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BYOE: An Apparatus for Exploring Small-satellite Estimation and Control

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BYOE: An Apparatus for Exploring Small Satellite Estimation and Control

Summary

The primary motivation for this experiment is for the instruction of Satellite control techniques through the usage of a common Satellite actuator (reaction wheel) and feedback sensor (rate gyroscope). The hardware features a single-axis rotating mock-Satellite that is used by small teams of undergraduate or graduate students in modular hands-on learning opportunities that teach Satellite estimation, sensing, actuation and control. The platform allows students to implement several custom designed Satellite control schema on hardware and compare simulated and actual performance results, thereby increasing conceptual understanding of how control gains affect the overall system dynamics (stiffness, damping, etc). This is accomplished on the hardware through the employment of a wireless embedded Satellite control board programmed with Simulink and a LabVIEW-based Base Station.

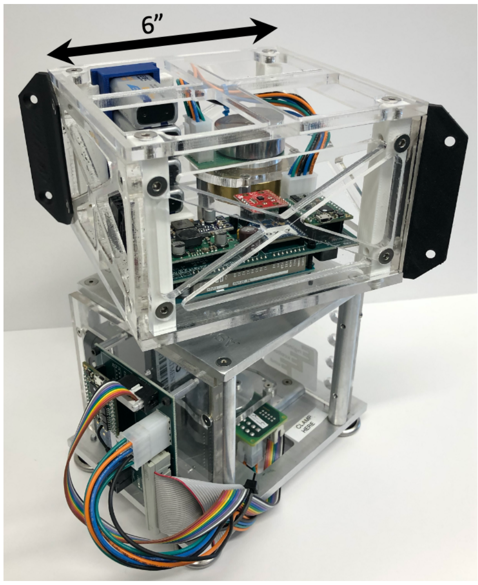

Figure 1: Satellite and Base Station

Figure 1 shows the main Satellite and Base Station without any additional modular accessories that are used in higher level courses. The small 6” x 6” x 4” Satellite portion includes a Maxon EC-motor and controller, reaction wheel, Inertial Measurement Unit (IMU) used to sense one axis of spin rotation rate/angle, XBee wireless transceiver to transmit and receive data, a custom interface printed circuit board, and an Arduino Due microcontroller as the primary processor.

Clear acrylic panel walls allow for student observation of the primary internal components. The co-axial Base Station includes a second Maxon EC-motor, controller, and encoder connected to a vertical shaft supporting the rotating Satellite. An XBee wireless transceiver is used for communication between the Base Station and Satellite, while a National Instruments myRIO embedded system allows for USB communication from the Base Station to a LabVIEW based graphical user interface (GUI) on a personal computer. Various attachments and accessories allow for multiple hands-on learning experiments for students at the undergraduate and graduate level. For example, a 3D-printed accessory can be installed to teach conservation of momentum principles, or mock solar panels can be added for more advanced Satellite control dynamics in senior/grad level courses. Thus, this highly modular experimental hardware is configured and currently used in multiple Aerospace undergraduate and graduate level lab activities and courses. The hardware was designed to be small, portable and cost effective. Currently, we have eight operational units in order to serve large student populations. The details of the software and hardware design, and how this hardware meets the learning goals for students in the curriculum will be discussed further in this paper.

Pedagogical Context

The hardware is physically and pedagogically modular and is used by students ranging from sophomores studying introductory satellite dynamics, to juniors in an attitude dynamics course, as well as seniors and graduate students studying a variety of control algorithms. This allows the investment in expensive hardware and development to efficiently span multiple levels and courses and benefit a large student population. In all core undergraduate courses in the University of Colorado Smead Aerospace Engineering Sciences department, students take a hands-on role to gather real data in order to compare and contrast to their predictive models developed through lecture based instruction [1], [2]. This particular experiment was based on similar modules developed when CU Smead Aerospace dramatically changed to include extensive hands-on learning and teaching in the Integrated Teaching and Learning Laboratory [3]. The pedagogical purpose is to enhance students overall understanding of fundamental engineering concepts through experiential learning while using up to date hardware and software in order to maintain pace with current technology. The use of this particular experiential learning apparatus in a lecture/lab connected environment builds upon an extensive amount of literature in active experiential learning [4], [5] and has repeatedly been shown as an effective strategy to enhance learning gains and retention [6].

An additional goal of this experimental apparatus is to give students exposure to commonly used satellite pieces of hardware and techniques. Many Aerospace applications use reaction wheels [7], which are a useful and practical example for the instruction of rotary motion principles such as torque, angular momentum, and rotational inertia. The hardware also allows for the characterization of common satellite sensors [8]; namely an IMU sensor board that includes a Micro-Electro-Mechanical Systems (MEMS) gyroscope and magnetometer. The design is mechanically durable and allows for expandable satellite analogs such as mock solar panels, a satellite despinning apparatus, and could even include thrusters in the future. With the exception of two custom printed circuit boards, all parts are either commercial off-the-shelf components or can be machined or fabricated in-house with a 3D printer, laser cutter, and traditional machine shop equipment (lathe, milling machine, etc.). The CU Satellite's primary control board is programmed through a Simulink-based embedded software suite and allows for student-designed control schemes ranging in complexity from junior level proportional-integral-derivative control to graduate level state space and pole placement techniques. The Base Station includes a National Instruments myRIO programmed in LabVIEW to run stand-alone, or while connected to a personal computer to provide a GUI. This GUI allows the user to visualize and store data from user controlled actuation commands and the response from the Satellite sensor signals that are transmitted to and from the Satellite. The GUI and co-located Base Station allow for a variety of experiments to: characterize and calibrate the Satellite's rotational sensors (gyros), estimate the reaction wheel and each Satellite's rotational moment of inertia, and estimate the transfer function from reaction wheel applied torque to angular position using a frequency sweep. In all experiments, the raw data is displayed to the user and saved through the GUI and the students post process the raw data in order to compare and contrast with models and demonstrate their theoretical understanding of the course learning goals. Throughout the process, students work closely with student assistants and faculty to understand the operation of the experiment but more importantly to understand and build the connections between experimental data and a fundamental understanding of the governing principles.

The cost per Satellite unit depends primarily on the engineering development labor costs which were not estimated. The hardware costs are largely due to the EC-motor and reaction wheel fabrication costs, but it is on the order of $700 per unit. The Base Station cost is on the order of $1400 per unit, with the largest contribution from the NI myRIO and EC-motor with integrated encoder. More cost details are shown in the enclosed Bill of Materials.

Sample Applications

The Satellite apparatus has a tiered level of applications. Students enrolled in core Aerospace engineering courses are first exposed to the apparatus in a sophomore level dynamics course. Students gain a deeper understanding of the apparatus and its capabilities as juniors in the core spacecraft attitude dynamics course. The apparatus is further used by seniors and graduate students in an upper level elective course that focuses on advanced control techniques and is cross-listed to provide vertical integration of seniors and entry level graduate students working on the same hardware but with various levels of difficulty.

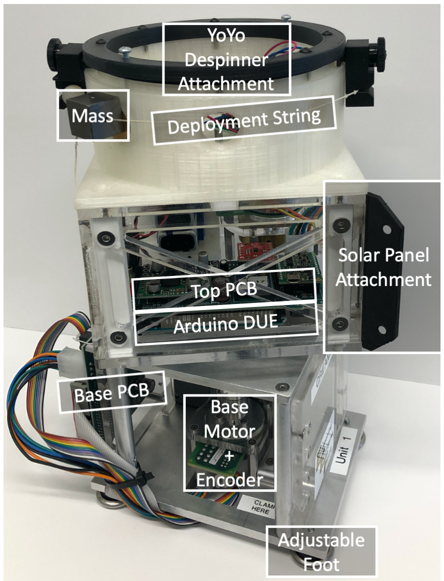

Figure 2: Yo-Yo Despinner Accessory

At the sophomore level, students become familiar with the Satellite hardware and basic operation of the apparatus. The primary focus is on using the LabVIEW GUI to first command the spacecraft to spin at a prescribed rotational rate using the base motor in order to demonstrate a spin stabilized Satellite. Then the students send a signal from the Base Station to the upper control board of the spinning Satellite to actuate a pair of electromagnets. When the electromagnets are actuated, a pair of masses wrapped around the cylinder of the Satellite with strings, are jettisoned horizontally from the Satellite and caught by a cage. This causes the Satellite to reduce rotation rate through the conversion of rotational momentum to linear momentum; otherwise known as yo-yo despinning in the satellite navigation community [7]. At this level, the students are provided with the rotational inertia of the Satellite, rather than measuring it, and are able to compare their predictions of angular deceleration using first principles to the data captured by the Base Station. Figure 2 shows the apparatus with the yo-yo despinner attachment indicating one of the two masses (the other mass is not shown), the attachment string wrapped around the Satellite and the mass which is held in place by the electromagnet housed inside the modular Satellite payload.

At the junior level the students are exposed to every aspect of the apparatus. Using the same LabVIEW GUI the students were first exposed to as sophomores, junior students now conduct several experiments to better understand the intricacies of the design. The first experiment allows the students to rotate the Satellite using the co-located base motor in order to calibrate the performance of the Satellite rate gyro in terms of bias and sensitivity and compare this to the ”true” rate as measured by the base motor encoder. During calibration, students can rotate the satellite by hand or under motor control, to get a hands-on ”feel” for the dynamics and friction in the system and to see how calibration is sensitive to input parameters. After the students have an understanding of the rate gyro measurements, they take data to calculate the reaction wheel moment of inertia by applying a specific torque to the reaction wheel motor while holding the Satellite stationary by hand. The rotational speed of the reaction wheel is then measured using hall effect sensors. The students conduct a similar experiment to estimate the spacecraft moment of inertia by commanding a specific torque to the base motor and measuring the resultant angular acceleration of the entire Satellite. These measurements are combined with an understanding of PID control theory taught in the lecture, to develop a set of control gains that will allow the Satellite to achieve specific performance objectives on angular position such as a 5% settling time in 10 seconds with a step angular pointing command of 0.5 radians. The students test their predicted control gains on the apparatus by entering them into the LabVIEW GUI and then observe and record the response data. Due to unmodeled dynamics, such as friction, the students then adjust their control gains based on the response of the true system and their understanding of control theory in order to achieve the desired real world performance.

Students in the upper division controls course take a similar approach to the junior level experiments but also incorporate more advanced modeling and control techniques. Mock solar panels are added to the Satellite to further increase the complexity and dynamics of the system. The apparatus with attached mock solar panels is shown in Figure 3.

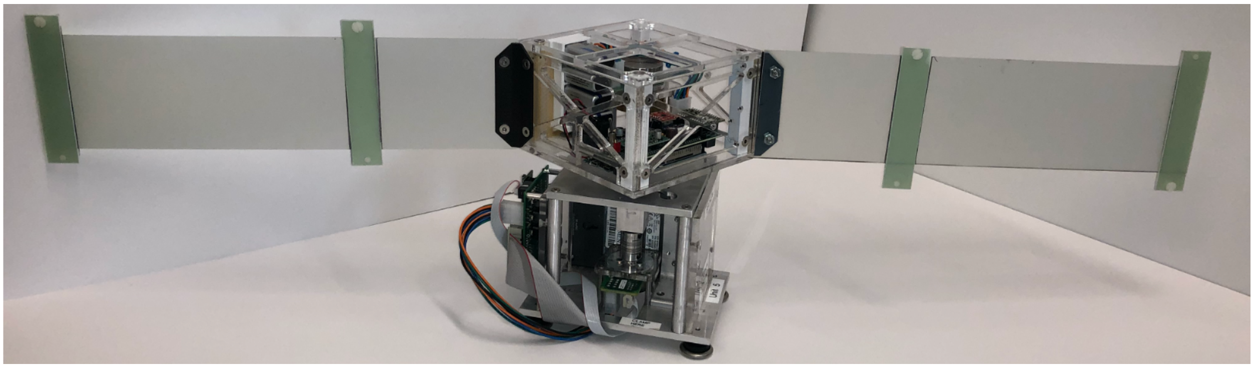

Figure 3: Mock solar panels attached

Students use the LabVIEW GUI to run a frequency response test in order to characterize and model the plant dynamics. The students implement a frequency sweep which commands a specific torque to the reaction wheel motor through a range of frequencies while measuring the angular velocity measurements from the gyroscope. Students are able to use this collected data to construct a model of the Satellite by comparing the input torque amplitude and phase to the output angular velocity amplitude and phase. The mock solar panels have been fabricated to exhibit resonance and anti-resonance dynamics in order to increase the complexity of the student-derived model and to highlight the capabilities of the frequency sweep modeling approach. The students incorporate this plant estimation with various control algorithms to achieve certain performance objectives in various lab activities through the course. At this upper level, the students write their own controller in Simulink and deploy the code to the Satellite's Arduino Due. The Simulink based coding architecture allows the students to easily translate their controller from simulation to the hardware in the same environment.

Apparatus Design: Overview

The satellite experimental lab concept was originally designed and built by CU Boulder Aerospace faculty and staff in 1998. The current version of the hardware and software took the original design and revised it with the objective to minimize the Satellite's overall volume while still allowing the operator to view all major components and see the interconnections. The revision allowed for adding wireless and embedded system technology, drastically reducing the size and cost, and allowing for eight replications of the hardware to handle more students. The current version of the apparatus uses a combination of commercially available components and custom parts along with an embedded system based software architecture. The mechanical and electrical components have been designed and positioned to allow students easy visual access to aid in their understanding of the underlying system. The software packages consist of Simulink on the Satellite and LabVIEW in the Base Station. The Base Station processor communicates with the CPU via USB and with the Satellite via XBee wireless communication. The Satellite is physically attached and co-located to the Base Station for compactness and to aide in the rate gyro calibration experiment but otherwise is a stand-alone package that could be removed from the Base Station and controlled from several meters away if desired.

Apparatus Design: Mechanical

The Base Station hardware platform is comprised of a motor, amplifier, and feedback sensors. The mechanical design of the Base Station is built around a Maxon EC-45 brushless motor and encoder combination. The motor drive shaft is connected to a bearing block to protect the motor from any off axis (radial) loads by constraining the motion of the upper Satellite to rotary motion alone. The bearing block is attached to the upper plate of the Base Station, the upper plate is attached to the lower plate with 4 vertical standoffs. Acrylic panels have been attached to the standoffs in order to provide some protection to the Base Station motor/encoder electronics as well as provide an attachment point for the Base Station custom printed circuit board (PCB) for the motor driver.

The standoffs are fixed to the Base Station lower plate with screws. The lower plate also has four adjustable feet which are used to level the base plate to ensure the upper Satellite spins true about its rotation axis. The base plate is clamped by the user to a solid surface with a hand clamp to ensure the entire system stays fixed and rigid during operation.

To meet the objective of avoiding a “black box” design, and having all internal components visible to the students, the Satellite body was fabricated using laser cut $\frac{1}{4}$-inch acrylic panels and 3-D printed corner braces and battery pack. Two side panels are identical to aid in manufacturing, one panel including attachment holes for the future addition of a physical gyroscope and the fourth side panel including attachment holes for the battery pack receiver. The bottom panel has several mounting holes to rigidly attach the custom electronics stack, the shaft coupling, and the standoffs to hold the reaction wheel motor. The top panel simply acts as a lid and to provide structural support for the four walls. A combination of 3D printers were used to create the upper board components as certain components had tighter tolerance requirements than others. The vertical standoffs are identical to aid in efficient manufacturing and were fabricated using a Lulzbot Fused Deposition Modeling (FDM) style printer, while screw holes were tapped using traditional machine shop equipment. The battery pack receiver was printed using a Markforged Mark II FDM style printer because of the increased complexity of mounting the receivers and the desire to have a tight tolerance between the custom battery pack and the receiver mounting rails. Also the Markforged Mark II printer allowed for Kevlar reinforcement to strengthen the battery receiver rails and the inclusion of geometry in the shape of the school mascot (CU Buffalo) on the reverse side as shown in Figure 4. The reaction wheel motor is attached to the standoffs with an acrylic laser cut face plate. The reaction wheel itself was fabricated from brass round stock and includes four perpendicular set screws which allows for adequate holding force onto the motor shaft while maintaining a high degree of symmetry thus mitigating wobble at high rotational speeds.

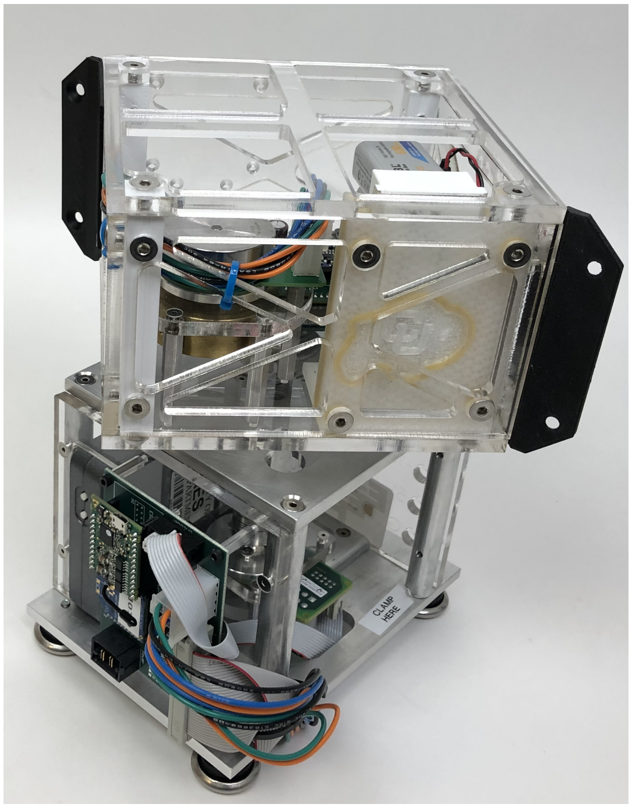

Figure 4: Satellie Side View

Apparatus Design: Electrical

The Functional Block Diagram (Figure 5) shows the overall apparatus and how the electro-mechanical components all communicate with each other through electrical connections.

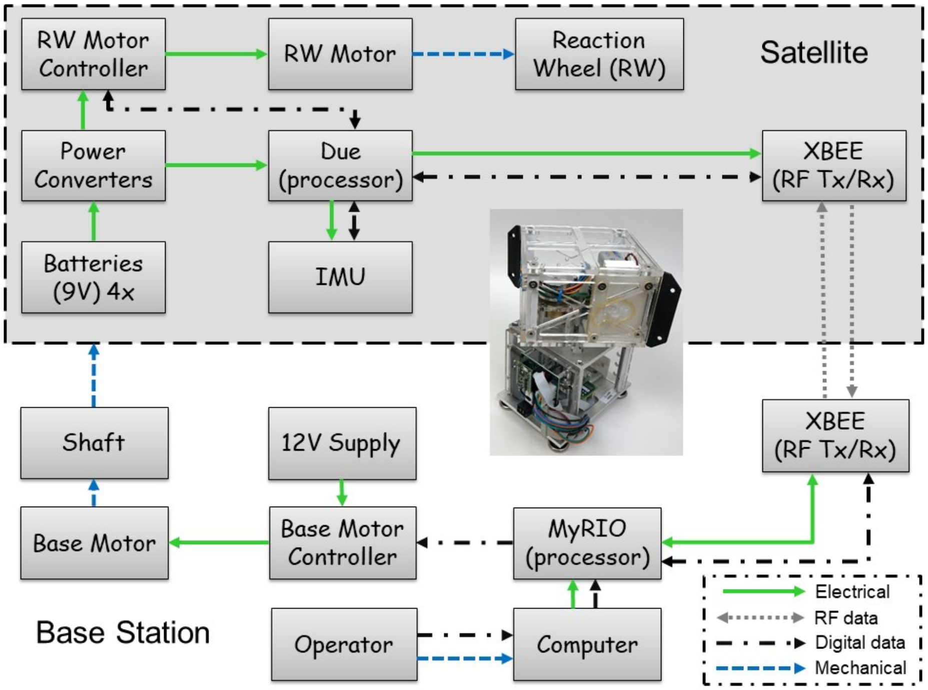

Figure 5: Functional Block Diagram

The Base Station electronics consist of a primary processor on the base unit which is a National Instruments myRIO real-time embedded device. The myRIO communicates through USB to the operator's CPU running LabVIEW. The myRIO is also electrically connected to the Base Station custom PCB which houses the Base Station motor controller board, XBee wireless communication module and power adapter.

The Satellite electronics are comprised of an Arduino Due and a custom PCB which houses two DC/DC power converters, a Sparkfun IMU, a Maxon motor driver, XBee wireless communication module, and off board connectors for the Yo-Yo Despinner apparatus and future additions such as a physical gyro. Figure 6 shows a top down view of the Satellite electronics. Note, the Arduino Due is hidden from view and located under the custom PCB board containing the DC/DC converters, IMU, etc.

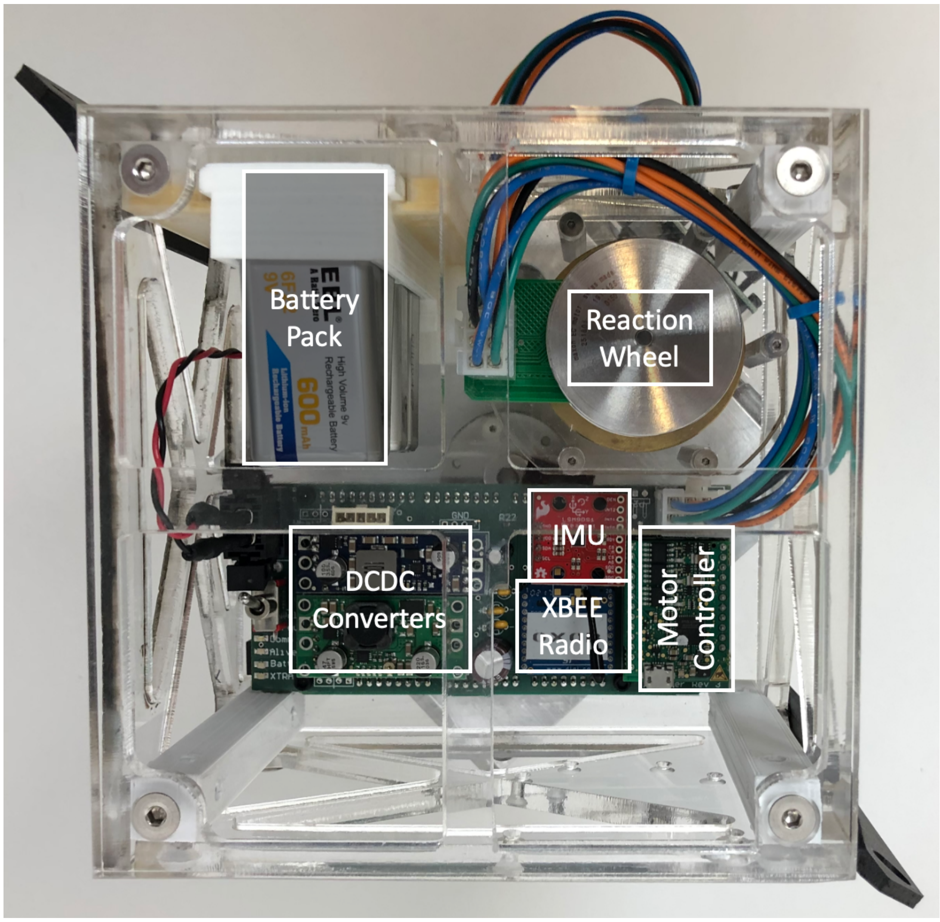

Figure 6: Satellite Top View

Apparatus Design: Base Station Software

The Base Station software is comprised of the myRIO embedded software and the operator LabVIEW software GUI on the CPU. The two pieces of software run parallel LabVIEW scripts on separate hardware but in communication with each other. The myRIO software is dedicated to sending/receiving information to/from the operator and either handling that information directly or passing commands to the Satellite via the XBee wireless link. The myRIO embedded real-time code sends torque commands to the motor driver, receives actual torque and encoder position information from the motor driver, creates and passes XBee commands based on information from the operator, and receives and parses information packets from the XBee wireless link before sending that information back to the operator.

The LabVIEW operator software GUI is primarily focused on taking user inputs and passing that information to the Base Station myRIO. The operator software has initialization, shut down and communication routines. The different configurations of the hardware are selected by the operator before the Base Station software is run and dictates the software mode until the operator exits the program. The different modes correspond to the different modular applications as detailed above. These modes construct and send specific packets at specific rates to the myRIO embedded controller which then passes the relevant information to the Satellite via the XBee wireless link.

Apparatus Design: Satellite Software

The Satellite software was written in MATLAB/Simulink for Arduino and runs on an Arduino Due micro-controller. The Satellite embedded software wirelessly receives user commands and sends information via the XBee wireless transceiver physically connected to the Due through Universal Asynchronous Receiver/Transmitter (UART) serial communication. The Arduino Due communicates to the Sparkfun IMU via Inter-Integrated Circuit (I2C) serial protocol and reads and records gyro information from the IMU. The Due also transmits desired torque commands to the reaction wheel motor driver and receives speed and motor current information from the motor driver as well. Lastly, the Due reads and records Satellite health and status information such as the battery voltage which is ultimately displayed on the LabVIEW GUI to indicate when the user should replace the batteries.

Similar to the Base Station operator software described in the section above, the Satellite embedded software contains several routines and has the ability to run different modes depending on the desired modular application. Most importantly, students are able to easily program custom Satellite controller designs using Simulink and program those designs onto the Arduino Due embedded system.

Conclusion

In this paper, an experimental apparatus used by students to explore rotational dynamics and satellite control fundamentals was presented. The equipment is used at the sophomore, junior, senior, and graduate levels as part of an experiential learning curriculum in the CU Boulder Smead Aerospace Engineering department. Employment of a modular apparatus for multiple stages of an engineering education curriculum allows for reduced storage needs and an easier justification of equipment and labor investment costs. Perhaps more importantly, students repeatedly encounter the equipment and explore different portions of the apparatus throughout the curriculum. Anecdotal feedback from the students on the learning gains from using real hardware and preparing them for future careers in engineering has been positive. This feedback has been gathered verbally in the lab and through five-year post graduation surveys. Future work may include more formal assessments of this apparatus specifically and an exploration on whether students learn and retain information better through this tiered approach using a modular experimental apparatus compared to an approach using independent experiments.

Bill of Materials

The bill of materials for a single apparatus are shown below for the Base Station (Table 1), the Satellite (Table 2), and the YoYo Despinner optional accessory (Table 3). Values for custom parts are approximate and include material and manufacturing costs.

Table 1: Base Station Bill of Materials

Part	Description	Vendor	Vendor Part #	Price (USD)	Qty	Ext
Base Motor	Motor and encoder for base	Maxon	469234	$224.10	1	$224.10
Screws	Base motor attachment screws	McMaster	92210A110	$0.04	3	$0.12
Standoffs	Standoffs for base motor plate	McMaster	93505A925	$0.44	4	$1.76
Motor plate	Base motor attachment plate	Custom	-	$30.00	1	$30.00
Shaft coupler	Shaft coupler for motor to bearing block shaft	McMaster	2464K16	$43.51	1	$43.51
Bearing block	Custom bearing block housing	Custom	-	$20.00	1	$20.00
Bearings	Bearing for bearing block	McMaster	3756T57	$9.64	2	$19.28
Shaft	Shaft for bearing block	McMaster	1257K113	$4.12	1	$4.12
Base PCB	Printed circuit board for base	Cutom	-	$100.00	1	$100.00
XBEE Radio	Base XBEE radio	Mouser	XB24-AWI-001	$19.00	1	$19.00
Base motor controller	Motor controller for base motor	Maxon	466023	$81.15	1	$81.15
NI MyRIO	MyRIO processor for base	National Instruments	783072-01	$750.00	1	$750.00
Base lower plate	Base plate for base	Custom	-	$30.00	1	$30.00
Feet	Adjustable feet	McMaster	9540K24	$0.16	4	$0.64
MyRio bracket	Angle bracket for myRIO	Custom	-	$20.00	1	$20.00
Base PCB plate	Laser cut plate for base PCB	Custom	-	$10.00	1	$10.00
Base front plate	Laser cut plate for base front	Custom	-	$10.00	1	$10.00
Base standoffs	Standoffs for base structure	McMaster	92210A241	$0.09	4	$0.35
Standoff screws	Screws for standoffs for base	McMaster	92210A110	$0.03	8	$0.27
Base top plate	Top plate for base structure	Custom	-	$30.00	1	$30.00
Bearing block screws	Screws to hold bearing block	McMaster	92210A110	$0.03	4	$0.13
Thrust bearing	Bearing between base and satellite	McMaster	6655K13	$2.21	1	$2.21
					TOTAL BASE	$1,396.63

Table 2: Satellite Bill of Materials

Part	Description	Vendor	Vendor Part #	Price (USD)	Qty	Ext
Shaft collar	Collar to attach satellite base to shaft	Custom	-	$25.00	1	$25.00
Satellite base	Laser cut base of satellite	Custom	-	$10.00	1	$10.00
Satellite side A	Arduino side of satellite	Custom	-	$10.00	1	$10.00
Satellite side B	Battery receiver side of satellite	Custom	-	$10.00	1	$10.00
Satellite side C	Other sides of satellite	Custom	-	$10.00	2	$20.00
Satellite top	Top of satellite	Custom	-	$15.00	1	$15.00
Satellite corner posts	Corner posts of satellite structure	3D printed	-	$5.00	3	$15.00
Solar panel brackets	Brackets to attach solar panels	3D printed	-	$7.00	2	$14.00
Battery receiver	Receiver for battery pack	3D printed	-	$15.00	1	$15.00
Battery pack	Battery housing for 9Volts	3D printed	-	$20.00	1	$20.00
9V batteries	Rechargeable 9V batteries	Amazon	EBL 9V	$4.33	4	$17.32
Reaction wheel motor	MAXON EC45 Flat	Maxon	251601	$105.20	1	$105.20
Reaction wheel	Brass reaction wheel	Custom	-	$40.00	1	$40.00
RW plate	Laser cut plate for motor	Custom	-	$3.00	1	$3.00
RW standoffs	standoffs for motor plate	McMaster	93505A438	$0.65	6	$3.90
RW standoff screws	screws for standoffs	McMaster	92210A110	$0.03	12	$0.40
RW motor screws	screws to attach RW motor	McMaster	92210A110	$0.04	3	$0.12
Arduino DUE	Satellite main processor	Amazon	Arduino Due	$33.97	1	$33.97
Satellite PCB	PCB for satellite top stack	Custom	-	$150.00	1	$150.00
Motor controller	ESCON 24/2	Maxon	466023	$81.15	1	$81.15
XBEE radio	XBEE radio for top	Mouser	XB24-AWI-001	$19.00	1	$19.00
IMU	LSM9DS1	Sparkfun	SEN-13284	$15.95	1	$15.95
DCDC Step up	Regulator	Pololu	S18V20ALV	$15.95	1	$15.95
DCDC Step down	Regulator	Pololu	S18V20AHV	$17.95	1	$17.95
Satellite screws large	Structure screws	McMaster	92210A241	$0.09	26	$2.34
Satellite screws small	PCB stack mounting screws	McMaster	91251A196	$0.11	4	$0.42
					TOTAL SATELLITE	$660.67

Table 3: YoYo Accessory Bill of Materials

Part	Description	Vendor	Vendor Part #	Price (USD)	Qty	Ext
YoYo housing	3D printed housing for YoYo	3D printed	-	$50.00	1	$50.00
YoYo electromagnets	Electromagnets for YoYo	APW	EML20mm-12	$28.60	2	$57.20
YoYo Brackets	Adjustable brackets to hold YoYo deployment masses	3D printed	-	$15.00	2	$30.00
YoYo PCB	Custom PCB for YoYo actuation	Custom	-	$20.00	1	$20.00
YoYo masses	Deployment masses for YoYo experiment	Custom	-	$25.00	2	$50.00
YoYo string and balls	String and attachment balls for YoYo masses	Custom	-	$5.00	2	$10.00
					TOTAL YOYO	$217.20

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