THE MARS PATHFINDER COMMERCIAL HARDWARE AND MICROGYRO (CHμG) EXPERIMENT: LESSONS ALREADY LEARNED

Douglas W. Caldwell*
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California 91109

Abstract

The Commercial Hardware and Microgyro (CHμG) experiment was designed to demonstrate the feasibility of using commercial off-the-shelf modules (PC Cards†) and microelectromechanical sensors (MEMS) on space missions and to obtain performance data on both in a deep-space environment so as to gain a better understanding of these two technologies which promise to substantially reduce the cost, mass and power of future spacecraft. Simultaneously, the experiment was designed to provide information and resources to Mars Pathfinder (MPF) which could enhance that mission's value.

For various technical and programmatic reasons, the experiment was radically descoped and the "commercial hardware" aspect of the experiment was virtually eliminated. This paper discusses the original concept, the problems encountered in its implementation, and the current state of the experiment.

1. Introduction

1.1 History

The concept for the CHμG experiment originated in March due to the potential availability of a slot in the VME chassis of the Mars Pathfinder (MPF) Attitude and Information Management (AIM) System. This slot was budgeted for EEPROM to store flight software but would possibly not be required. CHμG was designed to exploit this opportunity by providing information and resources which were useful for the MPF mission. Funding for the effort was obtained in April, primarily from the New Millennium Program as part of its efforts to quickly demonstrate breakthrough technologies in operational environments.

The most demanding aspect of the project was that it had to be developed, tested, and delivered for integration into MPF by the end of 1995, despite the fact that the proposed MEMS gyro existed only as a concept and that the electronics had to reside in a flight-critical subsystem of a JPL spacecraft. Both of these issues turned out to be more daunting than anticipated. By July the team was three weeks behind on a six-month schedule and it was apparent that something had to change. Various options were discussed by the team and, when all the factors were weighed, the best option appeared to be to pursue only the microgyro development and the electronics needed to support it.

This paper describes both the microgyro experiment which is still being pursued as well as the original concept so that the lessons learned are not lost.

1.2 Success Criteria

This experiment was to be considered successful if it provided technology demonstration value, Pathfinder mission enhancement, and early deliverables to the New Millennium Program (NMP). Table 1 shows how we attempted to quantify the contributions of the various success criteria in the technology, Pathfinder, or NMP domains for which CHμG would be judged. As it turned out, this quantification was instrumental in helping the team make the descoping decision. The following sections describe each of these elements in more detail.

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* Member AIAA.

† *PC Card* is a trademark of the Personal Computer Memory Card Industry Association (PCMCIA). PC Card and PCMCIA are used interchangeably throughout this document.

Table 1. Success Criteria and Quantification.

Success Element	Success Criteria	Tech.	MPF	NMP
Rapid Development	delivery within cost and schedule	20%		20%
MEMS Gyro	in-flight characterization of performance	20%		
PCMCIA Flash Memory	radiation data for Flash memories	20%		
Mars EDL	dynamic attitude data for all of EDL		60%	
Memory Capacity	provide additional non-volatile memory		30%	
Fault Protection	flight-qualification of very low cost rate sensor	20%	10%	30%
Cost Savings	show cost reductions using COTS macro-components	20%		50%

1.3 Technology Demonstration Value

The MEMS experiment will use a micro-machined gyro (microgyro). The space environment will provide the opportunity to gather performance data in a hard vacuum. Because of the very small feature sizes of micro-mechanical devices, the density of the operational atmosphere is a key operational parameter. Although these devices can and will be tested in a laboratory environment, extrapolations to space vacuum are not necessarily valid. This aspect of MEMS performance is presently unexplored. Although these first microgyros will have inadequate performance for inertial navigation, they will be sufficient to measure angular rates. In particular, a complement of three of these devices could provide fault-protection information (e.g., to de-tumble) for almost no mass, power, or volume.

Commercial components, standards, and processes were to be demonstrated using two of the credit-card size PC Cards developed for the notebook computer industry. The data acquisition functions for the gyro experiment were to be provided by a PC Card to simplify development. A high-density Flash-memory PC Card would demonstrate a low-cost 1 Gb (gigabit) non-volatile mass storage device (akin to a solid state recorder). Part of the effort was intended to gain a better understanding of the difficulties of using COTS components in a flight scenario. The use of commercial components could result in higher Single-Event Effects (SEE) rates due to energetic particles than is generally anticipated for JPL spacecraft. Part of the experiment was to measure SEE rates and demonstrate mitigation effects which are expected to be generically applicable to such components. This type of experiment cannot be performed in a laboratory environment. Although the Pathfinder environment is relatively benign from a radiation perspective, it provides a balance between the desire to enhance the mission and the desire to gain data from possibly-damaging radiation doses.

1.4 Value to Mars Pathfinder

The MEMS gyro experiment will provide inertial attitude rate information to help characterize the Pathfinder Entry, Descent, and Landing (EDL) operations. This information will be provided after post-processing telemetry data from the experiment. Pathfinder does not presently have sensors to provide this information. Additionally, the gyros may be of value during the cruise phase, particularly in the area of fault detection and recovery. The 1 Gb of non-volatile mass storage was to be available for non-critical storage (e.g., overflow science data or programs).

1.5 Value to New Millennium Program

As MEMS technologies are expected to play a significant role in NMP, it is expected that the early investigation a representative device will accelerate the deployment of others. Additionally, the use of microgyros for fault-protection can reduce NMP mission risk. It was hoped that demonstrating PCMCIA modules would demonstrate the ability to significantly reduce the cost of implementing flight experiments. While this aspect of the experiment has been dropped, commercial parts are being used extensively on the board and the

PCMCIA cards are being further investigated outside of the context of this experiment.

2. Microgyro Technology

2.1 Motivation

Although many MEMS experiments could have benefited from the MPF opportunity, the limitation of "no apertures" restricted the choices to inertial or atmospheric sensors, e.g., gyroscopes and pressure sensors. A gyroscope was very appealing to Pathfinder because no sensors were provided to observe the dynamics of the entry, descent, and landing phase (EDL); traditional gyros were too heavy to justify their inclusion.

There are many approaches to building a gyroscope; many varieties of spinning mass gyros ("iron gyros"), optical gyros, and resonating gyros have been qualified and used on spacecraft. In the last few years, the ability to build mechanical devices using the fabrication techniques of the semiconductor electronics industry has presented a new means of implementing gyros.

The microgyro effort was begun at JPL in December 1994. A survey of other efforts indicated that vibratory gyros had the best properties of any approach (relative to other micromachined gyros). A near-term performance target of 10 degree/hour bias instability was set and preliminary designs were investigated. While not sufficiently quiet to allow long-term inertial navigation, this performance is more than good enough for short-duration attitude maneuvers and fault-protection requirements. Moreover, it was felt that achieving this target would provide ample opportunities for determining the limits of the technology.

The support electronics for the microgyro posed a significant design challenge. The capacitive pick-offs of the microgyro provide a total capacitance on the order of picofarads and a signal-induced variation on the order of femtofarads. Very low noise preamps had to be located adjacent to the gyro to avoid lead capacitance and noise pickup. This is one of the areas where the ability to use commercial parts was valuable; the highest performance semiconductor devices (e.g., preamps) are not available in space qualified forms.

Figure 1 shows the configuration used for characterizing the microgyro's rate sensitivity, signal-to-noise ratio, scale factor, drift rate, environmental sensitivity, etc. The gyro and its support electronics are mounted within a bell jar which is, in turn, mounted on a rate table. The bell jar provides the vacuum environment necessary for proper operation of the gyro; even a small amount of air will damp oscillations because of the very small size of the mechanical features of MEMS devices. The microgyro and support electronics are mounted on a secondary plate within the bell jar so as to not require modifications to the jar's vacuum base. The vacuum base and the bell jar are elevated on "stilts" (approximately 30 cm long) to provide clearance for cables and the vacuum hose which must clear the rate table. The support equipment consists of a PC-based data acquisition system (provided by the Cassini Project), power supplies and, possibly, signal generators. The data acquisition system is connected to a remote workstation where data analysis is performed using LabVIEW.

The first MEMS gyro was fabricated in late June. As of the time of this writing (early August), a barely-discernible signal has been dragged out of the noise of the one device. Efforts are proceeding and it is expected that more detail will be available for the conference presentation.

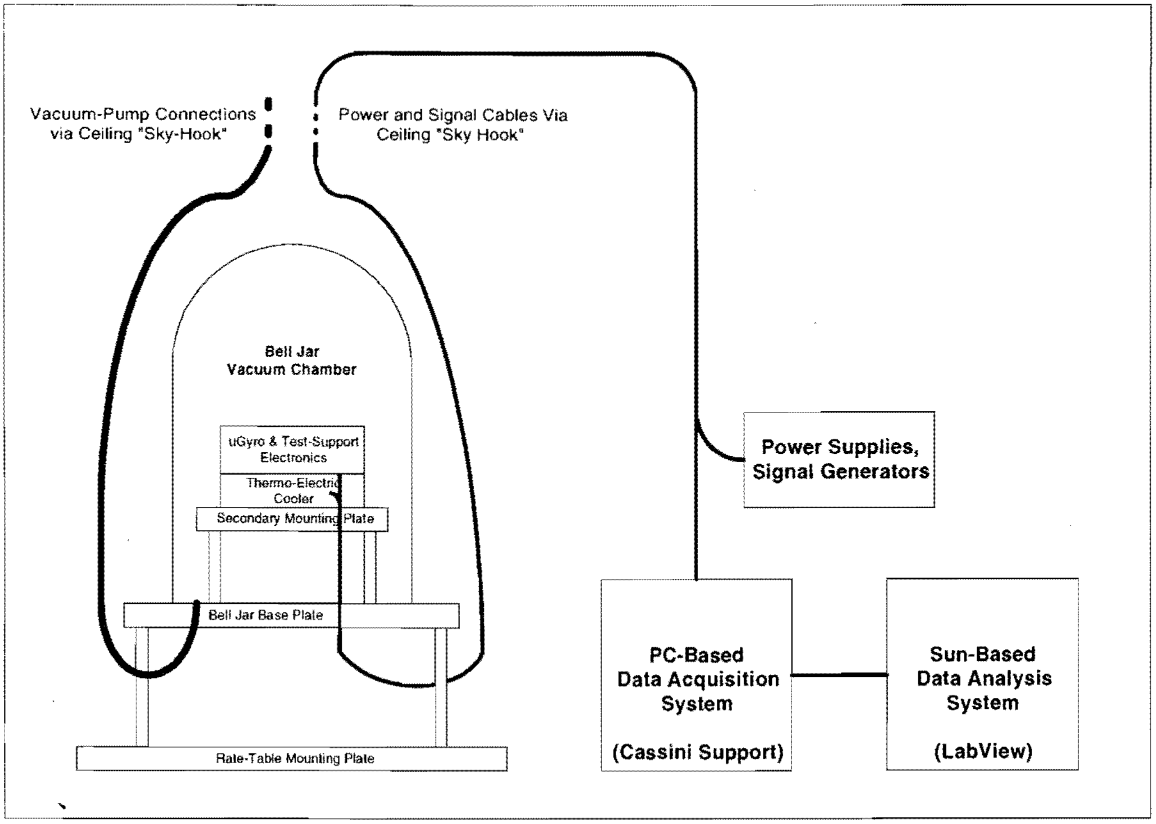

Figure 1. Microgyro Test Configuration.

3. PC Card Technology

PC Cards provide examples of commercial technologies and standards which can be exploited for spacecraft electronics elements. The technology offers a very compact and mature packaging approach, a simple communications interface which supports fault-isolation, and an existing product base which supports rapid prototyping and module development‡. One of the original goals of CHμG was to demonstrate two of these cards in a space environment.

As originally conceived, the experiment was to host two PC Cards in dual-height sockets. One of the cards would provide the analog and digital I/O support for the microgyro experiment. The second card would be a Flash disk with a capacity of 175 MB. Both of these cards were to be off-the-shelf items.

The National Instruments DAQCard-700 is a low-power analog input, digital, and timing I/O board in a PCMCIA Type II form-factor. The board contains a 12-bit successive-approximation A/D converter with 16 single-ended or 8 differential analog inputs, 8 lines of TTL-compatible digital input, 8 lines of digital output, and two 16-bit counter-timers. It is capable of sampling up to 100 kS/s into a 512 sample FIFO. Self-calibration reduces DC-offset errors to ±1 LSB (with a coincident code-range reduction to -2024 to +2023).

The SunDisk 175 MB Flash disk is the largest such device presently available. It presents the user with an interface which is identical to a hard disk and similarly non-volatile (and presumably SEE immune). Read times are 100 ns and write times are about 10 μs. This device was to be investigated as a

‡ Additional information on PC Cards is available in the poster-session paper by the author entitled "Using the PCMCIA Standards in Space".

candidate solid-state recorder for very low-cost missions.

The TID requirement for MPF is 500 rad. Since essentially all semiconductors can withstand at least this level, TID was not considered an issue. The MPF charged particle environment is dominated almost exclusively by the galactic cosmic ray background since it will fly near solar minimum. Part of the purpose of the experiment was to test the susceptibility of an entire commercial module to this particle environment. In the case of the Flash disk, it was desired to observe the effectiveness of the integral (56,64) Reed-Solomon code which protects data.

The thermal environment of the MPF AIM is -35°C to +50°C operating (-50°C to + 50°C nonoperating), a requirement which would appear to present a significant hurdle for commercial electronics. However, the microgyro would be only be exposed to the cruise environment which is a much more benign -5°C to +50°C. The lower limit of this range is just slightly outside the commercial temperature range but this was not deemed a problem since the microgyro experiment would terminate at the end of the cruise phase. The Flash disk would be exposed to the -35°C operating and -50°C nonoperating environments. SunDisk makes industrial temperature range devices and these have been tested down to -50°C operating.

PC Cards are designed for the terrestrial market; even in a tightly enclosed space such as a PC Card, convective heat transfer is very efficient. Some modifications are necessary for the space environment to improve thermal conductivity. If hermeticity is not a requirement, a possible solution is to simply fill the internal cavity with a thermally-conductive insulator (e.g., alumina-filled epoxy).

4. Experiment Overview

4.1 Functional Block Diagram

Figure 2 shows the major functional blocks of the original CHμG and their interconnection. Three single-axis micromachined gyros provide three axes of acceleration and sockets are provided for two PC Cards. The figure shows the "firewall" which protects the flight-critical VME bus from faults in the experiment. The interface to the VME bus is provided by a single FPGA (Actel 1280A) because of its demonstrated radiation tolerance and inclusion on the MPF Qualified Parts List. While the FPGA is supplied from the +5V VME power, the rest of the boarded draws power from a +30V supply which is less critical to system operation. Local power is completely isolated and current-limited. Additionally, the board is a VME slave (i.e., it cannot control the bus) so that it physically cannot corrupt the bus by initiating extraneous bus traffic ("babbling"). To the right of the firewall, parts selection is essentially unrestricted under the assumption that any faults caused by them will be prevented from affecting the host.

The VME interface was selected to ensure minimal impact on the host system. RS-232 and MIL-STD-1553B were considered but both require more resources (e.g., power and cabling) than the VME. Similarly, the range of experiments considered for the board is limited to those which do not require any access to the outside, either via cables or any form of aperture.

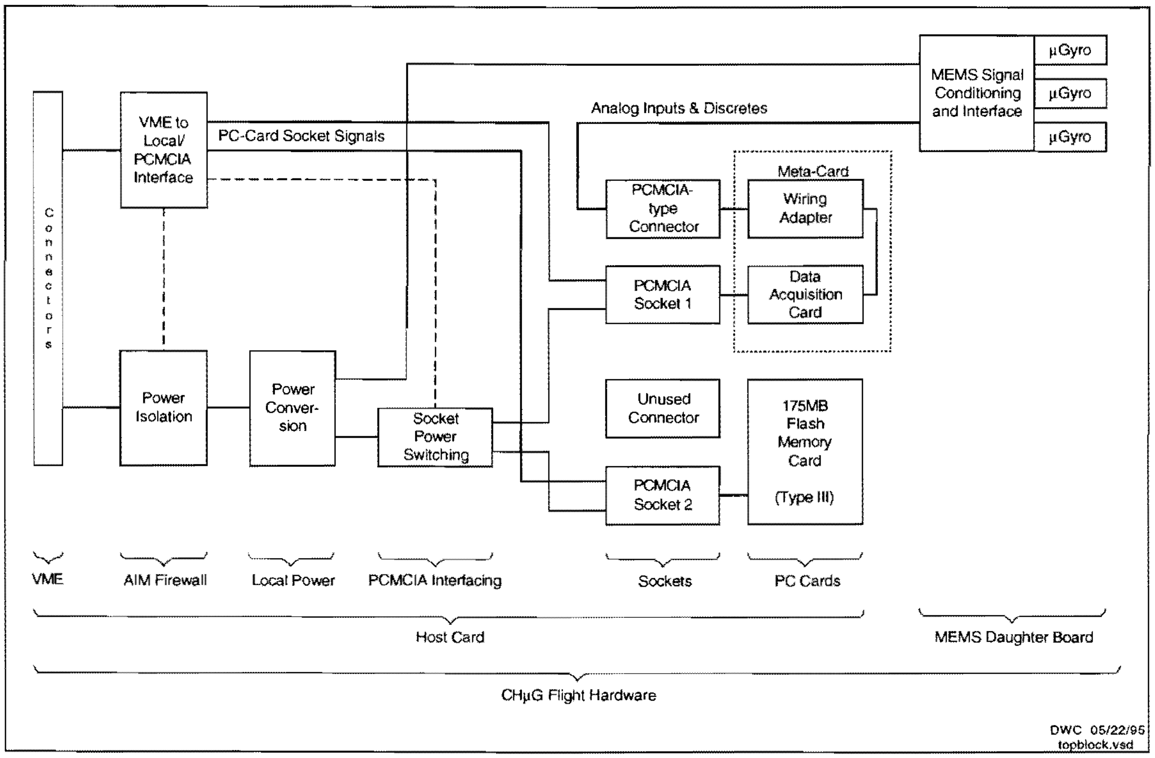

Figure 2. Proposed Functional Block Diagram.

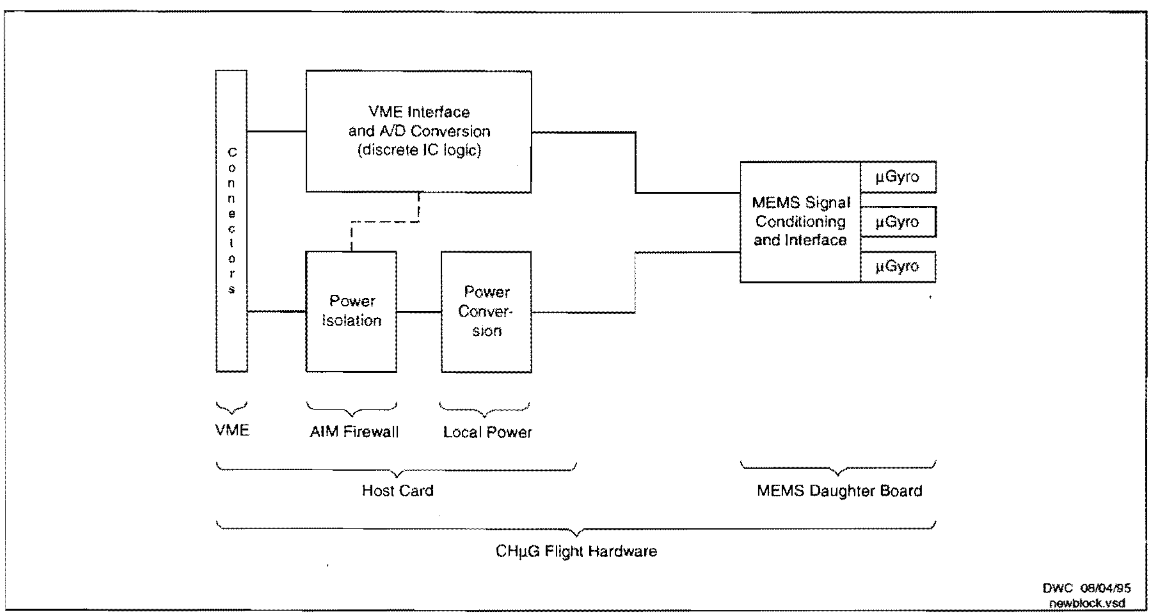

Figure 3. Current Functional Block Diagram

The current block diagram, Figure 3, shows the ravages of descoping. The PC Card support is gone as is the FPGA implementation of the interface. Instead, the VME interface and the data acquisition functions are implementing using simple integrated circuit functions (e.g., gates, latches, D/A converters). Sacrificing the FPGA was done primarily for schedule reasons. In addition to the time required for device design and simulation, the approved process for Pathfinder AIM FPGAs was for them to be programmed by Hughes (in order to control parameters relating to reliability). This process required three weeks lead time and, on top of the normal FPGA development cycle, this created a schedule risk. However, in making this change, the problem of finding qualified parts for the "firewall" became harder than simply acquiring one FPGA since more than one small-scale part would touch the VME interface. Fortunately, acceptable parts were available from the excess stocks of other projects.

The fundamental problem is illustrated in Figure 4 which shows the original board layout planform for the 6U-Stretch form-factor which is used on Pathfinder. The real-estate allocated for the microgyro support electronics was totally inadequate. Currently, these electronics occupy between three and four times as much space as planned. Although various ideas were explored for accommodating the gyro electronics, the ultimate solution required eliminating the PCMCIA experiment.

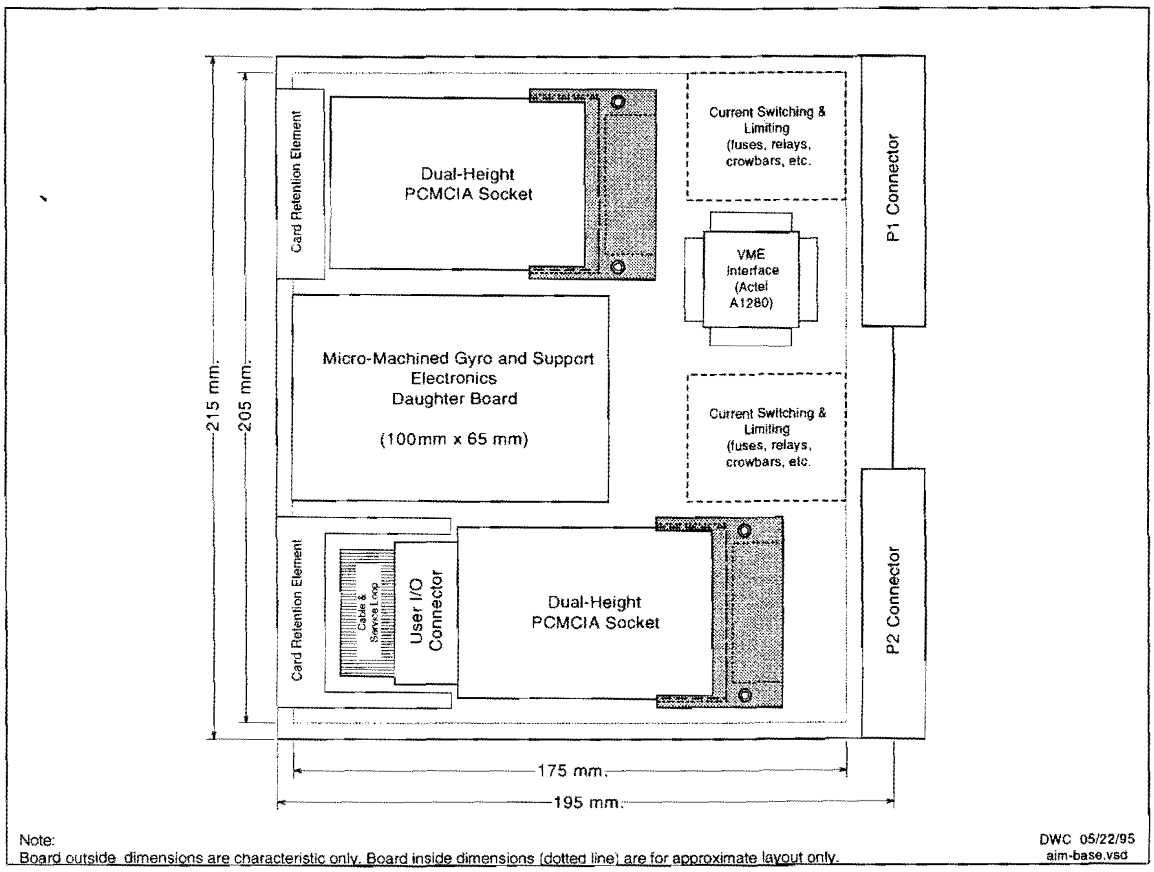

Figure 4. Original Card Planform.

5. Lessons Learned

We still don't know if CHμG will fly on Pathfinder. The use of the VME slot is contingent on additional PROM not being needed for the flight software. Right now, Pathfinder software is sufficiently large that the additional memory may well be needed. However, even without a flight, the effort itself has been worthwhile. If nothing else, we have learned a lot.

One problem which certainly contributed to the schedule slip was the lack of a properly-defined focus. In particular, we did not identify "demonstrate PC Cards in space" as the only requirement for that half of the experiment. The requirement tended to be thought of as "demonstrate PC Card technology in space." While only subtly different, the difference profoundly affects the outcome. Without the proper focus, we found ourselves trying to make a somewhat generic PCMCIA interface FPGA and a VME card which could be used by others. While these are worthy goals, they impeded our progress. Frequently, we found ourselves asking "How hard would it be to add feature XYZ?" Even asking the question slowed us down. Had we identified the FPGA and the VME carrier as necessary tools for demonstrating the PC Cards but which were to be discarded after the experiment, we would have quickly reached a very simple design.

But solving the digital interface problems would not have solved the gyro support electronics real-estate problem. This could only have been solved by having done more of the job earlier. This design was done; it just happened to be concurrent with the development of the whole package.

One might conclude that the fundamental lesson is not to take on a job which is not well understood. Certainly, the microgyro development problems, the inadequate support electronics real-estate, and the PCMCIA interface specification delay would have been substantially mitigated by knowing more initially. However, it is probably equally true that deadlines and the excitement of a fast-moving flight experiment motivate individuals to accomplish more than they might ordinarily do with the same time or fiscal resources. Certainly, the team members who participated feel that they would rather have tried and stumbled than to have never tried. We have already learned valuable lessons and our future endeavors will consequently be better.

6. Acknowledgments

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

As with any project, the technology doesn't make or break the effort; the people do. It has been a pleasure to work with a very capable team. Barry Goldstein first identified the possibility of a "ride" and asked the author for a conceptual design. He then presented the idea with Joe Savino to Kane Casani, the New Millennium Program Manager, who agreed to fund the work. Barry then pulled the people together to do the job and managed the project. Tony Tang and Roman Gutierrez have worked long hours to get a gyro to work and Randy Bartman has tried to keep other options open by talking with outside vendors. Greg Pixler, Brian Martin and Chris Stell worked minor miracles to design low-noise circuits which could extract a signal from the device. Edwin Montgomery and Tim Brooks designed the digital interfaces. Dale Brundige laid out a PWB with far too many traces for the space he was given. Gary Ortiz kept up with a dynamic mechanical configuration. D'Arcy Tyrell provided software support. Bruce Youmans provided gyro test and characterization support. The author provided overall system design and consistency with the Pathfinder design team.