AER821

Spacecraft Attitude Dynamics and Control

LABORATORY 4:

Gimbal Lab - Satellite Angular Position Controls with the use of Reaction Wheel and Control Moment Gyroscope (CMG)

Fall 2025

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C. Chan Rev 1.0

Department of Aerospace Engineering

0 General Safety Rules AND Regulations for Laboratories and Research Areas

The following safety rules and regulations are to be followed in all Aerospace Engineering laboratories and research facilities. These rules and regulations are to insure that all personnel working in these laboratories and research areas are protected, and that a safe working environment is maintained.

1.”Horseplay” is hazardous and will not be tolerated.

2. No student may work alone in the laboratory at any time, except to prepare operating procedures for equipment or data write-up/reduction/simulations.

3. Required personal protective equipment (PPE) will be provided by the Department for use whenever specified by the Faculty, Engineering Support or Graduate/Teaching Assistant, .i.e., hearing protection, face shields, dust masks, gloves, etc.

4. Contact lenses will not be worn in the laboratory when vapours or fumes are present.

5. Safety glasses with side shields and plastic lenses will be required when operating targeted class experiments as outlined in the experimental procedures. Splash goggles or face shields will also be provided and worn also, for those experiments which have been identified as a requirement.

6. Each student must know where the location of the First Aid box, emergency equipment, eye wash station is, if required in the laboratories, shops, and storage areas.

7. All Faculty, Engineering Support and Graduate/Teaching Assistants must know how to use the emergency equipment and have the knowledge to take action when an accident has occurred, .i.e., emergency telephone number, location, emergency response services.

8. All Faculty, Engineering Support and Graduate/Teaching Assistants, and Research Assistants, must be familiar with all elements of fire safety: alarm, evacuation and assembly, fire containment and suppression, rescue.

9. Ungrounded wiring and two-wire extension cords are prohibited. Worn or frayed extension cords or those with broken connections or exposed wiring must not be used. All electrical devices must be grounded before they are turned on.

10. All Faculty, Engineering Support and Graduate/Teaching Assistants, and Research Assistants, must be familiar with an approved emergency shutdown procedure before initiating any experiment.

11. There will be NO deviation from approved equipment operating procedures.

12. All laboratory aisles and exits must remain clear and unblocked.

13. No student may sniff, breathe, or inhale any gas or vapour used or produced in any experiment.
14. All containers must be labeled as to the content, composition, and appropriate hazard warning: flammable, explosive, toxic, etc.

15. The instructions on all warning signs must be read and obeyed in all laboratories and research facilities.

16. All liquid and solid waste must be segregated for disposal according to Faculty, Engineering Support or Graduate/Teaching Assistant instructions. All acidic and alkaline waste should be neutralized prior to disposal. NOTE: NO organic waste material is to be poured down the sink or floor drains. These wastes should be property placed in designed waste disposal containers, labeled and stored in the department's flammable storage cabinet which is ventilated and secured.

17. Good housekeeping must be practiced in all teaching and research laboratories, shops, and storage areas.

18. Eating, drinking, tobacco products, gum chewing or application of makeup is strictly prohibited in the laboratories and shops.

19. Only chemicals may be placed in the "Chemicals Only" refrigerator. Only food items may be placed in the Food Only refrigerator. Ice from any refrigerator is not be used for human consumption or to cool any food or drink.

20. Glassware breakage must be disposed in the cardboard boxes marked "Glass Disposal". Any glassware breakage and malfunctioning instruments or equipment must be reported to the Faculty, Engineering Support or Graduate/Teaching Assistant present.

21. All injuries, accidents, and "near misses" must be reported to the Faculty, Engineering Support or Graduate/Teaching Assistant. The Accident Report must be completed as soon as possible after the event by the Faculty, Engineering Support or Graduate/Teaching Assistant and reported to the Departmental Safety Officer immediately. Any person involved in an accident must be sent or escorted to the University Health Centre. All accidents are to be REPORTED.

22. All chemical spills are to be reported to the Faculty, Engineering Support or Graduate/Teaching Assistant, whose direction must be followed for containment and cleanup. Faculty, Engineering Support or Graduate/Teaching Assistant will follow the prescribed instructions for cleanup and decontamination of the spill area. The Departmental Safety Officer must be notified when a major spill has been reported.

23. All students and Faculty, Engineering Support or Graduate/Teaching Assistant must wash their hands before leaving targeted laboratories, research facilities or shops.

24. No tools, supplies, or any other items may be tossed from one person to another.

25. Compressed gas cylinders must be secured at all times. Proper safety procedures must be followed when moving compressed gas cylinders. Cylinders not in use must be capped.

26. Only gauges that are marked “Use no oil” are for Oxygen cylinders. Do not use an oiled gauge for any oxidizing or reactive gas.

27. Students are never to play with compressed gas hoses or lines or point their discharges at any person.

28. Do not use adapters or try to modify any gas regulator or connection.
29. There will be no open flames or heating elements used when volatile chemicals are exposed to the air.

30. Any toxic chemicals will be only be exposed to the air in a properly ventilated Fume Hood. Flammable chemicals will be exposed to the air only under a properly ventilated hood or in an area which is adequately ventilated.

31. Personal items brought into the laboratory or research facility must be limited to those things necessary for the experiment and safe operation of the equipment in the laboratories and research facilities.

32. General laboratory coats, safety footwear are not provided by the Department of Aerospace Engineering, although some targeted laboratories and research areas will be supported by a reasonable stock of protective clothing and accessories, i.e., gloves, welding aprons, dust masks, face shields, safety glasses, etc.

33. Equipment that has been deemed unsafe must be tagged and locked out of service by the Technical Officer in charge of the laboratory or research facility. The Departmental Safety Officer must be notified of the equipment lockout IMMEDIATELY!

34. In June 1987 both the Federal & Ontario Governments passed legislation to implement the workplace hazardous material information system or WHMIS across Canada. WHMIS was designed to give workers the right-to-know about hazardous material to which they are exposed to on the job. Any person who is required to handle any hazardous material covered by this act should first read the label and the product’s material safety data sheet (MSDS). No student is to handle any hazardous materials unless supervised by a Faculty, Engineering Support or Graduate/Teaching Assistant. The laboratory Technical Officer, Faculty, Engineering Support or Graduate/Teaching Assistant is responsible for ensuring that any hazardous materials are stored safely using WHMIS recommended methods and storage procedures. All MSDS must be displayed and stored in a readily accessible place known to all users in the workplace and laboratory

35. All the foregoing rules and regulations are in addition to the Occupational Health and Safety Act, 1987.

36. Casual visitors to the laboratory and research areas are to be discouraged and must have permission from the Faculty, Engineering Support or Graduate/Teaching Assistant to enter. All visitors must adhere to the safety guidelines and is the responsibility of the visitor.

37. Only the Safety Officer may make changes to these policies upon confirmation of the Safety Committee and approval of the Department Chair.

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1 Satellite Angular Position Control with Reaction Wheel

OBJECTIVE

To understand the purpose of using reaction wheel in satellite attitude control and to develop a closed-loop system with a compensator to carry out the angular position control

LEARNING OUTCOME

Upon the completion of Part 1, students should be able to demonstrate the followings:

- be familiar with the reaction wheel dynamic modeling
- know the mechanism of a reaction wheel
- formulate a closed-loop system with a PID compensator to carry out the angular position control with a reaction wheel

In the Reaction Wheel Lab, we have investigated the functionality of reaction wheel in satellite attitude control and the relationships between voltage and angular speed, and current draw and torque generated by the reaction wheel. In this lab, we are going to apply these relationships to model and control a satellite simulator as depicted in Figure 1. The satellite simulator shown in Figure 1 can be used either as a reaction wheel drive type or a control moment gyroscope (CMG) type.

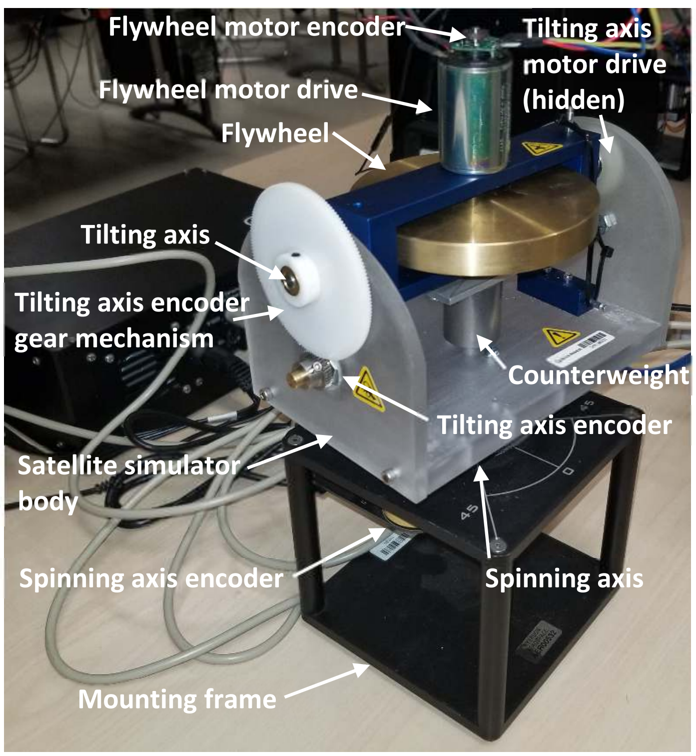

Figure 1: Satellite simulator

When use as a reaction wheel drive, the spinning axis is locked in place so to allow the flywheel to spin about the vertical axis only (as the configuration shown in Figure 1). By sending a voltage to vary the acceleration and deceleration of the spinning flywheel in both directions, the desired angular position of the satellite simulator can be reached. When use as a CMG, the flywheel spins at a constant speed while the angle of the tilting axis is modulated with a gear motor drive. By varying the angle of the tilting axis, the angular momentum of the spinning flywheel will generate a net torque about the spinning axis causing the satellite simulator body to rotate.

1.1 Dynamic Modeling of the Satellite with Reaction Wheel

Let us look at the equations that describe the angular motion of a reaction wheel. We know that torque from the motor is proportional to the current draw:

$$M = KI \tag{1}$$

The voltage across the motor is a combination of the resistance, the inductive reactance, and the back-EMF from the motor rotation:

$$E = RI + L\frac{dI}{dt} + K\frac{d\theta}{dt} \tag{2}$$

The total moment of inertia, J is the sum of the MOIs of the wheel and motor, $J = J_m + J_{disk}$. Derived from Newton's Second Law, the acceleration of the motor is affected by the applied torque and the motor friction:

$$M = J\frac{d^2\theta}{dt^2} + D\frac{d\theta}{dt} \tag{3}$$

We can summarize the equations of motion in state-space form:

$$\boldsymbol{x} = \begin{bmatrix} \dot{\theta} \\ I \end{bmatrix}$$

$$[\dot{\boldsymbol{x}}] = \begin{bmatrix} \frac{-D}{J} & \frac{K}{J} \\ \frac{-K}{L} & \frac{-R}{L} \end{bmatrix} [\boldsymbol{x}] + \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix} E \tag{4}$$

Alternately we can write conventional transfer functions:

$$\frac{\dot{\theta}}{E} = \frac{K/_{JL}}{s^2 + \left(D/_J + R/_L\right)s + \frac{(DR+K^2)}{JL}} \tag{5}$$

$$\frac{I}{E} = \frac{1/_L s + D/_{JL}}{s^2 + \left(D/_J + R/_L\right)s + \frac{(DR+K^2)}{JL}} \tag{6}$$

And thus the transfer function from voltage to torque is:

$$\frac{M}{E} = \frac{K\left(\frac{1}{L}s+\frac{D}{JL}\right)}{s^2+\left(\frac{D}{J}+\frac{R}{L}\right)s+\frac{(DR+K^2)}{JL}} \tag{7}$$

Since the wheel friction is very small compare to the total moment of inertia of the wheel and motor, we can thus neglect the terms associated with the wheel friction and reduce Equation (7) to the following form:

$$\frac{M}{E} = \frac{K\left(\frac{1}{L}s\right)}{s^2+\left(\frac{R}{L}\right)s+\frac{K^2}{JL}} \tag{8}$$

Now, to apply the torque generated by the reaction wheel to the satellite simulator body, we use Newton's Second Law of motion from Equation (3) and neglect the friction term:

$$M = J_s \frac{d^2\theta_s}{dt^2} \tag{9}$$

where θ_s and J_s are the angle of rotation and moment of inertia of the satellite simulator body respectively. Take double integration of Equation (9) yields the following expression for θ_s and *M*:

$$\frac{\theta_s}{M} = \frac{1}{J_s s^2} \tag{10}$$

Parameters used for Equations (1) to (8) are pre-determined from testing and measurements. Table 1 shows the parameter values and nomenclatures used for the reaction wheel and motor dynamic model.

Parameter	**Symbol**	**Value**
Motor Resistance	R	5.3 Ω
Torque/Current Constant	K	0.022 Nm/A
Moment of Inertia (Motor)	J_m	1.4×10^{-6} kg · m^2
Inductance	L	580×10^{-6} H
Wheel Mass	M_{disk}	0.8 kg
Wheel Moment of Inertia	J_{disk}	1.0323 kg · m^2
Satellite Moment of Inertia	J_s	0.0022 kg · m^2
Current	I	A
Voltage	E	V
Torque	M	Nm
Motor Speed	$\dot{\theta}$	rad/s
Satellite Rotation Angle	θ_s	rad

Table 1: Reaction wheel and motor parameters

Before we apply the above equations to control the reaction wheel, we have to know the physical and electrical limits of the apparatus so to prevent any cause of permanent damage done to it during operation. Table 2 shows the absolute limits of the reaction wheel apparatus.

Parameter	Value
Max. Motor Voltage	±12 V
Max. Current	±0.870 A

Table 2: Absolute limits of the reaction wheel apparatus

IMPORTANT NEVER touch the spinning flywheel when the motor is running!

1.2 Pre-lab Exercise – Closed-loop model with a PID compensator to perform angular position control

Before conducting the actual experiment, you should be able to use the transfer functions in Equations (8) and (10) and the techniques you have learnt from Lab 2 to construct a closed-loop model with a PID compensator to carry out the angular position control. The input of your model should be angular position in degrees and the commanding signal of the model should be voltage. Your PID compensator should be able to compensate the disturbance and send out the appropriate voltage value to control the angular position of the unit. Figure 2 shows an example of a closed-loop angular position control model with a PID compensator. You have to figure out the transfer function that governs the reaction wheel model and the appropriate gains of the PID compensator to complete this closed-loop system.

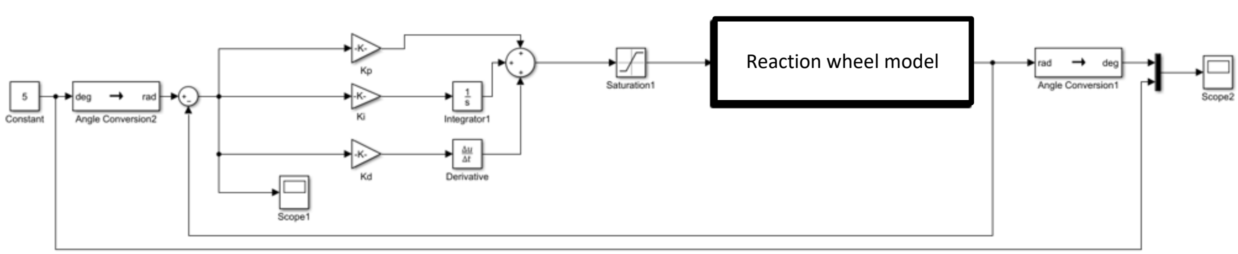

Figure 2: Closed-loop angular position control model with a PID compensator

1.3 *Actual Closed-loop angular position control with a PID compensator*

Based on the results from Section 1.2, construct a closed-loop angular position control system to conduct a hardware-in-the-loop demonstration. You can download and use the model file: **gyroscope_RW.slx** as seen in Figure 3 as a template to construct your model. Use angle commands in degrees of 0, ±1, ±2, and ±5 to run your system and observe the corresponding system response of each command. Compare the results of your simulation model in Section 1.2 with the actual system response here.

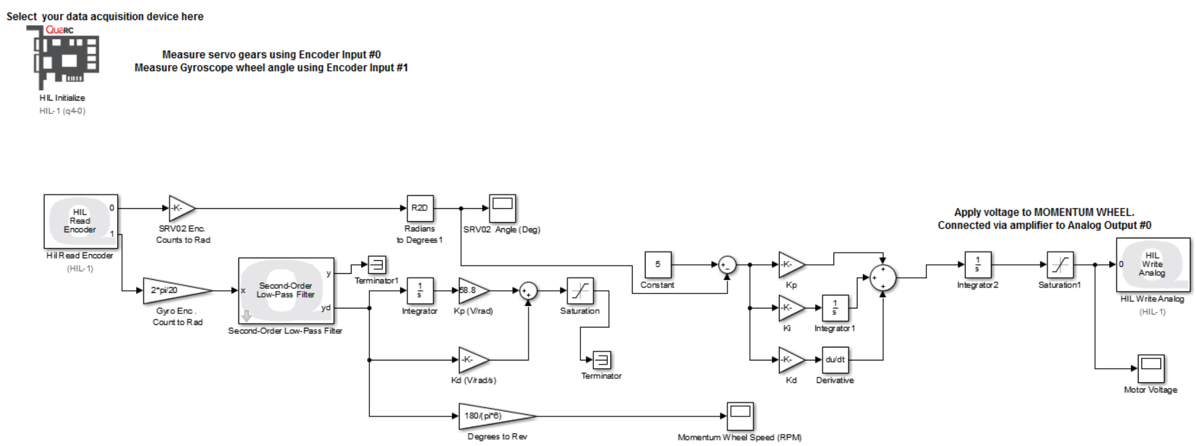

Figure 3: Actual closed-loop angular position control system with a PID compensator

2 Angular Position Control with Control Moment Gyroscope (CMG)

OBJECTIVE

To understand the purpose of using the CMG in satellite attitude control and to develop a closed-loop system with a compensator to carry out the angular position control

LEARNING OUTCOME

Upon the completion of Part 2, students should be able to demonstrate the followings:

- physical setup of the CMG and its data acquisition and control devices
- know how to use the MATLAB M-file and MATLAB Simulink model to run a real-time hardware-in-the-loop application via a user-defined GUI (Graphical User Interface)
- formulate a closed-loop system with a PID compensator to carry out the angular position control with a CMG

2.1 Dynamic Modeling of the Satellite with CMG

When the satellite simulator depicted in Figure 1 operates with the CMG as its attitude control unit, the flywheel will rotate at a constant speed with its spinning axis aligned parallel to the horizon initially. The net torque used to rotate the satellite simulator, τ_s is produced by the change of angular momentum (L_{disk}) of the flywheel disk according to the expression:

$$\tau_s = \frac{dL_{disk}}{dt} \tag{11}$$

Assuming the angular momentum of the system is conserved and friction is negligible, the rate of change of the disk angular momentum is then:

$$\frac{dL_{disk}}{dt} = J_s \omega_s \frac{d\theta}{dt} \tag{12}$$

where J_s is the moment of inertia of the satellite simulator, ω_s is the angular speed of the satellite simulator, and $\frac{d\theta}{dt}$ is the rate of change of the tilting axis. The rate of change of the tilting axis $\frac{d\theta}{dt}$ is directly proportional to the voltage applied to the tilting axis motor drive. We can determine their relationship (e.g. gain, K_{ta}) experimentally by measuring the rate of change of the tilting axis corresponds to a constant voltage with the tilting axis encoder. Therefore, we can deduce the following expression:

$$\frac{d\theta}{dt} = K_{ta} V \tag{13}$$

Table 3 shows the parameter values and nomenclatures used for the satellite simulator with the CMG configuration.

Parameter	Description	Value	Unit
K_t	Motor torque constant	0.02	N-m/A
L_m	Armature inductance	0.580	mH
$V_{nominal}$	Norminal voltage of the flywheel motor (CMG mode)	12	V
J_m	Flywheel motor armature inertia	1.4e-6	kg-m^2
$I_{nominal}$	Flywheel motor operating current (CMG mode)	0.23	A
R_{disk}	Flywheel radius	0.0508	m
M_{disk}	Flywheel mass	0.8	kg
J_{disk}	Flywheel inertia about spin axis	1.0323	kg-m^2
J_g	Gyro module inertia about spin axis	0.002	kg-m^2
J_{ta}	Flywheel assembly inertia about tilting axis	0.00045	kg-m^2
$K_{ta,enc}$	Tilting axis encoder gear mechanism ratio	1/4	N/A
$CPR_{ta,enc}$	Tilting axis encoder resolution (in quadrature mode)	4096	counts/rev
$CPR_{disk,enc}$	Flywheel encoder resolution (in quadrature mode)	20	counts/rev

Table 3: Satellite simulator (CMG mode) parameters

IMPORTANT NEVER touch the spinning flywheel when the motor is running!

2.2 Pre-lab Exercise – Closed-loop model with a PID compensator to perform angular position control

Before conducting the actual experiment, you should be able to use Equations (11) to (13) and the techniques you have learnt from the previous sections to construct a closed-loop model with a PID compensator to carry out the angular position control. You can refer to the model in Figure 2 as a starting point and leave K_{ta} as an unknown parameter for now until you determine its experimental value in the next section.

2.3 Actual Closed-loop angular position control with a PID compensator

Based on the results from Section 2.2, construct a closed-loop angular position control system to conduct a hardware-in-the-loop demonstration. You can download and use the model file: **gyroscope_CMG.slx** as seen in Figure 4 as a template to construct your model. Use angle commands in degrees of 0, ±1, ±2, and ±5 to run your system and observe the corresponding system response of each command.

Compare the results of your simulation model in Section 2.2 with the actual system response here. You may want to compare the calculated controller commands (i.e., before the saturation block) with the actual commands sent to the motors. To what extent can you ‘trust’ your theoretical analysis of system performance? Also comment on the system response of the CMG vs that of the Reaction Wheel.

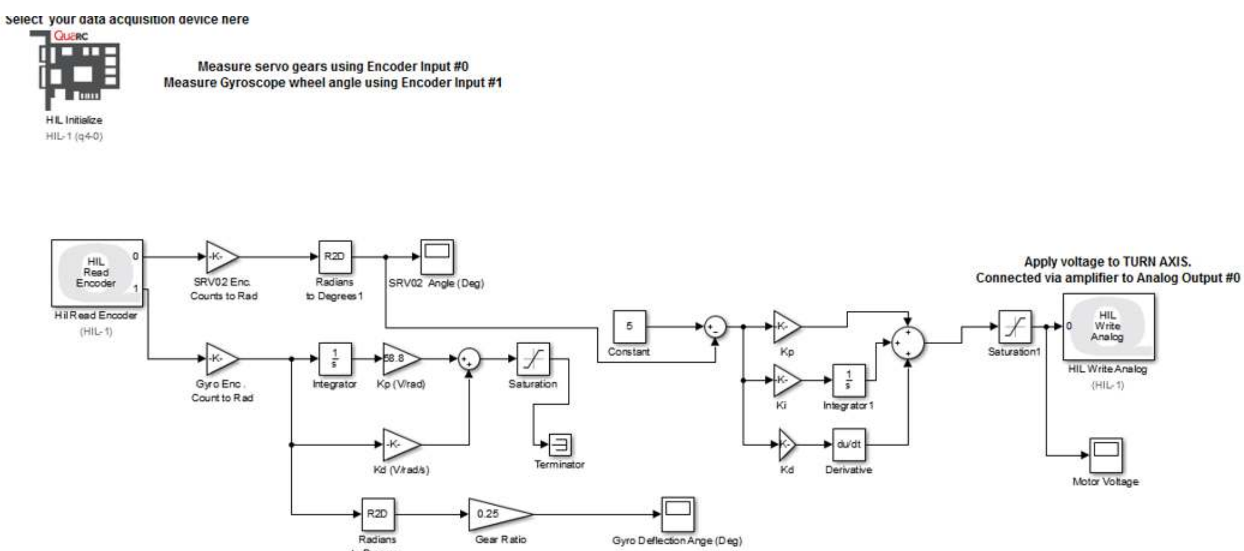

Figure 4: Actual closed-loop angular position control (CMG) system with a PID compensator

3 References

1) Enright, John and Cresnik, Primoz. AER821 – Spacecraft Attitude Dynamics and Control, Hardware Lab 1: Reaction Wheels. Department of Aerospace Engineering, FEAS, Ryerson University, Toronto, 2016.
2) Enright, John and Cresnik, Primoz. AER821 – Spacecraft Attitude Dynamics and Control, Hardware Lab 2: Closed-loop Control of Reaction Wheels. Department of Aerospace Engineering, FEAS, Ryerson University, Toronto, 2016.
3) Giurgiutiu, Victor and Lyshevski, Sergey Edward, Micromechatronics – Modeling, Analysis, and Design with MATLAB, Second Edition. CRC Press (Taylor & Francis Group), Boca Raton, 2009.