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CoM Estimation of Grasped Objects via Cost Effective Sensors

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Abstract. A cost effective alternative to the tactile and torque based sensors used in previous centre of mass (CoM) estimation literature was investigated. Tactile sensing systems are often not commercially available, very costly, or the processes involved in making them are not easily copied by those without substantial resources [3]. The core aim of the paper was to design an alternative to higher cost tactile sensors. The final prototype uses three force sensitive resistors in a triangular arrangement, capable of measuring both the magnitude and direction of the force applied to the sensor as a whole. Due to noise in the data and the number of data-points collected a suitable CoM estimation model was not able to be built. Despite this the paper was able to produce a low-cost sensor prototype (totalling less than £15), which with further investigation could become a useful alternative to more expensive tactile sensors.

1 Introduction

The ability for a robot to explore and gather information about the CoM of objects through interaction can increase success in tasks such as stacking, packing and grasping. This is especially useful when those objects do not have an even density throughout, pushing the CoM away from the volumetric centre and making it difficult for their CoM to be estimated from vision-based sensors alone. Given that it is certainly not rare to find objects consisting of different materials and densities in the real world, it is of great importance that we equip robots with the necessary sensors to handle them.

1.1 Related Work

Previous works have been written on CoM estimation using graspless [13] (where the object is not grasped but pushed or otherwise manipulated) and grasp based methods utilising tactile sensors. Approaches vary in the sensors they use to conduct their tests, some focus on using MEMS based tactile sensors [3] [6], which have gained popularity in recent years. Others attempt to use force sensors on joints [12] or as part of the gripper mechanism. However, the high cost of manufacture for MEMS based sensors and the lower, but still high cost of multi axis force and torque sensors make employing them costly. Despite much literature on tactile sensors [10] [11] [9] [7], and the use of tactile sensors in CoM estimation [4] [8], research into truly low-cost tactile sensors including the cost of manufacture is far lesser. The Digit [5] created in partnership with Facebook AI Research aimed to create a low-cost tactile sensor open source and freely available, but it's cost at around $300 per sensor remains too high for most smaller papers.

1.2 Contribution

This paper aims to explore the use of truly inexpensive sensors to recreate results that have been achieved with custom, more expensive 'tactile' sensors. Investigating the creation of new sensors by utilizing low cost, commercially available hardware and 3D printing to estimate the CoM of grasped objects. The principal aim is to manufacture a tactile sensor prototype for less than £50 with similar ability to more expensive sensors. We shall then test it's effectiveness in CoM calculations of grasped objects.

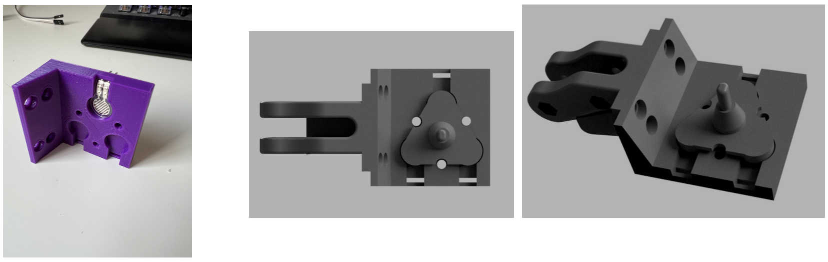
2 Implementation

2.1 Arm Hardware

The arm used for these experiments is the BNC3D's open source Moveo arm [1]. This arm was chosen because it is open source and mostly 3D printed, allowing for easy adjustments to parts and creation of new gripping methods if required. It is also larger and has more degrees of freedom than most other open-source arms, which will allow experimentation with more complex arm movements and control of heavier objects.

2.2 Sensor Design

Fig. 1: New sensor design



(a) Sensor base (final design)

(b) Sensor platform and base design (final design)

The design consists of a base containing three FSRs with a three-legged platform placed on top which interacts with the gripped object. The platform puts any force placed onto itself into the base and thus the FSRs which, via a voltage divider, causes a voltage change on the output. As there are three FSRs per finger, each finger can determine the precise direction of the force applied to it and thus the amount of force applied in that direction.

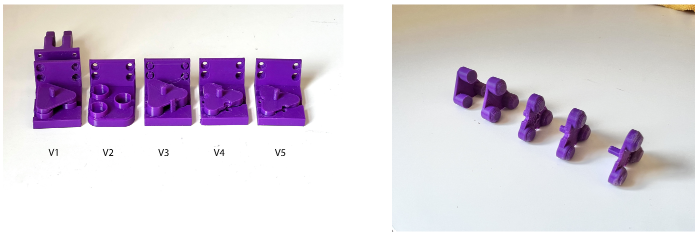


Fig. 2: New sensor design

(a) Sensor versions v1 to v5

(b) Platform versions v1 to v5 (left to right)

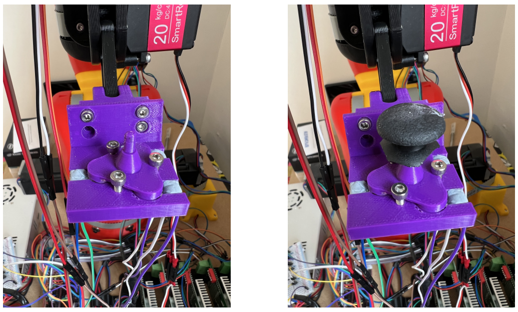


Fig. 3: Final design

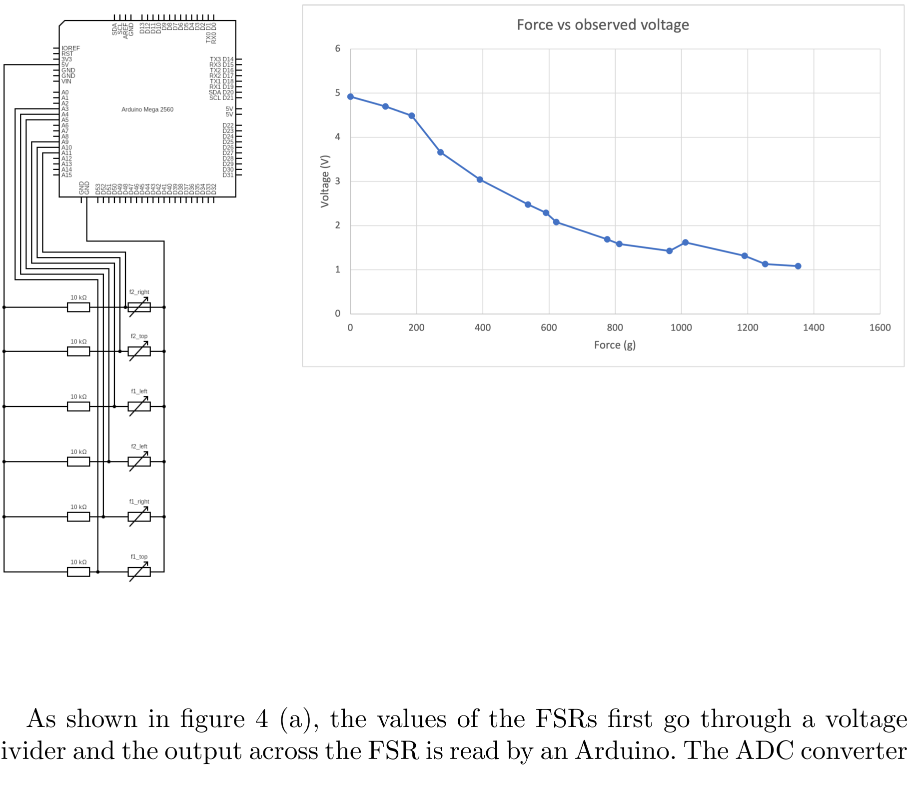
(a) Sensor base (final design)

(b) Sensor platform and base design (final design)

The final sensor design shown in figures 3 and 4 was made slightly wider compared to the initial version and included slots for the ends of the FSRs to protrude through. These slots along with the adhesive used, prevents the wires that attach the FSRs to the Arduino from moving when the arm is in motion, preventing unnecessary noise and skewing results. The final design of the platform also increases the height of the column that holds the rubber gripper. This increases the size of the moment at the base when directional force is applied to it. Increasing this moment means more force goes directly into the sensors, instead of sliding the platform along the base in which some force would be lost as the platform contacts the base at its edges. This was a major factor throughout the design process, as the platform contacting the sides of the base, or the screws, and putting some of its force into the FSRs would cause inaccurate results to be given. Therefore, the final design creates a large amount of friction between the feet of the platform and the FSRs by using a small amount of adhesive on each of the feet to bond the platform's feet to the FSRs below. Ideally, and in future versions this connection would use a more permanent adhesive - but to maintain the ability to adjust platform placement and allow new iterations of the base without permanently joining the FSRs to the base, blue tac was used.

The total cost of this sensor is £12.04 including the cost of the 3D printed material used, 3 FSR sensors and screws required. Putting it very firmly within the cost boundaries set out for this paper and making it a very low-cost sensor overall.

Fig. 4: New sensor design


(a) FSR circuit diagram

(b) FSR Force vs Voltage graph

As shown in figure 4 (a), the values of the FSRs first go through a voltage divider and the output across the FSR is read by an Arduino. The ADC converter on the Arduino Mega2560 has a 10-bit resolution, giving values between 0 and 1024.

Figure 4 (b) shows the actual voltage across the voltage divider as measured by a multi-meter when force is applied to it. This shows high sensitivity for the range set out, with a close to linear response. This is very useful as it shall mean the ADC values collected will closely match the force applied without manipulation.

The direction and magnitude of the force applied to the sensor is calculated by taking a ratio of the ADC values and multiplying these by the vectors from the origin to each of the three points on the equilateral triangle formed by the FSRs. This then gives us a 2-dimensional vector for the force applied to the sensor, who's direction is the direction of the force on the sensor and whose magnitude is the magnitude of the force in that direction.

$$\begin{aligned} R_1 &= \text{ADC value read at FSR1} \\ R_2 &= \text{ADC value read at FSR2} \\ R_3 &= \text{ADC value read at FSR3} \end{aligned}$$

Starting at the centroid of the equilateral triangle formed by the FSRs, assuming the length of each side is 1 and the triangle has coordinates for each sensor $FSR1(0,0), FSR2(1,0), FSR3(\frac{1}{2}, \frac{\sqrt{3}}{2})$:

Where $P(X,Y)$ is the coordinates for the centroid of a triangle:

$$P(X,Y) = \frac{(x_1 \sin 2A + x_2 \sin 2B + x_3 \sin 2C)}{(\sin 2A + \sin 2B + \sin 2C)}, \frac{(y_1 \sin 2A + y_2 \sin 2B + y_3 \sin 2C)}{(\sin 2A + \sin 2B + \sin 2C)}$$

$$= \frac{(\sin(120) + \frac{1}{2} \times \sin(120))}{(\sin(120) + \sin(120) + \sin(120))}, \frac{(\frac{\sqrt{3}}{2} \sin(120))}{\sin(120) + \sin(120) + \sin(120)}$$

$$= \frac{1}{2}, \frac{1}{2\sqrt{3}}$$

Then calculating the vectors of each of the three sensors from this point, and normalising gives us:

$$\begin{aligned} \vec{\text{FSR1}} &= \langle -\frac{\sqrt{3}}{2}, -\frac{1}{2} \rangle \\ \vec{\text{FSR2}} &= \langle \frac{\sqrt{3}}{2}, -\frac{1}{2} \rangle \\ \vec{\text{FSR3}} &= \langle 0, 1 \rangle \end{aligned}$$

This then allows a resultant vector to be created by composing the FSR vectors:

$$\vec{\mathrm{Force}} = R_1 \times \vec{\mathrm{FSR}}1 + R_2 \times \vec{\mathrm{FSR}}2 + R_3 \times \vec{\mathrm{FSR}}3$$

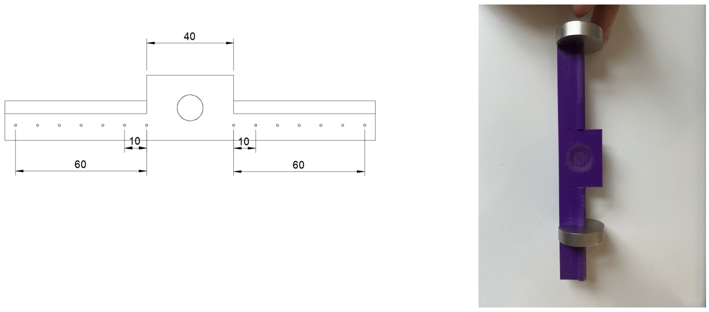
This resultant two-dimensional vector gives the force in the X and Y directions of each sensor, taking the three sensor values and turning them into a simple representation of the directional force applied.

Software Code for this paper, including code discussed in the Testing Methodology can be found at https://github.com/tomemmerson/arm_com_estimation .

3 Testing Methodology

The procedure for testing the ability of the arm to calculate the CoM of an object shall be conducted by manipulating an object whose CoM can be easily calculated.

Fig. 5: Weight holder design



(a) Weight holder diagram (diagram in mm)

(b) Weight holder with weights

Figure 5 shows a 3D printed object with very little mass (around 2g), to which masses can be added along it's length.

To collect data from the sensors, a simple wrist movement was devised in which the grippers shall grip the weight holder and then the arm's wrist shall twist right 45 degrees, then back to centre, then left 45 degrees and back to centre again.

Tests shall be conducted with a single slotted mass placed at one of the 12 positions along the weight holder and repeated three times for each position (6 positions on each side of the holder). Giving a total collection of 36 data points. Sadly this is not as much data as could be hoped for; due to issues with the wrist motor and the length of time the motors could run for, this was settled on as the minimum amount of data to be useful.

The code for this paper, along with the 3D STL files for the parts and weight holder can be found at https://github.com/tomemmerson/arm_com_estimation .

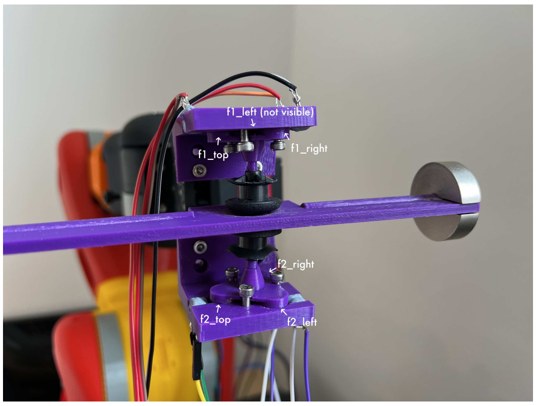
4 Results

The raw results for this paper can be found on Kaggle [2] .

During the testing, it was noticed that the motor controlling the wrist was not able to turn the weight holder at 16 micro-steps/step and at the speed set. Sadly, there was not the ability to replace this motor with a larger one because of the space that the 3D printed part had allotted for it and there was not time to redesign and reprint this part to fit a larger or geared stepper motor.

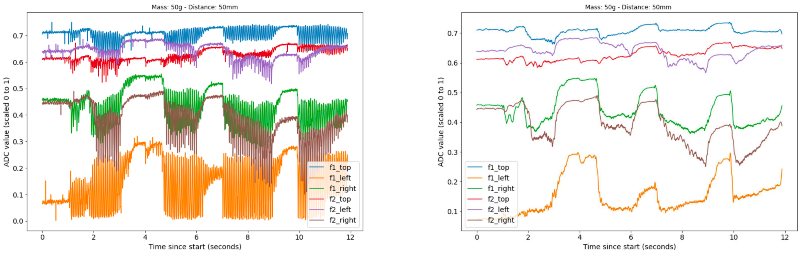
In order to provide enough torque to rotate the weight holder, micro-stepping was removed, the speed of the motor was reduced (as the torque of a stepper motor is reduced at higher speed and micro-step settings) and the current was increased from 0.3A (it's rated current) to 0.6A. This did create enough force to turn the weight holder even with the masses at 80mm from the center, however it did cause a large amount of noise in the data collected as each step caused a jolt in the motors operation which can be seen in the results.

Fig. 6: Gripper starting position, with sensor names labelled



An example of the gripping technique used in testing can be seen in figure 6. This figure also shows the sensor names used in subsequent figures and in the data collected. Sensor 1 (with FSRs prefixed with 'f1' in the example) starts on top and Sensor 2 (prefixed with 'f2') starts on the bottom. In the example the 50g weight is placed at the +80mm position. The arm would then rotate the weight holder to the right (as viewed from the image), back to it's initial position then left and back to initial position again.

Fig. 7: Raw and smoothed sensor values



(a) Raw sensor values from 50g, 50mm test

(b) Smoothed sensor values from 50g, 50mm test

In the raw data (figure 7 (a)) from the sensors each step of the motor can be seen as a spike in the data. Evident in each of the samples of the raw data are 4 distinct sections where the motor turns right, then back to centre then left then back to centre. These spikes and their respective dips (caused by the oscillation created by the initial step), do not necessarily mean that the CoM cannot be calculated. In fact, the oscillations themselves may be useful in determining the CoM of the object, as different weights at different points of the weight holder will cause oscillations at different frequencies, which may then aid in the CoM estimation. However, to build a model based on the oscillations created by this motor, would likely render it ineffective when the motor was replaced and the oscillations removed from the system.

To provide data that would be similar to data collected when the motor was replaced, a Savitzky-Golay filter was applied. This smooths out the oscillations, making their effects on any model lesser and giving a clearer indication of the general trends. Figure 7 (b) shows this smoothed data for a single test run. In this we can see that the data no longer has the oscillations seen before but still maintains it's useful features such as timing of the peaks and general trends that were observed in the oscillations.

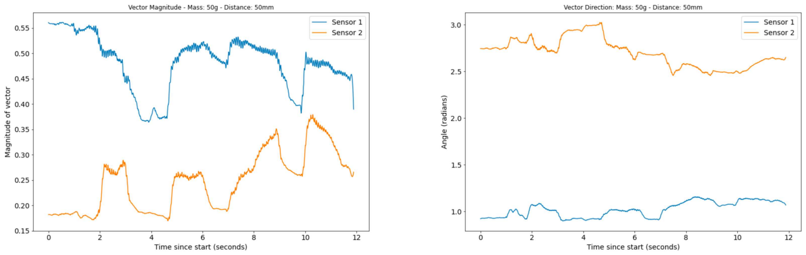


Fig. 8: Vector calculations

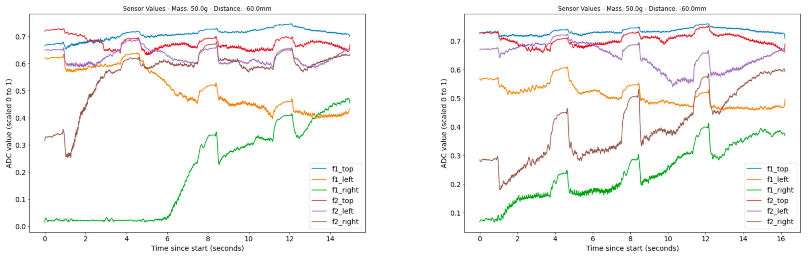
(a) Magnitude graph

(b) Direction graph (Sensor 1=f1, Sensor 2=f2)

When assessing the force placed on the sensor it is useful to use the vector representation described in the sensor design section of this report as it normalises the values from each of the sensors to into the overall direction and magnitude of the force applied to the sensor. Calculating these vectors from the force applied to each FSR using the technique described, and then plotting their magnitude and angle gives the plots shown in figure 8. What we observe is that the direction of the forces applied to each sensor does change with the rotations of the arm but does not change significantly in either sensor. This is likely due to the force applied by the gripper servo, which will constitute most of the force in the system, making the effects of the rotation on the weight holder small in comparison, thus creating only small changes in the direction of the overall force. Despite this, the resolution of the data does allow us to view even these small changes in force applied.

A correlation was investigated between the magnitude or direction of the forces on each sensor and the CoM of the weight holder, however no significant correlation exists. It is very possible that there does exist a more complex relation between the data collected from the sensors and the CoM of the weight holder, but any attempt to create a ML model from it is very likely to lead to overfitting given the small sample size. It was expected that there would be an easily marked correlation in the force vectors of the initial hold caused by the weight on the weight holder providing a smaller or larger moment dependent on how far it was from the grip point; this was not observed. A few possible reasons for this are:

Fig. 9: Stuck sensor example



(a) Example of f1_right stuck

(b) Rerun of same test, f1_right not stuck

1. Sensor errors - During design it was noticed that because of the tolerances between the platform and the base of the sensor, it was possible that some force would go directly from the platform into the base due to friction between the two, bypassing the FSR; while the space was increased between the platform legs and the sides of the base it cannot be ruled out that this was causing an effect on the sensors ability to register all forces effectively in all directions. Where and when the platform may contact the base (not through the intended sensors) could add a fair amount of randomness into the data and thus explain the large amount of variation found between tests. Figure 9 shows two -60mm tests. During the first (a), the sensor f1_right gives almost no reading until 6 seconds into the test. Whereas the second (b), gives a reading from the very start, this could indicate an issue where the force that should have gone into f1_right going directly into the base, bypassing the FSR.

2. Sensitivity - The resistance of FSR sensors is inherently non-linear, while was shown that for the range of force measured the output should be close to linear it will not be exactly linear. Non-linearity in the sensors may explain some of the variance between tests, as small changes in force would create much larger large changes in the ADC output. As the FSR vector calculations assume that the force and ADC output are linearly correlated then this would lead to errors in the vectors produced.

3. Noise - As was initially discussed, because of issues with a stepper motor in the arm a large amount of noise was introduced into the system, causing oscillations that are very evident in the data collected. While work was done to reduce this and smooth out the signals received, this is likely a significant contributing factor in the unreliability of the data retrieved.

5 Conclusion and Future Work

A cost effective alternative to costly tactile sensors for use in CoM estimation was investigated. This sensor costs less than 1/10'th of the price of other low cost commercially available tactile sensors [5], making it a very attractive sensor for low-cost applications. While a mixture of adverse circumstances and prototype issues effected this paper's ability to determine the effectiveness of the sensor. The sensor itself displayed that it is capable of detecting small changes in the direction and magnitude of the force applied to the gripper, which with further investigation could become a useful alternative to more expensive tactile sensors.

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