charged by a Maxim MAX713 ASIC, and the 5V and 12V output is generated by Vicor DC/DC converters. The 12V regulator can be commanded off by a PIC microcontroller, but the 5V regulator is always on. However, there is a special 5V line on the power bus to power the CDH subsystem and the PIC in the power subsystem. This enables the CDH to command the ordinary 5V line to be turned off.

Communications

The communications subsystem is responsible for downlink and uplink communications with ground control, and also for crosslink communications with the other spacecraft in the formation.

The Engineering Prototype employs an RFM wireless transceiver from RF Monolithics, Inc. for both downlink and crosslink.[7] A PIC acts as a TNC, buffering the dataflow between the RFM and the CDH, and repackaging the packets.

Orion CDH

The Orion CDH design went through several changes in the Tradeoff and Development cycle. When this project started in early 1998, our desire to advance the state of the art in small spacecraft computing power combined with a predicted need for high performance led us to consider an Intel (formerly Digital) SA-110 or SA-1100 StrongARM microprocessor based design. The StrongARM microprocessors currently have the best MIPS/watt rating, and the fastest SA-1100 processor running at 200 MHz only consumes 500 mW. Another factor is that the StrongARM processors are thought to be the most resistant to radiation effects of the non-rad hard microprocessors.

A StrongARM evaluation platform (Brutus) was acquired, and development began. The Linux operating system we choose was not well supported on this platform until early 1999, so progress was slow. However, by March 1999 we interfaced the Brutus to the I^2C data bus populated with three test nodes. The Brutus could send commands to the nodes, as well as acquire data.

By this time the challenge of having to develop Linux into a spacecraft operating system loomed, and this task seemed too large given our aggressive schedule. SSDL already developed the Chatterbox and Ooz operating systems for the Sapphire and Opal satellites respectively. The predicted need for high computing performance was still only a predicted need. So the decision was made to switch to a platform that SSDL was familiar with: the Motorola 68332 based Vesta board. In the space of three months the Chatterbox operating system was modified with removing Sapphire specific routines, and Orion specific routines were added. The new commands enable the spacecraft operator to control various subsystems on the I^2C bus, acquire data from the subsystems, and communicate with a ground station through the prototype communications subsystem. This CDH subsystem is an integral part of the Engineering Prototype.

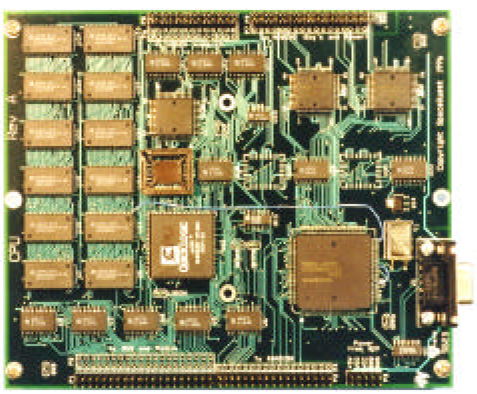

Figure 3. SpaceQuest CPU module.

Recently the opportunity to fly the SpaceQuest CPU with the Bektek operating system arose, so we are in the process of acquiring units that can be interfaced with the Engineering Prototype. We estimate this to happen during early fall of 1999.

<u>Serial data bus</u>

The spacecraft data bus is based on the I^2C specification. This requires that all subsystems on the data bus have an I^2C adapter built in. Because of this we choose to include a PIC16C73A or PIC16C74A microcontroller in each subsystem.[8] These microcontrollers are manufactured by Microchip, and have 4 KB ROM, digital I/O lines, PWM output and A/D channels in addition to RS-232 and I^2C interfaces. The inclusion of these microcontrollers enable us to offload low level control of certain subsystems from the CDH. For example, in the case of the Propulsion Subsystem, the CDH only has to tell the PIC that thruster #3 should fire for 2 seconds at 40% duty cycle starting 5 seconds from now. The PIC will carry out the command at the requested time. Another advantage is the reduced amount of wiring required. Instead of having to run separate data lines to each subsystem, the subsystems can now be daisy-chained on the I^2C data bus. We are also investigation fault-tolerant technologies for this subsystem.[9]

<u>Auxillary Control</u>

The Auxillary Control subsystem is required to assist in GPS signal lock-on. The three coils consist of 300 turns of magnet-wire on an aluminum frames mounted on the inside surface of three side-panels.

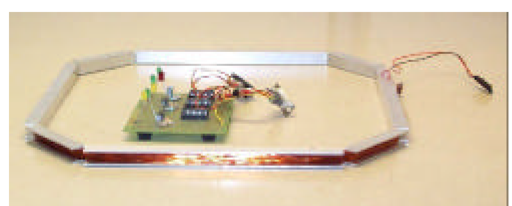

Figure 4. Torquer coil with driver electronics.

This system is capable of generating a magnetic moment of $5\ Am^2$, which is equivalent to $1.25 \cdot 10^{-4}$ Nm at 500 km altitude. The amount of current through the coils is controlled by a PIC16C74A microcontroller through power MOSFETs. This subsystem also includes the necessary 3-axis magnetometer to determine any rates that the torquer coils need to minimize.

Propulsion system

The Propulsion subsystem is the primary means of attitude and position control once GPS lock has been acquired.

The engineering prototype of the Propulsion subsystem consists of one valve commanded by a PIC16C74A microcontroller, and two LEDs simulating another two thrusters commanded by the same microcontroller. The PIC micro is interfaced to the I^2C data bus.

Orion-Emerald Concept

The chance to fly one Orion spacecraft with the University Nanosatellites poses both an opportunity and a challenge. It is an opportunity, because we will be able to fly Orion, but it is a challenge, because we have to accomplish the Orion mission goals with only one spacecraft. Since the Orion mission is intended to demonstrate formation flying technologies, we needed to find stand-ins to play the part of the other satellites in the formation. Fortunately the Stanford-Santa Clara Emerald Nanosatellite team was willing to add this joint-mission concept as one of its experiments. The mission of the Emerald project has multiple goals, but it can be summed up as a mission to promote and support robust distributed space systems through technology demonstration and validation.[10] The main points of this complex mission that are interesting to us are interspacecraft communication, position control by drag-panels, and position determination through the use of the Global Positioning System. It is clear that the Emerald mission meshes well with that of Orion.

The details of the Orion-Emerald mission are still evolving. So far we identified three possibilities for this joint mission:

1. Three-vehicle formation
2. Two vehicle formation
3. Point-to-point visitation

These possible mission scenarios are outlined below:

Three-vehicle formation

In this scenario, the Orion spacecraft and both Emerald spacecraft maneuver together. Adaptation of this mission is not very likely, since the Emerald spacecraft will likely not have enough control authority to prevent them from drifting apart

Two-vehicle formation

In this case, the Orion spacecraft maneuvers with one Emerald spacecraft. The Orion satellite would hold its position in an parking box relative to one of the Emerald spacecraft as the Emerald maneuvers. The size of the parking box and the tolerances around Orion are the same as in the original mission. The goals of position determination and control are also the same. The tolerances would be tightened to demonstrate fine control for a period of time, and this experiment would be repeated at intervals.

Point-to-point visitation

Here the Orion spacecraft visits each drifting Emerald spacecraft. In this mission the Orion spacecraft would alternate between parking boxes around each of the Emerald spacecraft. After spending some time in the parking box next to one Emerald, it would maneuver into the parking box relative to the other Emerald. The size of the parking box and the tolerances are again the same as in the original mission. This scenario would present a good opportunity to test various control algorithms for the translational maneuver. Since the Emerald spacecraft would likely drift apart, the maneuvers would likely become more difficult as time passes. Then the tolerances would be tightened from time to time as in the pervious scenario.

The last two scenarios are the most likely candidates for the joint Orion-Emerald mission. Whichever scenario we choose, the Orion spacecraft will have to demonstrate the same degree of position and attitude determination and control as in the original Orion mission. In addition, we will have three spacecraft in close proximity to each other determining their position and attitude, communicating that information in real time to the other spacecraft, and reacting to that information also in real time. The possibility also exists for the Orion spacecraft to carry the same lightning detection payload as the Emeralds, providing a validating mission of the demonstrated formation flying techniques. Therefore these mission scenarios will allow us to accomplish all of the original Orion mission goals.

Orion-Emerald Development to Date

Since many of the Orion team members also work on the Emerald project, the two teams benefit from the efforts of the other team. Because of this, and in the interest of commonality, the Orion team adopted some of the same protocol and hardware standards as the Emerald team. This will ensure that a joint experiment with Emerald will have minimal impact on the overall Orion design.

Future timeline

The future timeline of the Orion project is determined by the predicted launch date of the University Nanosatellites on board the Space Shuttle. The general timeline is illustrated on figure 5. Launch is currently scheduled for late 2001. Accordingly, the "flight equivalent" components of the Engineering Prototypes will be substituted by "flight identical" components. These "flight identical" units will be identical to the flight units in every way, except in suitability for the space environment. This will be complete by the end of 1999. The only exception is the Propulsion subsystem, which will have to go through another round of trade off studies.

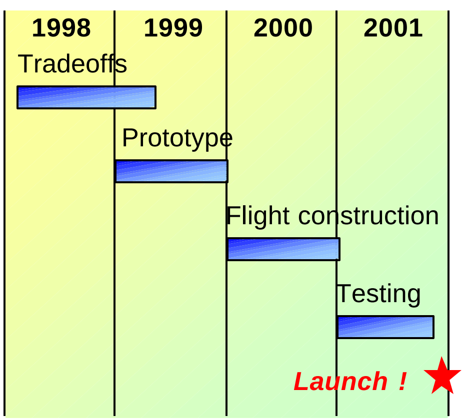

Figure 5. Orion project timeline.

In the year 2000 we will build the flight vehicle, and perform functional testing. In 2001 we will perform environmental testing on the flight vehicle including thermal-vacuum, thermal-cycle, and vibration testing. This will be followed by more functional and operational testing prior to delivery for launch integration.

Challenges

A particular challenge is to design, build, test and verify a cold gas propulsion system that can be safely launched on a manned Space Shuttle mission. We have a good basic design, but we have to go the extra mile to ensure maximum safety. We certainly appreciate and understand the legitimate and valid safety concerns associated with carrying a payload pressurized to 3000 psi in the cargo bay of the Space Shuttle.

In particular, we already consulted with engineers at the Johnson Space Center who were involved with the SAFER and AERCAM projects, and we will use components similar to those two projects. We have also involved Space Shuttle and Air Force safety officials who are taking a close look at our design. We will also have the high pressure side of the Propulsion subsystem manufactured by an experienced government contractor. The prototype and flight units will be assembled and tested in a clean room approved for this type of work.

Conclusion

This paper outlined the current status of the Orion project. The Engineering Prototype is built, and undergoing evaluation. The original mission plan is modified to accomplish all goals in a formation with the Emerald University Nanosatellites.

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