Satellite Attitude Determination and Contol

**H. Bolandi,
M. Haghparast,
F.F. Saberi,
B.G.Vaghei and
S.M. Smailzadeh**
Electrical Engineering Department, Iran University of Science and Technology
1684613114, Iran
M. Haghparast (corresponding author)
Mehran_haghparast@live.com

Abstract

Attitude Determination and Control Subsystem (ADCS) is one of the vital subsystem of satellites which has a significant role in performing satellites missions. On-Board Electronic (OBE) is the main part of this subsystem which executes attitude determination and control algorithms. In this paper design of OBE of ADCS in IUST-SAT is presented. Design of this equipment is carried out based on requirements and constraints which are extracted by hierarchical design procedure. Satisfying design constraints and achieving functional requirements simultaneously, is a major task, which is carried out successfully in this paper. Also for verification of performance of this equipment before a satellite's launch, in this paper a novel and low-cost real-time hardware in the loop test bed is provided. The presented test bed is capable of assessing ADCS's equipments in a real-time condition. Finally, performance of designed OBE is investigated by implementing detumbling and initial attitude acquisition control modes in the hardware in the loop test bed.

1. Introduction

In order to perform planned missions of satellites after injecting in orbit, ADCS is responsible for stabilising and pointing a satellite to a specified target. Today Imaging and communicating with ground stations and other satellites are common missions of modern satellites which demand accurate pointing to a specified target; hence ADCS is an important part of all modern satellites [1]. This subsystem has different parts including, sensors, actuators and OBE. Among these parts, OBE is the main part of this subsystem, whose duty is to determine the attitude of a satellite with respect to a reference frame and also control of attitude to a desired condition. This equipment not only must perform ADCS functions, but also must survive in hostile conditions of space, which makes design of this part a critical task [2]. In this paper design of OBE for IUST-SAT is presented. After design stages, due to importance of assessing performance of OBE, verification process is necessary. This point must be considered that verifying ADCS's equipment, demands for 6-DOF simulator, thermal and vacuum chamber and weightless condition in laboratory environment [3]. Creating such conditions are so complicated, high-cost and demand for extensive hardware equipment [4]. Air bearing is one facility which has a long history for testing ADCS [3,4]. Although this facility provides attractive capabilities to test ADCS's equipment, this test bed is complicated and especially high-cost. Also because of negligible generated torque by magnetorquers, this facility is not applicable for assessing fully magnetic ADCS. As a result presenting a low-cost and applicable procedure for verifying ADCS's equipment has significant importance in ADCS design. For satisfying this requirement, in this paper a novel real-time hardware in the loop test bed is provided. Presented test bed is capable of verifying ADCS's equipment and algorithms in real-time condition.

The rest of this paper is organised as follows. Section 2 describes OBE requirements and configurations. The features and specifications of designed OBE are explored in section 3. Section 4 describes hardware in the loop test bed. In section 5 results of practical test of OBE in executing two attitude control modes are explored. Finally section 6 gives conclusions.

2. OBE Design Based on Hierarchical Design Procedure

High importance in design of space systems like satellites demands a systematic and hierarchical design procedure [5]. *Figure 1* demonstrates a hierarchical design procedure based on European Cooperation for Space Standardization (ECSS) [5]. In this hierarchical procedure, the first step is defining satellite missions. Then based on defined missions, the general

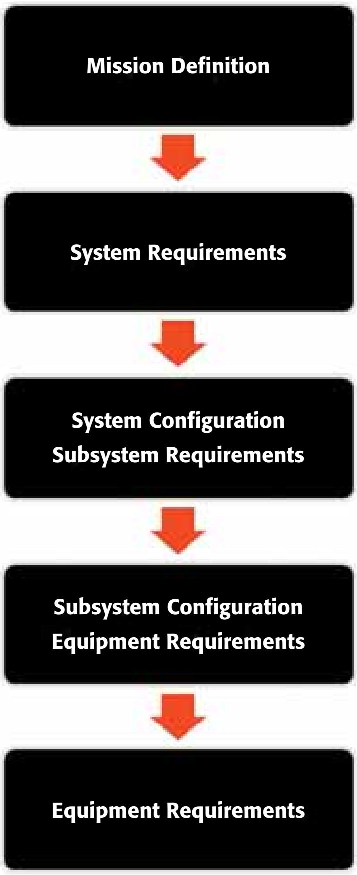

Figure1: Design Stages for Satellite Equipment Based on ECSS

requirements of the satellite are extracted. In the next step, satellite configuration (defining a satellite's subsystem), and subsystem requirements are extracted based on system requirements. Next step deals with describing the subsystem configuration (selecting required equipment in each subsystem) and requirements of equipment. In the final step, the design is carried out, based on requirements of equipment. The design of OBE of ADCS in this paper is done based on mentioned hierarchical procedure.

IUST-SAT is a student satellite designed for LEO orbit and its mission is imaging from specified area of the Earth. This satellite contains many subsystems including Image Payload Subsystem (IPS), Electrical Power Subsystem (EPS), On-Board Computer Subsystem (OBC), Store & Forward and Communication Subsystem, Structural Subsystem (STR), Thermal Control Subsystem (TCS) and ADCS which in this paper we focus on this subsystem. The mission of ADCS in this satellite is to track the Earth magnetic field vector. To achieve defined mission, this subsystem is equipped with four coarse sun sensor represented in [6], one 3-axis magnetometer and three magnetorquers represented in [7] and [8] respectively. *Table 1* shows mission requirements and configuration of ADCS of IUST-SAT.

Parameter	Comment
Mission	Tracking The Earth magnetic Field Direction
Control Modes	**First Mode:** Detumbling Mode **Second Mode:** Initial Attitude Acquisition Mode
Sensors	Four Coarse Sun sensor
	One 3-axis Magnetometer
Actuators	Three Magnetorquer

Table 1: Mission requirement and configuration of IUST-SAT's ADCS

2.1 Requirements and Constraints of OBE

Design of OBE of ADCS depends strictly on its requirements and constraints. Mission requirements are the functions that must be performed by OBE. These functions for OBE can be categorised as sampling sensors, driving actuators, executing attitude determination and control algorithms, fault detection and isolation in equipment, receiving commands from ground station through telecommand and sending data to the ground station through telemetry. Also there are many constraints in designing OBE, which must be considered in every stage of design from conceptual to critical design [5]. For this purpose, the design of OBE, not only must satisfy constraints in mass, size, power consumption, operational and storage temperature range, but also must survive against cosmic radiation and mechanical shocks. Satisfying design constraints and achieving functional requirements simultaneously, is a vital task which is considered in design of OBE in this paper. *Table 2* states constraints which we are faced in the design of OBE.

Specification	Value
Maximum Power	0.75 W
Operational temperature range	−10°C to 50°C
Storage temperature range	−30°C to 70°C
Mass	< 1000 gram
Size	$< 200^{mm}\times200^{mm}\times40^{mm}$
Total Doze	$>$ 5krad
Vibration	$>$ 15 g

Table 2: OBE design constraints

2.2 OBE Configuration Design

Design of OBE is divided into two parts: hardware design and software design. Hardware design concerned

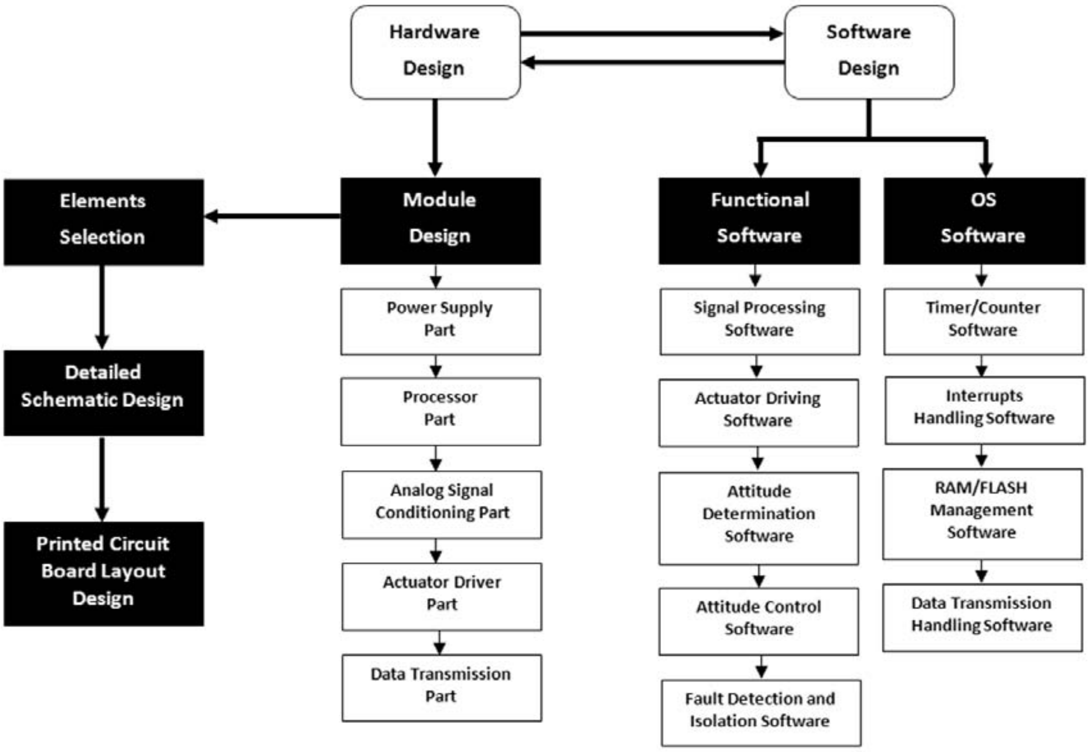

Figure 2: OBE Hardware and Software Configurations

with all the hardware aspect of board including modules design, selecting proper elements, drawing a detailed schematic of board and drawing printed circuit board layout. Software design dealing with all on-board software, containing operating system (OS) software and functional software. *Figure 2* shows hardware and software configurations design.

2.3 Hardware Design

OBE hardware includes processor part, power supply and reference voltages part, analogue signal conditioning part, actuators driver part and data transmission part. The Processor is the unique intelligent element in the board whose main task is to execute attitude determination and control and OS software. Main factors in choosing a proper processor is power consumption, processing speed, IO ports, size of flash and data memory, timers and counters, package and standard data transmission protocol support. In designed OBE a microcontroller from 8051 microcontroller family has been selected which in addition to proper specifications, has a history of use in different space missions[9].The magnetorquers driver is another part of the board which controls magnetic moment of magnetorquers precisely. Integrating magnetic torque driver board, in OBE part, caused saving in mass, size and also interconnections in satellite. Analogue signal conditioning part is another part of board includes instrumentation amplifiers, multiplexers and a high accuracy analogue to digital convertor, which converts analogue data of sun sensors and magnetometer to a 16bit digital data and send it to a microcontroller through Serial Peripheral Interface (SPI) protocol. Also OBE is equipped with a transfer data buffer which together with microcontroller, provides ability to receiving command and data from ground station and sending data to ground station through UART protocol which is a reliable data transmission protocol [10]. *Figure 3* shows functional block diagram of hardware with connections to other equipment of satellite.

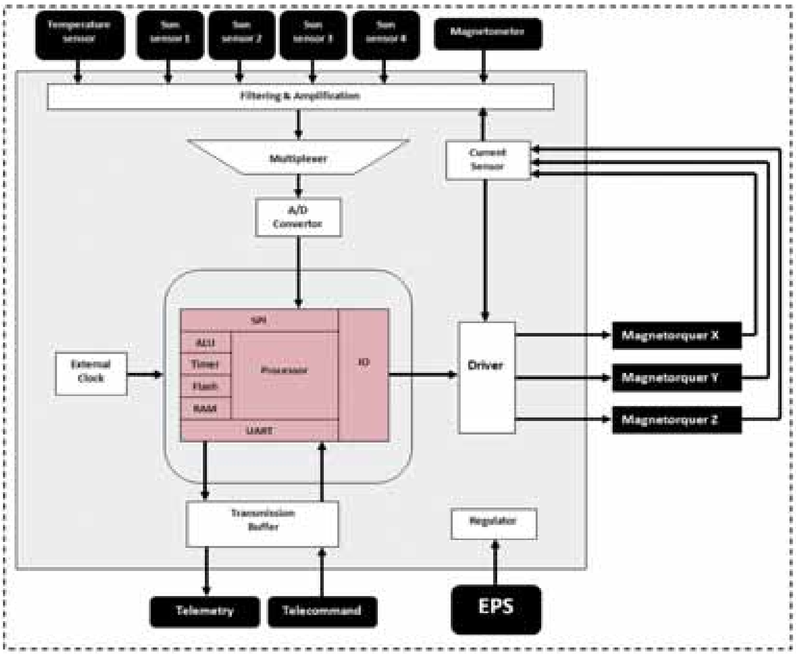

Figure 3: Hardware design diagram

2.4 Software Design

On-board software of OBE is divided into two main parts including OS software and functional software.
OS software modules are illustrated in *Figure 2*. Timer/counter part deals with extracting real time which is very important for executing periodic functional software. Interrupt handling part deals with controlling interrupts and executing interrupt service routines by their priority. RAM/FLASH management part is concerned with management of saving and loading data to/from temporary and permanent memory which is very important, because vital data and commands such as current control mode and data must be retrieved after unwanted microcontroller reset occurrence. Data transmission handling, deals with sending and receiving data through standard UART protocol with pre specified specifications.

Functional software modules are also illustrated in *Figure 2*. The Sensor signal processing software is concerned with sampling a sensor's signal and also implementing signal processing for noise reduction. Actuators driving software extracts proper IO commands based on control commands received from attitude control software. Attitude determination algorithms deals with computing satellite attitude with respect to a reference frame. This software includes satellite position determination algorithm, reference magnetic field and reference sun vector data extraction and also an attitude

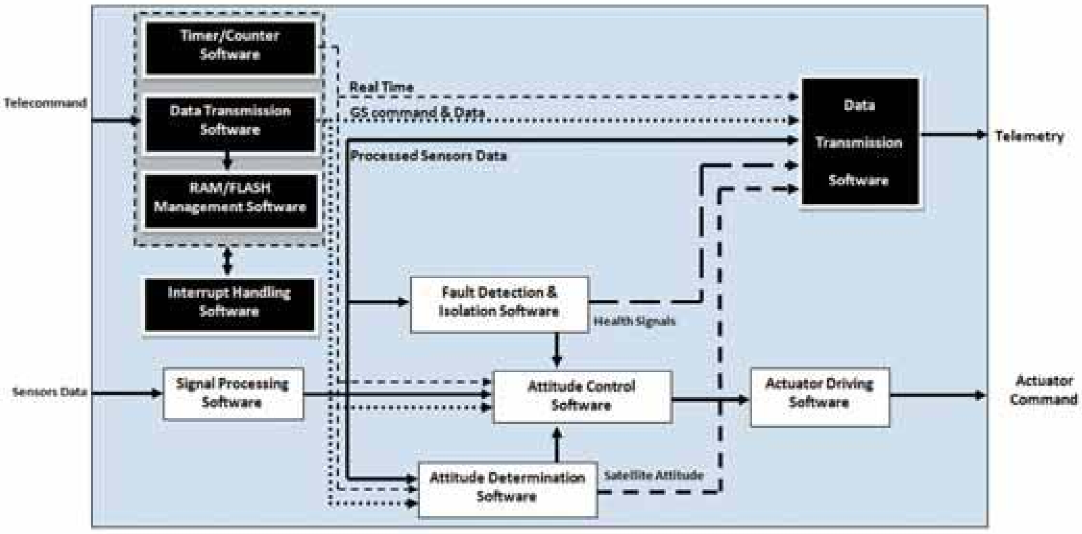

Figure 4: Software design diagram

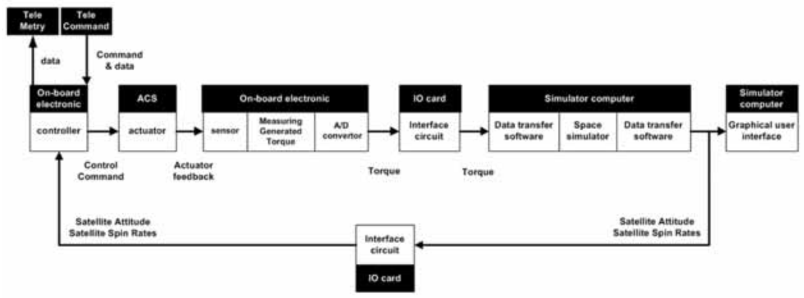

Figure 5: Closed loop diagram of hardware in the loop test bed

determination algorithm which is based on sensors data and reference data extracts the satellite's current attitude. Attitude control algorithm extracts proper command for magnetorquers based on current control mode and current attitude. This point should be considered that algorithm design is strictly dependent on control modes and required attitude determination and control accuracy in each mode. Also functional software part includes fault detection and isolation algorithms which extract health signals of ADCS, based on a simple signals range check algorithm. *Figure 4* shows functional block diagram of on-board software.

3. Features of OBE of ADCS

Based on mentioned hardware and software configuration, OBE of ADCS in IUST-SAT is designed. The final product has many special features including:

- Sampling and processing sensors data.
- Implementing reference earth magnetic field and reference sun vector extraction algorithms.
- Implementing satellite position determination algorithm.
- Implementing attitude determination algorithm.
- Implementing attitude control algorithm.
- Implementing actuator control algorithms and sending control commands to actuators.
- Implementing fault detection and isolation algorithms and continues health monitoring of subsystem's equipment.
- Receive commands and data from ground station through telecommand and executing command.
- Sending data to ground station through telemetry.
- Sampling temperature sensor and monitoring thermal condition of OBE.

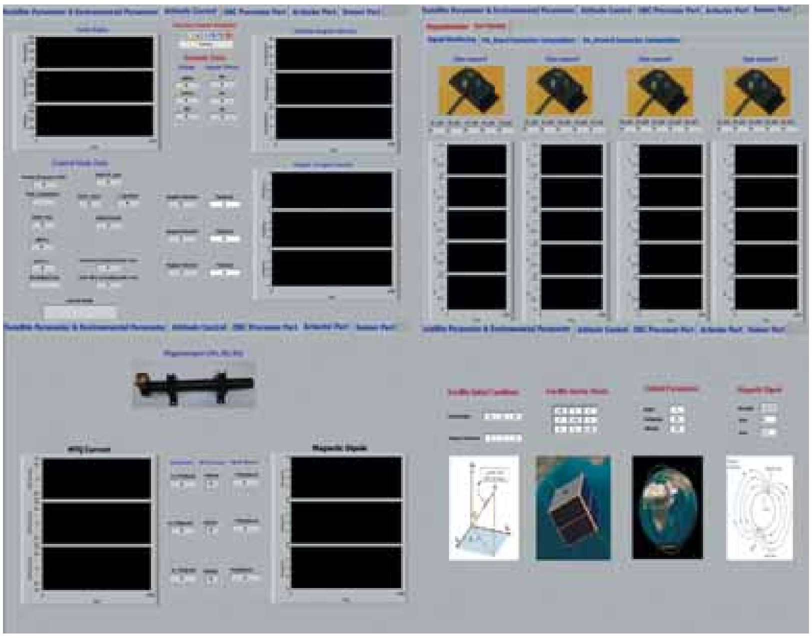

Figure 6: Graphical user interface

Table 3 shows main hardware specification of OBE. Comparing this Table with Table 2 demonstrates that all design constraints are satisfied via presented design.

Specification	Value
Processor	8051 Family
Voltage	±5 v
Power	0.5 W
Digital IO	20
Analog input	25
Data Transfer Protocol	UART
Operational temperature range	–20°C to 60°C
Storage temperature range	–40°C to 80°C
Mass	950 gram
Size	$190^{mm} \times 190^{mm} \times 37^{mm}$
Total Doze	5krad
Vibration	15 g

Table 3: OBE specification

4. Hardware in the Loop Test Bed System

Verification of ADCS needs for 6-DOF simulator, thermal and vacuum chamber, weightless condition and also modelling of satellite's dynamics. To overcome this problem one solution is to select hardware in the loop (HIL) approach, where it is a low-cost and applicable, test bed. Novel presented test bed in this paper provides the ability to test all equipment of ADCS. Hereof real-time modelling of space condition is implemented in simulator computer which provides ability to real-time test of ADCS of any satellites with various specifications and arbitrary orbital parameters. Configuration of HIL contains three main parts including simulator computer, an interface circuit and ADCS, which is test object. *Figure 5* shows a closed loop diagram of test bed.

4.1 Simulator Computer

Simulator computer provides a simulation base in HIL. The tasks of simulator computer can be expressed as
(1) Modelling of ADCS space environment.
(2) Providing a graphical user interface for monitoring specified variables.

Accurate modelling of satellite dynamics and space conditions has major importance in the design of the test bed. For satisfying this requirement, a software simulator is implemented in SIMULINK environment of MATLAB. In this simulator, modelling is done based on high fidelity mathematical models, e.g. modelling of orbital dynamic is done based on kepler equation for Elliptical orbits [11]. Modelling of the Earth magnetic field is done based on dipole model of magnetic field [12]. Modelling of satellite attitude is implemented based on euler's equations [11]. Also to modelling disturbances, four common disturbances in low earth orbit are considered including gravity gradient, aerodynamic, geomagnetic and solar radiation torques [12]. After implementing simulator model, next step is to execute simulator model in real-time mode. For this purpose capabilities of MATLAB and LABVIEW are used based on presented procedure in [13].

Second task of simulator computer is to provide a graphical user interface for monitoring ADCS. Graphical user interface is designed in LABVIEW in and it is possible in this user interface to select satellite specifications, initial attitude and orbital parameters. Also it's possible to monitor attitude of satellite, output of equipments, real time, health signals and many other variables which provides global monitoring on performance of ADCS. *Figure 6* shows designed graphical user interface in LABVIEW.

4.2 Interface Circuit

As it is depicted in *Figure 5* data should be transmitted between OBE and simulator computer through an interface circuit. In HIL test bed, PCI-1710 IO-card from ADVANTEC, is selected which guarantees reliable, parallel and 16-bit data transmission. *Figure 7* shows HIL test bed and ADCS equipments including OBE, three magnetorquers, a 3-axis magnetometer and two course sun sensors.

5. Implementing Attitude Control Algorithms in HIL Test Bed

In this part, test result of implementing attitude control algorithms in HIL test bed is presented, where attitude determination results are extracted from simulator model. Here, detumbling and initial attitude acquisition control modes are implemented in OBE and obtained result will be compared with result of simulations based on references [14, 15]. In detumbling mode the mission is to reduce tumbling of satellite, originated from injection of satellite in orbit by launcher [16] and in initial attitude acquisition mode the mission is to orienting satellite Z axis toward the earth magnetic field vector [15]. The magnetic control law for detumbling mode is Kbdot control law as follow [14]:

$$\bar{M}_{damping} = -K_{damping}\dot{\vec{B}}. \tag{1}$$

where $\bar{M}_{damping}$ is magnetic moment vector, generated by magnetorquers, $\dot{\vec{B}}$ is vector of derivation of the earth magnetic field and $K_{damping}$ is constant design coefficient. Proof of detumbling is presented in [14]. Also based on [15], a useful control law for initial attitude acquisition is as follow:

$$M_{align} = K_{align}\vec{B}\times(\vec{k}\times\vec{B}). \tag{2}$$

where $\vec{k}$ is unit vector of Z axis of satellite and K_{align} is constant design coefficient. As expressed in [15] it is possible to execute these two modes simultaneously as follows:

$$\begin{aligned}\vec{m} &= \vec{M}_{damping} + \vec{M}_{align}\\ &= K\dot{\vec{B}} + K_{align}\vec{B}\times(\vec{k}\times\vec{B}).\end{aligned} \tag{3}$$

The parameters of simulation are chosen as follows, satellite orbit is a circular LEO with 700km altitude and 65° inclination. Satellite moment of inertia in principle axis is I_{xx}=4.9 kgm^2, I_{yy}=5.1 kgm^2 and I_{zz}=1.55 kgm^2. Initial tumbling of satellite is considered as $\omega_x = 3$ deg/sec, $\omega_y = 3$ deg/sec, $\omega_z = 3$ deg/sec. The magnetorquers produce maximum moment about 4Am^2. Design constant coefficients are considered $K_{damping} = 10^5$, $K_{align} = 10^5$ based on resultant presented in [15]. Also for actual simulation some practical consideration such as noise in measuring the earth magnetic field is considered. To avoid undesired effect of noise on control law, adjusting a threshold for KBdot algorithm is useful, for this purpose the following algorithm is proposed:

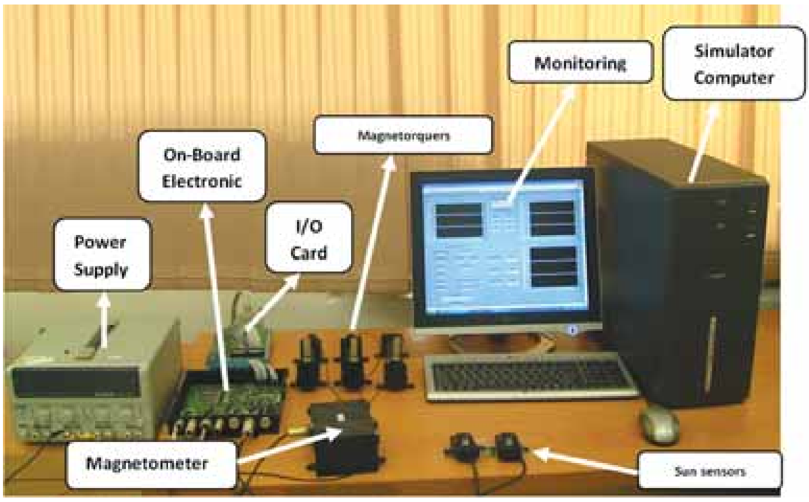

Figure 7: Hardware in the loop test scheme bed and ADCS equipments

$$\begin{aligned}&if\ -Threshold \le \dot{B}_i \le Threshold\\ &M_{damping} = 0\\ &i = x, y, z\,.\end{aligned} \tag{4}$$

where this algorithm ignores small deviation of the earth magnetic field due to measurement noise. Choosing a proper threshold depends on magnetometer specifications, but in HIL test bed this parameter depends on quantisation error of converting analogue data of magnetic field to digital data, and here threshold is selected 50nT. *Figure 8* illustrates diagram of hardware in the loop test bed for detumbling and initial attitude acquisition test.

Figure 9, 10 and 11 illustrate spin rate and tilt angle (angle between Z axis of satellite body and the Earth magnetic field vector) of satellite, obtained by control law of equation (3). It's observed that tumbling is damped after nearly 4000 second. Also tilt angle is reduced to less than 5.5° in nearly 6000 second. It could be easily observed that there is oscillation in tilt angle. This tilt is result of considering threshold in control law; however this threshold decreases effect of noise on control mode. *Figure 11* illustrates generated magnetic

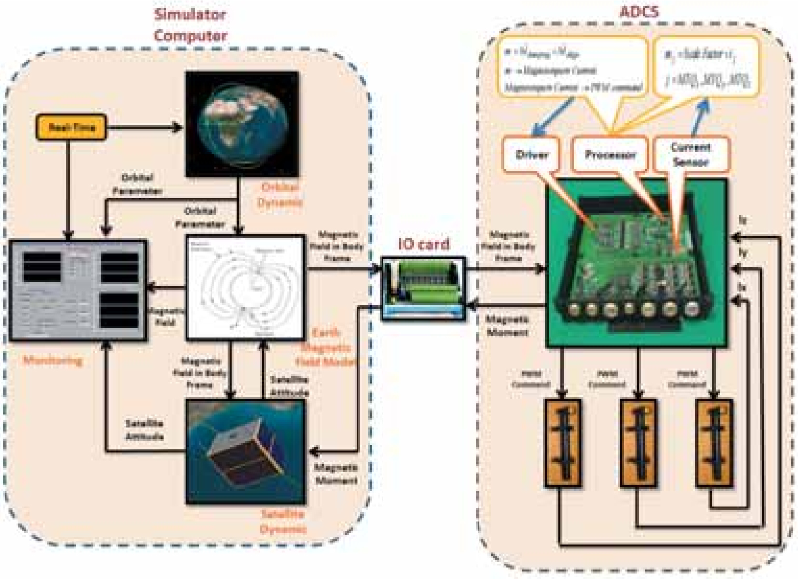

Figure 8: Diagram of detumbling and initial attitude acquisition test in HIL test bed

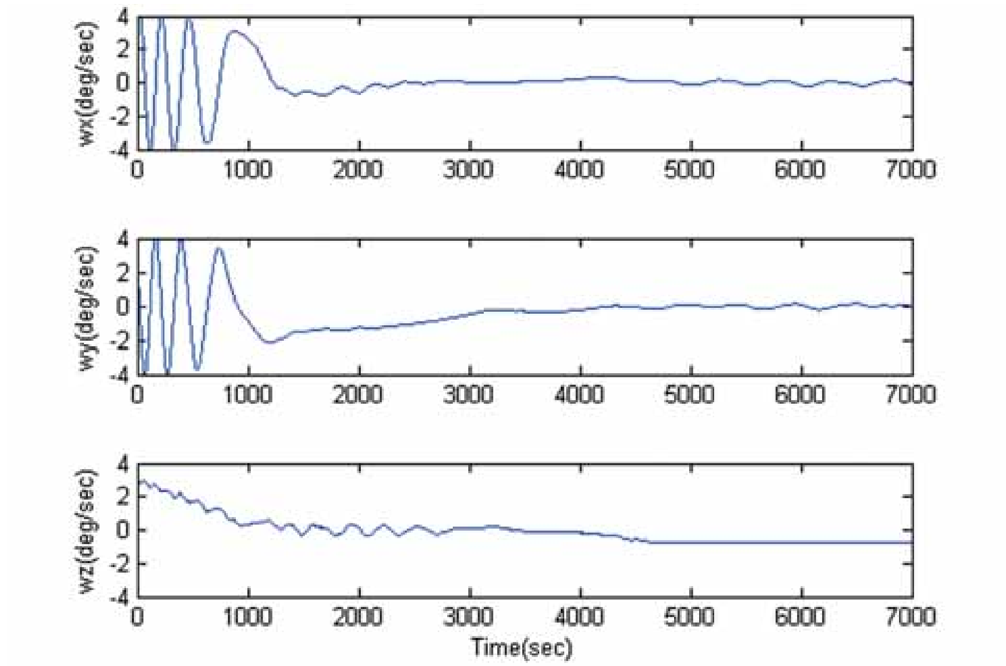

Figure 9: Spin rate of satellite in simulation result

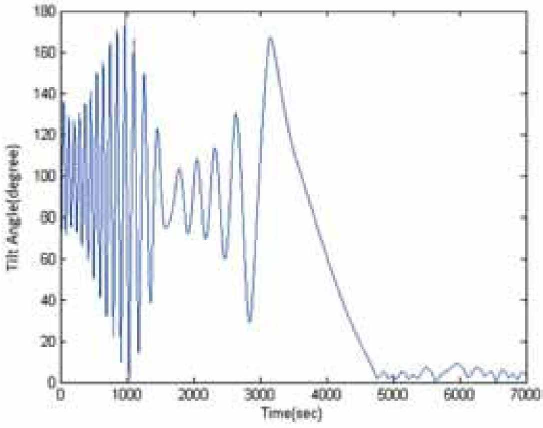

Figure 10: Tilt angle in simulation result

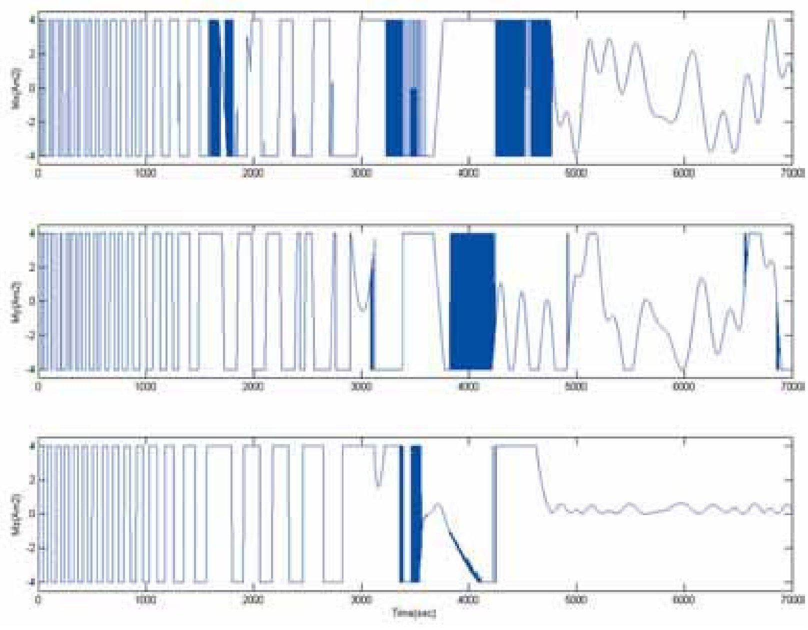

Figure 11: Magnetic moments of magetorquers in simulation result

moment of magnetorquers in this mode. It's observed that most of the time duty cycle of magnetorquers is 100% and maximum moment is generated.

Figures 12, 13 and 14 illustrate results of real-time HIL test. In this case tumbling of satellite is damped after nearly 4000 seconds and also tilt angle is reduced to less than 5.5º in nearly 6000sec. These results show that designed OBE is capable of executing control law accurately and planned mission for ADCS is achieved.

Table 4 presents the simulation and practical results. This Table shows duration time for damping tumbling and also duration time for pointing toward the Earth magnetic field vector. Here, rate <0.3 deg/sec is considered as criteria for damping of tumbling, and tilt angle <5.5 deg is considered as criteria for pointing toward earth magnetic field vector.

Comparing simulation and practical results shows some deviation among these results. We can express reasons for this deviation as follows:

1. In simulation, computed magnetic moment by control law is directly used as magnetic moment applied to satellite dynamics model. But in the practical case computed magnetic moment will be converted to current control commands, and these commands will be applied on magnetorquer's drivers. Since like any actual control system there exists errors in controlling current, these errors cause deviation between simulation results and practical results.
2. In simulation, time constant of magnetorquers are not considered in which cause a very small deviation between simulation results and practical results.
3. The major source of deviation is originated from the A/D and D/A conversion for transmission data between OBE and the simulator computer, which lead to deteriorate the practical results. Note that since in orbit operation of OBE, there is no need to transfer data between the OBE and the computer, so the mentioned error is not problematic.

6. Conclusion

In this paper the design of OBE in ADCS was presented. Design has been done based on mission requirements and design constraints of equipment. It was shown that the designed equipment satisfies all functional requirements and constraints. Also with considering importance of verifying performance of this equipment before launching a satellite, a real-time HIL test bed has been provided. The presented test bed is capable of testing all ADCS's equipment. Finally performance of OBE has been investigated and proper performance of this equipment in performing control mission was illustrated by HIL real-time test. For this purpose detumbling and initial attitude acquisition control mode was executed by OBE. However there are some deviations between simulation and practical results but these deviations are not critical and OBE performs attitude control mission properly.

7. References

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Initial Rate			Simulation Result		Practical Result	
ω_X (deg/sec)	ω_Y (deg/sec)	ω_Z (deg/sec)	tilt damping duration (sec)	rate damping duration (sec)	tilt damping duration (sec)	rate damping duration (sec)
1.5	1.5	1.5	6200	3500	6080	3700
2.5	-1.5	-2	3600	3100	3580	3000
2.5	-2.5	-2.5	6100	3900	6250	2900
2	3.5	3.5	6050	4280	6180	3400
3.8	0	3.8	3600	3300	3610	1100
1	3	3	4250	2650	4300	3100
2.5	2.5	2.5	6000	3400	6100	3500

Table 4: Result of simulation and implementation

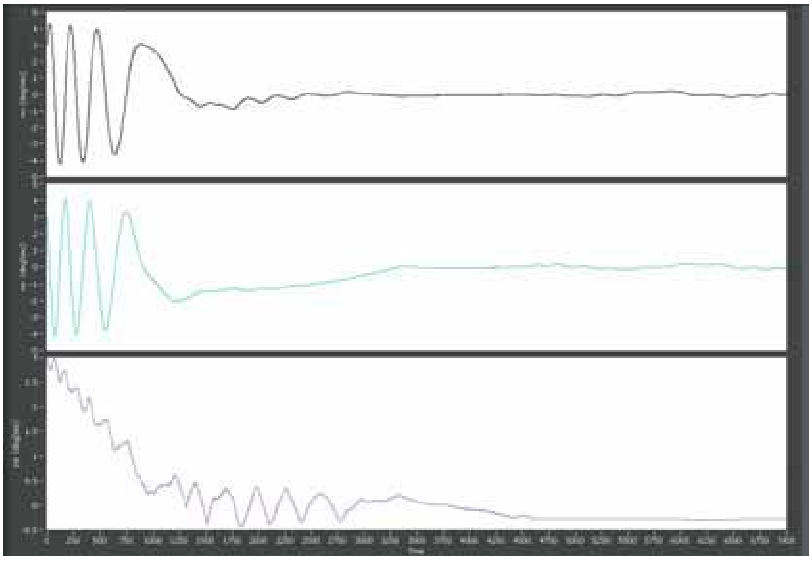

Figure 12: Spin rate of satellite in HIL test bed

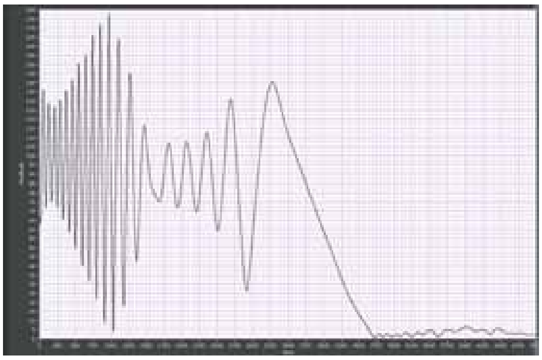

Figure 13: Tilt angle in HIL test bed

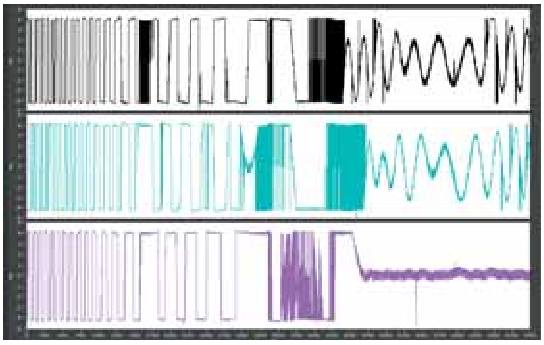

Figure 14: Magnetic moments of magetorquers in HIL test bed