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An IMU for You and I

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An IMU for You and I

Abstract

Analyzing dynamics in three dimensions is challenging for students. This is because certain concepts become more complicated moving from two dimensions to three dimensions (e.g. moment of inertia) while others become both more complicated and less intuitive (e.g. angular momentum). As the number of interacting bodies grows, this is only further exacerbated.

One of the fundamental skills necessary to navigate this increasing complexity is the ability to correctly express quantities in different reference frames. However, students often find the mathematics for translating between different frames to be dry and abstract, particularly if introduced early in a course. Thus, they may not gain the understanding of concepts, such as rotation transformation matrices, Euler angles, or quaternions, that they need for later success.

In order to address this problem, a five-week long project on identifying a consumer application that would benefit from an IMU data logger was developed for an intermediate dynamics course. Over the course of the project, students are tasked with developing hardware for their application, collecting data from an IMU, and presenting that data in a relevant, graphical form. This project places the mathematical tools that students need to learn in the context of a compelling, real-life situation, thereby making them more relevant. It also connects abstract mathematics to a specific hardware implementation, providing a valuable hands-on learning experience that is often missing in this type of class. Finally, because the project focus is self-selected, students are intrinsically motivated and generally more engaged with the material than they would be otherwise.

This paper provides details of the organization of the project and the methods by which students were evaluated. Survey data which gauged student perceptions of the project, including their ability to apply key concepts, use campus resources, and capture and process IMU data, is also presented and used to assess project effectiveness. This data shows that students valued the IMU project and the opportunity to work with hardware, and generally found the project helpful in learning the mathematics necessary to relate different reference frames.

Introduction

Undergraduate mechanical engineering students find it difficult to analyze the dynamics of rigid bodies in three dimensions. This topic is usually developed during a second course in dynamics that comes later in the curriculum, often entitled "intermediate dynamics" or "advanced dynamics." One reason students struggle is lack of preparation: they may have misconceptions about dynamics that were unresolved by their first dynamics course. This issue is relatively easy to diagnose using concept inventories and similar instruments[1-3] and limited instruction will usually "fill the gaps." However, even well-prepared students are often challenged by the added complexity that comes from working in three dimensions in intermediate dynamics. Much of this complexity arises because orientation and rotation axes are arbitrary in three-dimensional analysis instead of being restricted to a single axis that is perpendicular to a plane as in two-dimensional analysis. The practical implications in moving from two to three dimensions are numerous. A single, scalar angle can encode rotation in 2D, but a more complicated description involving at least 4 scalars is required in 3D. Moment of inertia is a scalar in 2D, but becomes a tensor in 3D. Angular momentum is relatively easy to understand in 2D but unintuitive in 3D.

To successfully navigate these and other challenges, students need a working knowledge of the mathematics required to express quantities in different reference frames. The specifics involved include rotation transformation matrices, Euler angles, axis-angle representation, and quaternions. However, these tools appear abstract and boring to students to whom it is unclear why they are necessary, particularly if introduced early in a course. In order to motivate students to learn these useful transformations, and thereby put them on a good footing for the rest of an intermediate dynamics course, a project was developed in which students were tasked with developing an inertial measurement unit (IMU) data logger for a consumer application. During this five-week long project, students were responsible for brainstorming and justifying an application, becoming familiar with IMU hardware, developing code for expressing IMU orientation in different ways, building supporting hardware and collecting data for their application, and presenting the case for their application alongside graphs summarizing their collected data.

The IMU project was hypothesized to benefit an intermediate dynamics class in several ways. In general, project-based learning should help students better learn material, as this is supported by the literature.[4] In particular, because the project provides an opportunity to use the mathematics needed to describe reference frame orientation within a compelling context, it should help students better learn this material. The associated research question is: does this project help students better understand and apply the mathematical tools associated with 3D orientation? In addition, because students are seeing a practical, concrete example of how what they are learning can be applied and have the opportunity to "get their hands dirty" using modern hardware, there should be increased student engagement. Other, similar projects in dynamics have shown this benefit. [5-7] Increased engagement should be supported by the fact that the project offers students the opportunity to customize their learning, allowing them to choose a specific application area of interest to them, which has also been shown to drive student engagement.[8] The associated research question is: do students enjoy the project and does it motivate them? In a class that can be theoretical and abstract, it is difficult to understate the importance of this benefit.

The IMU project is easy to implement, as feedback to students can generally be handled in a weekly check-in meeting, lowering the teaching burden. The project is also short, which allows other projects to be implemented as part of the same course.

The remainder of this paper presents details for implementing the IMU project as part of a senior-level, intermediate dynamics course. It also presents quantitative and qualitative student feedback regarding the implementation and its effectiveness, providing insight about the two research questions posed previously. Overall, this feedback suggests the IMU project is effective in helping students learn transformations important for intermediate dynamics as well as other practical skills. Conclusions, as well as suggestions for further improving or adapting the project, close the paper.

Project Description

The IMU project was incorporated as part of a senior-level technical elective in intermediate dynamics that had junior, senior, and graduate students enrolled. The project was used for teaching and assessment in addition to homework, quizzes, exams, and other projects in the course. It ran for five weeks and was weighted as 10% of the overall course grade. Prerequisites for the project include knowledge regarding introductory dynamics, circuits, and basic programming. Undergraduate students tackled the project in teams of two; graduate students were asked to complete the project on their own.

To kick off the project, students were presented with background information about what an IMU is and how it works as well as some common applications where IMUs are used commercially or for research. Then students were presented with the overall aim of the project: collecting and processing IMU data for a compelling consumer application.

Each week of the project had its own goal and deliverable. The deliverable was presented during a five minute in-class appointment with the instructor each week to help students remain on track. Additional details on deliverable assessment are provided in the project assessment section below. Table 1 presents a brief description of the goal and deliverable for each of the five weeks of the project as taken from the project handout. The complete project handout, as presented to students, is also available at the end of this paper in Appendix A.

Table 1: The goals and project deliverables by week.

Week 1	**Goal**: Get your IMU up and running. Can you get your IMU to turn on, interface with a computer, and log data? You should ensure you can change what is written in the log file so that only the outputs you need are recorded. **Deliverable**: A live demonstration of your IMU logging data during our team meeting time.
Week 2	**Goal**: Validate the output of your IMU (ie confirm it is providing the correct orientation data). To do this, you will write a MATLAB script to convert orientation data from one of the sensor outputs (quaternions, Euler angles) to a rotation transformation matrix. You can use the rotation matrix representation to easily plot measured orientation. **Deliverable**: A demonstration of your MATLAB conversion script and discussion of your testing procedure.
Week 3	**Goal**: Determine an interesting consumer application for your IMU and then design and build mounting hardware appropriate to that application. **Deliverable**: The case for why an IMU would benefit your application and the design/build of your mounting hardware.
Week 4	**Goal**: Collect data specific to your consumer application and present it in an intuitive, graphical form. I encourage you to write a MATLAB script to demonstrate the orientation over time using custom graphics. **Deliverable**: Your application specific data, how you collected that data, and progress towards presenting results graphically.
Week 5	**Goal**: Develop a presentation highlighting the development and data related to your application. **Deliverable**: A showcasing of your project to the class. You should include many of the things you have already accomplished including: the case for your consumer application, design of the mounting hardware, data collection procedure, and graphical results. Make your presentation both fun and informative!

Project Resources

Each student team was provided with a set of hardware that included: one SparkFun 9 DOF Razor IMU[9], one USB type B cable, one microSD card and card adapter, one 850 mAh lithium-ion battery, and one battery bag to store their battery. A photograph of this collection of physical hardware is provided in Figure 1. They were also pointed to the Sparkfun Hookup Guide[10] for tips on setting up the IMU and getting it to log data when connected to computers using different operating systems.

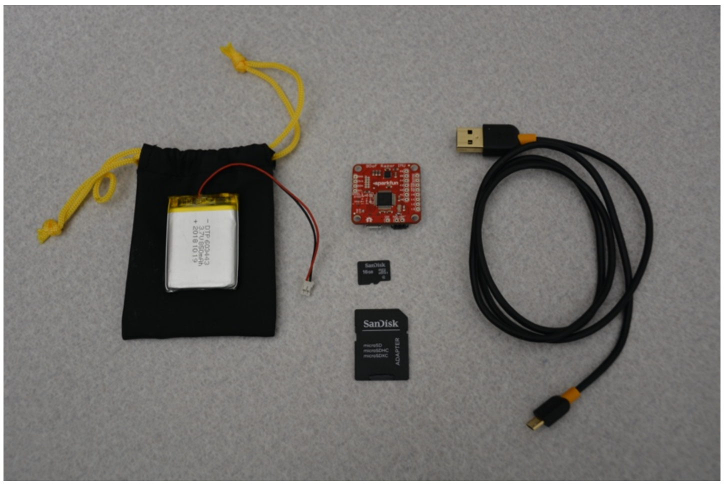

Figure 1: The supplied components for the IMU project.

In addition to the physical hardware, students were provided instruction during the lecture portion of the course on the different transformation representations: rotation transformation matrices, axis-angle representations, Euler angles, and quaternions. They also had access to campus Makerspaces in order to build mounting hardware or other application specific components; students primarily used 3D printing and laser cutting to manufacture their designs if they used these resources.

Project Assessment

Students were required to have a check-in meeting with the instructor during class once a week for the first four weeks of the project. They received either a complete or incomplete grade based on the week's deliverable. Completing a check-in successfully by supplying the specified deliverable was worth 1% of the course grade; the check-in deliverables were previously listed in Table 1. If students were unable to complete a check-in during class, they were required to meet the instructor during office hours that week and could receive half credit for a complete check-in at that time. This helped to keep students on track and ensured that any teams that were struggling received additional help as they needed it.

Students were also required to present their application, hardware, and data to the entire class at the conclusion of the project. This presentation was worth 6% of the course grade. Students were provided a detailed rubric regarding the evaluation of their projects as shown in Figure 2. This rubric was used to assess student performance in six categories: sensor validation, consumer

IMU Project Rubric

Category	Score				
	4	3	2	1	0
Sensor Validation Orientation Data Conversion Utility and IMU Testing	**Thorough** The program to convert IMU orientation data (quaternions, Euler angles) to a rotation matrix is correct and well-documented. A systematic process is used to confirm orientation measurement about all axes.	**Complete** The program to convert IMU orientation data (quaternions, Euler angles) to a rotation matrix is correct, but may lack documentation. An ad-hoc process is used to confirm orientation measurement about some axes.	**Incomplete** The program to convert IMU orientation data (quaternions, Euler angles) to a rotation matrix has minor errors. An attempt is made to confirm orientation measurement, but it is inconclusive.	**Cursory** The program to convert IMU orientation data (quaternions, Euler angles) to a rotation matrix has major errors. An attempt is made to confirm orientation measurement, but it is inconclusive.	**Missing** No program is provided to convert IMU orientation data (quaternions, Euler angles) to a rotation matrix. No attempt is made to confirm orientation measurement.
Consumer Application Case for Using an IMU in Your Application	**Compelling** A reasonable case is developed for why this particular application is interesting and would benefit from an IMU. Significant evidence from outside sources is used to support the argument.	**Convincing** A reasonable case is developed for why this particular application is interesting and would benefit from an IMU. Little to no evidence from outside sources is used to support the argument.	**Unconvincing** A questionable case is developed for why this particular application is interesting and would benefit from an IMU. The argument makes some assumptions or assertions unsupported by fact.	**Weak** A questionable case is developed for why this particular application is interesting and would benefit from an IMU. The argument is illogical or substantially unsupported by fact.	**Missing** No case is developed for why this particular application is interesting and would benefit from an IMU.
Sensor Mounting Hardware Design and Manufacture	**Excellent** A design suitable for the application is developed. The manufactured hardware works as expected and effectively secures the IMU.	**Acceptable** A design suitable for the application is developed. The manufactured hardware has minor flaws, but secures the IMU.	**Unacceptable** A suitable design for the application is developed. The manufactured hardware has major flaws and cannot secure the IMU.	**Poor** An unsuitable design for the application is developed leading to hardware that cannot secure the IMU.	**Missing** No mouting hardware is designed or manufactured to secure the IMU.
Data Collection Procedure for Collecting Orientation Data	**Thorough** A logical procedure is followed to collect application specific data. The data collected is sufficient to capture most user behavior expected in this application.	**Complete** A logical procedure is followed to collect application specific data. The data collected is sufficient to capture some user behavior expected in this application.	**Incomplete** A questionable procedure is followed to collect application specific data, leading to data that may only capture a small fraction of the user behavior expected in this application.	**Cursory** An illogical procedure is followed to collect application data, leading to data that may not capture any of the user behavior expected in this application.	**Missing** No application specific data is collected.
Data Representation Graphical Representation and Interpretation of Orientation Data	**Captivating** The way the orientation data is presented is innovative and helpful to the application's users. The interpretation of the data is well-reasoned and insightful.	**Informative** The way the orientation data is presented is likely to be helpful to the application's users. The interpretation of the data is well-reasoned.	**Uninformative** It is unclear if the way the orientation data is presented will be helpful to the application's users. The interpretation of the data is questionable.	**Distracting** The way the orientation data is presented is likely to be confusing to the application's users. The interpretation of the data is incorrect or incomplete.	**Missing** The orientation data is not presented.
Project Presentation Documentation and Oral Presentation	**Excellent** Visual aids are used appropriately and information is presented in a logical order. Effective presentation skills (pacing, eye contract, etc.) are used throughout. The presentation is polished.	**Acceptable** Visual aids are referenced for major points, but could be better developed. Information is reasonably organized. Effective presentation skills (pacing, eye contact, etc.) are evident but could be improved.	**Unacceptable** Visual aids are used somewhat, but do not seem to be important to major points. Information seems disorganized. Effective presentation skills (pacing, eye contact, etc.) are used infrequently.	**Poor** Visual aids are lacking or not included. Important information is missing. Effective presentation skills (pacing, eye contact, etc.) are rarely or never used.	**Missing** No project presentation is submitted.

Figure 2: The assessment rubric used to evaluate the final project presentations.

application, sensor mounting, data collection, data representation, and project presentation. Each rubric category was scored on a zero to four scale (missing, poor, unacceptable, acceptable, excellent) according to descriptions provided on the rubric.

In general, students came up with interesting applications for the project including IMU monitoring of table tennis motions, soft robot angle measurements, and characterization of lower leg motion while running. All teams were able to complete the project successfully, generating and reporting meaningful data.

Student Feedback

To determine how successful the project was in terms of its implementation and meeting learning goals, students were asked to provide feedback regarding the project on a survey that asked them to rate certain project aspects on a five-point Likert scale and answer some free-response questions. The survey form is provided in Appendix B. All nine students enrolled in the class completed the survey. The overall response to the project was positive. Students indicated the project helped them appreciate how dynamics could be used in a consumer application. They also indicated it helped them better develop skill in representing orientations in three dimensions and, at least to some degree, additional ancillary skills.

Student responses to questions related to the primary goals of the project are shown in Figure 3. Subplot A indicates that for most students, this was their first exposure to the IMU as a sensor (a few students indicated having used an IMU previously in research) while subplot B indicates that all but one student agreed that the project helped them see how dynamics could be used in a consumer application. All of the students agreed that the project helped them practice converting between different orientation representations as shown in subplot F, with nearly half of them strongly agreeing. This suggests the project was successful in helping the students learn these important mathematical tools. Because not all of the tools (rotation transformation matrices, Euler angles, quaternions) were required to be used by all groups, there is a mixture of agreement regarding whether the project improved understanding for each specific representation in subplots C through E. Thus, it seems reasonable to conclude that the project was helpful both in teaching students the mathematics needed to express quantities in different reference frames as well as showing intermediate dynamics is useful in a real-life setting.

Figure 4 captures student responses regarding ancillary skills they may have developed as a result of the project. Here the results were more mixed. Based on subplots B and C the majority of students felt the project did help them in experimental planning and data capture and in learning new ways to produce visualizations in MATLAB. However, few students found the project provided practice in producing physical hardware using campus MakerSpaces. This is likely because many teams ended up producing their sensor mountings using off-the-shelf components and did not need to use the campus facilities.

Finally, Figure 5 presents results regarding how much students enjoyed the project and how well they thought it was implemented. All but one student (who gave a neutral rating) indicated they enjoyed working on the project overall, and all students agreed, with over three quarters of them agreeing strongly, that they appreciated the opportunity to work with physical hardware during

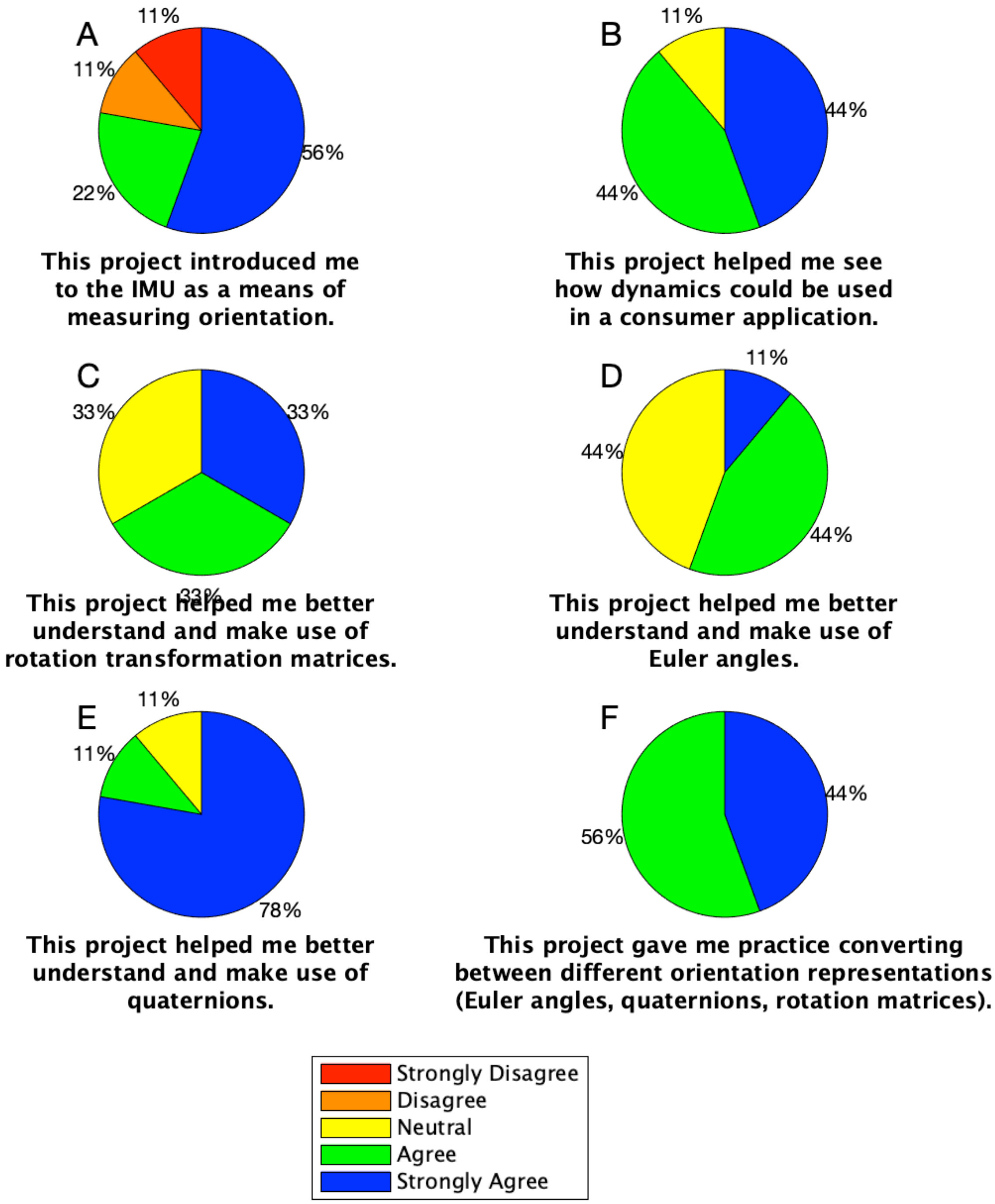

Figure 3: Student responses to questions regarding the project's effectiveness regarding learning goals. Prompt A evaluates student familiarity with IMU hardware. Prompt B assesses if students see how dynamics could be used in a consumer application. The remaining prompts assess student skill development regarding mathematics of orientation and reference frames with regard to (C) rotation transformation matrices, (D) Euler angles, (E) quaternions, and (F) overall.

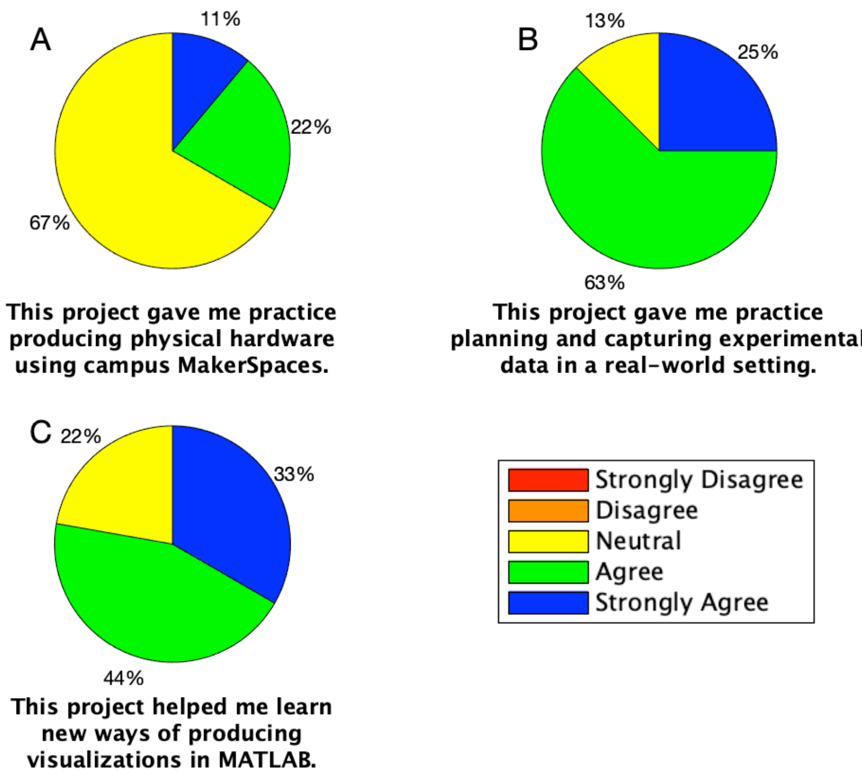

Figure 4: Student responses to questions regarding the development of ancillary skills. The prompts assess student skill development regarding A using campus MakerSpaces, B planning and conducting experiments, and C producing MATLAB visualizations.

the project. In addition, students generally agreed that the information provided for the project, guidance from the instructor, and the project workload were all reasonable.

The written comments provided by students provide additional insight into how they perceived the project. All of the student comments are provided in Appendix C. In response to the prompt about what part of the project they enjoyed the most, students indicated a range of activities. Two students indicated the agency they had in choosing their application or what kind of data they wanted to collect as the biggest highlight. Three students indicated that calibrating the IMU or visualizing the IMU data was the most enjoyable part. Two students indicated data collection as a highlight. Finally, two students indicated designing the apparatus or prototyping as the best part. The diversity of these responses seems to indicate that many different aspects of this project can appeal to students and it stands to reason that this can help motivate and engage students during different phases of the project.

Responses to the prompt regarding the most significant things learned from the project are also very diverse. Two students mentioned that being able to use different orientation representations (the primary learning goal) was the most significant thing learned. However, students also reported learning about the importance of troubleshooting hardware and collecting data, making comments like “I learned how to plan an experiment and collect data. There’s always a need for being careful.” and “It is important to check and double check hardware before testing to ensure

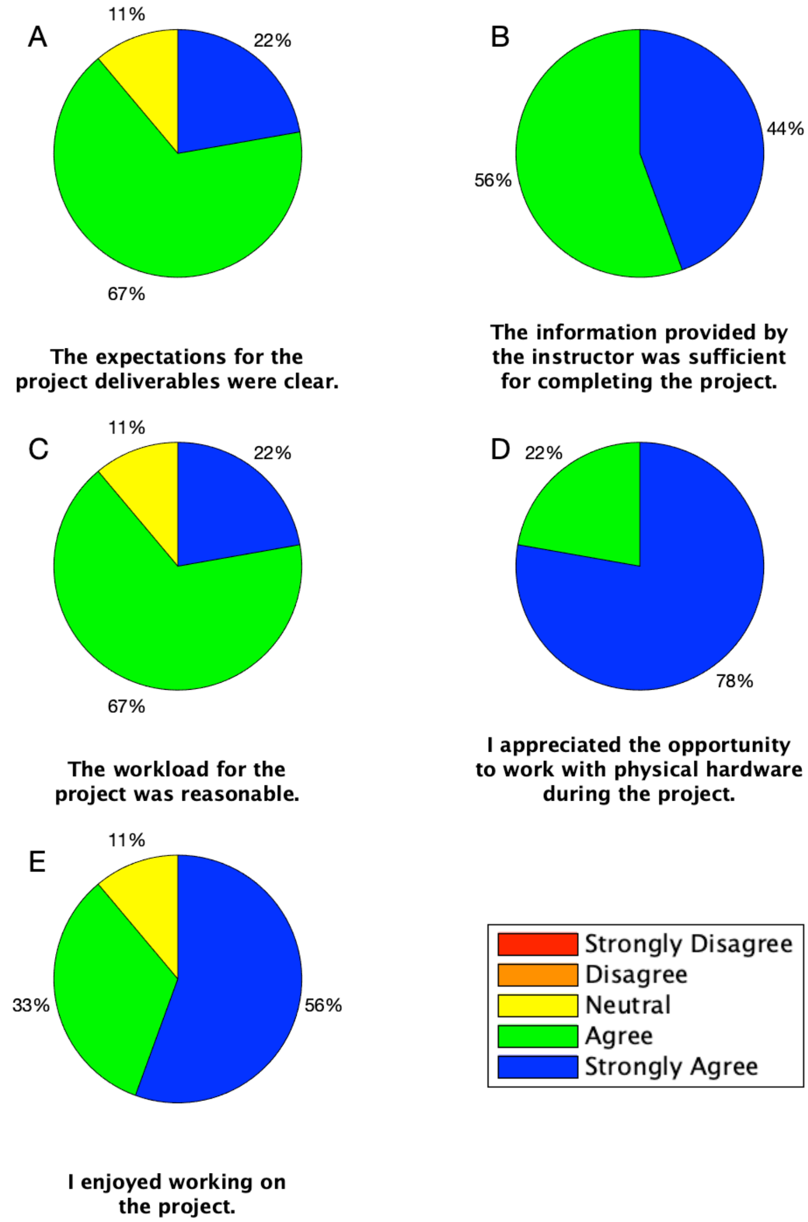

Figure 5: Student responses to questions regarding the project implementation. The prompts assess (A) clarity of the expectations, (B) sufficiency of provided information, (C) project workload, (D) student enjoyment of working with hardware, and (E) overall student enjoyment.

the right data is being collected." This suggests that the project helped students realize the importance of careful hardware calibration and data collection and how this could impact results.

Future Improvements

The students made several suggestions for improving the project. Some students mentioned they could use more guidance regarding selecting an application. This suggests it might be helpful to have students make an initial proposal for their consumer application in week two of the project, enabling them to get feedback from the instructor and other members of the class before settling on a final application in week three and fleshing out details.

Students also mentioned they would like a more time to work on the project, either to further develop their hardware during the application development phase in week 3 or to do a more in-depth data collection and analysis in week 4. Although I think the short timeline of the project is a strength, I could see that splitting week 4 into two weeks: a preliminary data collection week and a final data collection and visualization week to give students that chance for more considered analysis.

The project could be easily scaled for a longer timeframe simply by including multiple IMUs and requiring students to investigate the relative motions of multiple bodies. This might be an interesting direction to explore in future course offerings. The project could also be a springboard from which students could research the hardware and sensor fusion algorithms used to make orientation measurement possible.

Conclusions

Students are highly motivated to participate in a project that involves IMU hardware during a course in intermediate dynamics. This provides a valuable hands-on experience in a class that can often be theoretical and abstract. A project involving this hardware can also be used to teach the mathematics most important to reference frames and orientation in context, thereby motivating students to better grasp these concepts early in the course. Finally, because this project asks students to identify a consumer application in which an IMU would be beneficial, it provides an opportunity for students to think creatively and entrepreneurially about how dynamics and their engineering skill set connects to their broader lives.

Acknowledgements

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Appendix A: Project Handout

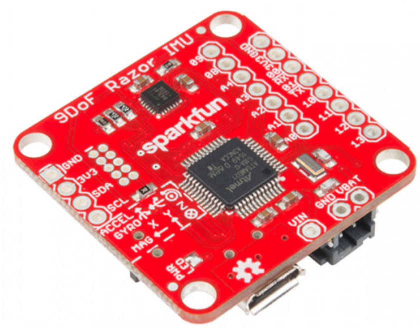
MECH 4XX/6XX Project 1 | Professor X
Spring Semester – 2019 | **Due: Feb 22, 2019** | X University

Project 1: An IMU for You and I

Background

An IMU (Inertial Measurement Unit) can be used to determine an object's orientation over time. An IMU typically combines three sensors: a three-axis accelerometer for measuring linear acceleration, a three-axis gyroscope for measuring angular velocity, and a three-axis magnetometer for measuring the earth's magnetic field. The data from these sensors are combined in a process called sensor fusion to determine orientation.

IMUs were originally used as part of navigation systems for ships, aircraft, missiles, spacecraft and other vehicles. As they have grown smaller and more inexpensive, they have been incorporated into more consumer products. For example, your smartphone contains an IMU as an orientation sensor. IMUs are also increasingly common in sports- and gaming-related technology.



Project Goal

In teams of two, you will have the opportunity to identify a consumer application that could benefit from an IMU data logger and design software and hardware that will enable your data logger to be deployed and generate quality data. Using campus MakerSpaces, you will realize your hardware and then proceed to collect application-specific IMU data. You will translate the orientation data provided by the IMU into different mathematical representations and write code that will present the orientation data in a way that is meaningful to your consumer.

Objectives

At the end of this project, you should be able to:

- generate a list of consumer applications where measuring rigid body orientation would be valuable
- design and manufacture a sensor housing using campus MakerSpace resources (e.g. Solidworks, 3D Printing, Laser Cutting, etc.)
- set-up an IMU to log data for a particular application, by setting options such as the sampling rate, data output, etc.
- convert IMU orientation data between different formats (quaternions, Euler angles, rotation matrices)
- present IMU orientation data graphically in a way that is meaningful to your application

Provided Materials

- one SparkFun 9 DOF Razor IMU
- one USB type B cable
- one microSD card and card adapter
- one 850 mAh lithium-ion battery
- one battery bag

Timeline and Deliverables

In order to help you stay on track during the project, each team will have a five-minute meeting with the instructor every week. Each meeting has a specific deliverable as outlined below.

Week One
Ends Jan 25

Goal: Get your IMU up and running. Can you get your IMU to turn on, interface with a computer, and log data? You should ensure you can change what is written in the log file so that only the outputs you need are recorded.
Deliverable: A live demonstration of your IMU logging data during our team meeting time.

Week Two
Ends Feb 1

Goal: Validate the output of your IMU (ie confirm it is providing the correct orientation data). To do this, you will write a MATLAB script to convert orientation data from one of the sensor outputs (quaternions, Euler angles) to a rotation transformation matrix. You can use the rotation matrix representation to easily plot measured orientation.
Deliverable: A demonstration of your MATLAB conversion script and discussion of your testing procedure.

Week Three
Ends Feb 8

Goal: Determine an interesting consumer application for your IMU and then design and build mounting hardware appropriate to that application.
Deliverable: The case for why an IMU would benefit your application and the design/build of your mounting hardware.

Week Four
Ends Feb 15

Goal: Collect data specific to your consumer application and present it in an intuitive, graphical form. I encourage you to write a MATLAB script to demonstrate the orientation over time using custom graphics.
Deliverable: Your application specific data, how you collected that data, and progress towards presenting results graphically.

Week Five
Ends Feb 22

Goal: Develop a presentation highlighting the development and data related to your application.
Deliverable: A showcasing of your project to the class. You should include many of the things you have already accomplished including: the case for your consumer application, design of the mounting hardware, data collection procedure, and graphical results. Try to make your presentation both fun and informative!

Grading

This project is worth 10% of the course grade. Successfully accomplishing each weekly checkpoint is worth 1%. If you are unable to accomplish a weekly checkpoint, you will have the opportunity to do so during office hours for half credit. The final class presentation is worth 6%. A rubric will be provided regarding the class presentation grading.

Appendix B: An IMU for You and I - Feedback Form

Please answer each question as it pertains to the IMU project.

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
The project introduced me to the IMU as a means of measuring orientation.					
The project helped me see how dynamics could be used in a consumer application.					
The project helped me better understand and make use of rotation transformation matrices.					
The project helped me better understand and make use of Euler angles.					
The project helped me better understand and make use of quaternions.					
The project gave me practice converting between different orientation representations (Euler angles, quaternions, rotation matrices).					
The project gave me practice producing physical hardware using campus MakerSpaces.					
The project gave me practice planning and capturing experimental data in a real-world setting.					
The project helped me learn new ways of producing visualizations in MATLAB.					
The expectations for the project deliverables were clear.					
The information provided by the instructor was sufficient for completing the project.					
The workload for the project was reasonable.					
I appreciated the opportunity to work with physical hardware during the project.					
I enjoyed working on the project.					

1. What part of the project did you enjoy the most?

2. What is the most significant thing you learned from the project?

3. What aspect of the project could be improved? How would you make an improvement?

4. Other project related comments.