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We have designed and builted and experimental facilty that will allow us to conduct experiements for validating advanced attitude control algorithms for spacecraft in a weightless environment. The acquired equipment and sofrware will greately enhance the capabilities of the School of Aerospace Engineering at the Georgia Institute of Technology for spacecraft-related research and education.

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Simulator Facility for Attitude Control and Energy Storage of Spacecraft

by

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FINAL REPORT

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1 Summary

We have designed and built an experimental facility that will allow us to conduct experiments for validating advanced attitude control algorithms for spacecraft in a weightless environment. The acquired equipment and software will greatly enhance the capabilities of the School of Aerospace Engineering at the Georgia Institute of Technology for spacecraft-related research and education.

The spacecraft simulator facility encompasses an Integrated Attitude Control System (IACS) and is based on a hemi-spherical air bearing with 300 lbf vertical load capacity having three rotational degrees of freedom as follows: ± 30 deg about the x and y axes (horizontal) and 360 deg about the z axis (vertical).

The major components of the IACS are given below:

- Spacecraft two-level brass platform.
- Reaction control system (RCS) comprised of eight adjustable, 5-lbf thrusters.
- Two high-pressure vessels made of composite material.
- Four Variable-Speed Control Moment Gyros (VSCMG's), specifically designed according to Georgia Tech specifications, with associated electronics support (including gimbal and motor servo-loop hardware).
- A two-axis Sun/star sensor.
- A three-axis magnetometer.
- A three-axis rate gyro capable of providing angular velocity information.
- An inertial dynamic measurement unit (DMU) for independent absolute angular position and velocity measurements.
- An on-board computer running at 750MHz with supporting AD/DA and I/O boards.
- An 11MBps wireless ethernet modem.
- A host computer running at 1.2GHz with associated software.
- Two rechargeable lead-acid batteries for on-board power and associate recharge electronics.
- Associated controller software (including the Real-Time Toolbox, C/C++ Compiler, SIMULINK® and xPC Target® Toolbox with Embedded Option) from Mathworks.

Control laws are designed off-line using standard software (MATLAB®/SIMULINK®) and are downloaded via the wireless high-speed link to the on-board computer for implementation. The xPC Target® environment (with Embedded Option) from Mathworks [1] was chosen as the environment for controller implementation because of its flexibility and the easy of integration with the Real-Time Toolbox® and SIMULINK®.

The facility described herein will allow experimental research relating to attitude control and energy storage of spacecraft in orbit. This facility will be instrumental in supporting the AFOSR research grant F49620-00-1-0374 with title "Nonlinear Spacecraft Control with Applications to Combined Attitude Tracking and Energy Storage" as well as the Educational Partnership Agreement (EPA) established between the Space Vehicles Directorate of the Air Force Research Lab at Kirkland AFB, New Mexico and the School of Aerospace Engineering at Georgia Tech (2000-AFRL/VS-EPA-15). The scope of the latter EPA is to support the implementation of combined attitude and energy storage control laws using VSCMG's on the ASTREX facility at AFRL. The ASTREX is a large-scale simulator facility (about two orders of magnitude the size of the IACS). In the past it has been used as a testbed for dynamics and control experiments on large flexible space structures. It was recently refurbished to accommodate new CMG's and attitude sensors to allow testing of advanced algorithms for combined large angle attitude maneuvers with simultaneous power and momentum management. The IACS has been designed with the ASTREX facility primarily in mind. The load capacity, moments of inertia and torque capability of the Georgia Tech IACS facility have been scaled properly with respect to the ASTREX facility.

The IACS designed and fabricated under this DURIP award (AFOSR award No: F49620-01-1-0198) is unique among US academic institutions owing to the flexibility of actuator selection (RW/MW/CMG/VSCMG/RCS) and sensor selection (star sensor/gyros/magnetometer/DMU) is offers.

With the anticipated addition of vision sensor equipment (requested under a pending DURIP proposal to AFOSR), the IACS facility will be able to support a plethora of several Air Force and other DoD programs, such as spacecraft formation flying, rendezvous and docking, combined attitude and energy storage for satellites in Low Earth Orbit and precision tracking and pointing of orbiting spacecraft.

2 Overview of the IACS platform

The IACS (Integrated Attitude Control System) spacecraft "bus" consists of a 32 in brass hub that is supported on a hemi-spherical air bearing. It contains various spacecraft components, such as an onboard industrial computer, attitude and rate sensors, four variable speed CMG's (Controlled Momentum Gyros), pneumatic components for the cold-gas (nitrogen) thruster system, etc. Figures 1 and 2 give a schematic and a photograph of the completed facility, respectively.

The spacecraft platform is a cylindrical structure with two doughnut-shaped circular platforms. This design was chosen among several others, because it is compact and because it offers great flexibility in mounting the spacecraft components. The location of the equipment on the platform has been as symmetric as possible, to allow easy balancing of the platform. Balancing (geometric center be at the same location as the gravity center) is important in order to ensure a torque-free environment. Balancing of the IACS is achieved via a set of adjustable counter-weights. These are shown in Fig. 3.

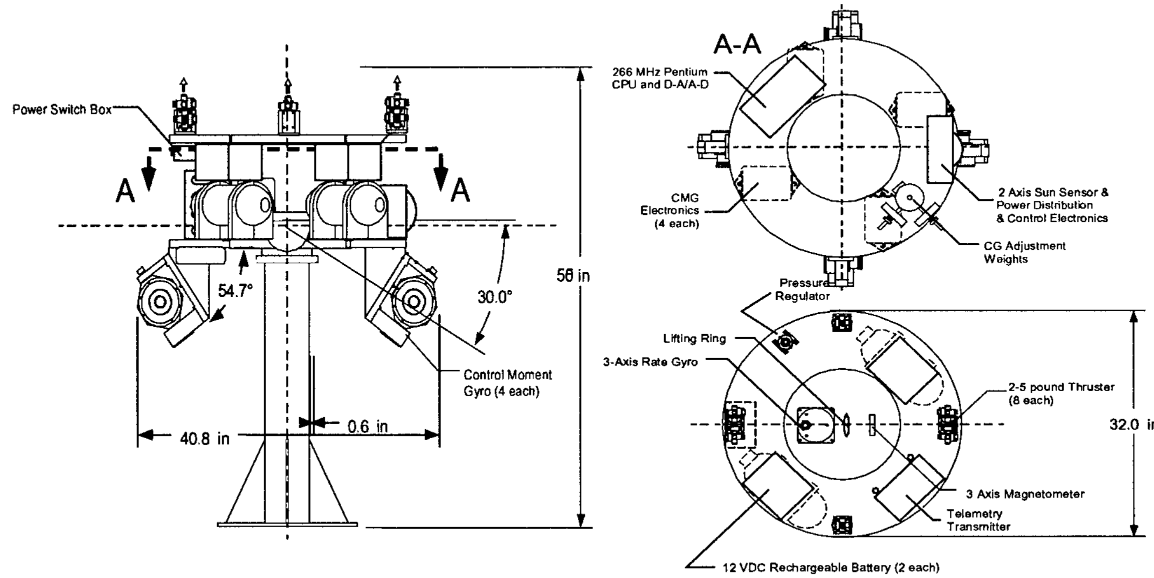

Figure 1: *A schematic drawing of the IACS spacecraft simulator facility.*

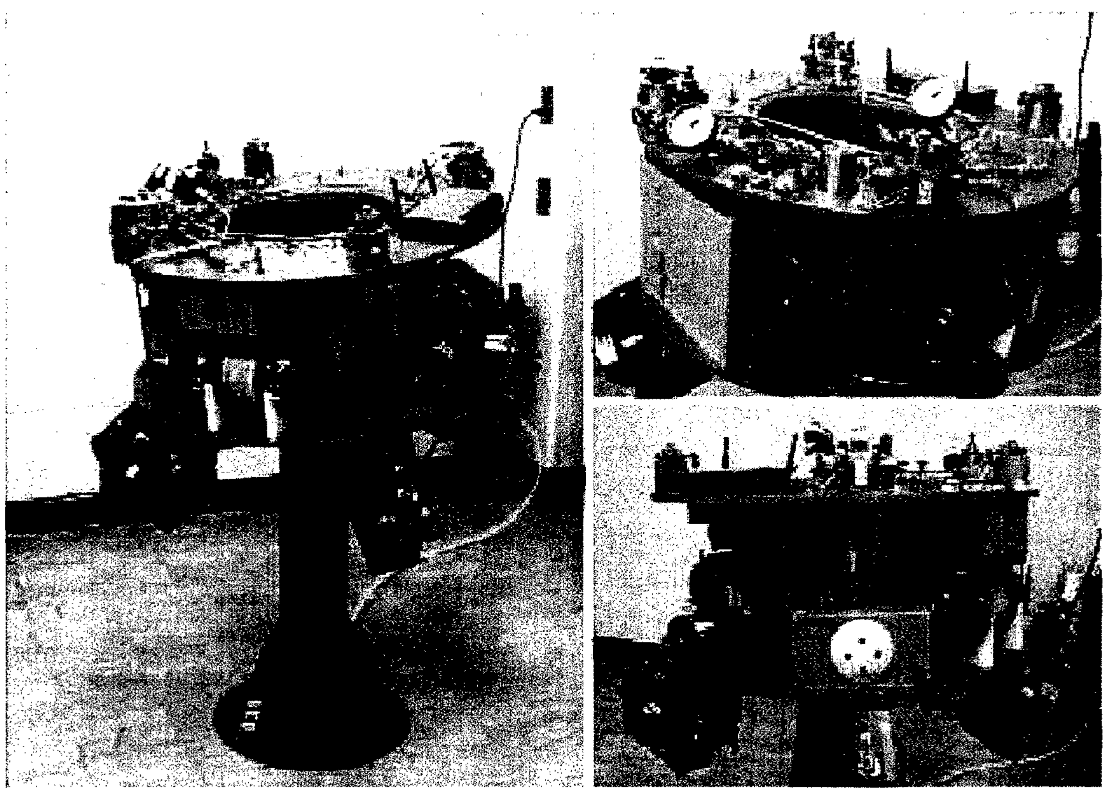

Figure 2: *The completed IACS spacecraft simulator. It is located on the ground floor of the Montgomery Knight building at the Georgia Tech campus.*

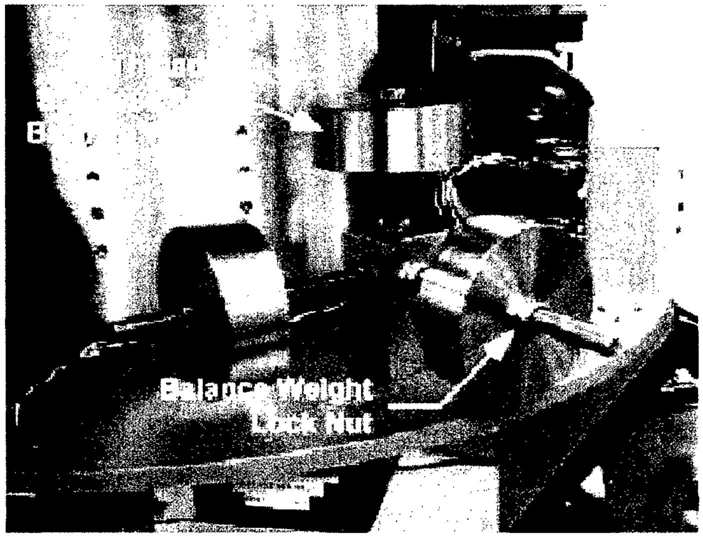

Figure 3: *Adjustable weights for balancing the IACS. Although great care has been devoted to a symmetric distribution of the weight, small offsets can be compensated by moving these counter-weights.*

3 Pneumatic System

3.1 Air bearing

The air bearing that supports the IACS platform is located on top of a pedestal structure (3 ft high) and allows the platform to move without friction 30 deg about the two horizontal axes (roll and pitch) and 360 deg about the vertical (yaw) axis. The bearing, shown in Fig. 4, is the SRA-300 spherical air bearing, designed and manufactured by Specialty Components Inc. It is made of 6061 aluminum alloy hard-coated with Al_2O_3 and can support up to 748 lbf of vertical load when operating under 80 Psi air pressure. The operational pressure is supplied from the shop air supply. The shop air is filtered to remove oil and humidity to provide clean and dry air to the cup of the air bearing. The complete diagram of the pneumatic connection is shown in Fig. 5.

3.2 Thruster Reaction Control System

The Thruster Reaction Control System (TRCS) for the IACS consists of:

- eight adjustable, 5-lbf (maximum) thrust jet valves grouped in two pairs one with three thrusters and one pair with one thruster each.
- one manually adjustable pressure regulator
- two 225-in^3 gas storage tanks
- a -4 AN fill fitting with a fill line vent valve
- a high pressure check valve

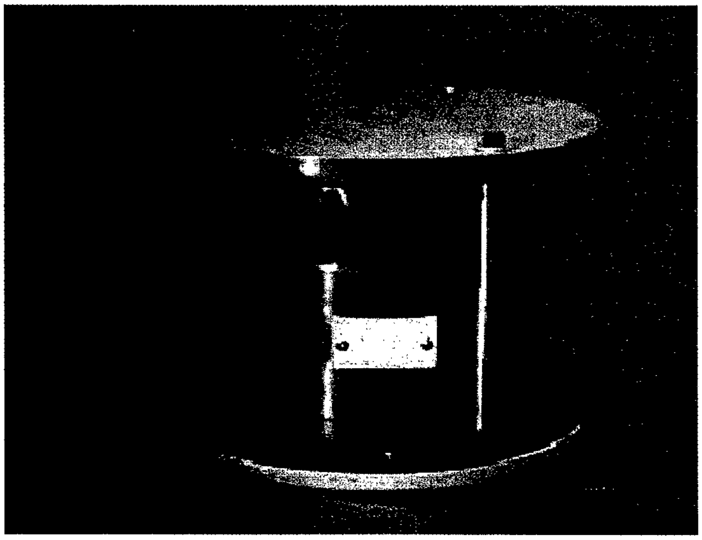

Figure 4: *The SRA-300 hemi-spherical air-bearing; picture provided by Specialty Components Co.*

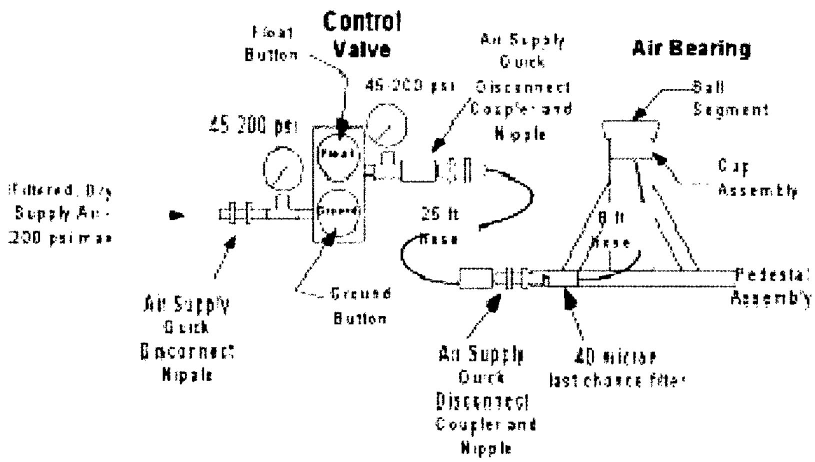

Figure 5: *Pneumatic diagram for air bearing.*

- a filter with a supply pressure gauge
- a regulated pressure gauge
- a thruster supply vent valve

The gas storage tanks are charged through the -4 AN fill fitting with high pressure gas provided by two external nitrogen gas bottles (under 3600 Psi each). The pressure regulator regulating the pressure from the gas storage tanks is used to set the gas pressure on the thruster. Each pressure can be directly read from the two pressure gauges on the platform via pressure transducers. After charging the gas tanks and completing the experiments, the remaining gas on the pressurized lines can be relieved through the fill line vent valve and the system vent value, respectively. Figure 6 illustrates the outline of the pneumatic system and Figs. 7-8 annotate the TRCS system on the IACS platform. As shown in Fig. 9, a thruster module consists of a solenoid valve, outlet nozzle,

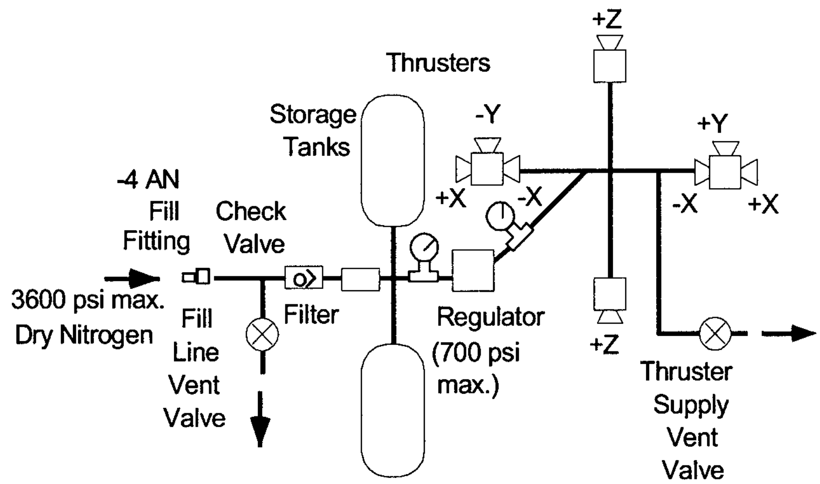

Figure 6: *Schematic of the thruster reaction control system (TRCS).*

pressure adjustment fitting and pressure test port. The On/Off signal from the Power Switch Electronics box lets the solenoid valve open/close and accordingly set the thruster to be on/off, respectively. In addition, the force exerted by the thruster can be set by adjusting the chamber pressure adjustment fitting by inspection of the test port pressure.

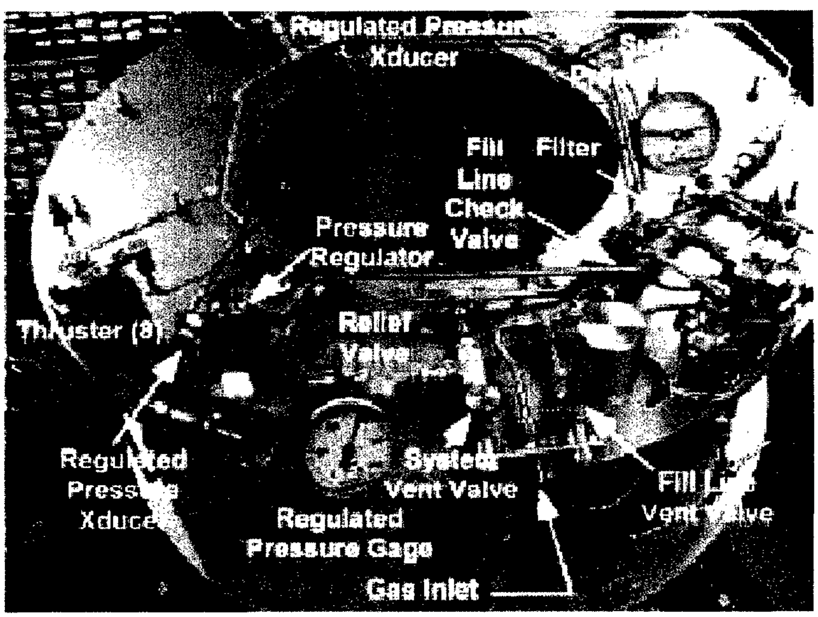

Figure 7: *The realization of the thruster reaction control system on the IACS platform.*

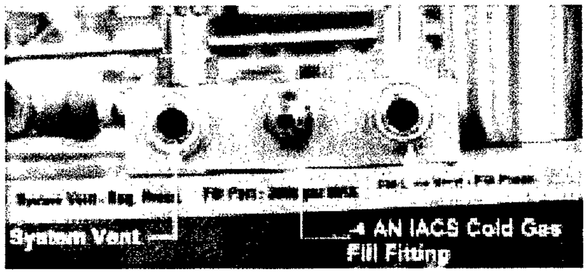

Figure 8: *The high pressure -AN4 fill line fitting and the vents for the TRCS.*

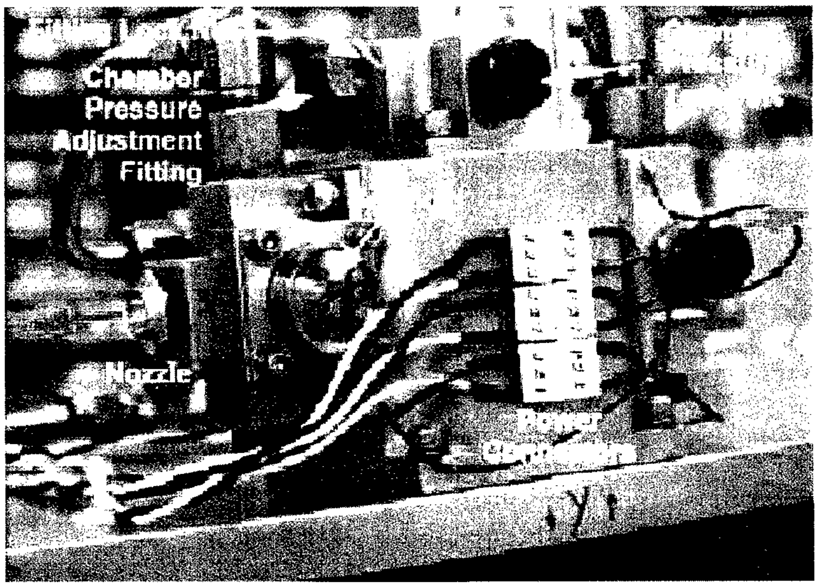

Figure 9: *Thruster module.*

4 Electronics

4.1 Target (on-board) Computer

An industrial embedded computer (ADLink NuPRO-775 Series) is used for data acquisition, data recording, and controller implementation via the Matlab xPC Target® Environment [1]. The CPU of the NUPRO-775 is based on the Intel Pentium® III 750MHz processor with on-board memory 128MB DRAM and 128MB disk-on-chip allowing real-time data acquisition, processing, and data recording. The connection to the host computer is done in the xPC Target® Environment via an Ethernet wireless LAN connection. The wireless LAN router (DLink DI-713P) and the USB adapter (DLink DWL-120) make it possible to transfer data at speeds up to 11Mbps. This is enough for real-time monitoring and signal gathering in the host computer.

The target computer system has three data acquisition interface cards installed. Two analog input cards (NI PCI-6023E from National Instruments) are used to measure the analog voltages from the rate gyro, magnetometer, and sun sensor. Another analog output card (NI PCI-6703 from

Table 1: *Channel specification for PCI6023E card.*

Channel #	Signals
Analog to Digital Converter	
ACH0	Gimbal position 1
ACH1	Gimbal position 2
ACH2	Gimbal position 3
ACH3	Gimbal position 4
ACH4	Magnetometer X axis[1]
ACH5	Magnetometer Y axis
ACH6	Magnetometer Z axis
ACH7	Rate gyro X axis
ACH8	Rate gyro Y axis
ACH9	Rate gyro Z axis
ACH10	Sun sensor Z axis
ACH11	Sun sensor X axis
ACH12	Not connected
ACH13	System supply voltage sensing
ACH14	Pressure transducer 1
ACH15	Pressure transducer 2
Digital Output	
DIO0	Rotor mode for CMG1
DIO1	Not connected
DIO2	Rotor mode for CMG2
DIO3	Not connected
DIO4	Rotor mode for CMG3
DIO5	Not connected
DIO6	Rotor mode for CMG4
DIO7	Not connected

National Instruments) is used to control the VSCMGs. In addition, a digital I/O function in the PCI-6023E card generates commands for the thruster valves and the CMG/RW mode commands. The channel signals for these cards are shown in Tables 1-3.

Figure 10 shows the target computer and the wireless LAN router on the IACS platform.

4.2 Sensors

Sun Sensor

The sun sensor (by ACEi, Corp.) utilizes a sensor array that finds the average location of the brightest light spot in its field of view (±20 deg vertical/horizontal). It outputs an analog error signal between 1.5 V and 3.5 V for each axis. A signal of 2.5 V in both axes indicates the brightest point in the center of the field of view with an average scale factor of 44 mV/deg.

Table 2: *Channel specification for PCI6023E card.*

Analog to Digital Converter	
Channel #	Signals
ACH0	Rotor speed of Gimbal 1
ACH1	Gimbal rate 1
ACH2	Rotor speed of Gimbal 2
ACH3	Gimbal rate 2
ACH4	Rotor speed of Gimbal 3
ACH5	Gimbal rate 3
ACH6	Rotor speed of Gimbal 4
ACH7	Gimbal rate 4
ACH8	Auxiliary channel 1
ACH9	Auxiliary channel 2
ACH10	Auxiliary channel 3
ACH11	Sun sensor X axis
ACH12	Not connected
ACH13	Not connected
ACH14	Not connected
ACH15	Not connected
Digital Output	
DIO0	Thruster valve command 1
DIO1	Thruster valve command 2
DIO2	Thruster valve command 3
DIO3	Thruster valve command 4
DIO4	Thruster valve command 5
DIO5	Thruster valve command 6
DIO6	Thruster valve command 7
DIO7	Thruster valve command 8

Table 3: *Channel specification for PCI6703 card.*

Digital to Analog Converter	
Channel #	Signals
VCH0	Gimbal command 1
VCH1	Gimbal command 2
VCH2	Gimbal command 3
VCH3	Gimbal command 4
VCH4	Rotor Command 1
VCH5	Rotor Command 2
VCH6	Rotor Command 3
VCH7	Rotor Command 4

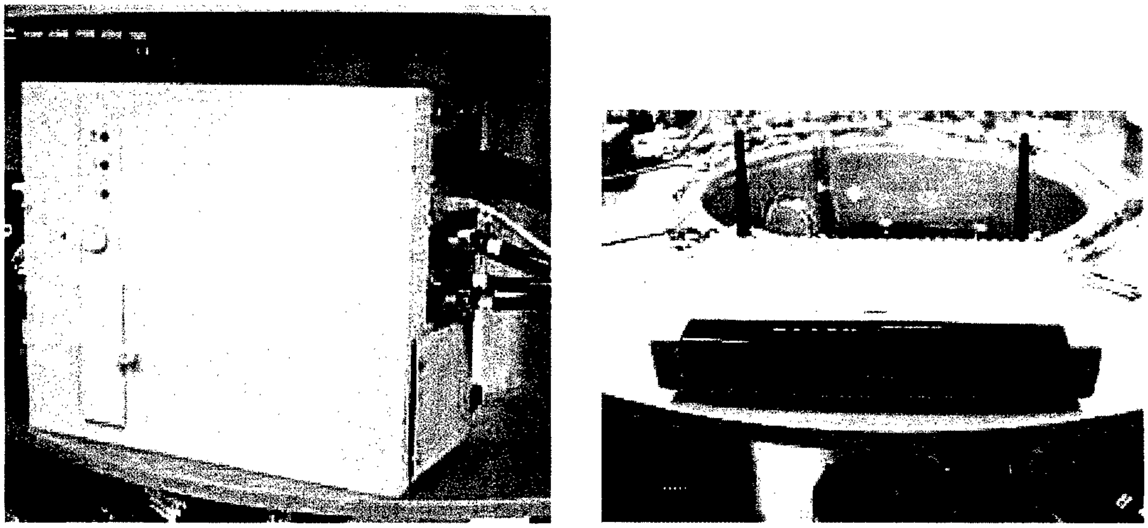

Figure 10: *Target (on-board) computer and wireless LAN router.*

If the light source is not within the specified ± 20 degree field of view, the output will be random. The best-recommended source for a "Sun" is a 20 W/12 V halogen lamp located between 6-8 ft from the IACS. The resolution level of the sun sensor is 0.05 deg and 1σ noise level is 0.05deg.

Although it is possible to use the sun sensor in a ambient light environment, offsets may occur; it is thus recommended to use the sun sensor in a relatively dim environment. Figure 11 shows the sun sensor unit installed on the outside of the power switch box.

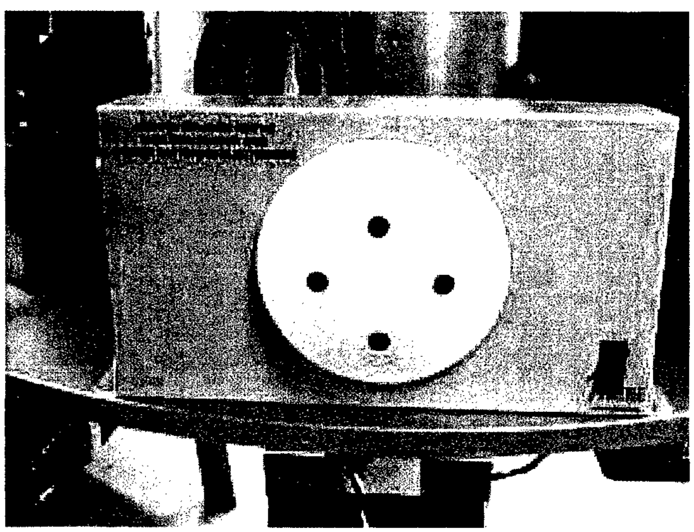

Figure 11: *Sun sensor and power switch electronics box.*

Rate Gyro

The gyroscope rate sensor is a RG02-3201 by Humphrey, Inc. It provides direct measurements of the inertial angular velocities in the body frame in all three axes. The range of the angular rate is ±30 deg/sec in each axis and the corresponding output voltage range is ± 2.5 V. The resolution level of the gyro is 0.029 deg/sec and 1σ noise level is 0.027 deg/sec. Figure 12 shows the RG02-3201 rate gyro.

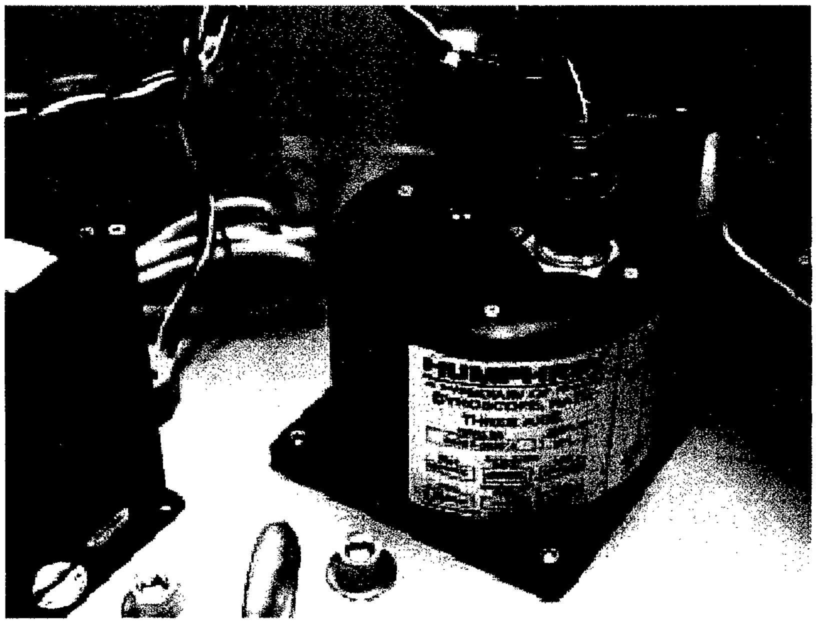

Figure 12: *Rate gyro sensor.*

Magnetometer

In order to detect the absolute orientation of the IACS, a magnetometer (FM02-0101 by Humphrey Inc.) is used. Three-axis analog signals corresponding to the strength of the Earth's magnetic field aligned with the magnetometer measurement axes are provided. Since the Earth's magnetic field can be assumed constant over time used to conduct each experiment, these measurements can be processed with the rate measurements to find the relative orientation of IACS platform with respect to the Earth. The resolution level of the magnetometer is 0.0006 Gauss and 1σ noise level is 0.0002 Gauss. Figure 13 shows the FM02-0101 magnetometer on the IACS platform.

Dynamic Measurement Unit

Although not required, an additional inertial, dynamic measurement unit (DMU-Dynamic Measurement Unit by Crossbow, Inc., Model DMU-AHRS) has been installed on the IACS platform to supplement the RG02-3201 rate gyro and the sun sensor/magnetometer. Internally, the DMU-AHRS combines linear accelerometers, rotational rate sensors, and magnetometers with a Digital Signal Processor (DSP) unit. It can provide stabilized, application-specific outputs such as Euler angles compensating for deterministic error sources within the unit. With this feature, it can measure roll and pitch angles of ± 90° and heading angle of ± 180°. The angular rate range is ±150 deg/sec and the accelerometer range is ±2 g. The DMU measurement data are sent to the host computer via an RS-232 serial port. The signal

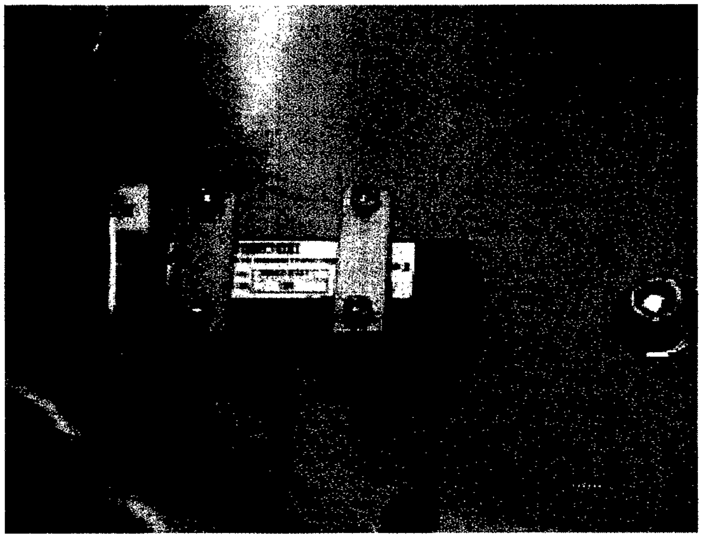

Figure 13: *Magnetometer FM02-0101*

resolution and noise levels for the DMU-AHRS are shown in the Table 4. Figure 14 shows

Table 4: *DMU-AHRS raw sensors specifications*

Sensors in DMU-AHRS	Resolution	1σ noise
Rate sensor [deg/sec]	0.073	0.17
Accelerometer [G=9.81 m/sec^2]	0.001	0.0015
Magnetormeter [Gauss]	0.0006	0.001

the DMU-AHRS unit installed on the IACS.

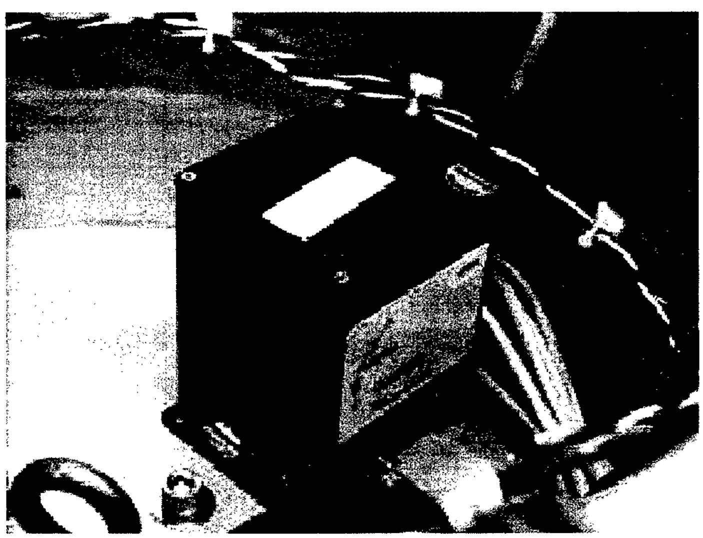

Figure 14: *The dynamical measurement unit DMU-AHRS.*

4.3 Actuators

CMGs/VSCMGs

As illustrated in Fig. 15, each CMG module is composed of a brushless DC motor which acts as the gimbal motor, a potentiometer measuring the gimbal rotation around the gimbal axis, and another brushless DC motor acting as a wheel motor coupled with the momentum wheel. The gimbal rotates within ±90 deg in accordance to the gimbal angular velocity command. The wheel motor is operated in either angular speed or torque command according to the CMG operation mode. It is worth-mentioning that Control Moment Gyros are extremely expensive devices and are rarely found in small sizes, as those required by the IACS. Moreover, off-the-self CMG's work under constant rotor speed commands and thus cannot be used for coordinated attitude and energy storage. The IACS variable speed CMG's (VSCMG's) were thus specifically constructed by Guidance Dynamics Corp. for Georgia Tech to meet the needs of the project.

Figure 16 shows a dis-assembled VSCMG while Fig. 17 shows the complete schematic of the Georgia Tech VSCMG.

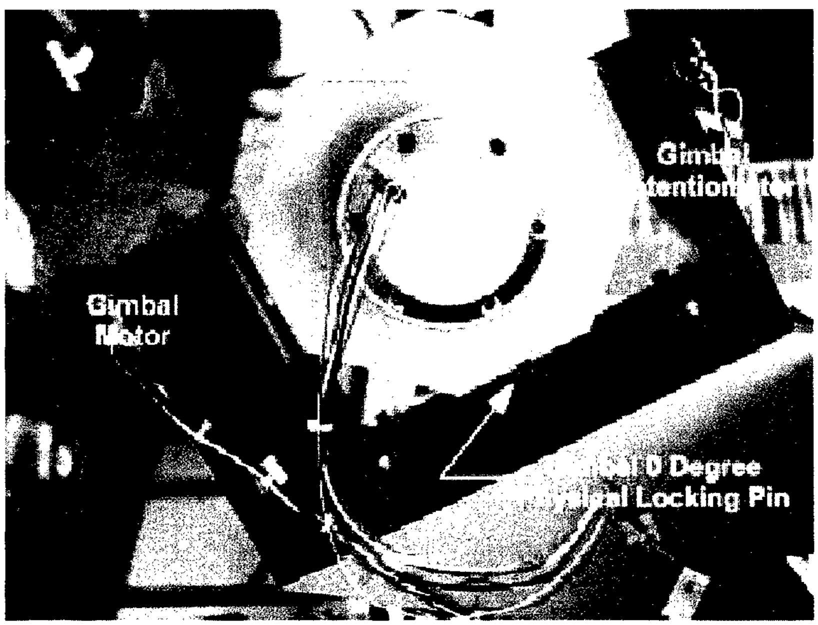

Figure 15: *Main components of the CMG/VSCMG.*

Each VSCMG can operate either in a purely CMG mode, a VSCMG mode or in a Reaction Wheel (RW) mode. In the CMG mode, each CMG generates a maximum output torque of 170 mNm along the CMG axis with a maximum preserved angular momentum of 1.29 Nms at a maximum wheel speed of 3000 RPM. In the VSCMG mode, each CMG generates a maximum output torque of 283 mN with a maximum continuous output torque of 250 mN. In addition, the CMG device can be used for a reaction wheel by locking down the gimbal angle to a fixed orientation. Figure 18 shows the rear side of the gimbal motor. Locking the lock-down screw at the desired gimbal angle allows the CMG to run as a reaction wheel. In

Figure 16: *A look at the dis-assembled Georgia Tech CMG/VSCMG.*

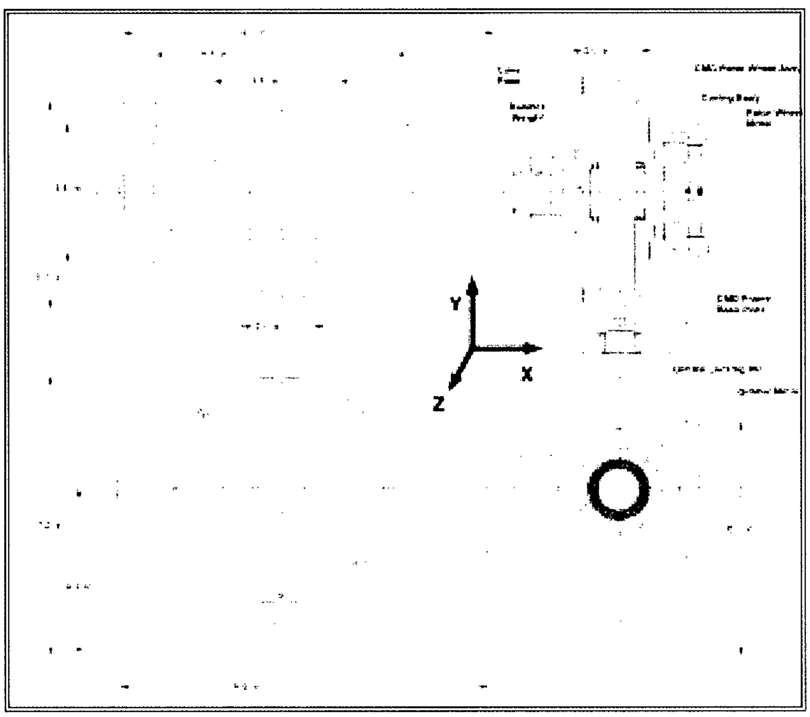

Figure 17: *Schematic of the CMG/VSCMG.*

this mode, the maximum reaction torque is 283 mN along the wheel rotation axis.

Figure 18: *Gimbal lock description. Used in reaction wheel (RW) mode*

CMG Controller Box

The CMG controller box provides the interface between the analog command signals and the individual brushless motors on the CMGs. Each CMG controller uses two analog command inputs including gimbal angular velocity command and wheel speed/torque command, and one digital input to determine the CMG mode (CMG or VSCMG/RW). Also, the CMG controller box provides the feedback signals which consist of gimbal angular position, gimbal angular rate, and rotor speed; see Fig. 19. The CMG controller includes two PID servo-

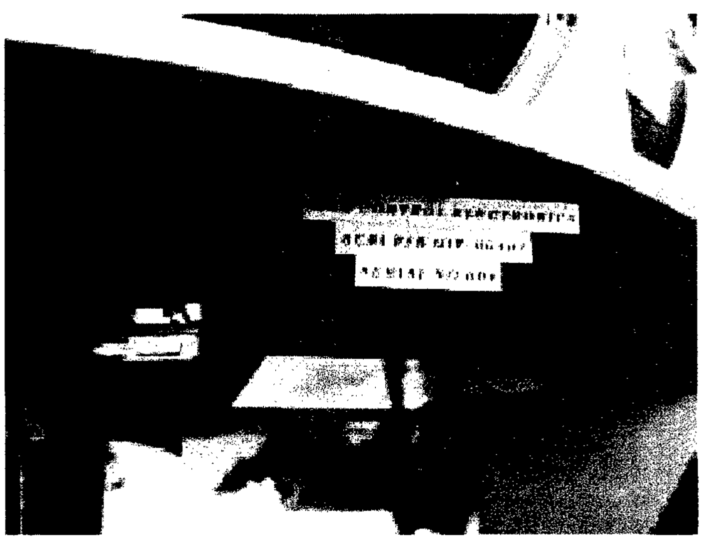

Figure 19: *The VSCMG controller box.*

loop that close around angular rate for the gimbal motor and around the speed of the rotor motor (in the case of CMG mode) or around angular rate for the gimbal motor (in the case of VSCMG/RW mode[2]. These controllers are programmed and implemented through the 8bit, one-chip micro-controller PIC16c774 utilizing the potentiometer on the gimbal axis for the gimbal angle and the hall effect sensors inside the rotor/gimbal motor for detecting the angular rate.

Thruster Electronics

The solenoid valves of each thruster module are driven by digital I/O signals from the target computer which is amplified in the Power Switch Box. The minimum operational pulse width is 15 ms, which corresponds to a bandwidth of the thruster of about 67 Hz. The thrusters can be operated in PWPM mode. This allows the implementation of continuous torque profiles. Figure 20 shows the eight channel valve driver circuit.

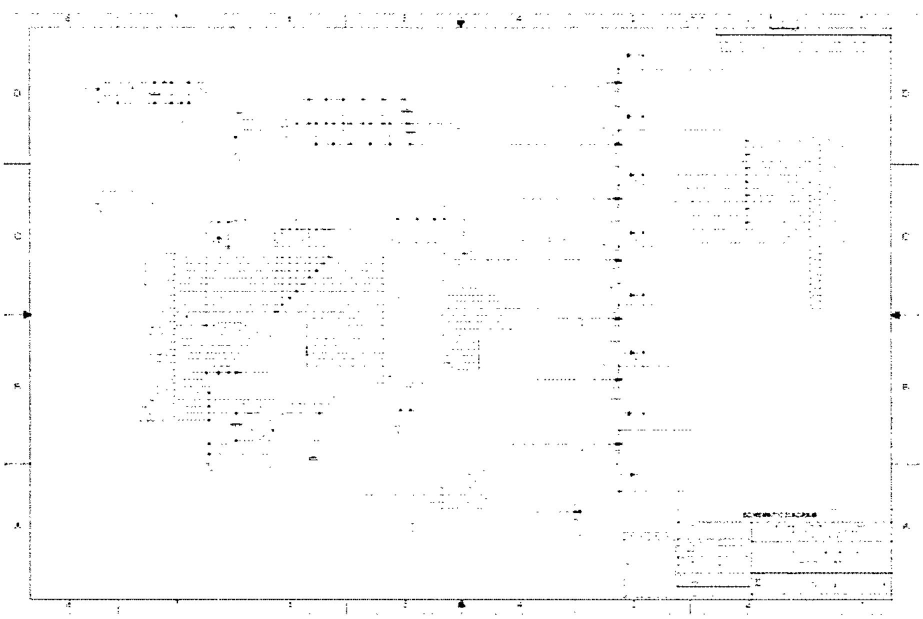

Figure 20: *The Thrust valve driver circuit*

4.4 Power system

Power Switch Box

The switch box is the main user interface for powering the individual components of the IACS. It also controls the type of power to be used on the platform ("on-board" battery power or power from an external source). It is also used as the interface for the charging unit. In order to provide power to the IACS, two rechargeable sealed lead-acid batteries rated at 12 V/25 Ah are connected in series to provide 24 V. Figure 21 shows the switch box and Fig. 22 depicts one of the rechargeable batteries.

[2]The wheel motors are operated in open-loop mode in the case of VSCMG/RW mode.

Figure 21: *The power switch box.*

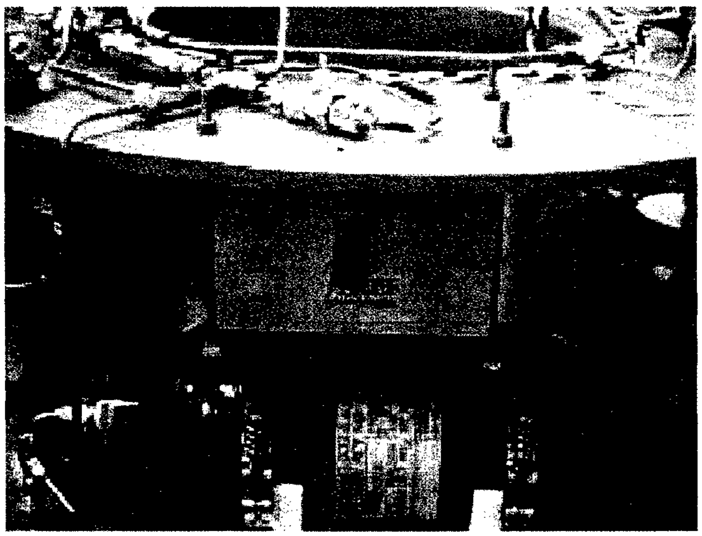

Figure 22: *One of the rechargeable battery with one of the thruster gas tanks below.*

5 Miscellaneous Views of the IACS and Specifications

Several views of the completed and installed ICAS are shown below. They include "bird-eye" views of the whole system.

5.1 IACS Performance Specifications

Table 5 summarizes the physical performance specifications of the IACS. In addition, Table 6 summarizes the physical and electronic specifications of the sensors installed on IACS.

References

[1] Mathworks, "xPC Target User's Guide," On-line document, http://www.mathworks.com/, 2001.

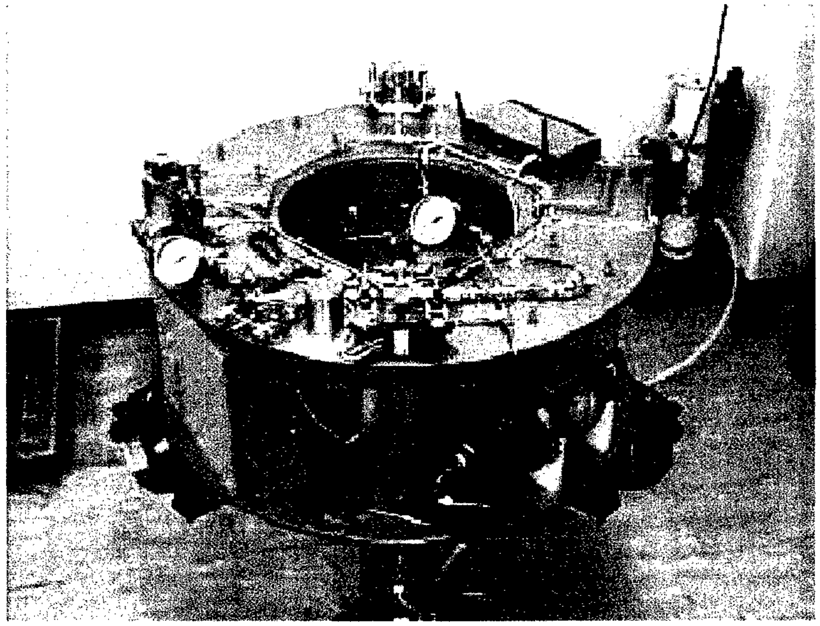

Figure 23: *Perspective view of the IACS shows clearly how every part is integrated into the completed system.*

Figure 24: *Bottom view of the IACS. It shows the CMG controller box attached underneath the bottom plate and the wiring to the CMG's.*

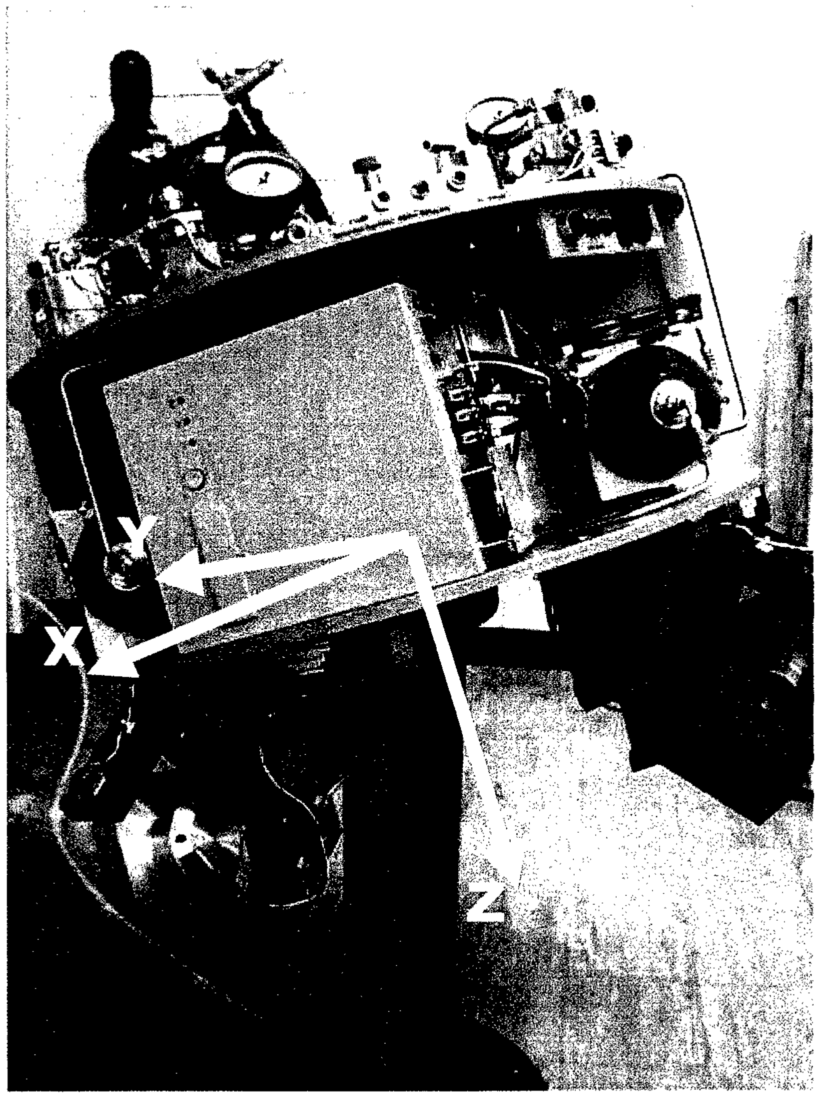

Figure 25: *The body-axes definition for the IACS. The* x*-axis is designated as the roll axis, the* y*-axis is designated as the pitch axis and the* z*-axis is designated as the yaw axis.*

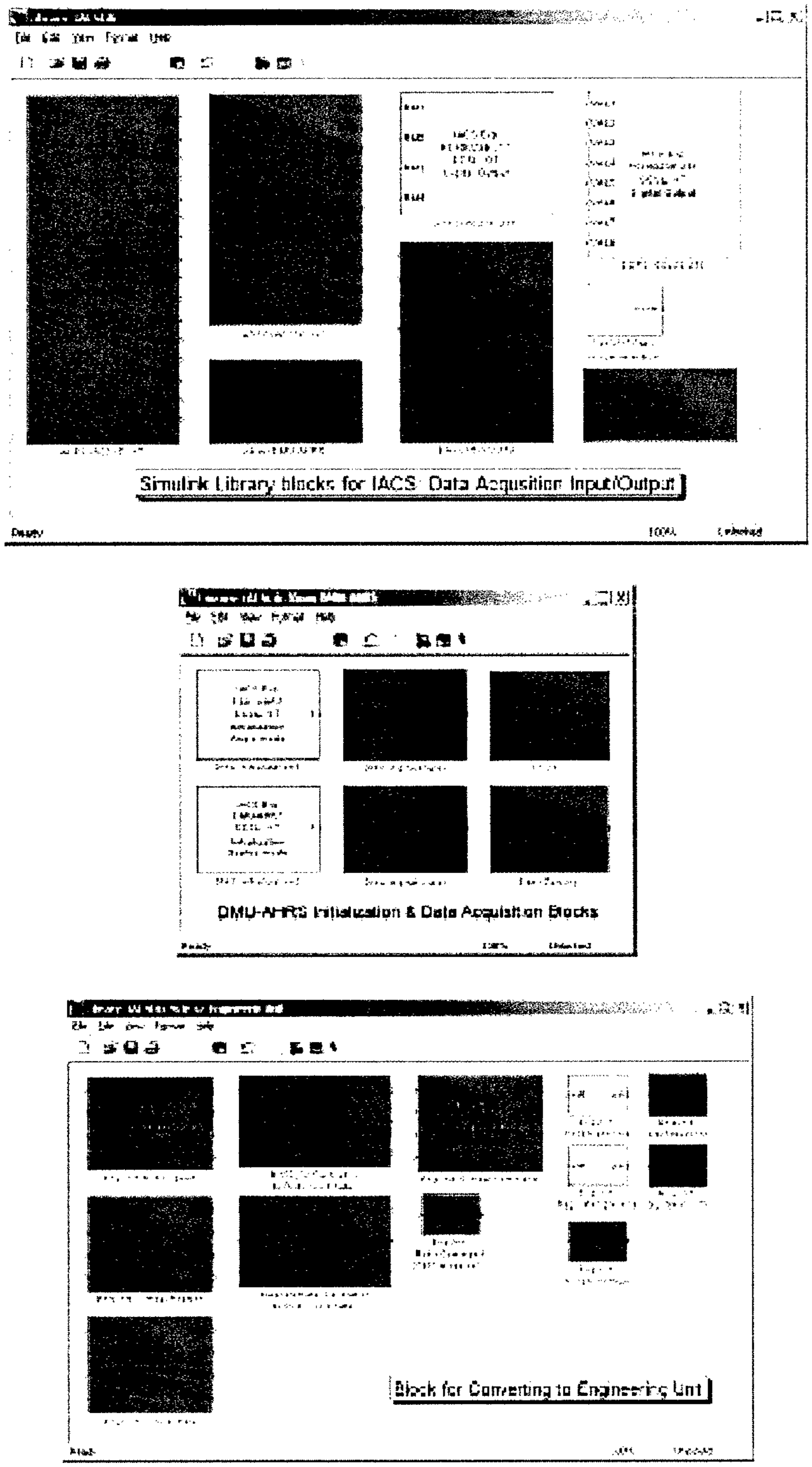

Figure 26: *The SIMULINK® block library for the IACS consists of the data acquisition block set, including the DMU-AHRS digital data acquisition block, analog and digital data output blocks, and converting blocks to physical units in accordance with the each sensor's calibration data.*

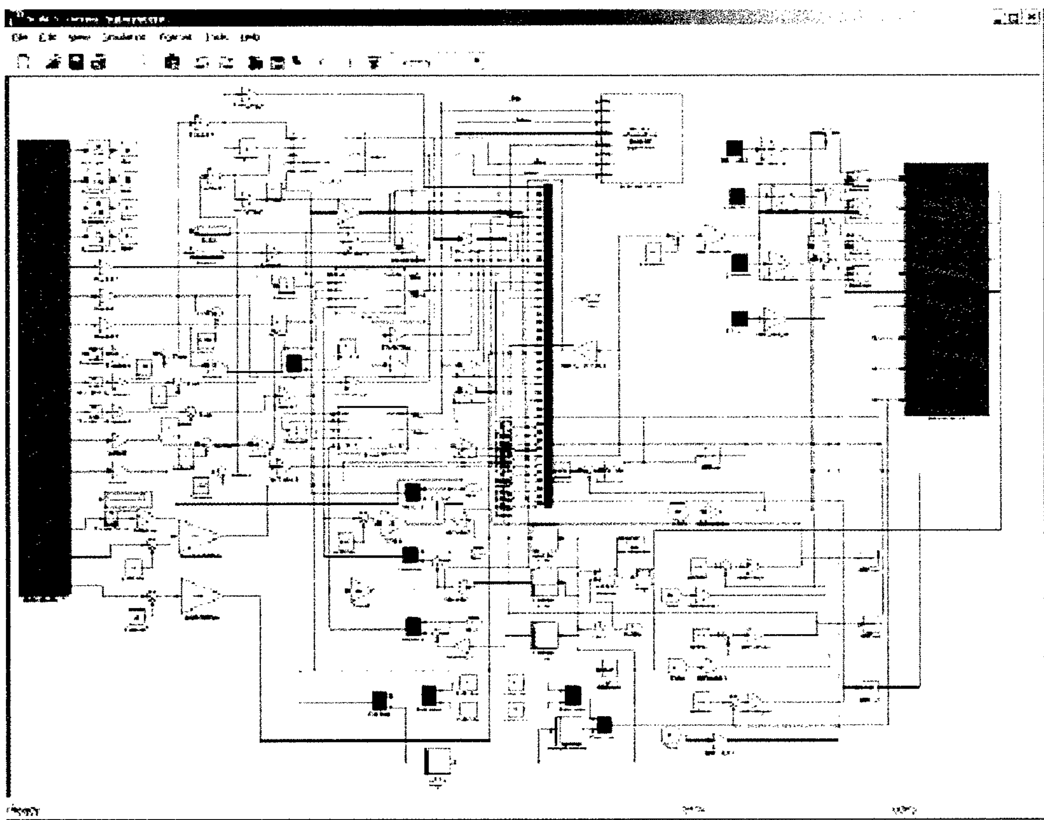

Figure 27: *A Simple attitude control demonstration program written in SIMULINK®. It uses IACS library blocks for data acquisition and various other SIMULINK® blocks for computation, signal processing and data recording.*

Table 5: *IACS design specifications.*

Performance parameter	Value	Remarks
Total Weight	295 lbs	maximum
Moment of Inertia (I_x)	15.16 kg-m^2	estimated
Moment of Inertia (I_y)	14.62 kg-m^2	estimated
Moment of Inertia (I_z)	29.15 kg-m^2	estimated
CMG Output Torque (per wheel)	280 mNm	3000 RPM, ($\dot{\gamma}$) = 13.3 deg/s
CMG Angular Momentum (per wheel)	1.29 Nms	
Thruster torque (X-axis)	2.36 Nm	maximum
Thruster torque (Y-axis)	2.36 Nm	maximum
Thruster torque (Z-axis)	4.71 Nm	maximum
CMG/RW Acceleration (X-axis)	1.22 deg/s^2	2 CMGs/Single RW @1500 RPM
CMG Acceleration (Y-axis)	1.26 deg/s^2	2 CMGs
CMG Acceleration (Z-axis)	1.8 deg/s^2	2 CMGs
RW Acceleration (X-axis)	1.06 deg/s^2	Single RW @1500 RPM
RW Acceleration (Y-axis)	1.10 deg/s^2	Single RW @1500 RPM
RW Acceleration (Z-axis)	1.1 deg/s^2	Two RWs 1500 RPM
Thruster Acceleration (X-axis)	8.44 deg/s^2	Average set level
Thruster Acceleration (Y-axis)	6.01 deg/s^2	Average set level
Thruster Acceleration (Z-axis)	7.35 deg/s^2	Average set level

Table 6: *The physical and electronic specification of the sensors.*

Sensors		Available range	Min. Resolution	1σ noise	Remarks
DMU	Accelerometer	±2G	0.001G	0.0015G	1G=9.81m/sec^2
	rate gyro	±150	0.073	0.17	deg/sec
	magnetometer	±1.25	0.0006	0.001	gauss
RG02-32 Rate gyro		±30	0.029	0.027	deg/sec
FM02 Magnetometer		±0.5	0.0005	0.0002	gauss
Sun sensor		±20	0.05	0.05	Deviation angle, deg
Regulated pressure X-ducer		1000	1.394	0.696	psi
Supply pressure X-ducer		5000	2.929	1.582	psi
CMG	Gimbal position	±100	0.1563	0.6	deg
	Gimbal Rate	±22	0.02	0.25	deg/sec
	Rotor speed	3500	3	33	rpm
Power consumption		270W continuous, 400W peak.			