THE OPAL SATELLITE PROJECT : CONTINUING THE NEXT GENERATION OF SMALL SATELLITE DEVELOPMENT

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Abstract

The Satellite Systems Development Laboratory (SSDL) in the Department of Aeronautics and Astronautics at Stanford University was created in an effort to promote a new philosophy about building satellites. The main tenets of this philosophy include the design and construction of reliable spacecraft that are smaller, developed within a one year time frame, and employ cheaper "off-the-shelf" parts. As a result of these criteria, one must take an alternative approach to the engineering project, including rapid prototyping of hardware, careful evaluation of mission requirements, and an overall approach which emphasizes development of the whole system rather than individual subsystems. The result is the Satellite QUIck Research Testbed, or SQUIRT class of satellites.

These smaller SQUIRTs are limited of course, weighing only 25 pounds and having the size restrictions of a 16 inch diameter by 9 inch high hexagon. However, the range of applications still available to these small wonders has hardly been scratched. These satellites still have the traditional major subsystems, such as power, communications, and data & command processing, which allow them a great deal of flexibility in supporting a wide variety of payloads, both scientific and otherwise. The first satellite being developed in this laboratory is SAPPHIRE, which carries on board specially machined infrared microsensors, as well as a camera and a voice synthesizer which can broadcast messages over amateur radio frequencies.

This paper will discuss the design of the SSDL's second SQUIRT satellite, OPAL (Orbiting Picosatellite Automated Launcher). The main focus of this satellite will be to attempt to demonstrate the feasibility of launching and communicating with a smaller secondary satellite. An introduction to SSDL and this project will be given, followed by a background and short review of the technical aspects of the main payload, the picosatellite module. A brief overview of the remaining system architecture will then be discussed. A few conclusions will describe the near-future plans for this project.

I. The SSDL and SQUIRTs

The process of developing satellites has recently come under great scrutiny. The trend of designing big-budget, big-scope spacecraft is all too familiar. These projects tend to undertake enormous tasks which invite a heavy volume of problems. Because of the complexity of these systems, the designs often lead to a segregation of the individual subsystem designs, in which case an engineer could work on a given task for the lifetime of the project without ever seeing or dealing with another area of the design. Moreover, there are system integration issues. The combination of these factors almost invariably lead to a design project which will not be completed on time, and will also overrun its economic budget.

The goal of the Stanford Satellite Development Laboratory (SSDL) is to de-emphasize the large-scale method of thinking and replace it with the philosophy that space-faring vehicles can be designed and built to be smaller, faster, and cheaper, while still undertaking contributive tasks and experiments. Such satellites need to be small, lightweight, modular, and still offer full hardware support (power, CPU, attitude control, etc.) for whatever payload is to be integrated on board. The end result is a class of satellites named SQUIRT, which is an anagram for Satellite QUIck Research Testbed.

The outline design of these satellites calls for a weight limit of 25 pounds and a size restriction of a hexagonal cylinder 16 inches in diameter by 9 inches high. The internal structure of the satellite consists of a series of stacked trays. Ideally, each subsystem receives space on its own tray. This satisfies modularity requirements and allows for easy access to components. The total cost of each satellite is targeted to be less than $50,000 (including travel costs to watch the launch!). Finally, one very important emphasis is the one-year total project time. This means that a SQUIRT is to be conceptualized, designed, and built all within one calendar year.

SQUIRT satellites obviously cater to experiments which are small in size and require limited power, but by no means does this limit their capability. There are many sensors and small experiments waiting to be flown that would otherwise be forced to wait until they could be incorporated into a larger project or shuttle mission. In fact, the SQUIRT restrictions could actually help the space industry in the sense that potential equipment to be flown on board will have an incentive to be designed smaller, faster, more power efficient, and less costly as well.

The first satellite designed under the roof of the SSDL is SAPPHIRE, a vehicle whose main mission will be to test the space-worthiness of some special infrared sensors designed at the Jet Propulsion Laboratories (JPL) in Pasadena, CA. Also on board SAPPHIRE is a black and white digital camera, a GPS receiver, and a voice synthesizer capable of broadcasting typed messages to Earth over amateur radio frequencies. With this project well under way, it came time to start considering the nature of the second SSDL satellite, which will be reviewed shortly.

II. The Picosat Mission

The first major task of the new design team was to define its own personal goals. By identifying these fundamental motivations, the group can be more focused on the task it wishes to accomplish, and can easily justify their actions. The design team identified our major goals as : 1) Gain systems engineering experience and help us prepare for our future, 2) Build a satellite and get it into space, 3) Help ensure the continuation of the SQUIRT program, 4) Have fun. In order to realize these goals, we decided that three concise tasks were required. The first task is to design and build a fully operational satellite, while adhering to the SQUIRT design guidelines. The second objective was to sufficiently document our work so that others may learn from and understand our design process. This will enhance both our learning experience and our ability to communicate our thought process. Finally, we propose to make a strong effort to publicize the SQUIRT program as much as possible through educational, industrial, and internet connections. With these purveying motivations defined, our first task was to choose a mission and then define the functional requirements of our satellite based on that mission.

The main mission for the satellite will be to demonstrate the feasibility of launching a smaller secondary object from the main spacecraft bus and collecting data from it. The secondary objects, dubbed "picosatellites", or "picosats", are themselves tiny, self-contained satellites. Each comes complete with a power source, sensors, and data transmission capability. The need for this mission arises from a desire to study in detail the Earth's magnetosphere.

Up to this point, one can take a vector measurement of the Earth's magnetic field at a single given point and at a single given time. Although a great deal can be learned from data of this type, it is still severely limited in scope. Magnetic fluctuations caused by solar flares and other such phenomena deserve a more detailed examination, which may require a vector sampling of the magnetic field simultaneously at many points over a more extended period of time. The proposed solution to this problem is to launch a number of small sensors away from a mothercraft during a suitably interesting magnetic event. These sensors would measure the magnetic field at a number of points and relay that information back to the mothercraft for as long as possible. This would provide scien-

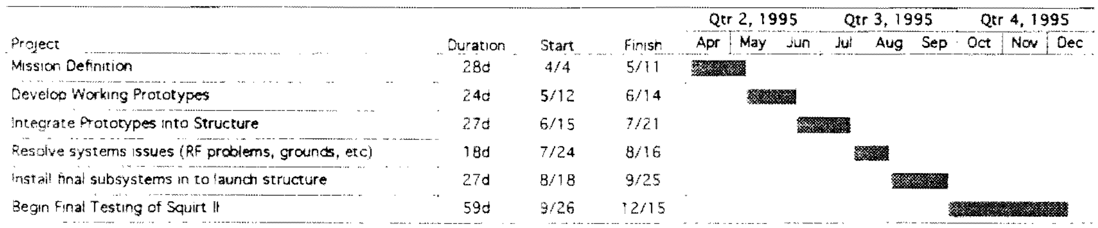

Figure 1 - *OPAL Timeline*

tists with a detailed time history of a more broad region of the magnetosphere, which is certainly more useful than the single-time, single-point method of data collection.

A project of this magnitude would possibly consist of a large mothership harboring perhaps hundreds of picosats the size of silver dollars. But in tandem with the new convention of thinking, it would be prudent to first develop a proof-of-concept satellite to show that launching a secondary object and collecting data from it are possible tasks. In addition, the rapid-prototyping of such a mission will reveal ahead of time many hidden problems and unforeseen issues. This is the motivation behind the second Stanford SQUIRT satellite: the Orbiting Picosat Automated Launcher (OPAL).

With the payload goal fairly well established from a conceptual standpoint, the mission functional requirements were determined. The satellite must be able to, in some fashion, launch a picosat along a designated spin axis, establish a communications link with the picosat, and then relay the received data down to Earth. The remainder of the satellite must contain enough power to support mission operations, enough processor support to reliably conduct those operations, and substantial structural support to survive launch and the space environment. These requirements were determined to be adequate to define a successful mission, and in turn drive the requirements for each subsystem.

III. OPAL System Overview

As the second SQUIRT vehicle, the OPAL team has the luxury of learning from the flagship SAPPHIRE satellite. Because the SAPPHIRE design group had no predecessors and had to build the SQUIRT program from scratch, the project will take about 20 months to complete. But as the second year satellite class, the OPAL team members were able to learn from the successes and mistakes of the SAPPHIRE project and set an ambitious goal of completing the OPAL satellite within nine months.

To conceptualize, design, build, and test a satellite within nine months requires a schedule that is both strict and realistic. Figure 1 shows the actual number of days that the team members have for each task. Despite the short development time, the emphasis will be placed on testing in order to resolve any problems that were overlooked during the development process.

The rapid completion time forced the team to carefully evaluate the system architecture of the satellite. Once the picosatellite module was selected as the main payload, an implementation strategy was developed (as seen in Figure 2) that allowed for various levels of complexity. The first level would accomplish the minimum requirements for mission success which would be to prove and characterize the Picosatellite launcher ability. The second level, which will only be initiated once the first level is completed, would be to test various Jet Propulsion Laboratory sensors, including accelerometers and magnetometers. The third level would include sensors and actuators whose control and data would be partially commanded from students at elementary or high schools. This implementation strategy would allow the OPAL team members to focus in on finishing the baseline project first before adding on any complexity that could potentially delay the completion of the satellite.

Time and task management are both critical issues in a project of this type. Regular meetings and well-defined responsibilities are crucial to the timely completion of the mission. Because the members of the OPAL design team are actually students of the Spacecraft Design class at Stanford University, the management and system level decisions are made in the weekly class meetings. Several students in the class have taken on the responsibility of being the lead engineer for each of the various subsystems. The purpose of this is not to set up a command hierarchy, but rather to assign a coordinator for each subsystem. Keep in mind that the program emphasizes system engineering over subsystem segregation, and most team members (whether they are a subsystem manager or not) take active part in more than one aspect of the design. This allows the idea of overall system design to flourish: when a conflict or design trade arises, a team member will be more apt to consider the overall effects of a choice on the satellite rather than how the decision will affect his own particular subsystem.

One of the goals of the OPAL team is to have all documentation including class and manager meeting minutes, current design configurations, design decisions and trade-off studies, announcements, and schedules available on the World Wide Web (WWW). With WWW access available throughout the Stanford campus, team members could instantly check on their current assignments and how another subsystem may affect the design of their own subsystem. An updated folder with hard copies of the latest documentation will also be maintained in the laboratory, but the students are encouraged to make the OPAL home page their primary and most frequented source of design and class information. Again, the emphasis here is toward complete information access, which in turn reinforces each team member's ability to view the project as a whole system.

IV. Picosatellite Module

With the system overview and project motivation clearly outlined, we may now turn our attention toward the more technical aspects of the satellite, beginning with the main payload module. The picosat module consists of the picosatellites themselves, a

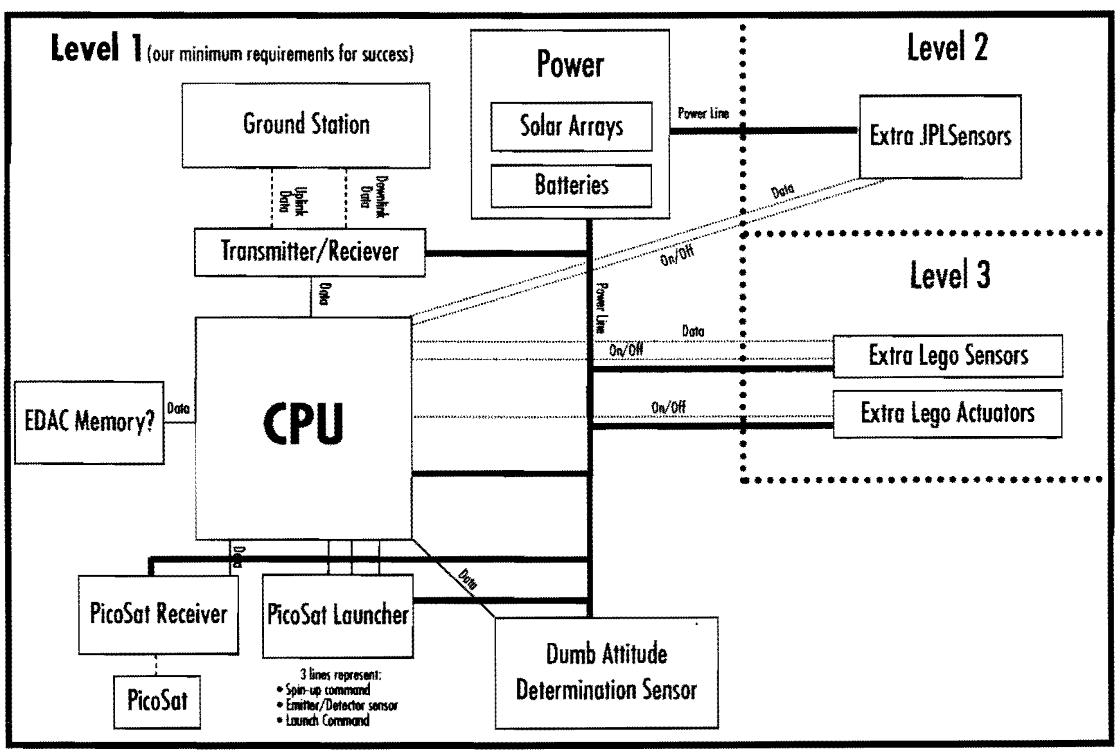

Figure 2 - OPAL Implementation Diagram

launching mechanism, and any additional hardware which is not supplied by the rest of the satellite. This extra hardware might include such items as supplementary power or an auxiliary communications link. All of these components will be located on a single tray on board the satellite (see Figure 4).

The picosatellites for this mission are much larger than their proposed descendants. Whereas the ultimate goal will be to create small space-faring disks the size of silver dollars, the picosatellites for the OPAL mission will be roughly the size of hockey pucks. These disks are about 3 inches in diameter and half an inch thick. Each has the capability to take data from a suitably small device (such as a magnetometer or accelerometer), and then convert and broadcast that data. The current prototype design uses an on-board transmitter operating on a 300 MHz frequency over a range of 10 meters. This will be updated, however, because the picosatellite mission requirements call for a final flight version with a communication range of up to one kilometer. The information to be gathered by each picosat will be accelerometer data. This data will provide valuable insight into the dynamics of each of these bodies during their venture away from OPAL. It will also be used to determine how well the launcher performs its task. See Figure 3 for a functional schematic of a picosatellite.

Two choices were available for the launching mechanism. Each choice satisfies the requirement of being able to launch a picosatellite at a speed of one foot per second (relative to the spacecraft) and with an angular velocity of one rotation per second (60 RPM). The first launcher choice is dubbed the "one shot". For this concept, each picosat rests on its own spring-loaded platform which is guided by an ACME screw with 1.5 threads per inch. A paraffin wax ring holds the system in place. When a launch is desired, a switch can be tripped, causing a current to be run through a thin wire or some other type of resistance heater. This heater melts the wax, causing the system to be released. This system is fairly well developed and looks to be fairly reliable and easy to implement.

The second choice for a launcher is the "repeater" model. This concept essentially employs a robotic arm that grips the picosatellite. For a desired launch, one motor provides the arm with forward linear motion along an ACME screw, another motor controls rotational motion, and a third motor controls the robotic grippers. Also, a reloading mechanism is required. Although complex, difficult to construct, and stocked full of failure points, this system has some key advantages : it can fire as many picosats as are stored on board, only one launcher is required, and the rotation rate and exit velocity can be more tightly controlled, allowing for a precise launch.

The selection of a launcher was a difficult one, but the choice was made to proceed with the more difficult "repeater" launcher for a few main reasons (see Figure 5). First, each exit hole required in the structure will take away valuable solar cell space, reducing available power. The repeater launcher potentially requires only one exit hole whereas the one-shot launcher requires one hole for each picosat. Since a part of the payload mission goals is to demonstrate repeatability, obviously more than one or two launches are required (in fact, the design goal is six). Therefore on this point the repeater launcher is much more attractive. Perhaps more importantly, however, is the simple fact that this mission needs to resemble the ultimate picosat project as much as possible. The scaled-up mission for picosats envisions hundreds of these objects being launched and sending back data. Clearly, loading a larger satellite with 100 silver dollar-sized holes and one-shot launchers is not a viable solution. A repeater model will most likely be used in this case. Therefore, a demonstration of one-shot type technology on OPAL's part will not be very productive toward this goal.

V. System Architecture

Now that the payload module and its components have been more formally introduced, we can examine how the rest of the satellite architecture is affected. After the implementation strategy was established, the team began the formal design of the OPAL satellite by determining how the overall mission requirements are carried down to the various subsystems. Due to the heavy influence and experience of SAPPHIRE team members, the OPAL team was able to quickly analyze

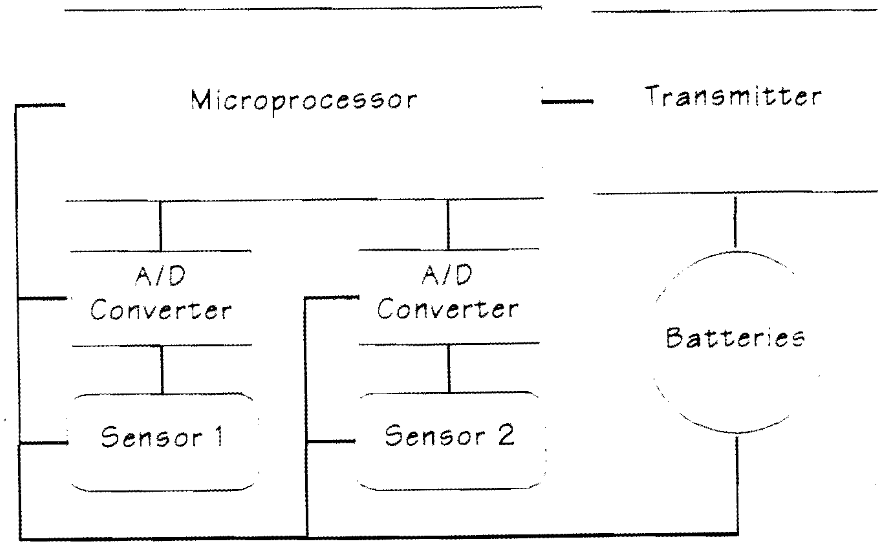

***Figure 3** - PicoSat Functional Schematic*

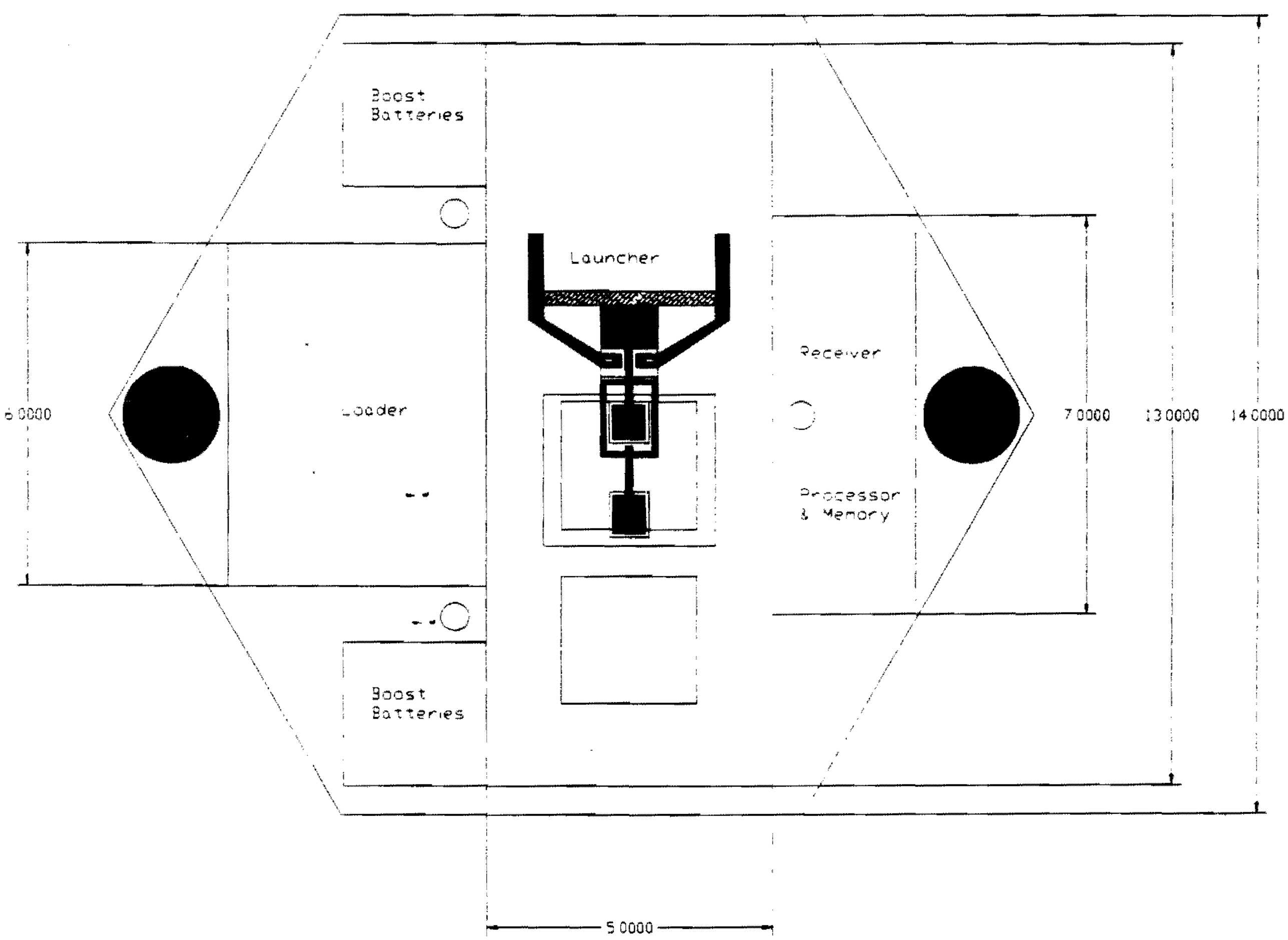

***Figure 4** - Layout of the PicoSat tray*

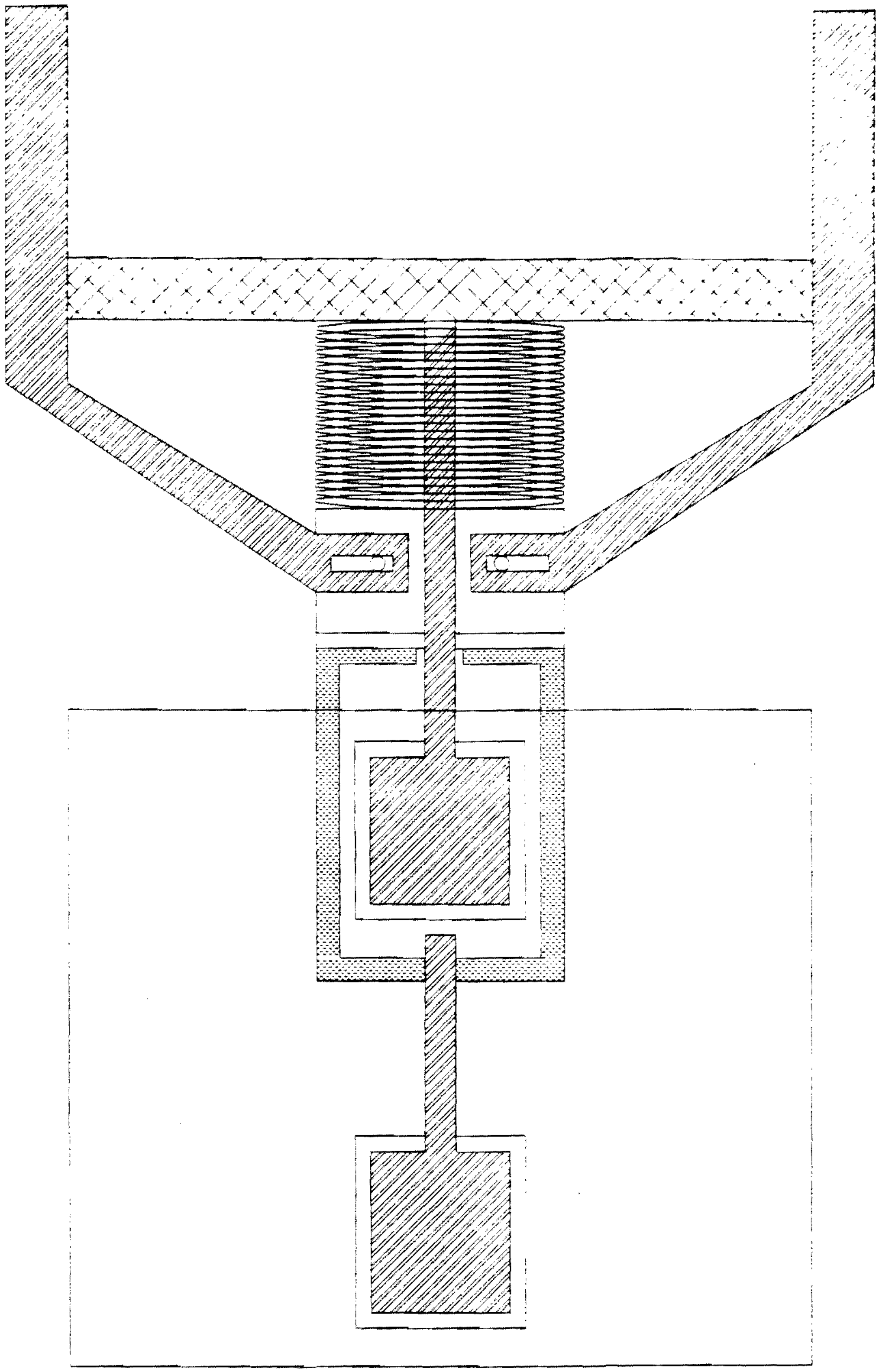

Figure 5 *- Close-up view of the launcher diagram*

PICOSAT LOAD/LAUNCH SEQUENCE

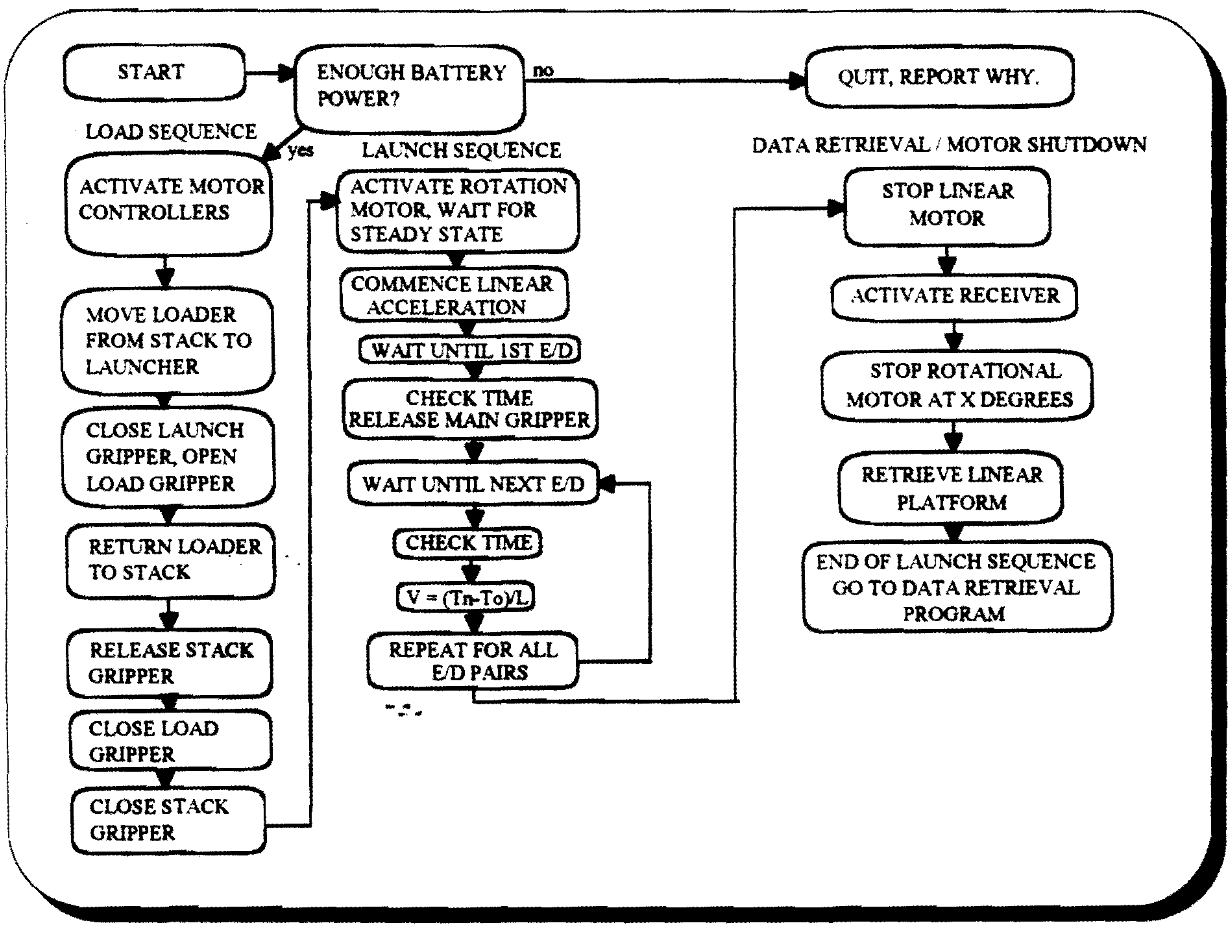

Figure 6 - PicoSat Load/Launch Sequence

the design alternatives and produce a series of formal trade-off studies that led to a baseline system design.

When the specific picosatellite requirements were determined and the repeater-style launcher was selected, the baseline structural design took shape. The internal tray layout of the structure was selected to optimize the inertia axes, so that the picosatellites could be launched along the spin axis of OPAL. In addition to the picosatellite payload, the power, communications, and processing subsystems were assigned specific trays. Electrical wiring resides on two opposite sides of the hexagonal structure and will provide more than 100 lines between the trays. A passive attitude control damper will be placed in the most convenient spot along the edge of the interior of the structure. The antenna, solar cells, and various sensors will be mounted on the exterior panels.

The system electronic architecture is based on simplicity and modularity. Figure 7 shows the functional electronic interfacing of the active components. The heart of the system is a Motorola 68332-based computer board that monitors and controls component activity, processes command inputs, and formats telemetry outputs. By and large the choice of this system over others had a great deal to do with the success that SAPPHIRE has had with it. Much of the software written for this board by SAPPHIRE team members turned out to be reusable. In essence, this is also a goal: to develop a standardized software package usable by any SQUIRT mission, present or future. The central operating system will talk to a single authorized user, who will be able to command satellite functions and download data. The software will have several data contacts, including a digital link with the communications system and the picosat module, and a number of analog-digital links. The A/D links will be handled in part by an A/D converter board which will then feed a digital signal to the CPU. Memory management and address selection techniques are key issues here. The system may appear complex, but in order to help fulfill the mission goals, the number of tasks to be performed are few: 1) the CPU must be able to tell a picosat when to launch, 2) it must be able to read and process

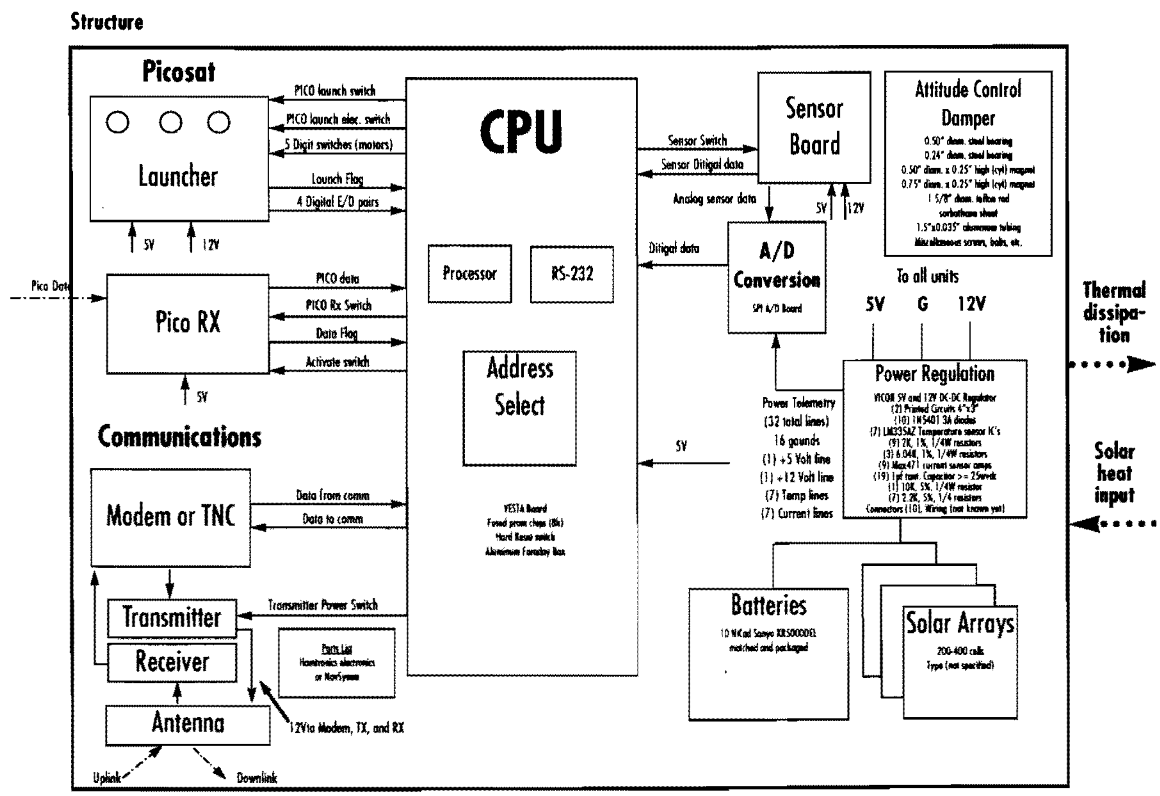

Figure 7 - *OPAL Functional interfaces*

data from the analog and digital links, and 3) it must recognize a valid user and be able to download data to that person.

The communications subsystem uses an off-the-shelf 1200 baud, Mode J, AFSK packet data system that uses both a hardware and software terminal node controller (TNC). As the gateway to OPAL, the communications subsystem must be extremely reliable. However, the selected transmitter and receiver to be configured for OPAL is not space-rated. Furthermore, neither SAPPHIRE nor OPAL have been subjected to shake and vacuum tests with all of the subsystems installed. Therefore, extra testing must be completed to ensure that the communications hardware can endure the space environment. Note that this communications subsystem should not be confused with the separate picosat receiver which will link directly to the processor.

The power subsystem provides an average of 8 watts collected from the solar panels. Power is stored in ten Nickel-Cadmium batteries and is regulated to provide both 5 and 12 volt lines. A preliminary power budget revealed that the power system provided more than enough power for OPAL to function. Extensive testing of the batteries has already been performed on the SAPPHIRE power system, so the focus of OPAL's power system will be to integrate the solar panels with the batteries and determine the effects of varying charge times as OPAL passes into and out of the Earth's shadow. Space readiness is not as big a concern for the power system because many of its components, including the solar cells, are space-rated.

A simple damper will provide the passive attitude control needed to ensure that OPAL will spin around one axis. Because it is highly desirable for the picosats to be launched along OPAL's spin axis, an energy dissipation method was required to damp out any angular rotations not about the axis of maximum inertia. The baseline design has steel ball bearings impacting a soft energy absorbing material (like neoprene) within a small tube.

VI. Conclusions

The future of this project will be an extremely busy one. At this time, the OPAL team has completed its paper study and is in the process of quickly prototyping the various subsystems. The goal is to have completed a working final model by early September, which will then undergo weeks of careful study and testing. Obviously, careful time management will be the key to staying on schedule, but this task is much easier than it would normally be since emphasis is placed on systems engineering. Tasks in one subsystem can be planned and coordinated to conform to those of another, so that the entire system can come more easily together as one functional piece. The major stumbling block to this goal is the problem of team attrition. A significant number of team members will either be unavailable or graduating in the near future, and a great deal of time and resources are required to replace those people and bring any new recruits up to speed on the project. This is why documentation is emphasized. The more clear and informative the project documentation is, the less time will have to be spent instructing others.

It is apparent that the SQUIRT program offers a degree of continuity as well. In industry, a great deal of time and effort is spent doing research and development on a product. However, once the product design is finalized, rapid production ensues and all of the following units are quickly and cheaply produced. A similar theme may be developing in the SQUIRT program, as it has been discovered that much of the SAPPHIRE hardware and software can be used on the OPAL mission as well. If this theme continues, it may be possible to set up a standardized set of subsystems that require only minor adjustments, depending on the mission. This could allow future SQUIRTs to be produced at a much faster and cheaper rate.

Clearly, the SQUIRT program offers a great deal to the future of space development. In the short term, the program makes available a platform for rapid prototyping and testing of space equipment, such as SAPPHIRE and OPAL. In the long term, the SQUIRT philosophy could potentially help redefine the manner in which all spacecraft are built. In order to make a spacecraft design a reality, emphasis must be placed first on making the whole system as simple as possible, while applying the smaller, cheaper, faster rules. It is firmly believed that with this sort of an attitude, mankind's presence in space will be a more secure one.

VII. Acknowledgments

The authors would like to thank the SQUIRT program's founder, Professor Bob Twiggs, for his guidance and support. Also we would like to thank Christopher Kitts for his experience and invaluable suggestions that keep us all on the right track. We thank all the mentors and members of the SAPPHIRE design team, without whom the task of designing OPAL and writing this description would have been much more difficult. Thanks go to Professor Tom Kenney and the group at JPL for developing the picosatellite project to its current point. Finally, we thank all of the members of the OPAL design team for their superb effort and hard work.