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Article

Design of a Dual Finger 3D Printed Gripper with a Low Cost ToF-based Force Sensor

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Abstract - This study examined the use of a low-cost *Time-of-Flight* (ToF) sensor to measure forces on a robotic gripper. A novel dual low-cost Gripper with changeable Fingers was designed, and 3D printed. The gripper design was combined with a set of low-cost springs and the ToF sensor. Following a calibration procedure of the elastic means, the gripper leverages on the linear elasticity of the springs to convert the ToF estimated displacement into a force measurement. Calibration was performed with a 6 *Degrees of Freedom* (DoF) IIT FT17S/T miniature force sensor. An Arduino Uno embedded controller was used in order to design an end-user interface between the robotic gripper and the operator: a keypad allowed the setting of specific gripping forces and the readings of the fingers' displacement on the Arduino serial monitor. An OLCD external display was also implemented in order to improve the end-user experience.
This study showed that low-cost systems can be used in order to design, manufacture and integrate robotic devices: the precision and accuracy of such a solution has been discussed with consideration on how to improve the design through the integration of an OLED 128 x 64-pixel SSD1306.

Keywords: Low-Cost Robot, Robotic Gripper, Force Sensor, Time of Flight sensor.

Citation:

1. Introduction

In industry and other sectors, including the medical sector, robotic grippers have been implemented to grasp objects as shown in Figure 1 to replace humans due to safety concerns, such as lifting heavy car parts in the automotive industry to prevent human injury [1], precision in the medical industry, where evasive surgery requires high levels of accuracy, that may be difficult to perform with hands and many other clasping applications [2]. Thus, various solutions have been proposed and made to tackle these requirements. In this context it is important to notice that the integration of sensor within the robotic grippers inherently implies an increment of the overall device's cost [3] [4]. Such a cost is significant in the case of force sensor, and it has strong implication on the final decision whether to integrate or not integrate these sensor components. On the other side, the capability of the robot to perceive force provides (or not provides) a different set of skill to the robot. These considerations apply, in particular, to robotic applications in industry

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and in the medical sector, according to the tasks that the robot is designed to perform within the industrial environment or, for example, a surgical theater [5] [6] [7]. Many robotic grippers with force-sensing abilities have arisen to solve the safety and precision problems required in the industrial and medical sectors [8] [9]. This is particularly sensitive when good grasping capability are required [10] [11] [12]. Kuang et al., for example, recently published a review discussing the application of integrated force sensors, capacitive sensors, and strain gauges [13]. Nevertheless, these sensors may have a set of important limitations such as low sensitivity with the integrated force sensors, the large size of the capacitive sensor, and nonlinear readings from the stress gauge due to distributed forces [13]. Other concern on the implementation of these devices can also involve the typical high stiffness of commercial force sensor which does not match very well with the robotic manipulation of soft parts or, in the case of medical application, of soft tissues [5].

Figure 1 - An example of a 2-fingers commercial gripper with the UFACTORY 7-XArm Robotic Arm at the Robotics Lab, Liverpool Hope University

In this context, the robotic gripper of this paper hopes aims at tackling the aforementioned limitations with an approach which is based on the three main systems of Figure 2; a dual finger gripper, an end-user interface and a calibration procedure. The dual-finger gripper is based on a design embedding 3D printed parts, linear springs, and a ToF sensor. The decision to adopt a ToF sensor relies on the nature of the sensor and on its costs. During the development of the project other solutions were considered, however the ToF sensor presents the clear benefit of a compact design, proper reliability and – last but not least – reasonable cost. Achieving accuracy and precision of the gripper force by means of calibration using a IIT FT17S/T 6 DoF force sensor. End-user interface that will allow a user of the gripper to choose from different operations shown in Figure 2 such as manually setting a force.

This paper will discuss the materials and methodology used for the construction of a robotic gripper to tackle the 4 challenges the robotic gripper will address that are shown in Figure 2 proposal in Section 2. Section 3 will discuss the findings of the robotic gripper mentioned the success of solving the challenges. Section 4 will finally conclude on the paper with Section 5 mentioning further work that could be done to improve on the robotic gripper.

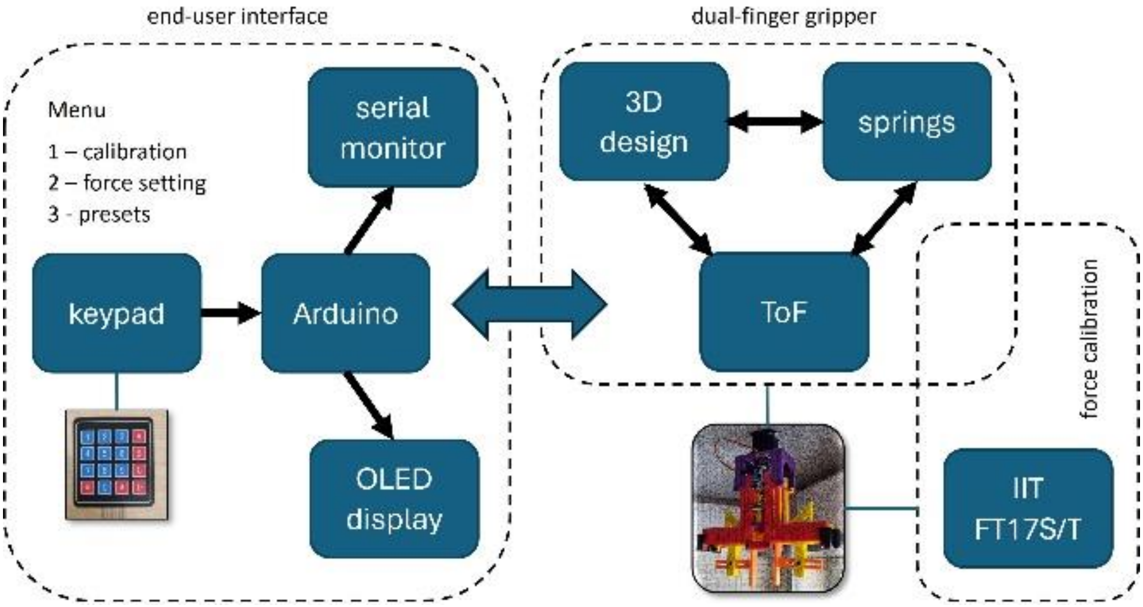

Figure 2 – Schematic of the proposed Robotic Gripper system embedding the end-user interface and the dual finger gripper with force sensitivity

2.Materials and Methods

In this section of the paper the schematic used in Figure 2 will be broken down to the methodologic process and materials required for each component of the Dual Finger gripper i.e. dual-finger gripper in Section 2.1, end-user interface in Section 2.2 and force calibration of the gripper in Section 2.3.

2.1. Dual Finger Gripper

A. Dual-Finger Gripper Operation

The gripper in regard to low sensitivity and large size shown in works of Kuang et al proposed using a low cost VL6180X ToF sensor, which according to the manufacturer, "measures absolute ranges from 0 to above 10 cm" and has a size of "4.8 x 2.8 x 1.0 mm" [13][14]. Having interchangeable grippers that are the shape of the object allows the grippers to have a distributed load when applying a force on an object e.g. using curved grippers when gripping a circular object compared with using grippers that are not curved. The use of springs when calculating force will eliminate the nonlinear readings observed when using devices such as strain gauges as springs behave linearly when within the elastic region and finally, a human interface will allow a user of the robotic gripper to be able to select a specific force as different objects have varying material properties i.e. breaking points and weights which could therefore require varying force to ensure the object doesn't break or the gripper is able to overcome gravitational forces when object is being lifted.

B. Design and Operation

Using Computer-Aided Design (CAD) software in this case Fusion 360 (Autodesk®), parts and assemblies were created to clasp objects (Figure 3), mount springs that will extend when the grippers experience a force that the ToF sensor will measure (Figure 4).

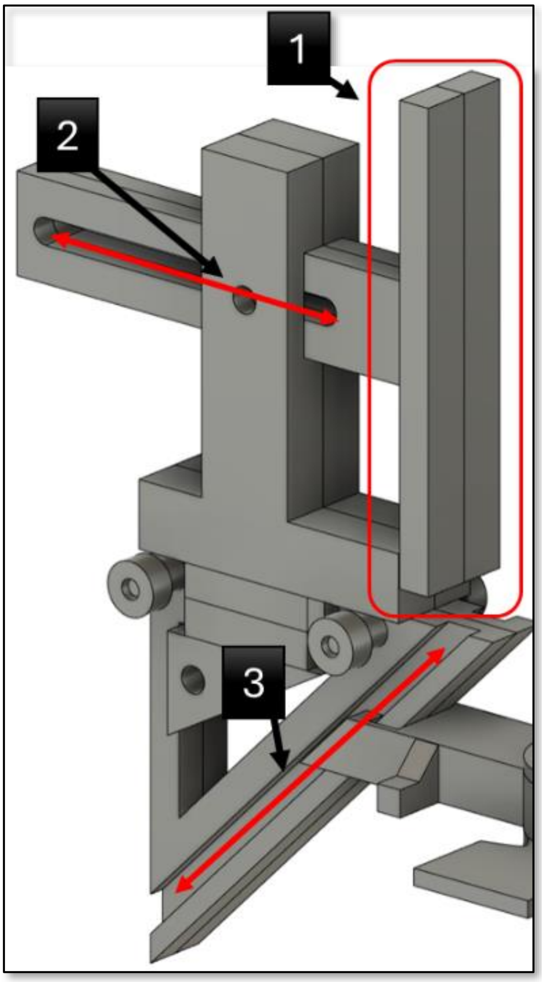

Figure 3 – Gripper assembly: (part 1) the gripper that can be interchanged for the specific object being picked e.g. a curved gripper rather than straight; (part 2) the adjustable interconnection space between grippers and (part 3) the groove which provides the translation of the rotational movement from the stepper motor into an horizontal movement of gripper

The gripper assembly (Figure 3) was designed to use interchangeable grippers that vary in shape to ensure forces were applied evenly (Figure 3 – part 1)) with gaps between them adjustable to accommodate objects of different sizes (Figure 3 - part 2). The movement of the gripper assembly to perform clasping was controlled by the ToF and spring assembly (Figure 4). The assembly translates motions from the stepper motor to the gripper assembly through the contact point in Figure 3 (part 3), which opens the gripper assembly when the ToF and spring assembly move up and vice versa. The mechanism of the system is illustrated in the Figure: basically, the main translational movement of the gripper's finger (1) is anchored to the sliding component (2) which is actuated through the main sliding movement reported in (3). The actuator activates such latter sliding translations which, in turn, allow the final horizontal translations of the fingers. The ToF and gripper assembly translate stepper motor movements to the gripper assembly using the tension of the springs, which are attached to the assembly in Figure 4 - part 1. The ToF measures the spring's extension (Figure 4 - part 2) when a force is exerted, as the stepper motor will move the ToF and gripper assembly when in operation. For example, closing the grippers will result in the ToF and spring assembly moving downward, extending the springs based on the forces experienced in the gripper assembly. To ensure the springs remain in the elastic region i.e., maintain a linear relationship between force and extension IR sensors were used to stop the operation of the stepper motor when passing defined limits. In this context, at this stage of the project, it is important to notice that we have not characterized the ToF on the perception of micro movements, rather we have relied on the performance parameter of this commercial product and then provided a design of the gripper mechanism such as this ToF sensor can perform on its range. In other words, the gripper, at the moment, is not designed to perform micro-movements which, in turn, would affect the movement sensitivity of the ToF vs small displacement.

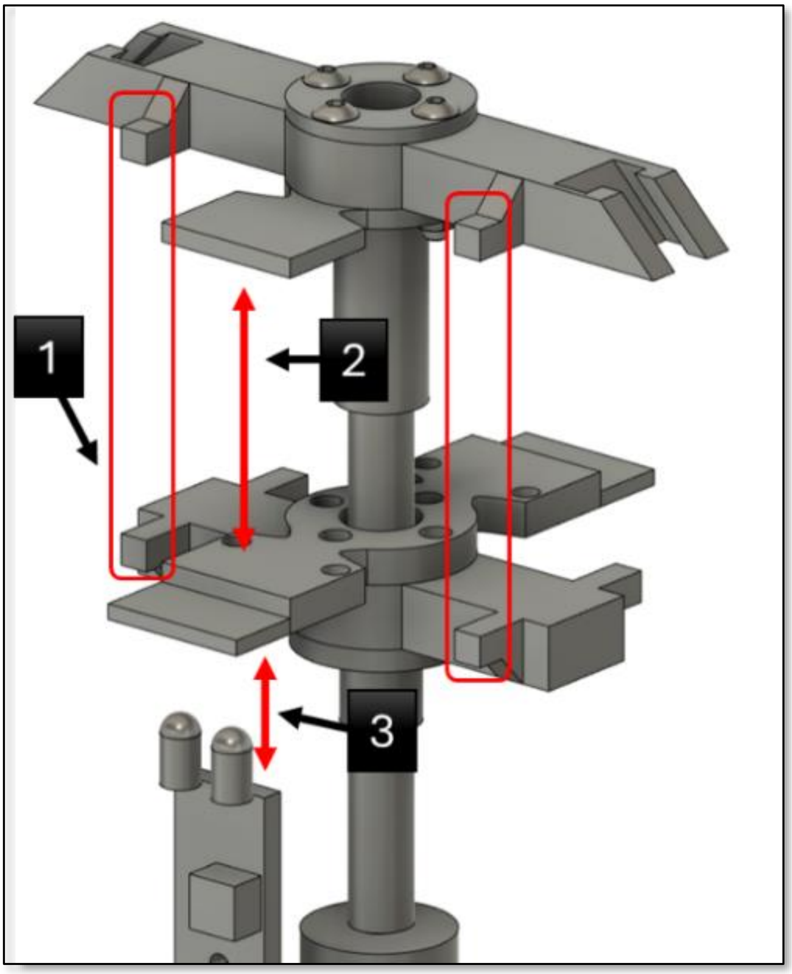

Figure 4 – Assembly of the ToF sensor and of the springs: (part 1) the housing where springs will be attached and extend due to the force experienced on the grippers; (part 2) the ToF sensor' plates which provides the measurements of the linear extensions of the springs and (part 3) the IR sensor which provides redundancy of the system and ensure springs will remain within their linear elastic region

Table 1: additional external devices to operate the gripper that were gotten from Amazon [15]

Item	Type	Quantity
Embedded Controller	Arduino Uno	1
Stepper Motor	RTELLIGENT Nema 17	1
Stepper driver	HALJIA A4988 Stepstick Stepper Motor Driver	1
ToF	DollaTek VL6180X	1
Keypad	AZDelivery Matrix Array 4x4 16 Key Keypad	1

Table 2: braces used to hold 3D components and devices

Item	Type	Quantity
Springs	8.5 x 47 mm	4
Screw	M3 x 8 mm	6
Screw	M3 x 12 mm	8

Screw	M3 x 16 mm	2
Screw	M3 x 20 mm	4
Bolt	M3	20
Rod	MUXSAM Screw Rod 100 x 8 mm	1
Couplings	HALJIA Stepper motor flexible couplings 5 x 8 mm	1

C. Additional Dual-Finger Gripper Materials

Additional materials were required to operate the robotic gripper such as an Arduino embedded controller to control the stepper motor, as well as provide a human interface where user inputs are sent to the device and outputs are visualized on the Serial monitor of the Arduino.

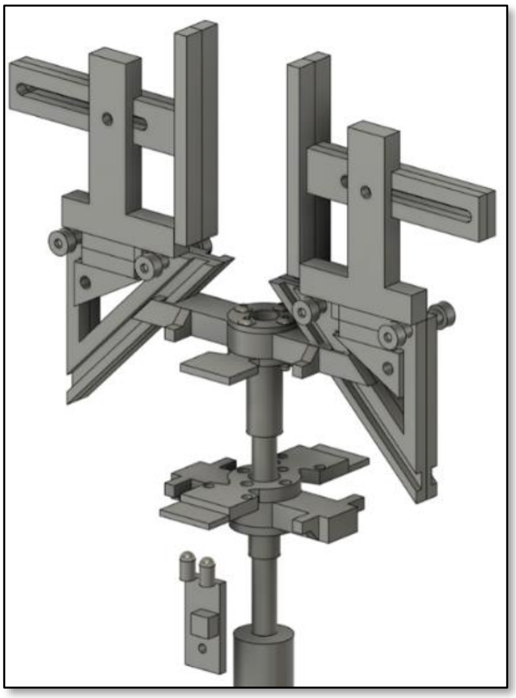

Figure 5 – 3D preview of the assembly of the Gripper, of the ToF sensor and of the springs

D. Robotic Parts Assembly and 3D Printing

The assemblies in Section 2.1.B, additional materials in Section 2.1.C, and additional CAD parts shown in Figure 5, were assembled in Fusion 360 to ensure cohesion with the parts before 3D printing, which was successful, as shown in Figure 5. The parts were 3D printed and assembled using parts from Table 1 and Table 2, as shown in Figure 6. Appendix A reports further details about the gripper design.

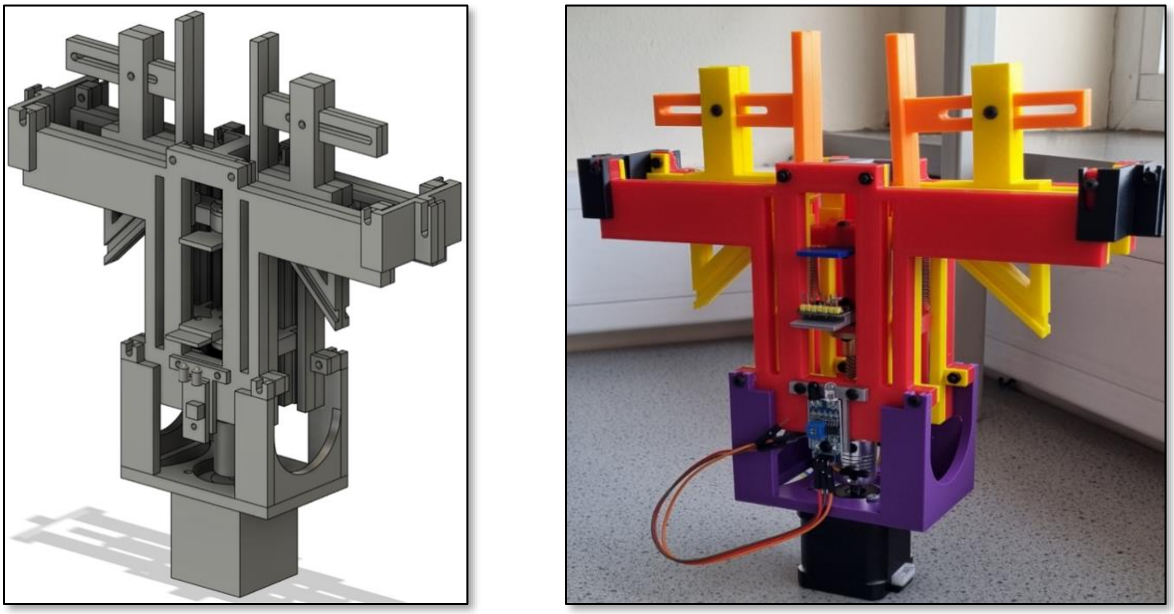

Figure 6 – 3D parts assembly of the complete robotic gripper design (left panel) and final result of the real system (right panel): the 3D parts are printed with an Original Prusa i3 MK3S+ 3D printer and assembled using the devices and components reported in the text description (Section 2)

2.2. End-User Interface

A. Arduino and external libraries

The Arduino Uno and additional Arduino libraries were used in the Dual-Finger gripper for operations incorporating external libraries from the official Arduino website i.e. "Keypad.h" and "Wire.h" [16].

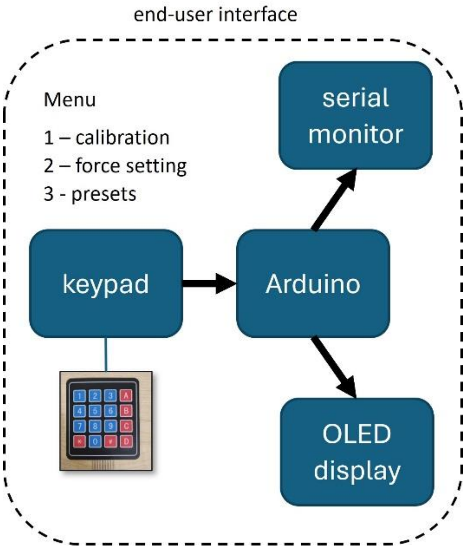

Figure 7 – The AZDelivery Matrix Array 4x4 16 Key Keypad which is integrated with a 3-choice menu (calibration, force setting and presets)

B. Keypad

To input data into the Arduino Uno to operate the gripper a keypad was used for user inputs as shown in Figure 7 incorporating libraries mentioned in Section 2.2.A.

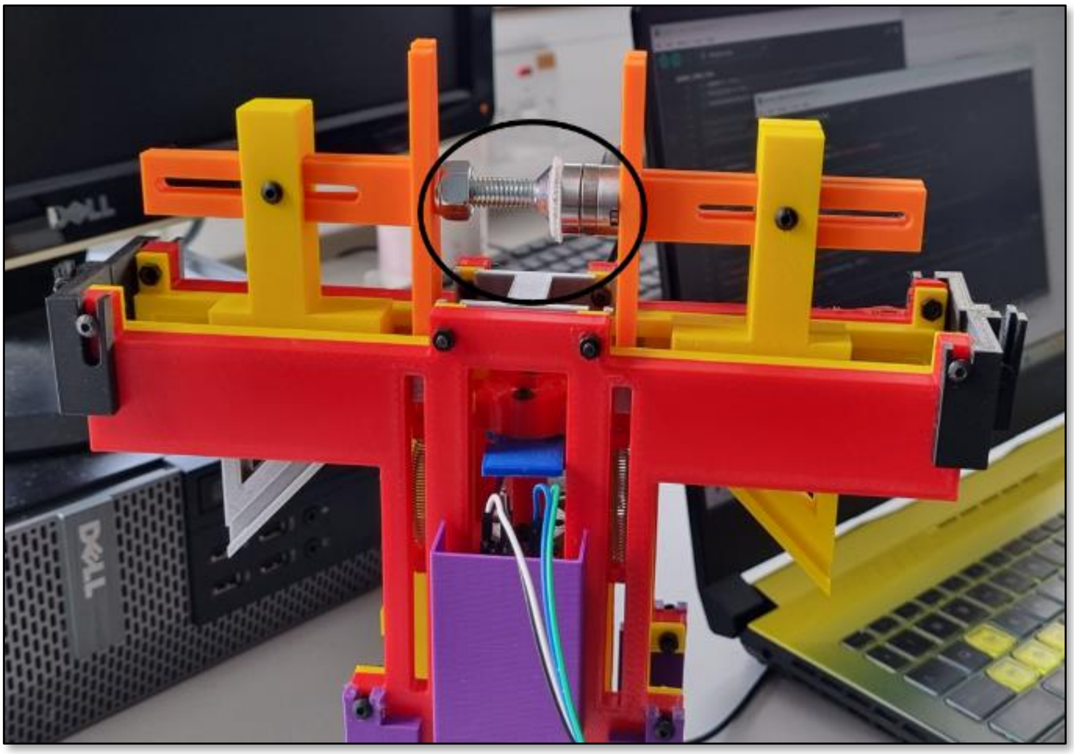

Figure 8 – The FT17S/T placed between the grippers to measure force

C. Serial Monitor

Using the serial monitor of the Arduino as an output, a user of the robotic gripper can input information using the keypad (Figure 7) to perform calibration, manually set a force for the gripper to clasp, and finally select preset forces that are programmed, into the Arduino. The figure also shows the main menu of the human interface to select operations. Appendix B reports further details about the software design.

2.3. Calibration

The robotic gripper was calibrated before operation to map extensions of the springs and forces exerted using equation 2.3-1. For the calibration procedure we use a senso of higher class, which provides force measurements on the 3 axes with a range of ± 50N, ± 50N and ± 70N, in the x, y and z axis, respectively and with a resolution of 10mN on all the axes. The sensor also allows the measurement of the torques on the 3 axes with a range of ± 0.5Nm and a resolution of 70μNm on all the 3 axis. Given the higher order of class of the IIT sensor vs the proposed device and its resolution parameters, the readings of the IIT device were taken as ground truth reference during the calibration process. The calibration process was performed five times using an IIT FT17S/T 6 DoF miniature force sensor [4] (Figure 8) to obtain the force F from the equation 2.3-1, and the readings from the ToF sensor providing the x values. At this stage, 5 trials were performed for the calibration procedure in laboratory conditions. A further set of in-field trials and laboratory tests under different (and controlled) conditions of the environmental parameters (i.e. temperature, humidity) could be performed, however, on this phase of development of the prototype, we have not design such as a characterization.

The results were then plotted on a graph (Figure 9) with an average of the results added to evaluate which K value using equation 2.3-1 would return the force set by the user when using the robotic gripper.

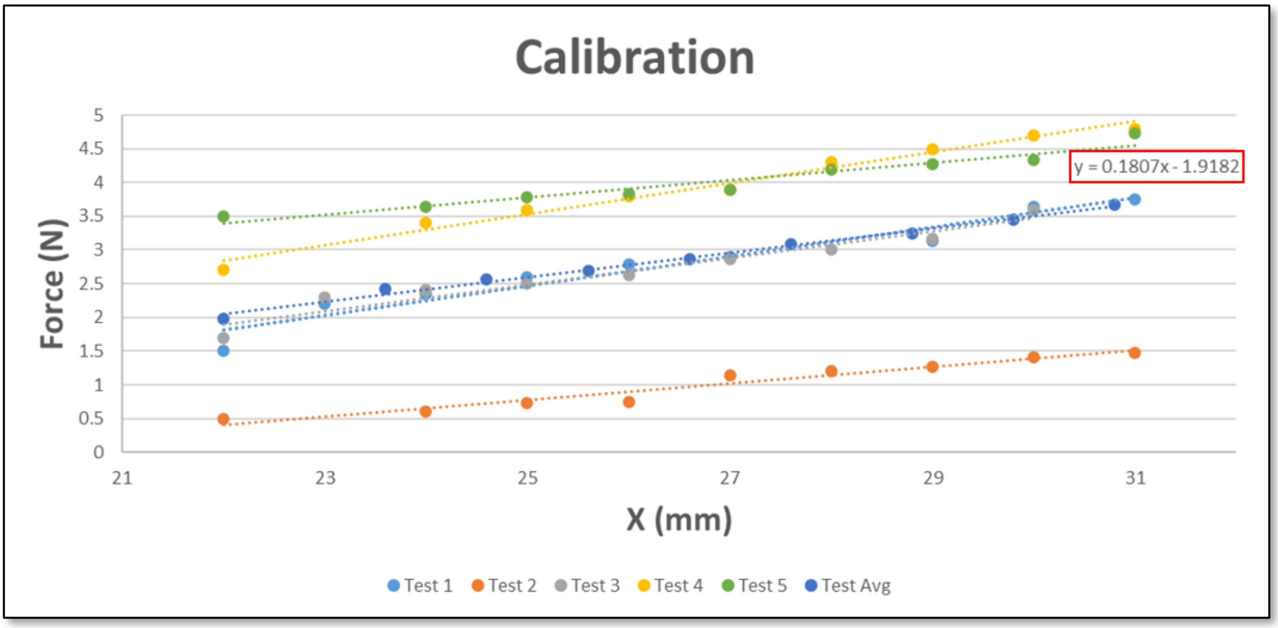

Figure 9 – Graph showing force against distance to find the value of K i.e. equation 3.6-1. It also shows an example of the equation for mapping force and distance for the average test in a red box.

Figure 9 shows that data points did not produce a straight linear line. The characterization of the gripper is performed under the condition of linearity and, more importantly, while using the device in a range of motion such as the spring are not mechanically stressed and operating in their linearity without going under plastic deformation. Thus, a line of best fit was made using Microsoft Excel, and the equation representing the line was used for mapping forces and distance.

$$F = Kx \tag{1}$$

3. Results & Discussion

The robotic gripper was set in order to grasp the FT17S/T force sensor with the two fingers of the gripper, as it is shown in Figure 8: this set up simulates the grasping of an object by the end-user through the setting of the input force on the keypad which is connected to the Arduino board. Table 3 shows (1) the results when the setting of this force is selected at 2.8 N on the robotic gripper and (2) the force outputs which is calculated and displayed to the end-user by means of the five equations derived from the calibration process (Section 2.3). It also shows the readings from the force sensor that were used to calculate the percentage of the *Relative Error* (RE) between the user input of 2.8 N and gripper output or, gripper output and force sensor which were tabulated using Equation 3-1.

$$\delta = \frac{|v - v_a|}{v} \, x \, 100 \tag{2}$$

The results show that when using the first equation the RE between the user input and gripper force returned the least error of 3.93%. However, when compared with the force sensor reading, gave a RE of 52.84% due to the large difference in force measured. The results also show that the fourth equation when used gave the least RE of 9.66% between the force sensor and gripper output. However, when compared with the user input had a 50.71 % RE due to the large difference between what the user set and where the gripper stopped to display the force.

The differences between user input, gripper force output, and force sensor readings may be due to three main factors. The first was data readings; both the ToF sensor and force sensor had fluctuation readings even when no force was applied to them. This could be due to the resolution of the sensors which would explain why the data collected in Figure 10 vary and are not grouped closer together. The second was friction: the grove that translates force from the gripper assembly to the ToF and spring assembly (Figure 3 – part 3) slides across each other which causes friction that potentially could affect the readings between the force sensor readings and gripper output. The third was the step sizes of the stepper motor: results from Table 3 show the difference between the set user input and output of the gripper was large and could be explained by large steps taken by the stepper that would result in the stepper motor stopping at a further distance than when receiving communication from the ToF that it has reached its desired distance and should stop.

To improve the accuracy and precision of the robotic gripper, the following could be done. Firstly, improve data collection from the sensors by digitally writing the forces onto a file rather than relying on the human eye to record data and use devices with a higher resolution to reduce the error between readings. The second would be to reduce friction between contact points by using ball bearings. Finally, reducing the step size of the stepper motor would potentially increase the resolution of the gripper as smaller movements would be achieved.

The proposed set up as well as the performed calibration could be further extended in order to obtain a better characterization of the system vs a set of different experimental and environmental conditions. An extensive validation, in fact, will provide a set of specific characteristics and performance parameters of the proposed design together with the limitations and the temporal conditions which will required the re-calibration of the system from time to time.

Table 3: results from setting 2.8N force on the Robotic Gripper. RE G/F is the percentage relative error of the gripper and set force. While RE G/S is the relative error of the gripper and sensor readings. The orange box shows the least RE between the gripper and user input, blue box shows RE between gripper and sensor that gave the least RE and the red box shows which data affected the average results

Test	Set Force	Gripper (N)	Sensor (N)	RE G/F (%)	RE G/S (%)
1	2.8	2.91	6.17	3.93	52.84
2	2.8	3.08	8.40	10.00	63.33
3	2.8	3.67	4.37	31.07	16.06
4	2.8	4.22	4.67	50.71	9.66
5	2.8	4.93	0.04	76.07	12225
AVG	2.8	4.04	6.12	44.29	33.98

4. Conclusion

This work presents the design of a 3D printed robotic gripper which integrates two mobile fingers combined with a compliant mechanism where low-cost commercial springs are used in order to estimate the applied force of the gripper. The mechanism is based on a calibration procedure where the estimation of the spring displacements is performed by means of a low-cost ToF sensor. The system performance was evaluated by means of the RE G/F, i.e. the percentage relative error of the gripper and set force - and RE G/S, i.e. the relative error of the gripper and sensor readings.

The paper shows that application of the ToF to measure force using the elastic behaviour of springs is feasible. The proposed design could be integrated with other solutions both in terms of design [17] and sensor technologies [18] [19]. At this stage the device is not certified, and further development would require in order to apply the gripper where precise and accurate manipulation are required. A proper set of laboratories trials and validation is also needed. Nevertheless, the system has been calibrated by means of a higher-class sensor, namely the IIT device [4], and therefore the device performance has been proven in a laboratory experimental set-up.

Further improvement of the design should also look at reducing the friction between the mechanism contact points to optimize the calibration and smoothness of movements. In this context, having a devices with higher resolution of the movement and with a reduction of the step angular displacement of the actuator would impact the accuracy and precision of the robotic gripper. Moreover, the use of an OLED screen mentioned in Figure 2 to output data would improve the human interface of the application by displaying robot operations as well as necessary outputs [20]. In this context we have already explored for the integration of an OLED 128x64 Pixel SSD1306 in order to display the gripper positioning.

A better characterization of the system combined with a validation under different conditions of the environment would provide a more complete overview of the capability of the designed we have proposed. With the perspective of using such a system on different industrial application s where the measurement of the force is imperative [21, 22].

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D.M.; supervision, E.S..

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Sample availability - The authors declare that no physical samples were used in this study.

Supplementary materials - Not applicable.

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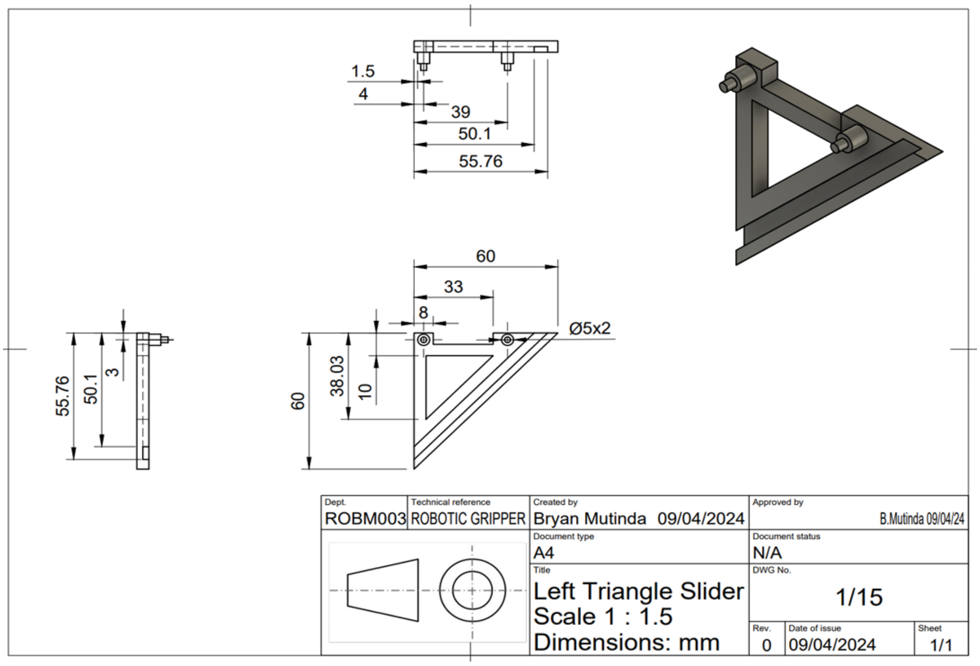
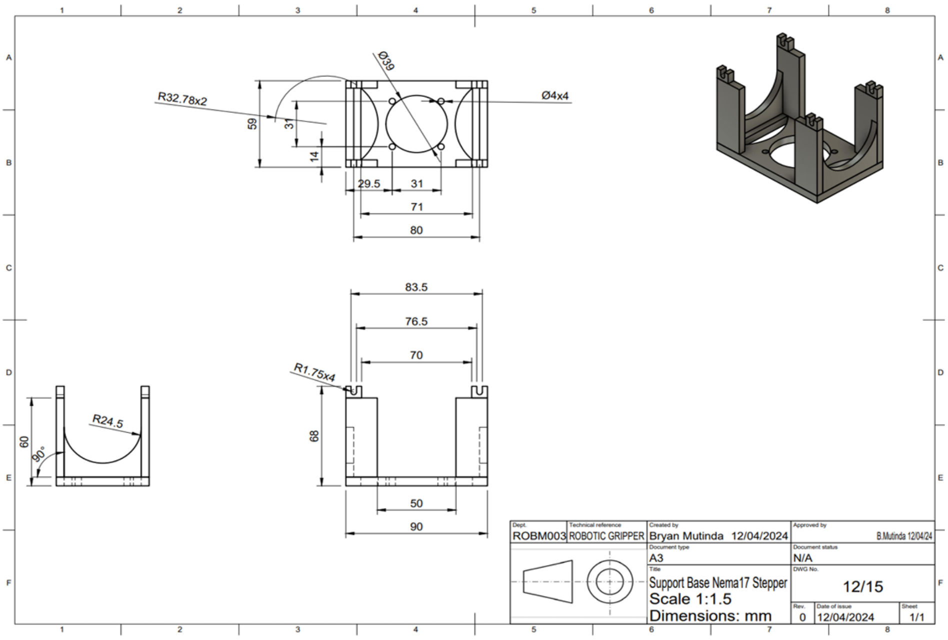
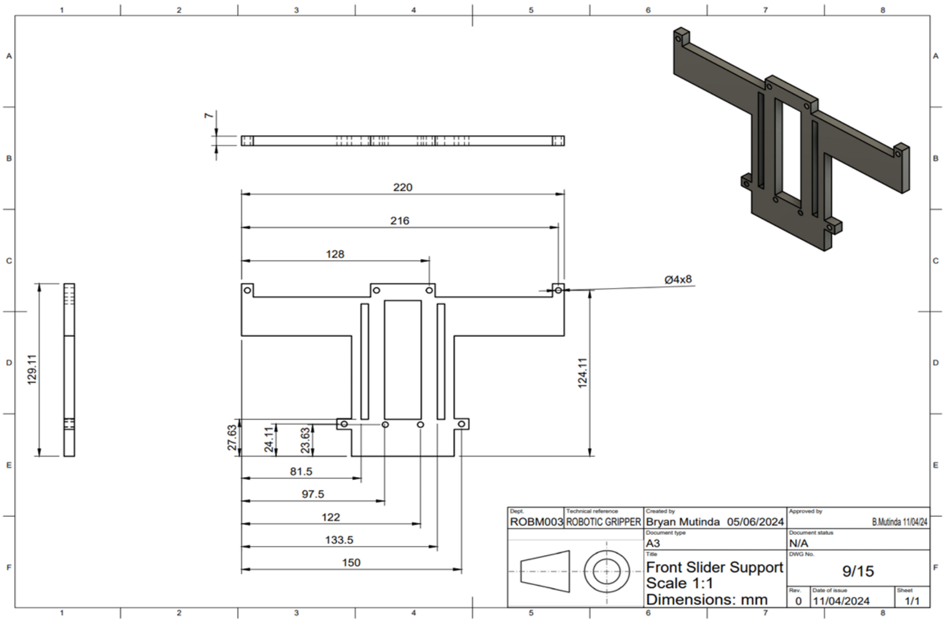
Appendix A

This Appendix reports some details of the gripper design: for each part of the gripper a mechanical design has been defined. Here we report some parts only. Further details are available on request. The assembly of these parts provides the final design which is shown in Figures 5 and 6 and then in Figure 8.



Dept. ROBM003	Technical reference ROBOTIC GRIPPER	Created by Bryan Mutinda 09/04/2024	Approved by B.Mutinda 09/04/24
		Document type A4	Document status N/A
		Title Left Triangle Slider Scale 1 : 1.5 Dimensions: mm	DWG No. 1/15 Rev. 0 · Date of issue 09/04/2024 · Sheet 1/1

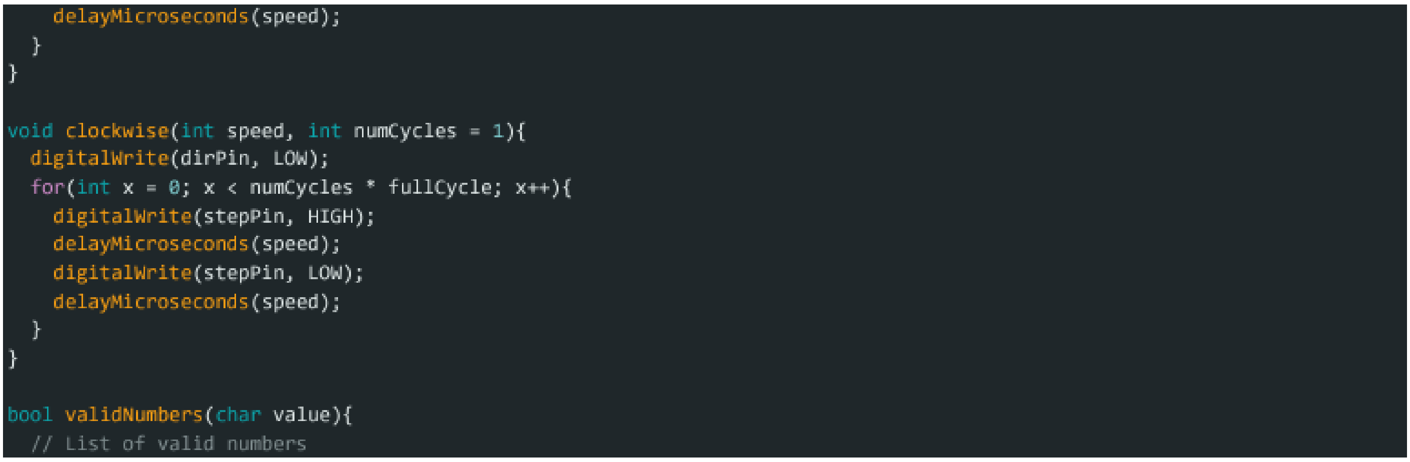




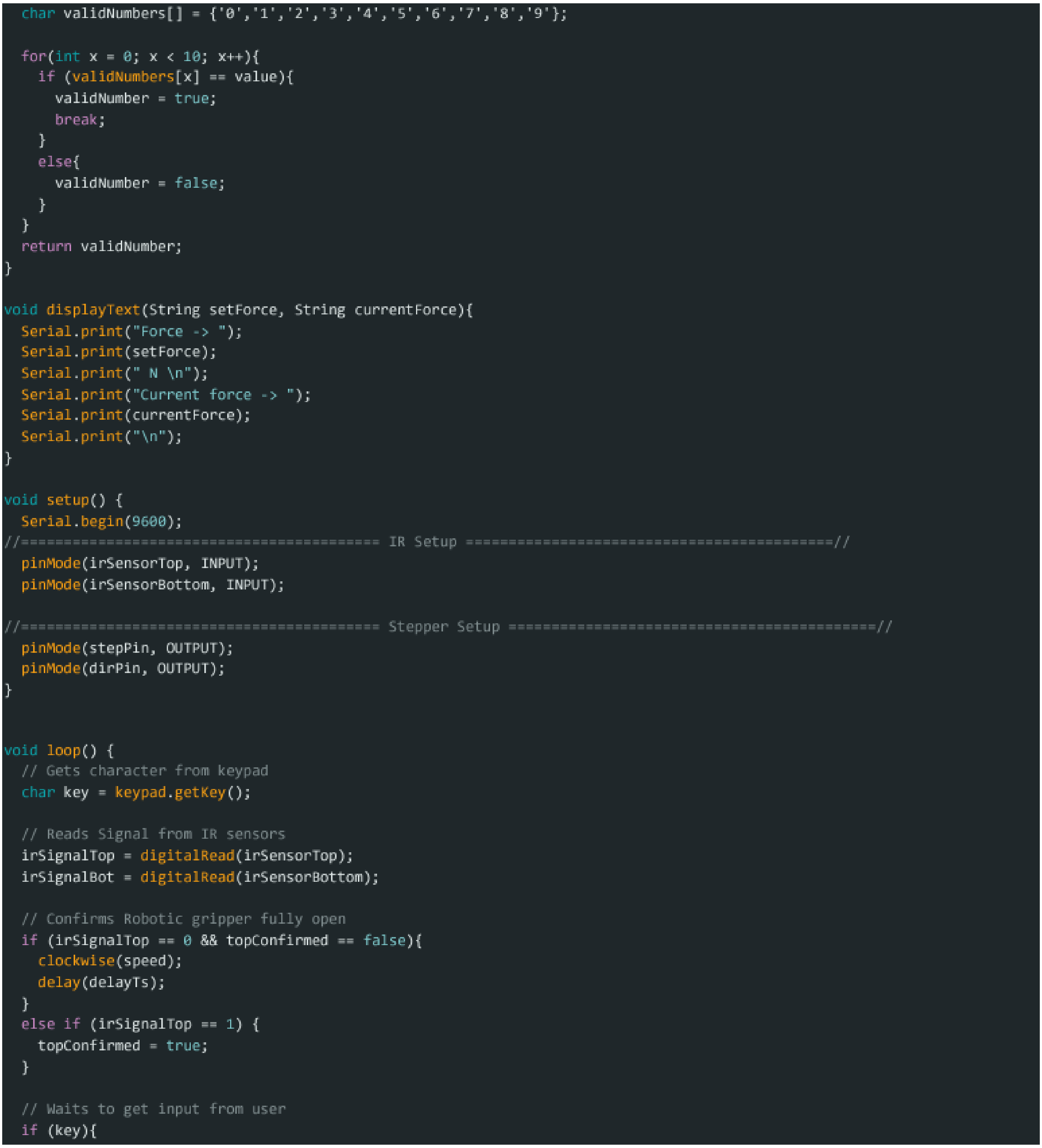
Appendix B

This Appendix reports some details about the Arduino software

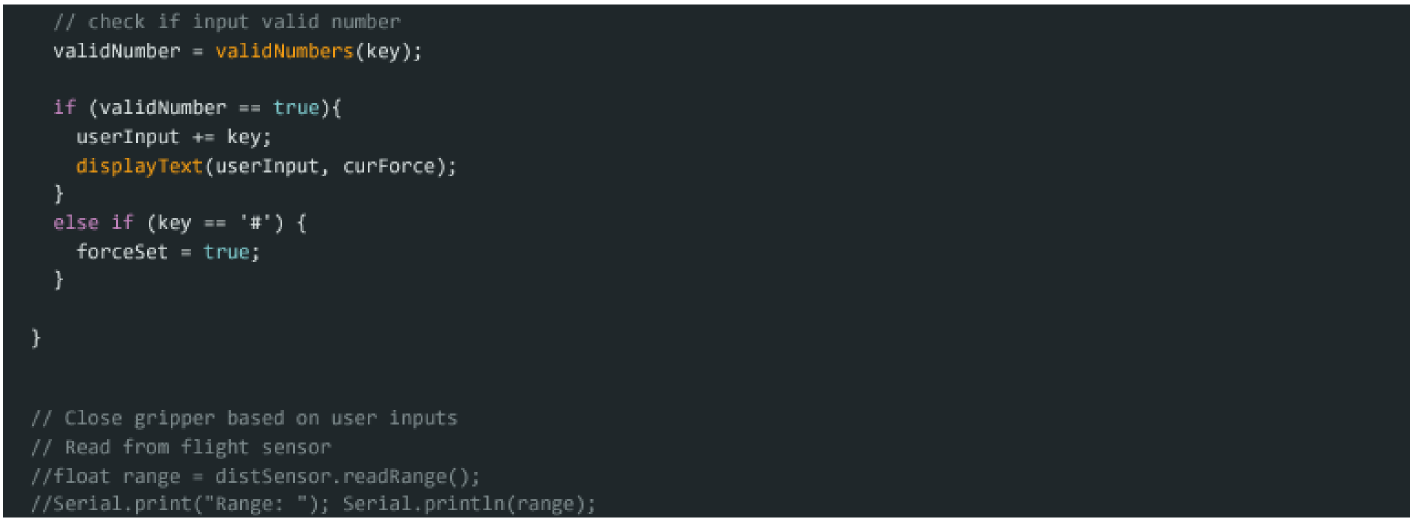
```
//========================================== External libraries ===================================//
#include <Keypad.h>
#include <Wire.h>
#include "Adafruit_VL6180X.h"

//========================================== IR pins =============================================//
#define irSensorTop 2           // Yellow cable
#define irSensorBottom 3        // Orange cable

//========================================== Stepper pins ========================================//
#define stepPin 4               // Blue cable
#define dirPin 5                // Green cable

//========================================== Flight sensor pins ===================================//
// On an arduino UNO:       A4(SDA) green, A5(SCL) yellow

//========================================== IR Variables ========================================//
int irSignalTop, irSignalBot;

//========================================== Stepper Variables ===================================//
int speed = 2000;               // lower increases speed higher reduces speed
int fullCycle = 200;            // Full revolution

//========================================== Flight sensor Variables ===================================//
Adafruit_VL6180X distSensor = Adafruit_VL6180X();

//========================================== General Variables ===================================//
bool topConfirmed = false;      // bool to set robotic gripper in open postion
String userInput = "";          // String for user to input values
String curForce = "121";           // String for user to input values
bool validNumber, validString, forceSet;
int delayTs = 1;

const byte ROWS = 4; //four rows
const byte COLS = 4; //four columns
char keys[ROWS][COLS] = {
  {'1','4','7','*'},
  {'2','5','8','0'},
  {'3','6','9','#'},
  {'A','B','C','D'}
};
byte rowPins[ROWS] = {10, 11, 12, 13}; //connect to the row pinouts of the keypad
byte colPins[COLS] = {6, 7, 8, 9}; //connect to the column pinouts of the keypad

Keypad keypad = Keypad( makeKeymap(keys), rowPins, colPins, ROWS, COLS );

//========================================== Functions ============================================//
void anti_clockwise(int speed, int numCycles = 1){
  digitalWrite(dirPin, HIGH);
  for(int x = 0; x < numCycles * fullCycle; x++){
    digitalWrite(stepPin, HIGH);
    delayMicroseconds(speed);
    digitalWrite(stepPin, LOW);
```



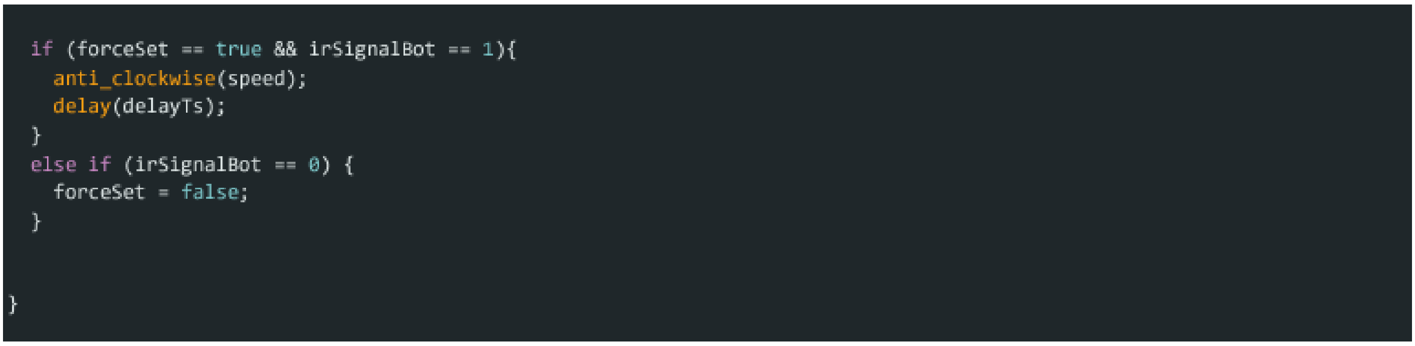
```
    delayMicroseconds(speed);
  }
}

void clockwise(int speed, int numCycles = 1){
  digitalWrite(dirPin, LOW);
  for(int x = 0; x < numCycles * fullCycle; x++){
    digitalWrite(stepPin, HIGH);
    delayMicroseconds(speed);
    digitalWrite(stepPin, LOW);
    delayMicroseconds(speed);
  }
}

bool validNumbers(char value){
  // List of valid numbers
```



```
  char validNumbers[] = {'0','1','2','3','4','5','6','7','8','9'};

  for(int x = 0; x < 10; x++){
    if (validNumbers[x] == value){
      validNumber = true;
      break;
    }
    else{
      validNumber = false;
    }
  }
  return validNumber;
}

void displayText(String setForce, String currentForce){
  Serial.print("Force -> ");
  Serial.print(setForce);
  Serial.print(" N \n");
  Serial.print("Current force -> ");
  Serial.print(currentForce);
  Serial.print("\n");
}

void setup() {
  Serial.begin(9600);
//========================================== IR Setup ==========================================//
  pinMode(irSensorTop, INPUT);
  pinMode(irSensorBottom, INPUT);

//========================================== Stepper Setup ==========================================//
  pinMode(stepPin, OUTPUT);
  pinMode(dirPin, OUTPUT);
}


void loop() {
  // Gets character from keypad
  char key = keypad.getKey();

  // Reads Signal from IR sensors
  irSignalTop = digitalRead(irSensorTop);
  irSignalBot = digitalRead(irSensorBottom);

  // Confirms Robotic gripper fully open
  if (irSignalTop == 0 && topConfirmed == false){
    clockwise(speed);
    delay(delayTs);
  }
  else if (irSignalTop == 1) {
    topConfirmed = true;
  }

  // Waits to get input from user
  if (key){
```



```
    // check if input valid number
    validNumber = validNumbers(key);

    if (validNumber == true){
      userInput += key;
      displayText(userInput, curForce);
    }
    else if (key == '#') {
      forceSet = true;
    }

  }


  // Close gripper based on user inputs
  // Read from flight sensor
  //float range = distSensor.readRange();
  //Serial.print("Range: "); Serial.println(range);
```



```
  if (forceSet == true && irSignalBot == 1){
    anti_clockwise(speed);
    delay(delayTs);
  }
  else if (irSignalBot == 0) {
    forceSet = false;
  }


}
```

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