AC 2009-2254: EXPERIMENTAL DETERMINATION OF TORQUE CONTROL CAPABILITY OF A MODULAR ROBOT ACTUATOR: AN UNDERGRADUATE RESEARCH PROJECT

Matthias Lang, University of Texas, Austin
Undergraduate Student, Mechanical Engineering Department, The University of Texas at Austin

Dinesh Rabindran, University of Texas, Austin
PhD Candidate, Mechanical Engineering Department, The University of Texas at Austin

Tricia Berry, University of Texas, Austin
Director of Women in Engineering Program, Cockrell School of Engineering, The University of Texas at Austin

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Abstract

The goal of this manuscript is to present the undergraduate research experience of the first author as a mentee in Graduates Linked with Undergraduates in Engineering (GLUE) initiative at the Cockrell School of Engineering in The University of Texas at Austin. GLUE is a retention and career development program developed and managed by the Women in Engineering Program (WEP) at The University of Texas at Austin (UT Austin). GLUE is designed to address undergraduate attrition and low rates of perseverance to graduate school. This mentoring program partners a senior graduate student with an undergraduate mentee to work on an engineering research project within the major of both the mentor and the mentee. The GLUE program will be five years old in Spring 2009.

This undergraduate research experience involved a project in the field of robotics. Safety in human-robot interaction is an issue that has received much attention in the literature recently. To make robot manipulators safe around humans, it is important to be able to control them in torque mode in addition to velocity control capability. The undergraduate research project presented in this paper focused on determining the motor current to output torque relationship for a commercial robot actuator, which in turn enables torque-based dynamic control. The mentee participated in an experimental project to determine the torque characteristics of a commercially available modular robot actuator. The outcome of this effort was a set of experimental data (torque to current mapping for the actuator) which then facilitates torque-based dynamic control of the modular manipulator assembled from these actuators.

Introduction

Why do research in robotics as an undergraduate? Because I neither had experience doing graduate level research nor did I have any introduction to the field of robotics through formal coursework or internships. Oxford defines research as “a careful study of a subject, especially in order to discover new facts or information about it” and “work that tries to find new products and processes or to improve existing ones[1].” Robotics is defined as “the science of designing and operating robots[2].” Both of those definitions were proven to be true as I progressed throughout my experience.

I was reluctant to enroll for the Graduates Linked with Undergraduates in Engineering (GLUE) class my sophomore year, which paired me with a great graduate mentor to conduct undergraduate research. The main focus of GLUE is to provide undergraduate students with a real-life perspective of graduate research and encourage students to pursue a degree beyond the completion of their undergraduate studies. Upon its completion, the class allowed me to take the following knowledge from it: gain research experience as well as technical writing and presentation skills, learn about the application process for graduate school, gain information about research opportunities, research in today’s industry, and get a perspective into life as a graduate student.

During my research I was able to participate in a robotics project and, consequently, appreciate some research issues in this exciting field. In many of today's robots that physically interact with humans, safety is a pervasive issue. This issue has to be addressed to improve the acceptance of robots in human environments. To improve the versatility and safety of robot manipulators it is important to be able to control these devices in both torque- and velocity-modes. In our study, we wanted to determine the relationship between current input and actual torque output for a commercially available modular robot actuator. The motivation behind this work was the need to accurately operate a modular manipulator by utilizing its dynamic behavior. In this paper I will take you through my research experience by providing a literature review, GLUE program details, our project's problem statement, methodology, results and conclusions, and suggested future work.

GLUE Program Details

GLUE gives undergraduate students the opportunity to gain practical research experience by pairing them with graduate students in their majors or with projects that match their interests. Undergraduate students assist with research projects and participate in a weekly seminar class where students share their research experiences, learn about research options in industry and academia, hear from panels of graduate students and engineers, and learn about graduate school and other undergraduate research options. Graduate students participate in career development workshops and gain mentoring, project management and teaching experience. The program also invites guest speakers that provide information on the topics most relevant to applying and getting through graduate school successfully.

The goals of GLUE are to:

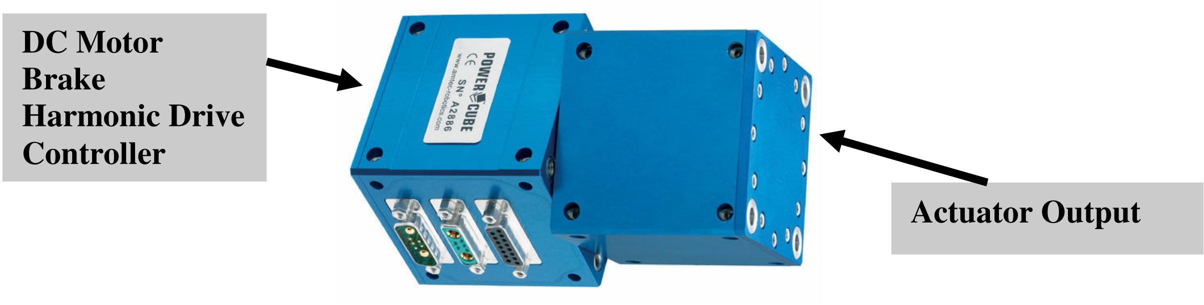
1. Contribute to the overall goal of WEP to recruit, retain and graduate women in the Cockrell School of Engineering at The University of Texas at Austin
2. Provide undergraduate students with the opportunity to experience research first-hand
3. Increase the number of female engineering students pursuing graduate degrees and research careers
4. Provide effective mentoring, career development and teaching opportunities for graduate students in engineering
5. Impart social responsibility to participants to give back through WEP to encourage others to pursue engineering in college or to pursue engineering graduate school

GLUE targets second and third year undergraduate women and second year and beyond graduate women. GLUE was founded by the Women in Engineering Program at UT Austin and is facilitated with support from engineering faculty and the Associate Dean for Student Affairs.

In a paper that specifically focuses on one of the GLUE participants, Rabindran and Berry[3] evaluate the impact of undergraduate research on the retention of students in the discipline of engineering and the possibility of them attending graduate school. Their work reflects the theme of the importance of undergraduate research that will be addressed in this paper as well. According to the pre-survey and post-survey of GLUE completed by the participant, it was shown that the participant gained valuable experience and progressed throughout the semester.

The set of criteria established by Rabindran and Berry[3] includes mentorship, contribution, adequacy, and technical communication. Based on these criteria, the GLUE program fulfills 75% of the requirements to successfully promote undergraduate research.

Research Project Description



(a) Powercube robot joint module

(b) Walking machine **(c) 7-DOF serial robot manipulator**

Figure 1. Picture of PR 110 joint module and some robotic systems assembled using this module[6]

In today's world, most robots are controlled in position-mode, that is, their operational objective is to move from one point to another along a specified path with a specified motion profile. Frequently, this means the robot or one of its arms will move from the starting position to the specified target position without regard to the forces (or disturbances) acting on it. For example, if you try to push on an industrial robot arm controlled in velocity-mode, it will not be disturbed from its commanded motion no matter how hard you push, unless, of course, you are able to provide so much force as to exceed the robot's torque capability. This is because, typically, such an arm uses high gear ratios and, often, links with high inertia. Due to the effect of the gear ratios and the high link inertias, the robot ‘seems’ more massive than it is when it interacts with its environment. This can be attributed to the amplification in apparent inertia due to the gear ratios. Nevertheless, this robot can be controlled to ‘behave’ like a lighter robot with certain limitations on its responsiveness (closed-loop control bandwidth). To do this, we use sensory feedback and, using certain algorithms, impose a dynamic behavior at the robot end-point. Most commercially available robots do not support the direct control of joint torques (or currents) – they allow only velocity-based control. Velocity-based control is not always the best option if the manipulator task involves making and breaking contact with its environment. Sometimes manufacturers allow joint torque control via joint current control. However the mapping between joint current and joint torque is not trivial and needs to be experimentally determined. In our project we determined this mapping for a commercially available modular robot actuator: the PR-110 powercube module from Amtec GmbH, Germany.

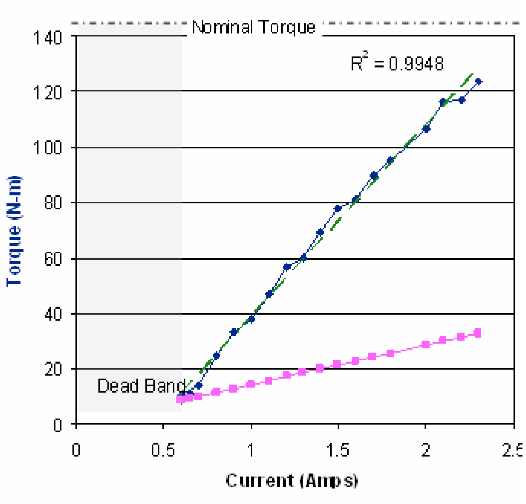


Figure 2. Mapping of Torque vs. Current for Powercube PR110 module determined by Rabindran et al[4]. The pink line represents estimated torque, the blue line shows the experimental torque data, and green dashed line shows a least square fit for this data.

A laboratory experiment similar to the one reported in this work was previously conducted by Rabindran et al[4]. During their preliminary experimental study on a PR-110 joint module, they found that there is a linear relationship between current input and torque output and that there is also a dead band at low current inputs (). We hope to extend those results by running a rigorous experimental test based on randomized and multiple tests for input current settings and also determining a closed-form equation relating the torque to current in both the positive and negative regions.

We will first take a closer look at the theory behind our experiments. The joint module is composed of a motor and gear train. The motor has a motor constant, K_{motor}, which according to Nise[5] will produce a motor torque, T_{motor}, according to the following relation:

$$T_{motor} = K_{motor}*I \qquad (1)$$

where I is the current supplied to the motor in Amps. The motor constant can be determined according to:

$$K_{motor} = T_{max}/I_{max} \qquad (2)$$

where T_{max} and I_{max} are the maximum torque and current, respectively, as supplied by the manufacturer in . The power-transfer from the motor to load can be expressed as:

$$T_{motor}*\omega_{motor}*\eta= T_{load}*\omega_{load} \quad (3)$$

where η is the efficiency specified by the manufacturer (). The symbol ω refers to angular velocity. The kinematic relationship is not affected by power losses:

$$\omega_{motor} = N*\omega_{load} \quad (4)$$

where N is the gear ratio (), the subscript motor refers to the quantities supplied by the actual motor, and the subscript load refers to the quantities supplied to the applied load after it has passed through the gear train. Therefore the relation between the motor and load torques is

$$T_{motor} = T_{load}/N \quad (5)$$

We wanted to work on improving the flexibility of control of robots, which also requires control in torque mode. The direct control of motor torques can enable a forgiving response of the robot which leads to improved safety. For this, the current to torque mapping for a robot actuator needs to be determined; however, knowledge of the dynamics of the mechanical system, in this case, a PR-110 robot joint with attached mass on a lever arm (), and electrical properties of the system are required as well. This leads us to the problem statements of our research project:

1. To test the actual torque output of the joint module at variable current inputs, and
2. To compare our results to the specifications listed by the manufacturer ().

In order to be able to answer the problems, we designed a set-up () where we understood and could control the dynamics of the mechanical system. The experimental testing that followed is described in the methodology section below.

Methodology

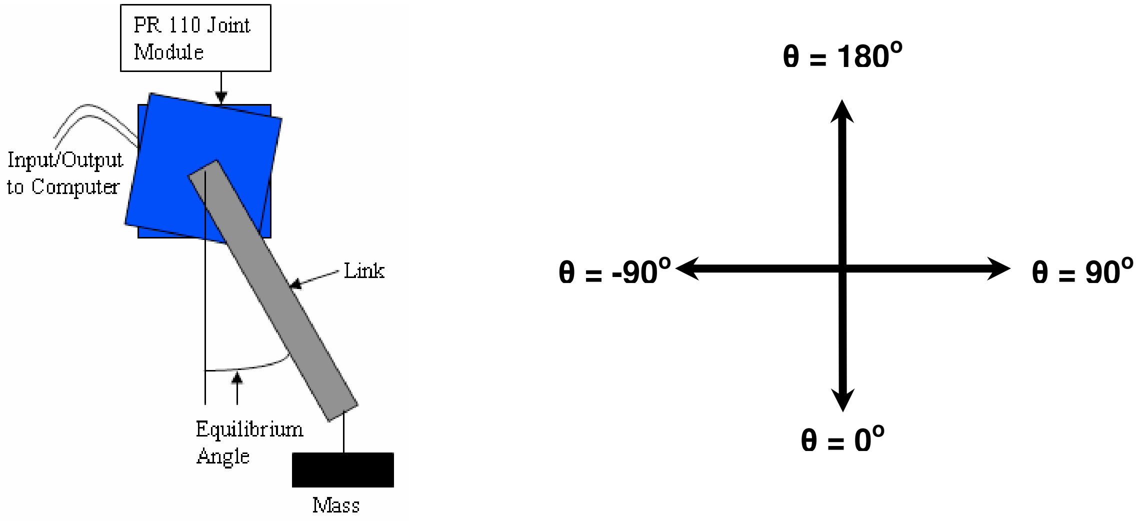


Figure 3. Schematic of setup with coordinate system.

We mounted a metal grate to the worktable, which allowed us to connect the PR-110 robot joint module (a) in a horizontal position that would allow us to take measurements in a vertical plane of rotation (under the influence of gravity). Attached to the motor was a link that is supposed to point straight down in order for it to be in the zero degree starting position of our "reference frame" (). However, to be rigidly attached, the link was offset at 45˚ from the square-face of the cubic joint module. We had to account for this fact while performing experiments and computing our results. The length and thickness of the link were measured and we used the Solidworks[7] CAD software to model the link to determine the total mass and center of mass of the link. In we show a photograph of our experimental testbed.

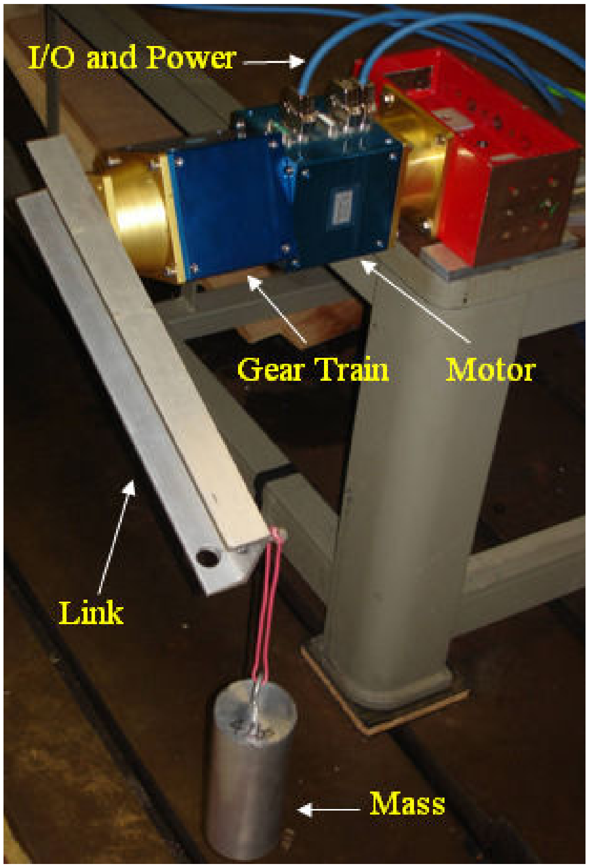
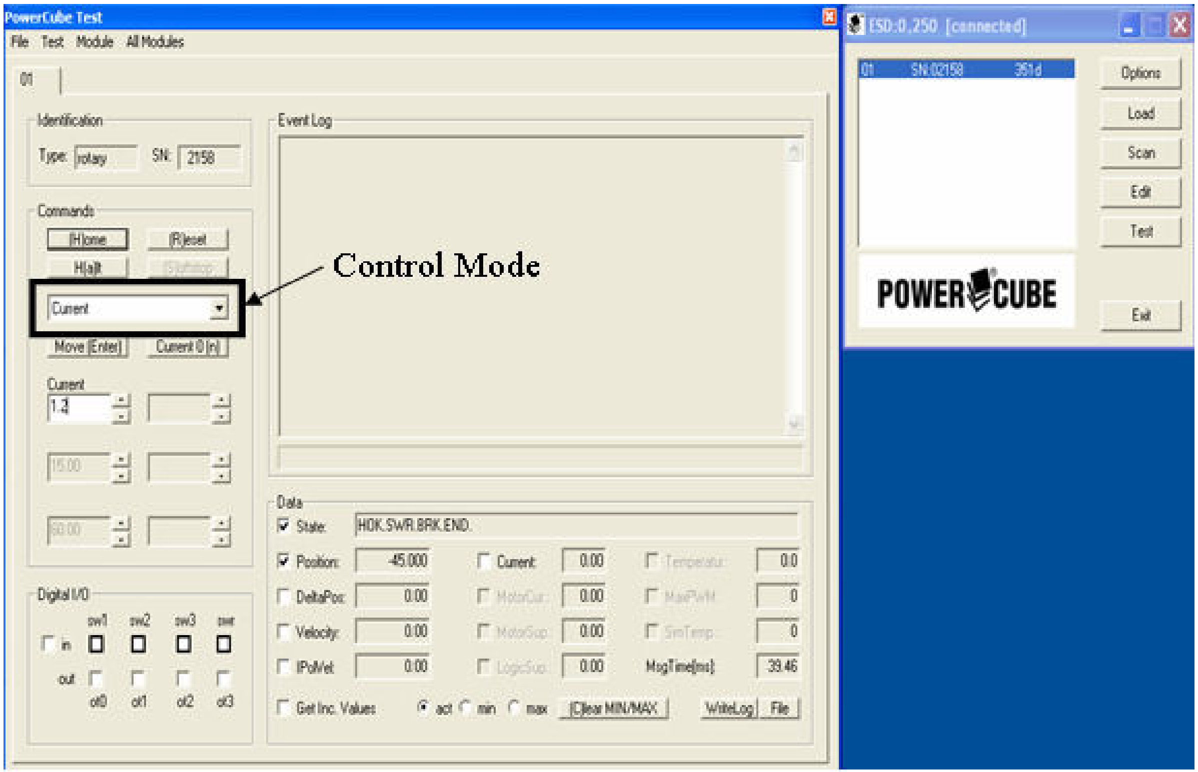


Figure 4. Photograph of the experimental testbed for measuring the current-torque mapping of the PR-110 module from Amtec GmbH, Germany.

We used the program Powercube.exe[8] () that comes with the module to control the input parameters and easily read off the output parameters. Our main objective was to study the effects on actual torque output when we varied the input current. In order to avoid getting "patterned" results, we decided to randomize the order of the input currents that we considered. Before starting each run/test, we had to return the link to the vertical position and attach the mass. The mass was hung from the very end of the link to allow it to swing freely and so that all the weight would act straight down in the vertical direction. A run/test was considered done once the link stopped moving and the position given as the relative angle of the joint model on the computer screen was no longer changing or fluctuating (in other words, readings were recorded at steady state). Since our testbed used hanging weights, it would not allow for rotations greater than 90˚; therefore, we made sure that the movement of the link would be restricted to the bottom left and right quadrants of our coordinate system (). However, if the movement was greater than 90˚ or -90˚, we would add as much weight as was necessary to restrict the angular displacement to less than 90° and restart our run/test.



Type: rotary SN: 2158

Current

Current 1.2

15.00

60.00

☑ State: HOK.SWR.BRK.END.

☑ Position:	-45.000	☐ Current:	0.00	☐ Temperatur:	0.0
☐ DeltaPos:	0.00	☐ MotorCur:	0.00	☐ MaxPWM:	0
☐ Velocity:	0.00	☐ MotorSup:	0.00	☐ SmTemp:	0
☐ IPolVel:	0.00	☐ LogicSup:	0.00	MsgTime[ms]:	39.46

ESD:0,250 [connected]

01 SN:02158 351d

Figure 5- Screenshot of control program[8]

We created a spreadsheet in Excel that had all the pre-determined constants (such as the motor constant (K_{motor}), gear ratio, length of the link on it and then filled in all the unknown parameters that depended upon experimental data (such as the angle of equilibrium). All the experimental data was easily read off from the program shown in .

With every experiment, there are always some sources of error present. For one, the motor of the joint module has a brake that will not allow it to move backwards. This could have caused steady-state readings to be slightly higher since the arm could have used momentum to swing above one of the break points. Friction within the joint module is another source of error. The oscillation of the hanging weights (although low amplitude) and not having a completely vertical plane of motion are other possible sources of error.

Results

Upon completion of the experiment and calculation of all the experimental values, we found that the estimated data we had determined before the laboratory tests did not match the experimental data. The motor was about 2.4 times stronger than the theoretical value at the maximum current input because all the actual output results were much higher than the theoretical output results (). To compute the theoretical values, we used the relation:

$$T_{est} = K_{motor}*I*N*\eta \qquad (6)$$

where T_{est} is the estimated torque output, I is the current input, N is the gear ratio, and η is the efficiency as specified by the manufacturer. The actual results were found using[9,10]:

$$T_{act} = g*\cos(\theta)*(L_{CM}*m_{CM}+L*m_{attached}) \qquad (7)$$

where T_{act} is the actual torque output, g is the acceleration due to gravity, θ is the angle of equilibrium, L_{CM} is the length to the center of mass, m_{CM} is the mass of the link, L is the length to the attached mass, and $m_{attached}$ is the amount of attached mass. We also found that at very low current inputs ($I < 0.53$A) there is a dead band (or no effective displacement of the link for a non-zero current input).

Conclusions

Based on our experimental data (), we found a linear relationship between the current input and actual torque output. In the positive torque region () the relation was:

$$T_{+} = 79.261*I - 37.688 \qquad (8)$$

And in the negative torque region (negative being clockwise rotation) the relation was:

$$T_{-} = 78.675*I + 39.048 \qquad (9)$$

where T is the actual torque output in Nm, I is the current input in Amps, and the subscripts +/- indicate the positive and negative regions of actual torque. Equations (8) and (9) have coefficients of regression of 0.9948 and 0.9941, respectively. Since these values are very close to unity, we can argue that a linear relationship is a good-fit for our experimental data.

We determined that the torque capacity of the PR-110 module we experimented with was much greater than the value provided by the manufacturer (); however, the fact that we have a linear relationship means that an efficiency value can be determined for the joint module. However, this efficiency needs to be specified over different current ranges since the efficiency changes as the current input is increased and the motor begins to heat up.

As mentioned in the introduction section, the control of torques leads to improved safety of any mechanical system. Now that we have a relationship of current input to torque output, we are able to design a controller around robots to safely respond to unexpected forces acting upon them. It also opens up a whole new level of control: torque-mode. In torque-mode, the joint's output torque can be changed as needed by varying the amount of current input to the motor. The mentioned path that a robot arm follows can also be controlled more safely. For example, we are able to vary the speed at which the arm moves through the specified paths as needed and the applied force can be changed as well.

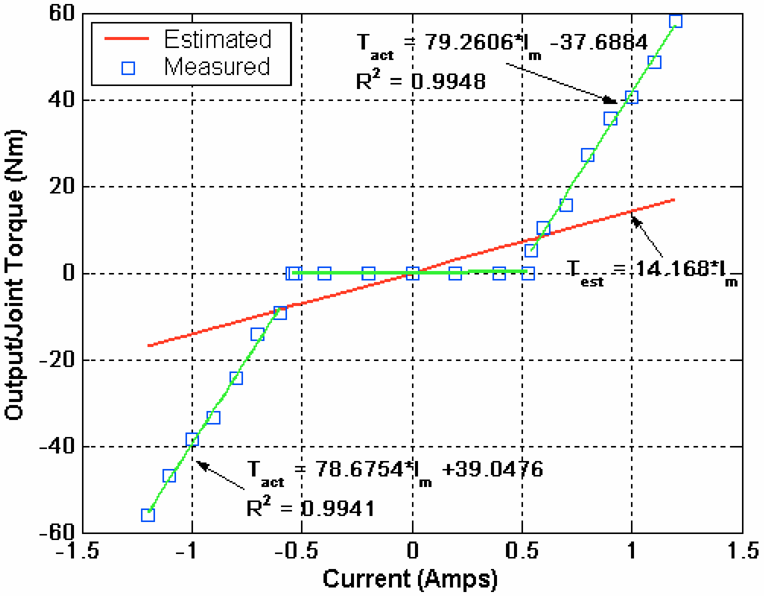


Figure 6. Mapping of Torque vs. Current for the PR110 Joint Module

Personally, I have learned that it takes a lot of motivation to be successful in graduate school. You need to be self-driven and set yourself manageable goals in order to keep your research in progress. I have also gained valuable technical writing and presentation skills and experience. I also feel better prepared than some of my counterparts when it comes time to start applying for graduate school, which I plan on attending.

Future Work

In the future we will want to carry out more research and find the reason for the actual torque being so much higher than the expected torque. We also want to be able to quantify the amount of friction that is present in the gear train at various current inputs, so that accurate efficiencies over different ranges of input current can be determined. For further testing, we also want to redesign our experimental set-up, so that the structure with the hanging weights is more rigid and we are able to use heavier weights to increase the range of currents that we operate on.

We tested the capability of the modular actuator to apply static torques. However experiments need to be run to characterize the torque performance of the actuator when loads are dynamically changing. Apart from the PR-110 module that we tested, there are other modules that are used to assemble a complete robot system: PR-90, PR-70, and the 2 degrees of freedom PW module. Current to torque mapping for these other modules would also have to be determined in order to have dynamic control capability for the entire robot assembled from them. Our current project is a proof-of-concept that such dynamic control capability is eventually possible.

Acknowledgements

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