Test Setup for Analysis of Torque on DC Motor Shaft and its Possible Applications

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***Abstract*—In this paper, we try to use a linear load cell to measure the torque acting on the shaft of a geared DC actuator. With the help of this measured parameter, we are analyzing several possibilities of this model to be used for different application. PID controller is used to making it a closed loop system to reduce the errors, as much as possible. With proper tuning of PID and calibration of the load cell, we can achieve position control without a rotary encoder. We are exploring the possibilities of using minimum sensors to achieve multiple actions to be performed by the actuator.**

***Index Terms*—Torque Sensor, PID, Load Cell, Actuator and Rotary encoder.**

I. Introduction

When it comes to real-world applications, we need sensors to know what is happening in our surrounding and generate proper control signals to adjust the system so that it can reach the desired goal. Some of the parameters that we need to measure on a DC actuator are position, temperature, current and torque. With the help of these parameters, we can achieve accurate actuation, get to know what is happening inside as well as troubleshoot what is going wrong with it.

The amount of force which causes an object to rotate about its axis is known as torque, and it is this quantity that causes an object to obtain angular acceleration. Torque sensors play a crucial role to measure the forces acting on the system, and when it comes to the field of robotics where, service robots are used to improve the efficiency of a human worker, the robot or the manipulator should not only sense the forces acting at its end effector but also the force that can act on the body so that humans can interact with it pretty well. This will also ensure that the robot is safe for humans to work with it.

The rest of the paper is organized as below. The problem statement, related works, system architecture and evaluation of the work are described in section II, III, IV and V respectively. Section VI discuss about the results. Section VII concludes the paper with conclusion.

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II. Problem Statement

Usually, in a robotic manipulator, it has a 6-axis torque sensor to measure the forces acting at its end effector in all directions. This type of torque sensor is expensive but having joint torque sensors gives an advantage over 6-axis torque sensors, the end effector force can be calculated from the joint torque values. In addition to that, we can know the forces acting on the entire body too. By analyzing the parameters like force, the manipulator arm can act accordingly depending on the task required. So, there is a need to develop a proper way to analyze the possible force or torque acting on each joint. This requires a proper setup for analyzing torque and other parameters. This motivated us to try in developing a setup for measuring torque and possible parameters. By analyzing these parameters, we might be able to implement impedance as well as admittance control.

III. Related Works

The joint torque sensor incorporated at the manipulator's joint takes in several other factors such as torque ripple noise caused by the harmonic driver, crosstalk error etc. while measuring the actual joint torques. Paper [1] proposed a method to reduce these unnecessary torque ripple and crosstalk errors which in turn makes the torque sensor to measure with much efficiency. The mechanics around the joint torque sensor induces several other forces, frictional constraints which makes the torque sensor to deform slightly. The circumstances under which the joint torque sensor works effectively, despite constraint moments and forces, are evaluated in the paper [2]. For a manipulator, an efficiency, lightweight, high power actuator is required. To measure the torque for this type of motors, special methods are required. The paper [3] articulates the inertial method and ball bearing friction method to measure the torque. Joint torque measured depends on the feedback loop mechanism used while formulating the torque in the electrical circuit. Continuous tuning of the electronic commutator requires structural and model change. A linear estimator method is proposed in paper [4], to estimate the torque angle relationship which is used in self-tuning torque control of BLDC motors. Sensing the torque acting on a body does not solve the problem much. It will be solved when the sensed torque is controlled so that it suits best for the application. Such control has been achieved by this paper [5] by using a PI controller and a test setup with on DOF arm which is a flexible body. There is no use if the torque

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sensor equipment is bulky as it cannot fit for small applications. This problem was solved in paper [6] by implementing a compact torque sensor that can be integrated with a robotic arm which has fingers. Coming to the applications of paper [7], it has implemented a tiny ball-shaped spherical load cell which is a size of the fruit. This, as it sounds, is used for measuring the forces acting on the fruit when it is stored in the warehouses or containers. Paper [8] has also implemented a PID controller with some strong mathematical background discussing the challenging included in achieving this. Considering a more complex approach paper [9] implemented an impedance control for two six DOF arms. Two six DOF arms work together to lift a common object and hence the equivalent torque measurements and analysis were discussed. All these proposed methods and implementations are great for research purpose, but when it comes to the practical product, it must be affordable without compromising on the quality and efficiency. Keeping this as a goal paper [10] has implemented a low-cost torque sensor using a harmonic drive. Most of the times torque control involves PID. PID control is as important as the designing of the robot. Paper [11] describes one such situation where a PID controller redefines the meaning of stability in case of a quadcopter. This paper describes how the quadcopter reacts on tuning the PID parameters to the extreme values and in turn, explains how important a PID control is. As a result of advancement in technology, the automobile industry is aiming to commercialize electric vehicles and autonomous vehicles. One such attempt is mentioned in the paper [12] where safety measurements of autonomous vehicles were taken into consideration. A PID control was implemented to achieve accurate steering turns and acceleration control. It even applies this control method for safe and effective braking. Paper [13] describes one such application where a robotic arm with five fingers can be controlled by a human hand in real time using a myoelectric sensor. In this case, torque parameters play a predominant role as the fingers all together should hold an object steadily without applying over torque. One more similar case where torque control plays a vital role is discussed in the paper [14]. Paper [15] describes the case where a robotic with a cutter as an end effector is used to cut the fruits. Here again, torque plays an important in cutting the fruits. If more torque is applied, then it might prejudice the branches of the tree.

IV. System Architecture

Our system consists of mainly three blocks; control, actuation, and feedback. The control block that comprises of Arduino, DC power supply, and motor driver shown in Fig. 1. The PID algorithm is implemented in Arduino to have better error correction and smooth operation. Then comes the actuator to which the load cell is attached to its shaft. As the load cell rotates when the actuator moves, the force acting on the load cell will be different at a different point, hence we will know the position it will be at. And when programmed properly we could use this setup to operate in different modes.

In order to find the position of the shaft properly, we should ensure that the setup is always kept as in the orientation as shown in the figure here, we can see that in this configuration the load cell used for measuring the moment of force acting on the object.

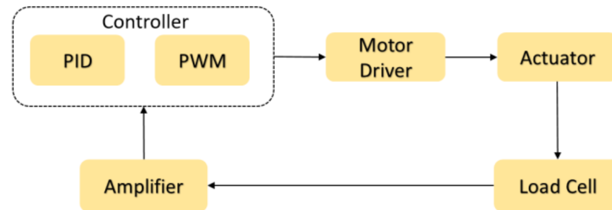

Fig. 1. System Block Diagram

In the load cell used here, there are strain gauges fixed at the location marked in yellow as shown in the Fig. 2, the strain gauge suffers tension and compression, this, in turn, changes the resistance of the strain gauge, which produces a voltage signal in accordance to the force applied.

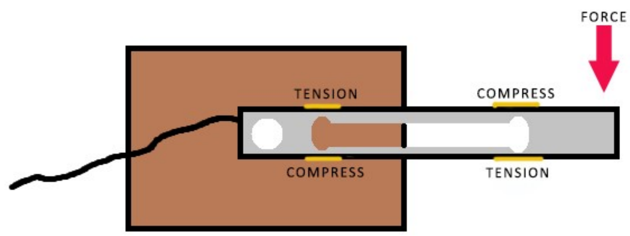

Fig. 2. 2D model of test setup

In this test setup, we have used several components to achieve our desired output and let's discuss them one by one.

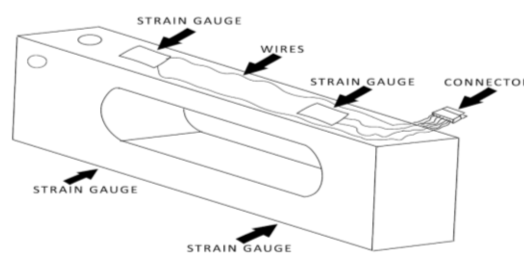

Fig. 3. Linear Load Cell

A. Load Cell

This is the main component of the system that is used to measure the force applied. Load cells are sensors used to measure weight, stress or force applied to an object or surface. Load cells can be made in many forms in accordance with the requirement and application. Some of the varieties are Hydraulic Load Cells, Pneumatic Load Cells, Strain Gauge Load Cell, Single Point Load Cell and many more. But here in our setup, we are using a bar strain gauge load cell as shown in the Fig. 3.

This load cell uses strain gauge resistors places at certain locations of the element to measure the deformation caused by the forces acting on the element. In the case of this bar strain gauge load cell, when torque is applied to the bar, the four strain gauges on it will experience compression and tension, out of the four two will measure compression and the other two will measure tension.

The strain gauges are connected in such a way that it forms a Wheatstone bridge and hence the small changes in resistance can be measured accurately. Thus, we will be able to measure the torque applied on the bar.

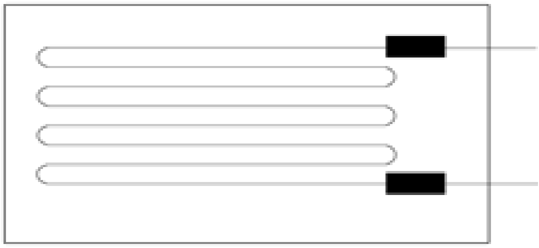

Fig. 4. Representation of a Strain Gauge

A strain Gauge is a device that measures the electrical resistance in accordance with the strain applied to the device, refer Fig. 4. Most of the strain gauges are made of thin wire, or foil, which is set up in a grid pattern such that when the grid stretches or compresses there will be a change in the resistance of the device and hence this can be measured.

In a Wheatstone bridge resistor are arranged in the configuration, applying (Vin) know the voltage at two terminals and we take the (Vout) output across the other two terminals as shown in the Fig. 5.

When the bridge is balance, i.e. R1/R2=R3/R4, then the Vout is 0. As any of the resistance value changes, the bridge goes unstable and there will be a Vout value, it can either be positive or negative according to the variation of the resistor and the output is proportional to the torque applied on the element. The Vout value is measured using the following formula

$$V_{OUT} = \left[\left(\frac{R_3}{R_3+R_4}\right) - \left(\frac{R_2}{R_1+R_2}\right)\right] * V_{in} \quad (1)$$

Hence if we replace any one of the resistors with a strain gauge, we can easily measure the force acting on the load cell. We can amplify the effect by replacing more resistors with strain gauge resistors. As we are measuring very subtle changes in the dimension of the element when torque is applied to it, we need maximum output value as possible. When all the resistors are replaced with strain gauge resistors

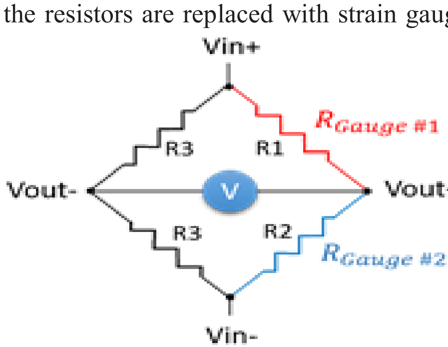

Fig. 5. Half bridge configured Wheat stone bridge

its known as a Full bridge strain gauge circuit

As torque is acting on the element there will be a change in resistance in all the strain gauges and the Wheatstone bridge will give the collective effect of the force. Even though we are having a full bridge configuration the output will be in the millivolt range as the change in resistance from each strain gauge resistor is significantly low. Hence it is really difficult for a 10-bit microcontroller operating at 5 volts to detect the output accurately, hence along with the load cell we have to use an amplifier to boost the signal for measurement.

B. *Load Cell Amplifier*

HX711 Load cell amplifier is used for boosting the signal generated from the load cell. It has on chip low noise PGA with selectable gains of 32, 64, and 128 respectively. It also has a 24bit ADC which gives high resolution. We integrated an Arduino development board to the module to sense the amplified signal, which will help in performing tasks by the microcontroller.

C. *Arduino UNO*

ATmega328P is used in this development board. The board has 20 pins of which 14 pins and 6 pins are digital input/output and analog input pins respectively. Out of the 14 digital pins, 6 pins can be used as PWM output pins. It had 16 MHz quartz crystal and a power jack, USB connection type also used for uploading code into the microcontroller.

D. *Motor Driver*

In this setup we have used NEX Robotics Hercules motor driver to run our high torque motor. It is a 6V-36V, 15 Amp motor driver and support up to 30 Amps load. This motor driver has a maximum PWM frequency and can be interfaced with 3.3V or 5V as logic levels. It even has optional current sensing option through ACS714 current sensor. It is a single channel motor driver. The driver is used to drive a motor with 120 kg/cm torque, with metal gears, that has got a maximum speed of 60 RPM.

E. *PID Controller*

There are two types of systems, namely open loop and closed loop system. In open loop system, there is no feedback to the controller and the only job of the controller is to give the command to make the system do a specific task, it doesn't consider about the errors that may or may not occur. These systems are highly unstable and are subjected to errors often. Whereas in the closed loop system, feedback taken from the output of the system and feed it back to the input. The error is calculated, and the corresponding control signal is generated so that the system always meets the set point. These systems are stable, and the type of controller and the proper tuning of the controller will ensure smooth working of the system.

PID controller algorithm is one of the most widely used controller algorithms in the industry. PID stands for Proportional, Integral, and Derivative, and it uses the combination of these three components to help the system to compensate for the changes in the system automatically. The mathematical model of a PID controller is as given in the equation. On looking at the block diagram, refer Fig. 6 we can get a broad idea about the PID control loop.

$$u(t) = K_p * e(t) + K_i * \int (e(t))d(t) + K_d * \frac{de(t)}{dt} \quad (2)$$

Where u(t) is the output of the controller, K_p is the proportional gain, K_i is the integral gain, K_d is the differential gain and e(t) is the error value at that time t. Sometimes all systems do not need all the three components to work properly. So, if we don't want one of the components, we can turn it off by simply take the gain of that component as zero.

The overall output from the PID block can be written as

Output = error now + error past + error future

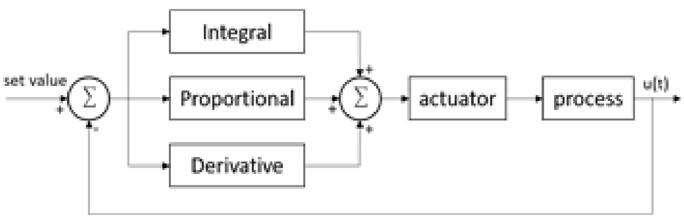

Fig. 6. PID control loop

If we think that the PID gains are tuned correctly then the system should give a smooth response, but it won't. The PID block itself can bring about instability in the system if proper corrective measures are not taken.

V. Evaluation

We have used the test setup to make it work in different modes. After calibrating the load cell for the desired response, the load cell was attached to the motor shaft as shown in the Fig. 7.

The first mode in which we made it operate is the stop mode. The motor will stop running when it detects a threshold force acting on it. In this form of control, we can ensure that the motor will apply only the set force when it meets a certain obstacle.

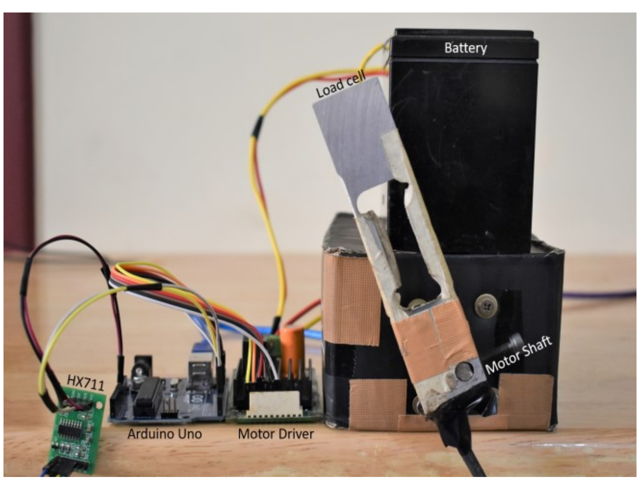

Fig. 7. Test setup

The second mode is, toggle mode. In this mode, the motor will switch the rotation from clockwise to anti-clockwise and vice-versa when a threshold torque is acting on it, in the opposite direction of rotation.

Another mode in which we made it operate is the following mode. In this mode, we apply certain force to the load cell, and the motor will respond in the same direction proportional to the force that we apply. This kind of operation is more useful when we want to move the motor to a position or need to teach the robot certain mover step by step. Do the presence of high torque available with the motor, we won't be able to move the motor shaft when it is turned off, but in this mode, it makes it easy to do that.

The fourth mode that we have worked on is the spring mode. Here, in this case, the shaft will rotate in the direction of the force applied, but when no force is acting on it, the shaft will get back to the initial position. We have checked the response time for this case, it is really depending on how well the PID gains are tuned. If we want to set a new initial position, a push button was configured to set the new position as the default point.

VI. Result

Our Experiments with the test setup show that getting the right PID gains is important to obtain a good response from the system.

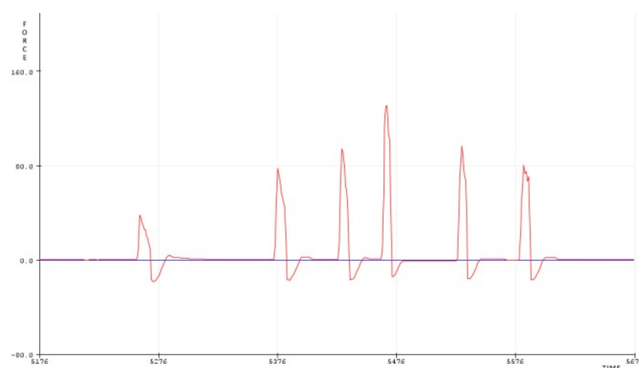

Fig. 8. Force vs Time graph

Manual tuning of the PID gains is tedious work. As discussed in the above section that proper tuning of the PID gains has a drastic impact on the stability of the system. Table I show some of the gains we have used and the corresponding settling time of the shaft when it was operated in the spring mode. Since the motor was running at a low RPM the response is not too fast but was able to achieve reasonable outputs.

The force vs time graph in the Fig. 8 shows the response we were able to achieve with the test setup. The Positive spike is due to the external force that we have applied, and the negative spike corresponds to the time when an external force is not applied, and the motor shaft starts moving the initial zero reference point it came from. We can achieve reasonably stable as well as quick response out of it. The initial force that was given to move to the point was similar all the time and we can see that from the graph, hence the response time too. The

TABLE I
TABLE OF DIFFERENT GAIN AND SETTLING TIME

K_p	K_i	K_d	Sampling	Calibration factor	Settling time (s)
200	400	0	0.01	318000	unstable
400	0	0	0.01	318000	unstable
500	375	25	0.01	318000	10.1
300	200	50	0.00125	318000	unstable
300	200	50	0.01	318000	4.3
350	210	30	0.0125	318000	3.4
500	300	130	0.0125	318 000	13
600	200	220	0.0125	318000	12
600	400	328	0.0125	318000	10.5
600	400	328	0.0125	318000	8
600	400	328	0.0125	318000	10.63
400	170	50	0.0125	358000	11.2
400	170	50	0.0125	358000	10.5
400	170	50	0.0125	358000	10.4
400	150	50	0.0125	358000	8.98
400	150	50	0.0125	358000	8.38
400	150	50	0.0125	358000	8.68
600	216	60	0.0125	358000	1.92
600	216	60	0.0125	358000	1.35
800	216	60	0.0125	358000	3.81
800	216	60	0.0125	358000	2.13
800	216	60	0.0125	358000	3.36

system very rarely overshoots and even, so it corrects quickly.

Even without using an absolute rotary encoder we were able to map the position of the actuator shaft decently. Though minor errors are there, caused by the loose wires, lack of precise PID gains as well as the imperfection due to the mechanical design, such as backlash, also adds to the inaccuracy of the system.

VII. CONCLUSION

With our proposed model and research made on the load cell to obtain torque, we were able to minimize the number of sensors which are required to measure the torque as well as the position of the actuator. In other words, we can say that we were able to achieve a few tasks performed by many sensors with a single sensor alone. Without the use of the rotary encoder, we can get the position of the actuator shaft. With simple algorithms and minimal setup with some drawbacks, we were able to make the system work in four different modes to a good extent. On introducing complex algorithms and mechanically more stable system, we can really improve the performance of the system. Being able to exploit the use of sensors available in a system, we can reduce the cost, make the system work even if one of the sensors malfunctions. This not only reduces the number of sensors but also decreases the space required for sensors in the robot. Resulting in lightweight, compact robots and cost efficient to some extent without compromising on quality and durability.

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REFERENCES

[1] In-Moon Kim, Hwi-Su Kim, Jae-Bok Song: Design of joint torque sensor and joint structure of a robot arm to minimize crosstalk and torque ripple in 2012 9th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI).

[2] Chanhun Park, Jin Ho Kyung ; Tae-Yong Choi, Hyun Min Do, Dong-Il Park, Byung-In Kim:Study on the requirements of joint torque sensors considering mechanical condition of the joint mechanism of a manipulator, in 2012 12th International Conference on Control, Automation and Systems.

[3] Pierre-Daniel Pfister , Yves Perriard:Torque measurement methods for very high speed synchronous motors in 18th International Conference on Electrical Machines in 2008, Pages: 1 - 5.

[4] F. Aghili :Self-tuning torque control of brushless motors, in Proceedings of the 1999 American Control Conference (Cat. No. 99CH36251) in 1999, Volume: 3, Pages: 1663 - 1667.

[5] Hosun Lee, Yonghwan Oh, Jae-Bok Song: Torque sensor based robot arm control using disturbance observer in ICCAS 2010 in 2010 Pages: 1697 - 1700.

[6] Tetsuya Mouri, Haruhisa Kawasaki, Kazumi Koketsu: Compact torque sensor for a robot hand in 2011 8th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI), 2011,Pages: 439 - 441.

[7] Ivan Muller, Renato Machado de Brito, Carlos Eduardo Pereira, Valner Brusamarello: Load cells in force sensing analysis -- theory and a novel application in IEEE Instrumentation & Measurement Magazine, 2010, Volume:13, Issue:1,Pages:15 - 19.

[8] Kiam Heong Ang, G. Chong ; Yun Li: PID control system analysis, design, and technology in 2008 International Conference on Apperceiving Computing and Intelligence Analysis, 2008, Pages: 53 - 56.

[9] Fabrizio Caccavale, Pasquale Chiacchio, Alessandro Marino, Luigi Villani: Six-DOF Impedance Control of Dual-Arm Cooperative Manipulators in IEEE/ASME Transactions on Mechatronics, 2008, Volume:13, Issue:5, Pages: 576 - 586.

[10] Byung-jin Jung, Byungchul Kim, Ja Choon Koo, Hyouk Ryeol Choi, Hyungpil Moon: Joint Torque Sensor Embedded in Harmonic Drive Using Order Tracking Method for Robotic Application in IEEE/ASME Transactions on Mechatronics, 2017 , Volume:22, Issue 4, Pages: 1594 - 1599.

[11] VNV Aditya Sharma and M Rajesh: Building a quadcopter An approach for an Autonomous Quadcopter in 2018 International Conference on Advances in Computing, Communications and Informatics (ICACCI) Year: 2018 Pages: 1252 - 1258

[12] Chandni C.K, Sajith Variyar V. and Guruvayurappan K : Vision based closed loop PID controller design and implementation for autonomous car in 2017 International Conference on Advances in Computing, Communications and Informatics, ICACCI 2017 Volume 2017-January, 30 November 2017, Pages 1928-1933

[13] U. J. Pai, N. P. Sarath, R. Sidharth, A. P. Kumar, S. Pramod and G. Udupa, "Design and manufacture of 3D printec myoelectric multi-fingered hand for prosthetic application," 2016 International Conference on Robotics and Automation for Humanitarian Applications (RAHA), Kollam, 2016, pp. 1-6.

[14] R. K. Megalingam, B. V. A. Gupta, T. U. Dutt and A. H. Sushruth, "Switch and thought controlled robotic arm for paralysis patients and arm amputees," 2013 IEEE Global Humanitarian Technology Conference: South Asia Satellite (GHTC-SAS), Trivandrum, 2013, pp. 243-248.

[15] R. K. Megalingam, N. Vignesh, V. Sivanantham, N. Elamon, M. S. Sharathkumar and V. Rajith, "Low cost robotic arm design for pruning and fruit harvesting in developing nations," 2016 10th International Conference on Intelligent Systems and Control (ISCO), Coimbatore, 2016, pp. 1-5.