Relationships Between Current, Angular Velocity, and Torque in Position-Controlled Servos

Samuel Pfrommer

March 16, 2015

Abstract

In the robotics literature, many balance and stabilization algorithms output a set of joint torques, one for each of the robot's actuators. This raises the barrier of entry for beginning researchers and hobbyists, who have to purchase expensive torque-controlled servos rather than conventional position-controlled servos. The purpose of this experiment is to determine whether it is feasible to accurately control the output torque of hobby servos by measuring in real time easily observed variables such as current draw and servo position. A series of experiments are conducted using a position-controlled HJ S3315D digital servo under various loads. The current and angular position are measured while the servo is working both with and against the load. The results show that once maximum speed has been reached, the shaft torque can be estimated using either current or angular velocity while the servo is rotating against the load. However, the 200 millisecond latency before maximum speed is achieved is prohibitively large for most practical applications. In the case where the servo and load are working in the same direction, there is no meaningful relationship between the torque and the velocity or current.

1 Introduction

Servomotors are commonly used actuators that take a command signal from an interface with an external controller [1]. This signal—typically conveying a desired position through pulse-width modulation—is supplied as an input to a small control circuit in the servo [1]. The control circuit then uses servo motor feedback to match as accurately as possible the desired position from the signal [1].

Lithium-ion batteries, affordable controller boards (Arduino), and simple servos have made robotics accessible to hobbyists. A large number of robotic devices (arms, crawlers, etc.) are available on the market. Often such robots use cheap, position-controlled servos that are mass produced for a wide range of applications. In contrast, the robotics research literature on robot stabilization and grasping typically focuses on torque-based algorithms, requiring an actuator that produces a specified joint torque.

The optimal setup would be to use servos dedicated to robotics, such as the Dynamixel MX-64, that allow for direct control of the goal torque [2]. However, these servos tend to be significantly more expensive than traditional hobby servos, which allow for only positional control [3]. By examining angular velocity and current flow, we hope to accurately express a desired output torque using standard hobby servos.

When it comes to measuring shaft torque, much research has been done using strain gauges [4] [5] [6]. This field has been studied extensively, with additional variations for special scenarios such as fingers, where space is limited [7]. However, this technique suffers from a few downsides. Strain gauges have an accuracy-stiffness trade-off, meaning that in order to obtain accurate torque readings large deformations of the gauge must be permitted. Hence, these systems often have either imprecise positional control or imprecise torque measurements. In addition, adding the stress gauge between the rotor and shaft is a complicated process that does not lend itself easily to modifying existing setups.

When it comes to using current as a feedback variable to control motor shaft torque, there is a theoretical proportional relationship between the two variables [8] [9]. Past studies have managed to estimate the shaft torque by measuring each of the currents in the three-phase windings and the angular position of the motor [6] [10] [11]. However, setting up the circuitry for measuring phase currents is difficult in motors where space constraints are an issue. In a later experiment using high-end Maxon motors, the load was successfully estimated using just the net motor current with 3% error using current feedback [12]. In this study, we attempt to further this research by examining DC motors that also include a servo controller element.

In addition, the relationship between angular acceleration/velocity and torque has been studied in the context of designing feedforward torque estimators in servo controllers [13]. In contrast, we try to measure torque by observing current and velocity of the servo without modifying or bypassing the built-in positional controller. Perturbations in motor speed in response to load variations have been studied for various speed control systems, as in [14]. Furthermore, algebraic approaches to constructing torque and velocity state observers have been attempted in [15] [16]. In this study, we analyze the change in attainable velocity of the servo under various loads with the purpose of controlling the torque, not the speed.

2 Experimental Setup

In keeping with the goal of using off-the-shelf servos, a low-end digital servo (HJ S3315D) was purchased for about $10 on Ebay and modified to provide positional feedback (Figure

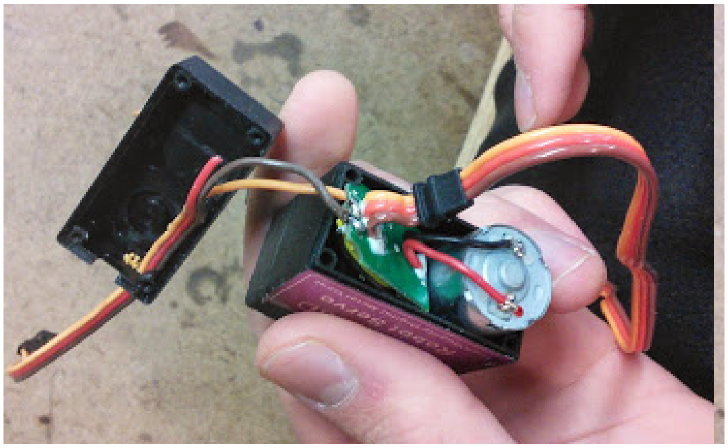

Figure 1: The modified HJ S3315D servo. The position feedback wire is soldered onto the potentiometer wiper and connected to the analog in pin on the Arduino.

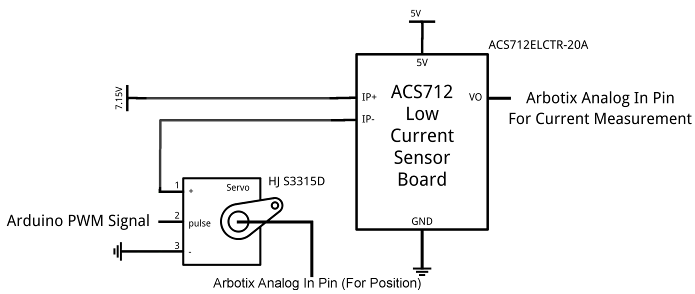

Figure 2: The schematic for the current measurement.

1). In order to read the position (θ) from the servo, a wire was soldered to the potentiometer wiper and connected to the analog in pin on the Arduino. No ground wire was necessary since the servo and Arduino share a common ground.

The current (I) was read using an ACS712ELCTR-20A sensor, wired as shown in Figure 2. The servo was supplied with 7.15V from a Castle Creations 10 amp BEC (CC BEC) and controlled with an Arduino-based Arbotix-M microcontroller.

A torque was exerted on the motor shaft by mounting a wheel 10 centimeters in radius concentrically with the servo horn (Figure 4). A variable weight was attached to a string spooled around the wheel. The weights and torque values are listed in Table 1.

3 Calibration and Data Acquisition

3.1 Current Calibration

When reading from the Arbotix controller, it is necessary to first transform raw data from the A/D converter, given in the

Mass(grams)	0	85	100	125	150	175	200	250	300
Torque(kg-cm)	0	0.85	1	1.25	1.5	1.75	2	2.5	3

Mass(grams)	350	400	450	500	550	600	650	700	750
Torque(kg-cm)	3.5	4	4.5	5	5.5	6	6.5	7	7.5

Table 1: The masses used and their respective torques. These masses were produced by filling water into a bottle, with an error of approximately ± 5 grams.

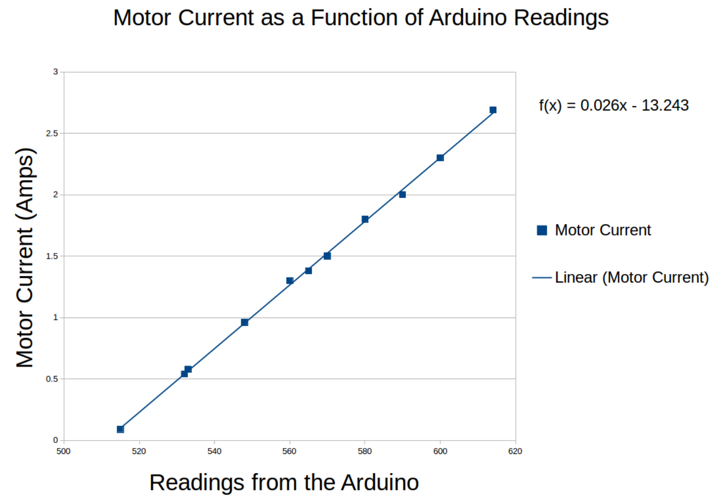

Figure 3: The relationship between current and controller readings, used for calibration.

0-1023 range, to standard units.

To calibrate the relationship between the readings D_{cur} from the controller s A/D converter and the motor current, a circuit was constructed using a variable resistor. By comparing readings from the controller to actual current measured with a multimeter, 11 data points were sampled and analyzed using linear regression (Figure 3). This provided the function:

$$I = D_{cur} * 0.0259A - 13.24A$$

3.2 Position Calibration

A similar process was used for establishing a relationship between the position readings P and the angular position. At the beginning and end ranges of the servo motion, the angle was measured with a protractor and the output from the controller was also recorded (Figure 4). Comparing the two yielded the following function:

$$\theta = (P - P_{min}) * \frac{\theta_{max} - \theta_{min}}{P_{max} - P_{min}}$$

where in this case P_{min} was 585, P_{max} was 56, and θ_{max} - θ_{min} was 153 degrees.

3.3 Measuring Current and Position Under Load

With calibration completed, we proceeded to measure current and position as functions of time under various loads. For each weight value, the wheel was rotated by 153° all the way forwards, lifting the weight up clockwise, and all the way backwards, lowering the weight back down. This process was repeated three times. On each forward run the servo was controlled to rotate at full speed whereas backwards the servo was slowed down to complete the run at approximately t=1, 3, and 5 seconds to avoid damaging the servo gears at the lower endpoint.

To avoid controller latency due to blocking on serial transfer to the host computer, the readings were buffered into an array and then printed to the serial output after each forwards

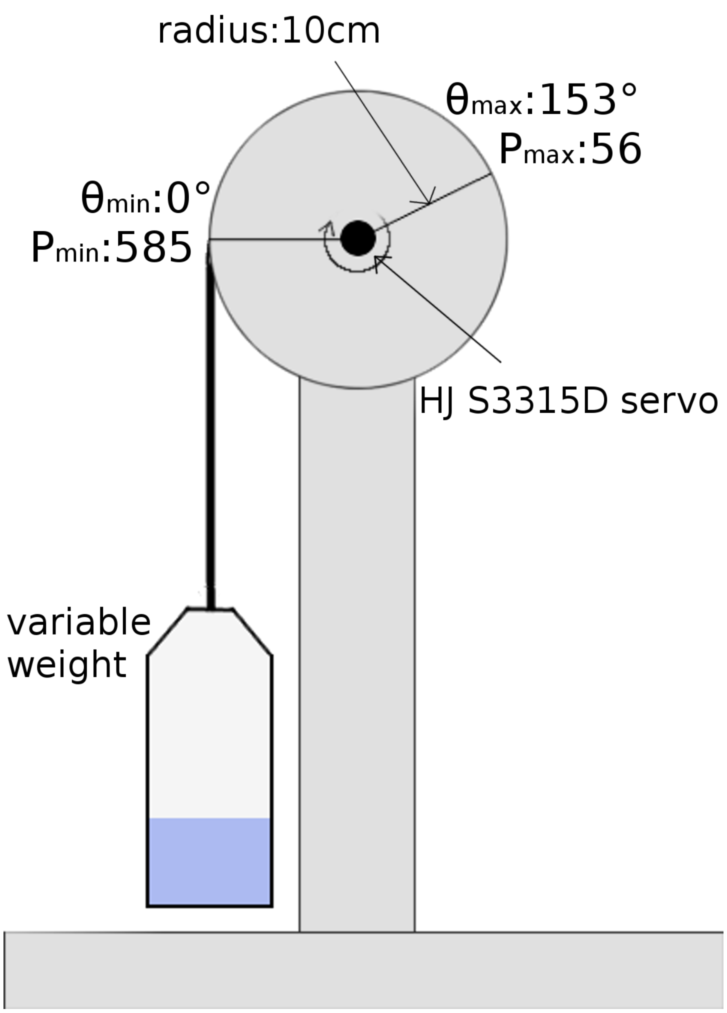

Figure 4: The experimental apparatus.

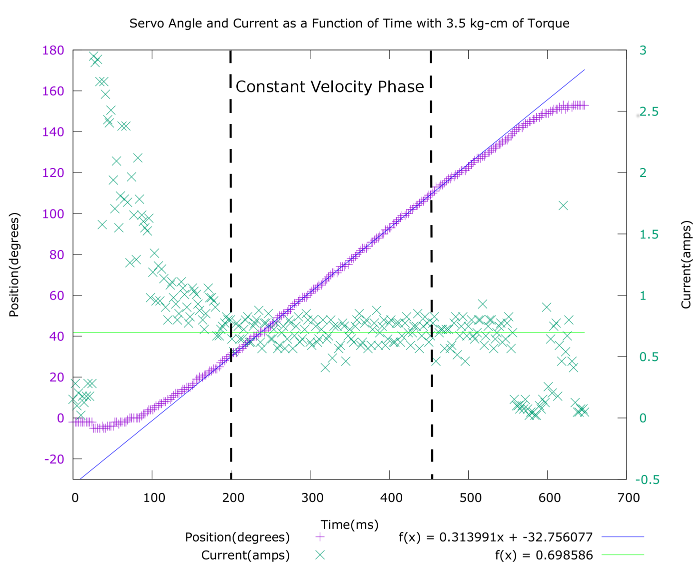

Figure 5: The first forward run for 350 grams. Note that both position and current regressions were performed on the constant velocity portion of the run, from 200ms to 200ms before the last data point.

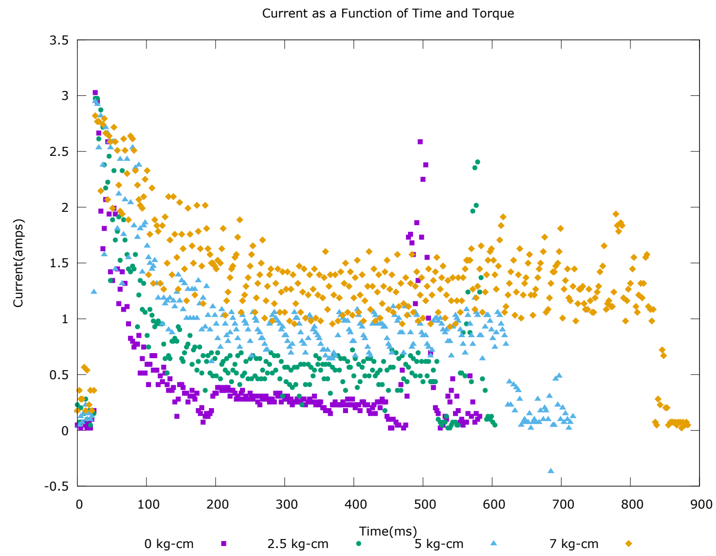

Figure 6: Current as a function of time for the 0, 250, 500, and 700 gram weights. The 700 gram run extends farther right since it took a longer time to pull up the heavier weight. Notice how the current increases as the weight gets larger. The spikes in the graph—most prominent at 500ms for the 0g run and at 580ms for the 250g run—show the deceleration after the weight has been pulled all the way up.

/ backwards run. Figure 5 shows an example of a typical position and current measurement as the weight is lifted up.

All the data, graphs, and images from this experiment are available on GitHub at `https://www.github.com/spfrommer/servo-experiment`.

4 Discussion

4.1 Working Against the Load

As seen in Figure 7, where the position graphs of the first forward run in each weight category were plotted side by side, the angular velocity gets progressively less as the load increases. Plotting the slopes of the position graphs as the blue data set in Figure 8 shows that this relationship is well approximated by a second degree polynomial. However, this is insufficient for most practical applications as there is a roughly 200 millisecond latency period before accurate deductions can be made from either position or current.

As the load increases, the servo logically draws more current (Figure 6); however, it is very noisy. After the acceleration phase, the current stabilizes around the mean during the constant velocity phase (Figure 5). In Figure 8, the mean currents for each load are plotted as the orange data set, with the error bars representing the standard error of mean for each run. Although the variance was large, as seen by the current data cloud in Figure 6, there were enough data points to give a small standard error (Figure 8).

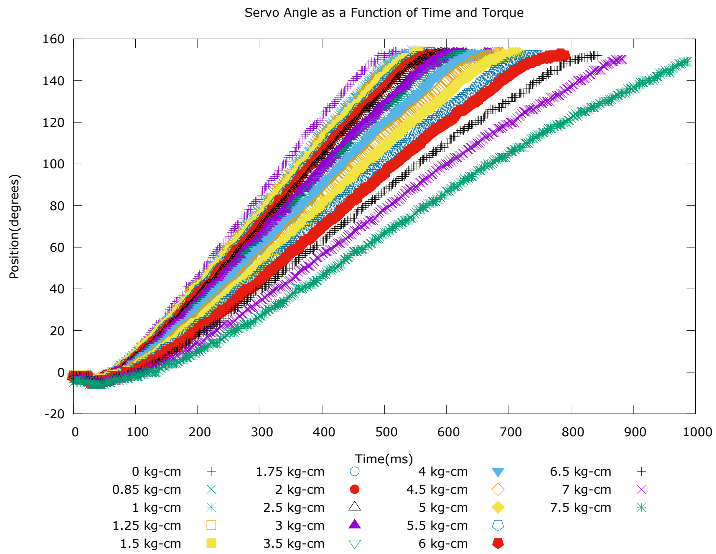

Figure 7: Servo position as a function of time for the first forward run of the different weights. Notice how the slope flattens as the load increases.

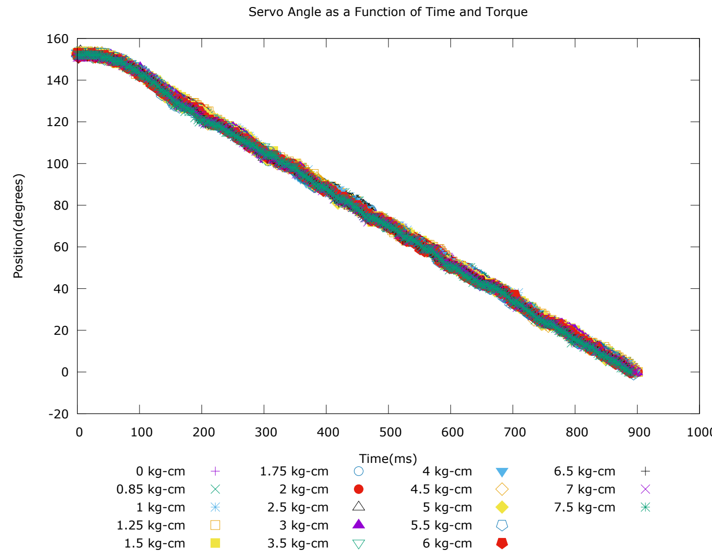

Figure 9: The position graphs of the different weights for the 1 second return trip. The shaft torque has no effect on the angular velocity.

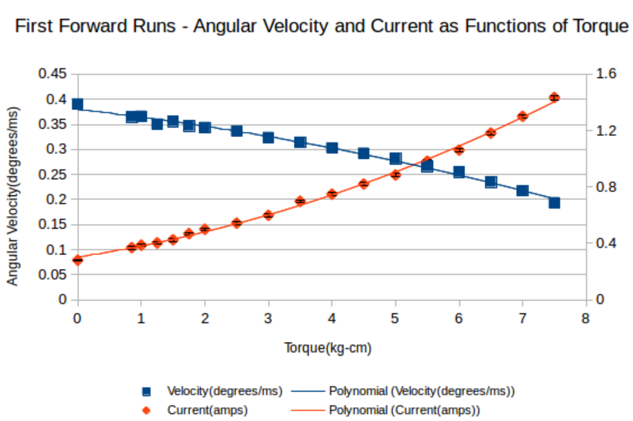

Figure 8: The angular velocity and current graphs for the first forward runs of the different weights. A quadratic fit works well in this case, and the standard error of mean on the current is small.

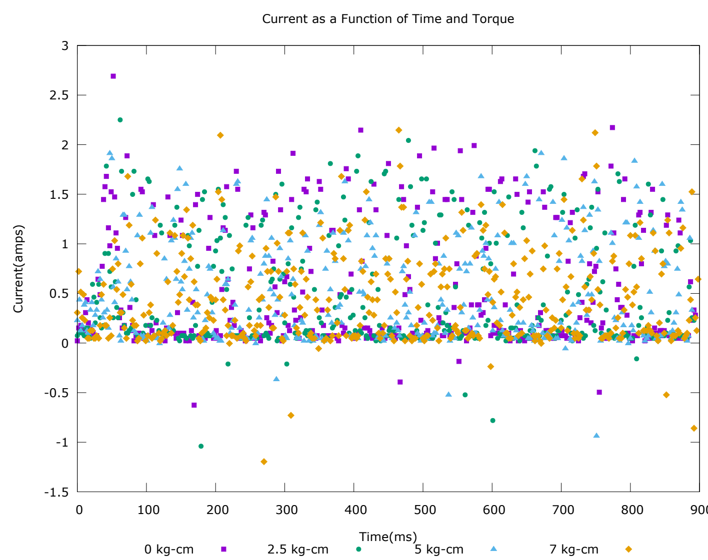

Figure 10: Current as a function of time for the 0, 250, 500, and 700 gram weights on the one second return trips. The data is too noisy to infer the load.

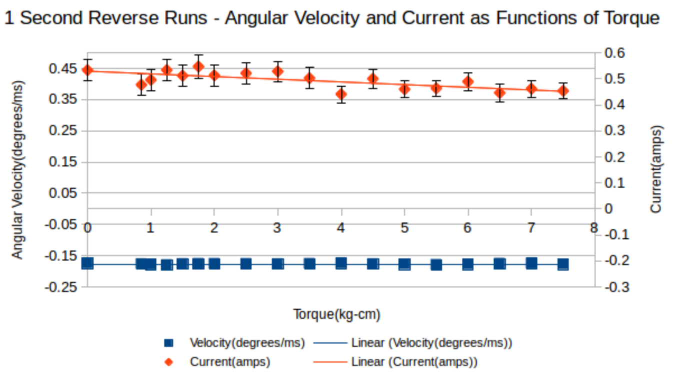

Figure 11: The angular velocity and current graphs of the one second return trips. There is no definitive relationship between the shaft torque and the current, and the velocity is constant. The line through the current data is just to guide the eye; the standard error of mean for each run is too large to determine the load.

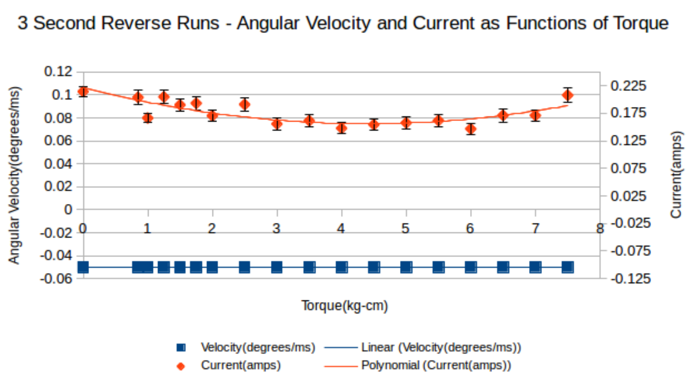

Figure 12: The position and current graphs of the three second return trips.

4.2 Working With the Load

As shown in the Figure 7, there is a strong correlation between the angular velocity and the shaft torque when the servo is working against the load. In the reverse case, however, there is no distinction; the servo rotates at exactly the specified velocity no matter the applied shaft torque, as seen in Figure 9 and the blue data points on the Figure 11. This makes it impossible to determine the load from the angular velocity or its derivative.

In Figure 10, it is clear that the current readings are noisy and meaningless. This could be due to torque ripple in the motor as the shaft rotates. The current readings do follow a roughly linear fit in Figure 11, but the standard error of mean on each of the data points is too large to reliably estimate the shaft torque.

On the three-second and five-second reverse runs, the current seems to take on a parabolic form, with the servo drawing similar current at upper and lower torque ranges (Figures 12, 13). If accurate, this means that the reverse relationship is no longer one-to-one, and every read current would have two possible loads associated with it. However, the standard error of the raw data is too large to draw a definite conclusion, and

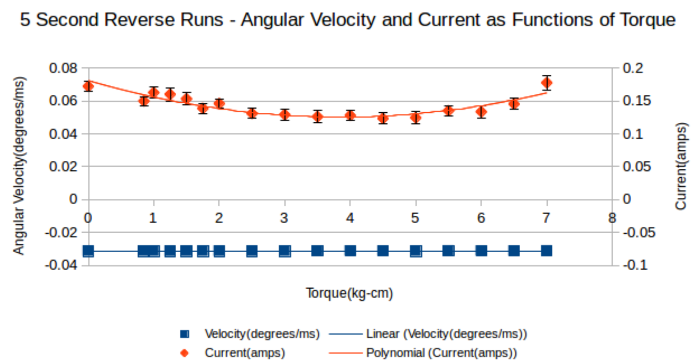

Figure 13: The position and current graphs of the five second return trips.

no mechanism has been found that would explain this effect.

Another factor which renders using the current as a predictor difficult is that the angular velocity has a far greater effect on the current than the load. This can be easily seen from Figures 11, 12, and 13; on the one second run, the current was about 0.5 amps, while for the three and five second runs the current dropped to 0.2 and 0.15 amps, respectively.

4.3 Speed Dependency of Return Run Currents

Without detailed knowledge of the servos' control algorithm, one can only speculate as to why the current increases with operating speed in the reverse direction. Presumably, the current spikes whenever the servo's position controller fights overshoot. We keep the positional steps $\Delta\theta$ constant and decrease the time step Δt for faster speeds. This means more position updates per unit of time, and hence more current spikes, explaining the increased average current flow with increased speed.

5 Conclusion

Our experiments show that both angular velocity and current prove to be accurate measures of shaft torque when working against the load, albeit with a 200ms latency that is impractical for most applications. In the reverse case, the load had no effect on angular velocity, while the current depended too much on velocity to give any indication of the shaft torque. For this reason, torque cannot be inferred indirectly from current and speed measurements.

Possible future research could be conducted in experimenting with different methods of processing the current data. Other indicators that were not investigated in this paper, such as angular acceleration, could also be examined for any relationship with the shaft torque.

References

[1] *Servo Control Facts*. Baldor Electric Company, 1998.

[2] "MX-64T / MX-64R." Tech. 2010. <`http://support.robotis.com/en/product/dynamixel/mx_series/mx-64.htm`>.

[3] Malek, J. "Electrical Characteristics of Servos and Introduction to the Servo Control Interface." *Pololu*. 3 Feb. 2011.

[4] Pfeffer, L.e., O. Khatib, and J. Hake. "Joint Torque Sensory Feedback in the Control of a PUMA Manipulator." *IEEE Trans. Robot. Automat. IEEE Transactions on Robotics and Automation* 5.4. 1989. 418-25.

[5] Yu, Y., T. Chaen, and S. Tsujio. *High-Stiffness and High-Sensitivity 3-Axis Force Sensor Using Strain-Deformation Expansion Mechanism*. Proc. of IEEE/RSJ International Conference on Intelligent Robots and Systems, China, Beijing. 2006. 4417-422.

[6] Asada, H., K. Youcef-Toumi, and S.K. Lim. *Joint Torque Measurement of a Direct-Drive Arm*. Proc. of IEEE 23rd Conference on Decision and Control, Nevada, Las Vegas. 1984. 1332-337.

[7] Yu, Y., T. Ishitsuka, and S. Tsujio. *Torque Sensing of Finger Joint Using Strain-Deformation Expansion Mechanism*. Proc. of IEEE International Conference on Robotics and Automation, Taiwan, Taipei. 2003. 1850-856.

[8] Kaiser, D. *Fundamentals of Servo Motion Control*. Parker Hannifin, 14 Sept. 2010.

[9] Koren, Y., and S. Malkin. "Torque and Speed Control of DC-Servomotors for Robots." *CIRP Annals - Manufacturing Technology* 33.1 (1984): 239-42.

[10] An, C. H., and J. M. Hollerbach. *Dynamic Stability Issues in Force Control of Manipulators*. Proc. of IEEE International Conference on Robotics and Automation, North Carolina, Raleigh. 1987. 890.

[11] Chunshan, X., W. Jianping, C. Guangi, and Z. Xifang. *Design of a New Current Sensing Device for Joint Torque Force Control of the Precision Assembly Robot*. Proc. of IEEE 5th World Congress on Intelligent Control and Automation, China, Hangzhou. 2004. 4609-613.

[12] Kapoor, A., N. Simaan, and P. Kazanzides. *A System for Speed and Torque Control of DC Motors with Application to Small Snake Robots*. Proc. of IEEE Conference on Robotics, Automation and Mechatronics, Germany, Aachen. 2004.

[13] Kaiser, D. "Fundamentals of Servo Motion Control - Disturbance Rejection." *Machine Design*. 1 Oct. 2001.

[14] Oishi, K., K. Onishi, and K. Miyachi. "An Approach to the Torque-speed Regulation of the Separately Excited Dc Motor Using a State Observer." *Electrical Engineering in Japan* 104.3. 1984. 93-99.

[15] Linares-Flores, J., J. Reger, and H. Sira-Ramirez. "Load Torque Estimation and Passivity-Based Control of a Boost-Converter/DC-Motor Combination." *IEEE Transactions on Control Systems Technology* 18.6. 2010. 1398-405.

[16] Mehta, S., and J. Chiasson. "Nonlinear Control of a Series DC Motor: Theory and Experiment." *Proc. of the American Control Conference*. 1997.