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A Low Cost Linear Force Feedback Control System for a Two-Fingered Parallel Configuration Gripper

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Abstract

This paper presents a simple linear control based force feedback for the gripper of a SCORBOT ER-4u robotic arm. The SCORBOT ER-4u is a 5 degree of freedom (DOF) dexterous robotic arm with a rigid 2-fingered parallel configuration gripper. A Flexi-Force Force Sensitive Resistor (FSR) is attached to one of the claws of the gripper and interfaced to a notebook computer using Arduino Uno microcontroller. The force sensor aids the robotic arm in three different ways: one, senses if an object has been successfully grasped, second determine the coefficient of friction of the object, and third prevent damage when the object will be grasped. The gripper along with the force sensor is calibrated prior to grasping objects. During calibration, samples of the object to be manipulated are used to establish the extents of the gripper on the basis of its grasping force. By following calibration pattern, the gripper is able to grasp objects with approximately the same coefficient of friction. Most importantly, it ensures that the object to be grasped is not damaged by applying sufficient amount of force based on the object's weight. The experimental analyses of the proposed work have shown interesting results to control both the SCORBOT ER-4u robotic arm and the force sensor for grasping masses, strictly conforming to the safety margin of the object.

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Keywords Mechatronics; Force; Friction; Calibration; Robotic Arm.

1. Introduction

For robotic arms, the end–effector is an indispensable component which physically interacts with the environment. The end effectors are commonly used for painting, welding, drilling and also for pick and place tasks. In addition to this, they are used for medical applications as well [1, 2]. In many cases handling of the target object is critical. To some extent, the design of the end of the arm tooling (which is the tool attached to the end effector), are task oriented which is quite expensive and time consuming. According to Kumar and Chand [3], many efforts have been made specifically to eliminate the human operator for three major reasons: First is to save labor costs, second is that a human can be bad for the product (when it comes to handling of products or the semiconductor devices) and third is that the product can be bad for human (handling of radioactive or corrosive components). Upon interaction with the target object, it is inevitable that some amount of force is exerted onto the object. This force must be controlled to finish the task successfully without damaging the product.

Controlling force exerted on an object upon grasping is very well implemented by the human hand. Its capability to apply just the right amount of force is likely to be unmatched in comparison with artificial prosthetic hands. However, researchers have strived to come closer in developing technologies which would mimic a human arm. To understand the concept of grasping, enthusiasts have studied the human arm which is said to have a total of 22 degrees of freedom [4].

An approach is taken by Rahman, Choudhury [5] to mathematically model the thumb and a finger of human subjects to generate a position profile with varying speed of the movements of the fingers. In this study, a force sensor was used to measure the bending angle of the human finger while performing a gripping like action. In [6], a Willow Garage PR2 robot was used to perform object grasping task using a tactile sensing based controller. It behaves by acquiring the hand mounted accelerometer data in real time

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and generates tactile signals to resort to one or the combined set of their proposed states to prevent slippage of the object. Moreover, Wettels, Parnandi [7] presented on Bayesian inference and biologically inspired algorithms for the control of the tangential forces for an anthropomorphic mechatronic prosthetic hand. In accordance with the biomimetic tactile sensor, the Kalman filter is used to remove noise from the acquired data for the calculation of the tangential force. Similarly, Takaki and Omata [8] focuses on strengthening a light–weight anthropomorphic robot hand to make it capable of exerting a large grasping force. Additionally, in [9], the anthropomorphic robotic arm is used to manipulate remote objects through teleoperation. The user manipulates the object through the linkage with a control rig. The force incurred in the robotic arm (which is used to interact with the object remotely) is fed back to the user.

Lin, Ren [10] uses a force imaging approach to tackle the problem of grasping and manipulation through demonstration. Deploying an image sensor (camera), a Fanuc robot is taught by a human how to grasp, pick and place an object. The Fanuc robot exactly mimicked what the human teacher demonstrated to it. In addition to this, Payeur, Pasca [11] presents a 16×16 FSR to recognize small sized 3D objects with the use of machine learning techniques. Though a reliable and a cheap solution for a rough visualization of 3D objects, this method does not work well with objects which are hollow or not easily seen or sensed.

Biologically inspired configurations of the human arm mostly use 2-fingered [12] or 3-fingered [13] grippers to facilitate the same task [2, 6-11] . As explained in Becedas, Payo [12], a 2-fingered flexible gripper attached with a force sensor using a proportional integral control method is used to grasp objects. The control scheme is simple for this system, however, it's modelling is highly complicated for manipulation of rigid and flexible objects.

From the surveyed literature, it can be said that an FSR is a versatile transducer to use for applications or components that require force analysis. The FSR is more reliable and accurate than the other transducers and can also depict force sensing characteristics. One of the primary objectives of robotics research is to develop systems than can operate autonomously. For a pick and place robotic arm, in the context of gripping, the major factor which should be looked at is the application of the right amount of force to grasp and lift an object without crushing it. This paper deals with Tekscan's Flexi–Force [14] FSR to measure the gripping force using a rigid 2-fingered parallel configuration gripper of the SCORBOT ER-4u [15].

2. System Overview

At the high level control, incorporated in this robotic arm platform is an intelligent vision system for object detection and recognition [16], and also a multi-layered feed-forward artificial neural network based kinematics algorithm [3]. The force feedback system is added to the existing setup for object grasping. This would be advantageous to the system for object manipulation as the risk of dropping or crushing the object will be reduced with the help of FSR. Currently, in the SCORBOT ER-4u, there is no sensor for providing force data when the gripper of the robot grasps any object. In this work, an approach has been made by using a low cost sensory design for a force feedback system in order to determine just the right amount of gripping force required by the gripper of SCORBOT ER-4u to grasp a uniform object. The force feedback system is developed using SIMULINK model for the parameters of the gripper of the SCORBOT ER-4u. Experimental study is discussed based on the behavior of Tekscan's FSR, the relationships with respect to the load, normal and frictional forces.

3. The Gripper and Force Sensor Specifications

The gripper is located at the end effector of the robot which is attached to the wrist of SCORBOT ER-4u. The gearing mechanisms enable it to open and close depending on the user's requirements. This gripper mimics the human thumb and index finger capable of holding, tightening and releasing an object. It has a maximum payload of 2kg and is driven by a 12V DC servo motor whose feedback is given by incremental optical encoders. The gripper can open up to 75mm (without rubber pads) and 65mm (with rubber pads). Both the fingers/claws of the gripper moves simultaneously (2-Finger Parallel configuration) to grasp objects.

The force sensor used for feedback in this research is a Flexi-Force FSR manufactured by Tekscan [14]. It is a 191mm long flexible force resistive sensor which is 0.203mm thick. The measuring range for this force resistive sensor is from 0N to 445N. However, to measure forces out of the stated range, an amplification technique can be used. In this application, the sensing range will not exceed 445N.

4. Communicating with the Gripper and the Force Sensor

The gripper is controlled through MATLAB using a USB connection. From the MATLAB command prompt, motor commands are sent to the MATLAB Toolbox for Intellitek SCORBOT's (MTIS) intermediary Dynamic Link Library (DLL) to the Intellitek's Name mangled DLL and then to the control box for actuation through the USB cable. The motor along with the gear mechanisms operate to give desired gripper positioning. The gripping range is from 0mm to 65mm (with rubber pads), hence, each gripper claw moves 32.5mm in order to fully close the gripper claws.

5. Force Sensor Calibration and Force Measurement

As stated in [14], the Flexi-Force FSR offers a repeatability of less than 2.5% along with a response time of less than 5μs. The whole sensing area of the FSR is subjected to different masses for calibration purposes. Since the FSR has a circular sensing area with a diameter of 9.53mm, a small puck with the parameters equivalent to the FSR sensing area was placed before putting masses to calibrate the sensor (Note: the actual mass of the puck was equal to 0.00024g which is considered to be negligible).

In Fig. 1, the FSR is attached to a Digital Measuring Scale (DMS), and a small puck is placed on top of it. The DMS is reset once the puck and the FSR are placed on it. Every time a mass is introduced, the reading from the DMS is used to find the force exerted onto the FSR and through Arduino Uno the corresponding voltage is determined.

A voltage divider circuit was preferred over the circuit in [14], this is because for the application, neither stepping up nor stepping down of the FSR range was needed. The load resistor R_L which is $20k\Omega$ is used to avoid saturation of FSR. Figure 1 shows a setup of the calibration process and Fig. 2 shows the electrical circuit diagram for interfacing the FSR to Arduino Uno.

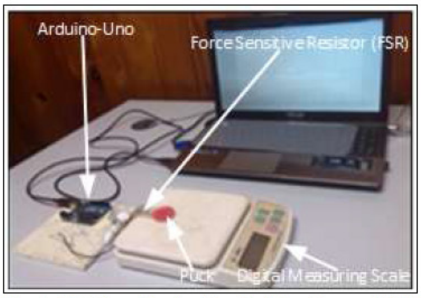

Fig. 1: FSR interfaced using Arduino Uno and MATLAB (with puck for calibration)

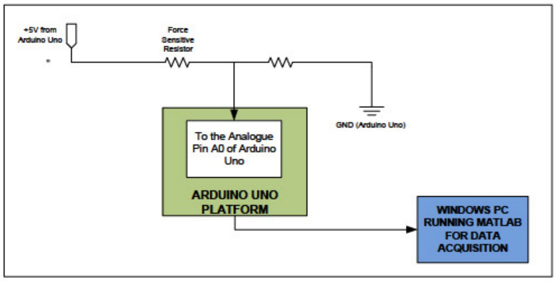

Fig. 2: Interfacing FSR to Arduino Uno and MATLAB

Using the circuit above, the FSR is calibrated using known masses. A graph is also plotted in real time using MATLAB to ensure consistent readings as the force applied to the FSR increases. From Fig. 2, the voltage at the analog pin A0 is:

$$V_{A0} = \frac{R_L}{R_L + R_{FSR}} \times V_S \tag{1}$$

V_S is 5V supplied by Arduino-Uno microcontroller. The input voltage at pin A0 is converted to an 8-bit value b because the microcontroller has 8–bit ADC. Hence, the input range for V_{A0} will be from 0–255 which will correspond to 0–5V, respectively.

$$V_{A0} = \frac{b}{255} \times 5 \tag{2}$$

In Fig. 3 the relationship between FSR and the Normal Applied Force is hyperbolic. In order to obtain a linear curve, voltage quantities are used. Figure 4 shows the relationship between the voltages at pin A0 and the normal forces applied to the FSR upon calibration. Using this relationship, the voltages represent how much force is directly applied onto the FSR.

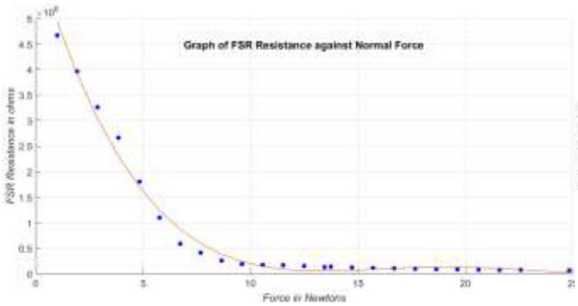

Fig. 3: FSR Resistance against the Normal Force

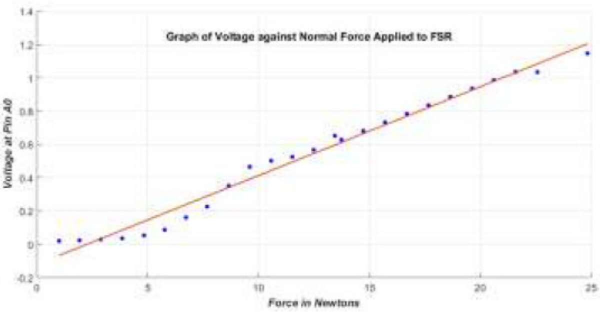

Fig. 4: Voltage against the Normal Force on FSR

From Fig. 4 it can be seen that:

$$V_{A0} \, \alpha \, F_N \tag{3}$$

Using *polyfit* command in MATLAB [17] which is based on Vandamonde's matrix [18], a linear equation was derived to represent the above relationship (4).

$$V_{A0} = 0.0534F_N - 0.1201 \tag{4}$$

From Fig. 4, the correlation coefficient R^2 for the graph is 0.9823, stating that the linear approximation is good enough. The standard error through instructions from Schmuller [19] was found to be 0.0252V, measures the amount of error in y (dependent data) for individual x (independent data). In order to quantify this error in terms of percentage, average of the actual y coordinate values are used and the percentage error was obtained as $\pm 4.7\%$.

6. Object Modelling and Development of Linear Force Control

In this paper we limit the objects to the following characteristics which are; uniform in size and shape, overall length or width or diameter of the object to be less than 65mm and the weight of the object to be grasped should not exceed 2kg. (payload of SCORBOT ER-4u). The force exerted by the 2-fingered configuration gripper of SCORBOT ER-4u is identical and normal to the object, which is represented by F_N (normal force). F_W is the weight of the object in Newtons, and μ is the coefficient of the static friction of the object (Fig. 5). Object modelling involves determining the weight of the object (F_W) from FSR readings. In similar manner, to relate the relationship between weight force and the sensor readings, another experiment was carried out by grasping known weights (F_W) in increments of 1N from 0N to 20N. This procedure was performed manually and for each weight, grasping was repeated several times to ensure minimum force is applied for successful grasp using the gripper of SCORBOT ER-4u. Readings were recorded for successful grasping of objects .i.e. minimum force required to successfully grasp objects. Figure 6 shows the experimental setup.

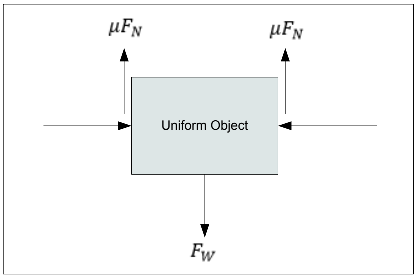

Fig. 5: Forces acting on the Object

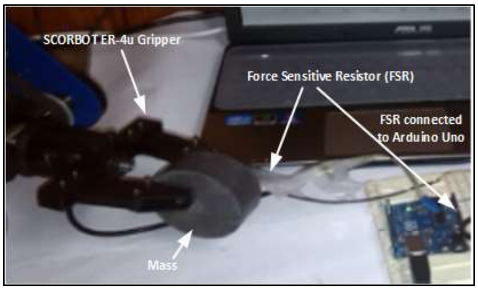

Fig. 6: Normal Force data logging using MATLAB

Analogous to section 5, the graphs of voltage and resistance are plotted as a function of weight force F_W.

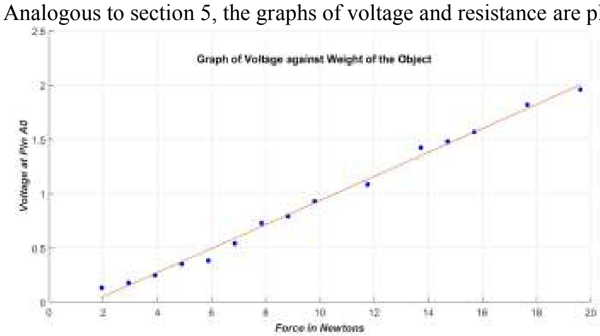

Fig 7: Graph of Voltage against the Weight of Object

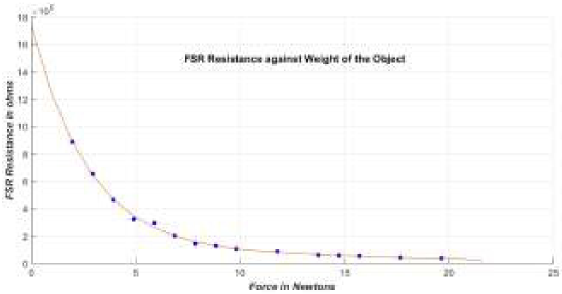

Fig. 8: Graph of FSR Resistance against the Weight of Object

Using the *polyfit* curve fitting algorithm in MATLAB, the linear relationship between V_{A0} and F_W in the above Fig. 7, is given by:

$$V_{A0} = 0.1107F_W - 0.1695 \tag{5}$$

The correlation coefficient, R^2 for Fig. 7 is 0.9937 and its corresponding standard error is $8.27 \times 10^{-9}V$. Using (5), the percentage error for the graph is $\pm 9.1 \times 10^{-7}\%$.

In section 5, it was seen that the FSR was turned into a force measuring device through calibration. The actual normal/grasping force can be found by equating (4) and (5), which gives rise to (6) below:

$$F_N = \frac{1}{0.0534}(0.1107F_W - 0.0494) \tag{6}$$

Equation (6) represents approximately the same value of grasping force F_N which must be provided by the gripper of the robot to successfully grasp an object with weight F_W without damaging it. Naturally, for grasping purposes, there is always a minimum force which must be applied based on the object mass, this is the limit up till where there will be no slippage. The similar goes for determining the maximum amount of force to be applied by the gripper such that the object is undamaged. In order to find this tolerance range, maximum and minimum values of grasping force (to the extent where the object is not damaged or slipped) will be used and the mean values for each will be used to generalize the tolerance range.

Fig.9 shows the procedure for object grasping based on the readings from the FSR. Each reading is compared with the stored value of grasping force and grasping will halt only if the reading from FSR is within the tolerance range of $(1\%F_N \leq F_N \leq 5\%F_N)N$, this is to ensure no slip nor damage is done to the target object. The first part establishes linear control using the data gathered upon calibration. The second part performs object grasping using the established control and indicates successful grasping of the object.

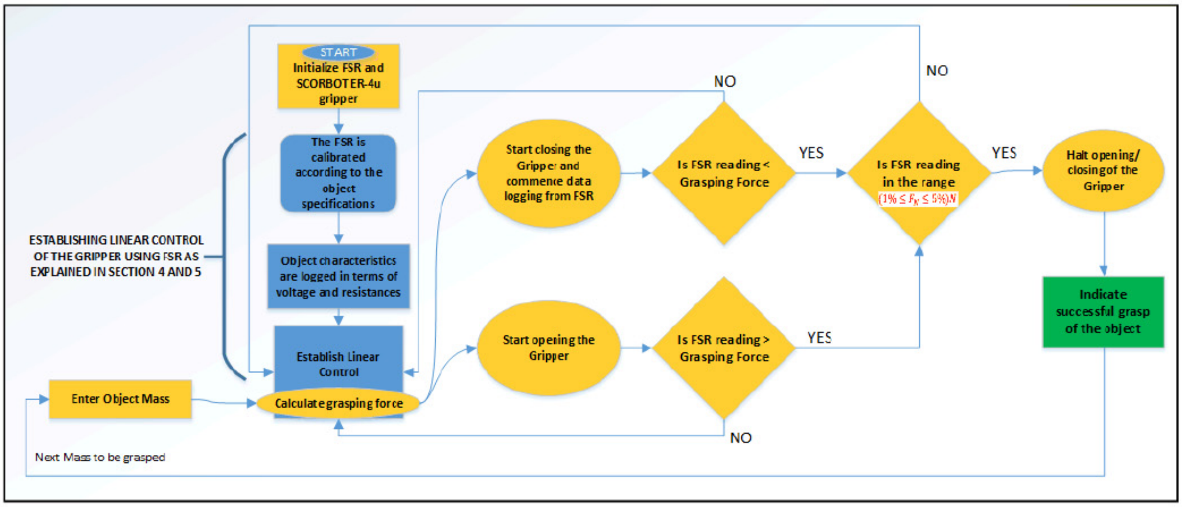

Fig. 9: Object Grasping Program flow

7. Discussion and Conclusion

Using the definition of the grasping force F_N derived previously, the gripper has been tested using masses of same coefficient of friction. Masses from 200g–1400g in increments of 200g were used to test the proposed linear force control of the gripper. Table 1 represents the calculated value (analytical) and the maximum and minimum extents of F_N(experimental values), to which there's no slippage nor damage to the object. The maximum tolerance value is +5% of F_N and the minimum tolerance value is -1% of F_N. This specifically means for successful grasping (no slip nor damage to the object) the normal/grasping force should be in the range $(1\%F_N \leq F_N \leq 5\%F_N)N$ for masses with the coefficient of static friction μ.

Table 1: Determining the Maximum and Minimum extents of grasping force

Masses Grasped (g)	Calculated value from Linear Control method (N)	Maximum Value for Force (N)	Minimum Value for Force (N)	Positive Error Range (N)	Negative Error Range (N)
200	3 14	3 27	3 03	0 13	0 11
400	7 21	7 38	7 20	0 17	0 01
600	11 28	11 90	11 00	0 62	0 28
800	15 34	16 40	15 26	1 06	0 08
1000	19 41	20 21	19 28	0 80	0 13
1200	23 48	25 32	23 33	1 84	0 15
1400	27 55	28 02	27 06	0 47	0 49
Average Value of Error				0 73	0 18
Maximum % Error				5%	
Minimum % Error				-1%	

Figures 10–13 below show the real time graphs while grasping masses of 200g, 400g, 800g, and 1200g. The highlighted points (x and y coordinates) in the graphs (Figs. 10–13), represent the end time, for which the gripper is successfully able to grasp the object. Note: After the stable response of the graphs (Figs. 10–13), the force goes straight to zero, indicating that the gripper has released the object.

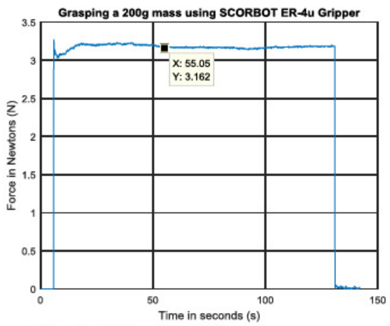

Fig. 10: 200g Object Grasping

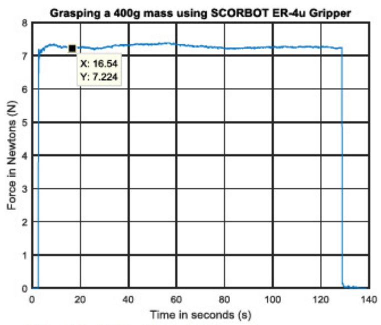

Fig. 11: 400g Object Grasping

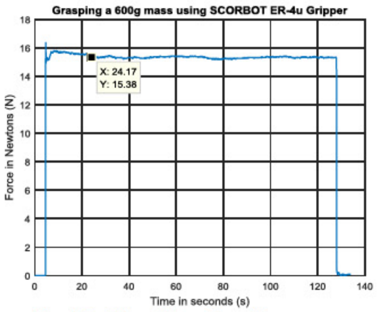

Fig. 12: 800g Object Grasping

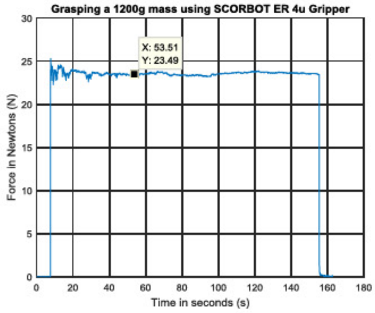

Fig. 13: 1200g Object Grasping

After the stable response indicated in Figs. 10–13, the force goes quickly to zero, indicating that the gripper has released the object. Using the program structure in Fig. 9, Figs. 10–13 shows the status of the gripper while performing a grasping action. It can be deduced from the graphs that in order to successfully grasp an object, the applied force must be within a certain range. In Figs. 10–13, the x-coordinate represents the end time and y-coordinate represents the force applied by the gripper to successfully grasp the object. The initial tolerance range for the gripper was set to +0.5N, but later when hardware testing was carried out, this tolerance range was changed to $(1\%F_N \leq F_N \leq 5\%F_N)N$ to achieve better results and ensure safety of the object (especially the risk of falling).For the tested cases, it can also be seen that if there's some change in the FSR reading, the gripper will try to readjust either by opening or closing the gripper. In addition to achieving linear force control, deploying the force sensor has other advantages. Through the readings of the force sensor, the status of the gripper can be easily monitored. As in the Figs. 10–13, the FSR is able to convey; impact detection (when the object is being first touched by the gripper), process of grasping (when the gripper is applying sufficient amount of force to grasp the object completely according to the derived linear F_N), final stable response (constant graph to indicate that the object is successfully grasped and there is no slippage).

In this paper, a force feedback system for the gripper of SCORBOT ER-4u robot was designed using linear control and tested on a real physical robot (acquiring feedback and acting based on linear force control in the real time). Initially, the FSR was calibrated and turned into a force measuring device. Then the force sensor was attached to the 2-fingered parallel configuration gripper of SCORBOT ER-4u and a linear relationship was derived between the normal/grasping force and weight of the object. Hardware tests were carried out to evaluate performances of the force feedback system. It was seen that the force sensor successfully indicated the status of the grasped object. Using the developed linear force control method, the objects were handled properly by applying adequate amount of force without damaging them. This works only for objects which have approximately the same coefficient of friction as that obtained from the calibration stage. The developed force feedback system is very versatile and materials costs less than FJD $100.00 (Fijian dollars including delivery charges). Future work will include optimizing and building more intelligent control for this robotic arm.

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