

Attitude Subsystem Development for an Educative Satellite Based on Reaction/ Momentum Wheel and Magnetic Torquing Coils^{*}

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Abstract. This paper shows the obtained results on the development of the attitude subsystem for a human resources training system at laboratory level in the satellite technology field. The educative satellite (ES) integrates several subsystems such as: structure, power, short range wireless communications, digital voice, sensors, flight computer and attitude control. The last constitutes the subject of this paper and is required to demonstrate both automatic maneuvering and automatic stabilization functions capabilities on the educative satellite. Two active stabilization approaches are employed for this subsystem, the first one formed by a set of six magnetic torquing coils that would provide the ES with light stabilization forces, and a versatile second one constituted by a reaction/momentum wheel which render stronger forces for maneuvering control purposes. The exposed system was projected as an intelligent stabilization module and therefore includes a dedicated microcontroller to perform both stabilizations tasks and communications with the ES flight computer. A description of the subsystem components, architecture, operating modes, control functions and preliminary stabilization results obtained in laboratory are presented.

Keywords: Attitude control system, educative satellite, training system, momentum wheel, magnetic coils.

1 Introduction

The reaction/momentum wheels are attractive because by adding or removing energy from a reaction/momentum wheel (flywheel), torque is applied to a single axis of a spacecraft, causing it to react by rotating.

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By maintaining flywheel rotation, called momentum, a single axis of a spacecraft can be stabilized. Consequently, several reaction/momentum wheels can be used to provide full three-axis attitude control and stability in a space vehicle, [1].

The attitude control and stability in satellites is very important to perform payload operation. In LEO remote sensing satellites it is required to allow camera pointing to specific regions of our planet in order to acquire high resolution digital images. The bigger the capabilities of the satellite to fine control the spacecraft pointing the better the results from high resolution digital cameras will be obtained. In the case of GEO communications satellites its pointing capabilities define its potential to transmit high bandwidth data with an efficient use of electrical power.

In commercial satellites the use of reaction/momentum wheels is necessary, however, in spacecrafts with masses under 60 Kgs this approach was very rare in the past decade. Mainly because of financial reasons, because the space rated mechanical subsystems were very expensive for this type of projects, [2].

For those reasons, most of the real small satellites (nanosatellites and picosatellites) employ passive stabilization schemes such as magnetic torquing bars. Some of them use active stabilization through magnetic torquing coils. Though, complex stabilization schemes as reaction/momentum wheels are very few in this type of missions, [3].

On the other hand, the last years and particularly in the picosatellite field (1 Kg of mass), a couple of missions are being developed with reaction/momentum wheels employing commercial-off-the-shelf (COTS) general purpose motors [4]. Taking into consideration that the small satellite field is remarkable by its huge potential to validate new technologies, it is possible to affirm that in the near future more small satellite missions will be instrumented with this versatile stabilization scheme.

For those reasons it is very important for the ES to include intelligent satellite stabilization hardware to allow satellite maneuvering demonstration capabilities. This eventually would conduct to elaborate tasks such as payload pointing towards specific targets and more important, to allow the users of the educative system to learn and understand the use of this important satellite resource.

It is important to mention that the ES is intended to be used as an educative tool in laboratories from High schools, Technological Institutes and Universities. Moreover, it is also planed to be employed in research laboratories to develop new solutions for real satellite subsystems. In this sense research in fields such as three axis stabilization, digital communications, satellite sensors, power systems, payload validation, flight computers, navigation autonomy, and satellite constellations, would be addressed with the support of this laboratory tool, [5].

Up to now we have detected only one commercial educative satellite system. It was originally developed by the US Air force and commercialized by Colorado Satellite Services, [6], at a starting price of 8,000 US dollars.

2 Architecture of the stabilization subsystem for the educative satellite

The goal of the ES is to emulate a satellite stabilization system by means of two active methods. One is the reaction/momentum wheel and the second one is a set of magnetic torquing coils. They will allow the studying and experimentation of ES behavior when changes or control be applied in its system actuators. Then that experience and knowledge would take us to the design and exploration of different stabilization control schemes.

The stabilization subsystem (SS) is made up of a flywheel driven by a DC motor obtained from a videocassette player and a set of six magnetic torquing coils, two different coils (coarse and fine) for each one of the ES structure axis. Three coils apply a coarse momentum while the other three provide fine momentum forces. The dedicated control is given by a PIC18F4431 microcontroller that is connected through serial port with the ES flight computer, this microcontroller unit (MCU) receives and processes commands from the flight computer. The command and protocol software was inherited from software developed in our laboratory for a 50 Kg microsatellite mission, [7]. The chosen PIC device has enough resources and capabilities to accomplish the tasks for this subsystem. In addition, the SS contains the electronic control interfaces between the microcontroller and the active stabilization actuators. They are composed by an H bridge for the motor (TA7291S from Toshiba) and six further H bridges (3 L293DD integrated circuits from ST Electronics) driven as hardware interface to control the magnetic torquing coils. Those parts were employed in protoboard tests and will also be used in the PCB stabilizing system for the educative satellite.

In order to carry out the motor control it was added a 1 pulse per round-trip encoder mounted in the motor along with the flywheel. This serves as feedback to the microcontroller. However the goal for the project is to increase the capabilities of the encoder to at least 16 pulses per round-trip in order to increase the control capacities. Besides, in case the motor could become obstructed it was aggregated an overcurrent circuit to protect both the motor and its driving H bridge. It was also aggregated a set of LEDs that indicate the behavior of control signals applied to the stabilization actuators.

3 Stabilization microcontroller

The chosen microcontroller is the surface mount 44 pin, PIC18F4431. This is an 8 bit CPU, 10 MIPS (Million of instructions per second) with 4 crystal modes of up to 40 MHz, 16 Kb flash memory, 768 bytes of RAM, 256 bytes of EEPROM memory, 36 I/O pins, low power consumption mode, in-circuit programming capabilities, software programming mode under serial mode control and, capabilities to drive several levels of interruption priorities. Furthermore, the MCU was selected by its dedicated hardware to generate Pulse Width Modulation (PWM) signals that in our case are employed to control the motor speed as well as to regulate the magnetic field intensity applied to the magnetic torquing coils. The PWM module has a resolution of up to 14 bits and was designed to provide a pair of fault bits with input gates at 2 pins of the MCU. One of them is dedicated to the SS to protect the motor by overcurrent. In cases like this, when one or both of the input pins become activated, all of the PWM outputs become turned off automatically.

The MCU has also a dedicated 3 input capture module intended for movement feedback purposes, which in our case is employed to drive the motor feedback. In order to communicate the MCU with the ES flight computer a serial port from the MCU is utilized for command reception. In addition, the MCU contains further hardware such as an I2C and an SPI ports, 4 timers and a high speed analog to digital converter.

4 Stabilization control approach with a reaction/momentum wheel

A reaction/momentum wheel is a stabilization active element destined to operate at high speeds (several thousands of RPM). When operated into a satellite its goal is to generate a resistant force against position changes produced by external disturbances coming from solar wind, microgravity changes and so on.

With the resources implanted in the ES a closed-loop control mode can be driven and also three different signals are used to allow control in open-loop mode.

Figure 1 shows the laboratory tests applied to the ES reaction wheel, while figure 2 shows the mockup of the satellite educative system at real scale.

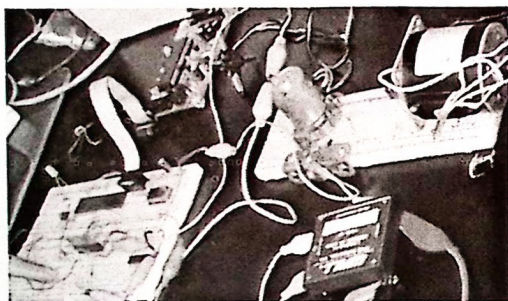


Fig. 1. Flywheel under laboratory Testing.

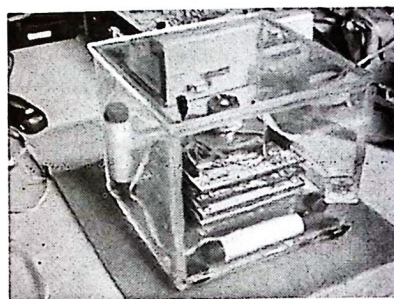


Fig. 2. Educational Satellite mockup at 100 % scale.

4.1 Open-loop stabilization control with momentum wheel

The open-loop control for the reaction/momentum wheel, is performed without feedback to the MCU. In this case 3 different signals are generated (sine, triangular and swath tooth) by the MCU through a PWM channel to drive the motor speed. The signals will be employed later to characterize the ES attitude control behavior.

4.2 Closed-loop stabilization control with momentum wheel

The closed-loop control of the reaction/momentum wheel is performed to establish the direction of rotation as well as the speed of the flywheel according with commands sent by the flight computer. The digital control performed by the microcontroller gets a feedback signal

from the motor encoder. In addition, a proportional integral (PI) control algorithm specially designed for speed control is executed in the microcontroller.

The global closed-loop control scheme employed to control the flywheel is shown in figure, 3.

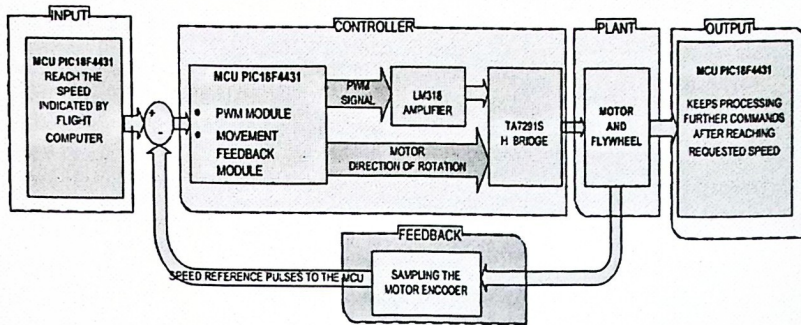


Fig. 3. Closed-loop scheme employed to control the reaction wheel.

Once the flight computer command reaches the MCU with specific data about flywheel speed, the command is executed by the MCU through a PI algorithm.

Testing procedures were applied with a personal computer running software to emulate the flight computer, figure 4. This software allows the user to select the command to be sent to the MCU (flight computer emulation) as well as the command preferences. The software admits the programming of control functions for the stabilizing system with only one command. This one includes specifications to drive the motor and therefore the flywheel, the magnetic torquing coils or any combination of them. As shown in figure 4 the stabilization command allows the user to define the motor control. For closed-loop operation the user selects the “*velocidad*” option and then the software enables the window titled “*Velocidad (rpms)*” where the user writes the RPM value to be controlled by the MCU. In the case of open-loop control the user selects the choice “*Fijar CT a motor*” and a left window receives the working cycle to be employed by the PWM module of MCU device. In the case of magnetic torquing coils the software can be used to control three axis of the educative satellite at the same time, but with only one coil per axis at a time.

In this way, with only one command the flight computer, and in this case the user, can test the whole stabilization system (flywheel and magnetic torquing coils) with any combination of preferences. Once the command is fully configured the user presses the button “*ENVIAR*” which sends the 14 byte command to the stabilization system. This command is then displayed in hexadecimal values in a window shown in the lower side of figure 4. In addition, with the window placed in the upper left side of figure 4, the software shows the answer delivered by the MCU as an answer to the received command.

From tests performed at laboratory, it is mentioned that the obtained closed-loop control is good when controlling the flywheel at high speeds. In addition, under this mode few other functions were integrated and worked successfully such as: turning off the motor, slowing

down the motor speed and, establishing a fixed working cycle in the direction of rotation. Every software function was individually tested and then the software was integrated to the global MCU software. It should be mentioned that the closed-loop operation at low speeds has deficiencies, therefore work is performed to enhance this behavior.

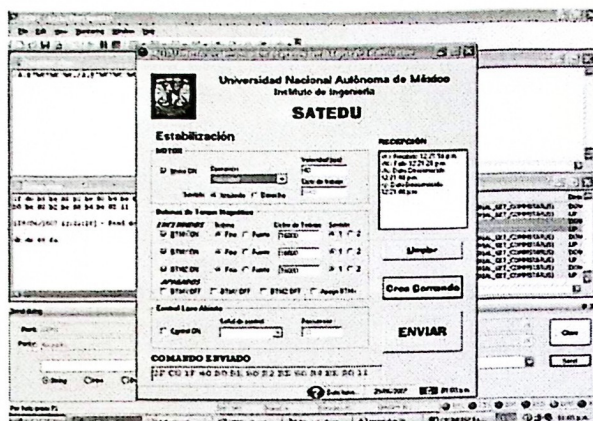


Fig. 4. Software employed to validate the control procedures elaborated for the flywheel, MTCs and its operative software.

In order to implement the PI control it is required to elaborate the mathematical model of the plant, to reach with this an optimal control for the system. In our case the plant is conformed by the reaction/inertial wheel and the motor. In addition, it should be added the required controller, seen this also as another well defined mathematical model. Therefore, with both of the mathematical models would be possible to achieve the corresponding stability and the frequency response analysis for tuning the controller. This process would take us to find values for the proportional and integral constants of the system.

However, in the case of the ES stabilization system we do not have enough information to create the suitable mathematical model. The experimental identification will be employed to obtain an empirical mathematical model. However as a beginning in this first working phase some values for the PI constants were assumed to implant the PI algorithm for the testing model within the MCU. This solution is acceptable taking into account that the flywheel will be employed mainly at high RPMs. Once the ES prototype is concluded, the experimental identification model will be used to obtain a mathematical model for the stabilization system. In this sense we will consider to employ an experimental method to adjust the controller constants. Specifically, the Ziegler-Nichols method to obtain a system response curve is being considered. With this data and based on certain characteristics of the curve it will be possible to obtain the value of the PI constants. However, to experimentally obtain this information, a strong experimental effort has to be made in order to get, acquire, store and process the information with the help of a MCU. Another solution to consider is related with the final motors that will be employed in the ES, they are general purpose motors. We will ask the manufacturer to provide the information to model the motor. Therefore this information will be discussed in a future publication.

Another reason by which the PI control does not work correctly is the flywheel encoder, because it only provides one pulse per round. This causes the MCU registers to overflow due to the existing long times between pulses. This problem can be solved by using a better flywheel with an encoder capable to generate at least 16 pulses per round, as those available for general purpose motors.

When the MCU finishes the PI calculation what it does is to fix a specific output to the PWM module based on that calculation. Then the motor will change its speed and therefore feedsback this process to the MCU through the encoder signal attached to the flywheel (which as said before is connected to the capture module of the MCU movement feedback). The last process closes the loop and takes the flywheel to the specified speed indicated by the flight computer command.

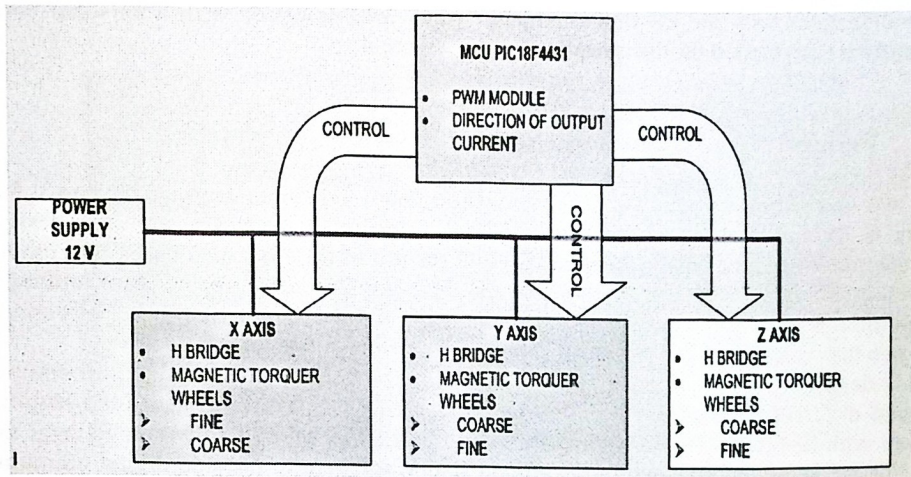


Fig. 5. Control of magnetic torquing coils through PWM performed by the ES MCU.

The magnetic torquing coils (MTC) as well as the momentum wheel are active stabilization elements. They are very important resources to develop complex 3-axis stabilized satellites as well as for stabilization of propelled space vehicles. In systems like these, the thrusting errors could cause the satellites to translate and this translation would be nearly impossible to correct, [8]. Both the reaction wheel and the MTC are highly controllable stabilizing media. One disadvantage of the reaction wheel is that it can become saturated, in which case momentum dumping would be required. However, this can be compensated by designing a wheel with a larger inertia than necessary. Another way to solve the problem would be the employment of the MTC to desaturate the reaction wheel. The MTC take advantage of the Earth magnetic fields to generate fine forces that orient a satellite in a desired position. Furthermore, the control forces are enhanced by employing ferrite nucleus coils, and when a magnetic field crosses them they generate a force according with the Faraday Law, emulating in certain way the principle of an electrical motor.

Under this stabilization method 6 coils from ES are driven by 6 PWM channels from MCU that control the magnetic field strength generated by them, as shown in figure 5.

In the case of the magnetic torquing coils, different tests were performed employing hard disk coils, since they closely emulate a real satellite MTC. The hard disk coils are attached to a good mechanical design and permanently exposed to a magnetic field generated by a magnet. The performed tests included: the establishment of the working cycle for each coil, the change of its working cycle, exchanging the use among them and the turning off procedure for each one of the coils, see figure 5.

5 Stabilization control with magnetic torquing coils

In addition, all the validated software processes were integrated in the main MCU software. Then the global stabilization software was successfully tested in laboratory employing communications with the ES flight computer which was emulated with a personal computer and software developed for this specific purpose, figure 4.

6 Printed circuit board for the stabilization subsystem

The two layer printed circuit for the stabilization board has dimensions of 89 mm x 89 mm, figure 6. It was elaborated with Protel DXP software, a powerful tool for design and manufacture of printed circuits boards. It allows the use of different data bases for components as well as the creation of new components and the possibility to aggregate them to the project. In addition, it enables the positioning of components and the automatic routing of connections between the components of the project in a very short time and in an efficient way.

In this design we had to consider several track widths because the stabilization components demand different intensities of current. Figure 7 shows the artistic view of the stabilization system with integrated flywheel elaborated with SOLID EDGE18 software. Several designs like this are being incorporated in the ground station software to provide digital animations in the visualization interface of the ES ground station.

7 Communications between stabilization board and the ES flight computer

The communications between the flight computer and the stabilization board are achieved by means of serial port. The flight computer sends command lines that contain 14 bytes, figure 8. The line includes a header, command specification and 1 byte of checksum, [7]. The last is aggregated to avoid information losses by effects of external noise or electrical interference. Once the command is received, the MCU becomes awaked and then stores it and verifies its integrity through the checksum. Then, it sends an acknowledge byte to the flight computer indicating if the command was okay or not. In this way the flight computer can decide, respectively, to finish or to resend the command to the MCU. Once the command is received by the MCU it proceeds to execute the orders given by the flight computer.

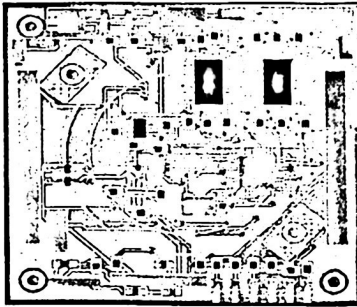


Fig. 6. PCB designed for the stabilization system.

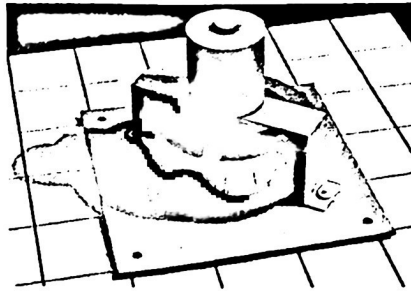


Fig. 7. Stabilization system view generated with SOLID EDGE18.

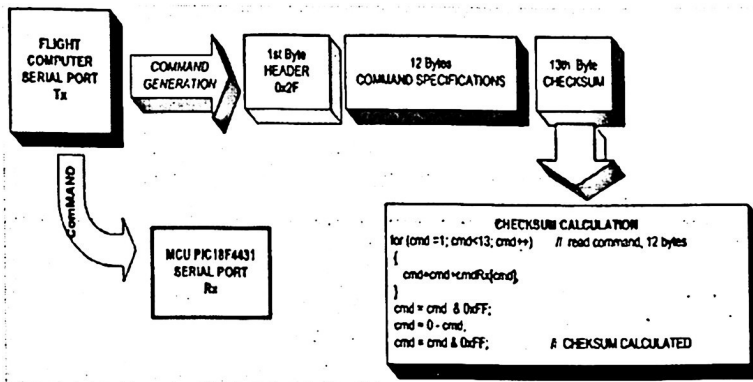


Fig. 8. Digital communications among MCU and flight computer.

8 Generated results and concluding remarks

The stabilization module for an educative satellite has been fully and successfully tested in laboratory protoboards. The control motor tests were performed in open-loop fashion applying 3 different type of signals (sine, triangular and swath tooth) to the motor. On the other hand the closed-loop control is good enough when controlling the flywheel at high speeds. In addition, under this mode few other functions were integrated and worked successfully such as: turning off the motor, slowing down the motor speed and, establishing a fixed working cycle in the direction of rotation. Every software function was individually tested and then the software was integrated to the global MCU software. It should be mentioned that the closed-loop operation at low speeds has deficiencies, therefore work is being performed to eliminate this behavior.

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good mechanical design and permanently exposed to a magnetic field generated by a magnet. The performed tests included: the determination of the working cycle for each coil, the change of its working cycle, exchanging the use among them and the turning off procedure for each one of the coils.

In addition, all the validated software processes were integrated in the main MCU software. Then the global stabilization software was successfully tested in laboratory employing communications with the ES flight computer which was emulated with a personal computer and software developed for this particular purpose. It is important to notice that the PCB for the ES flight computer is also about to be sent for fabrication and therefore was not ready for these testing procedures.

It is expected for the next months to have finished the PCB versions for at least: the stabilization subsystem, the flight computer, the voice card and the power subsystem. Therefore the integration procedures and preliminary ES tests and results are also expected to be finished for the end of 2007.

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