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ISTANBUL AYDIN UNIVERSITY
INSTITUTE OF GRADUATE STUDIES

PROVIDING TACTILE FEEDBACK TO A DRONE USER WHILE PICKING AN OBJECT

MASTER'S THESIS

Sheikh Shahmeer HASSAN

Department of Engineering

Mechanical Engineering Program

SEPTEMBER, 2023

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APPROVAL PAGE

DECLARATION

I hereby declare with the respect that the study “Providing Tactile Feedback to a Drone User while Picking an Object”, which I submitted as a Master thesis, is written without any assistance in violation of scientific ethics and traditions in all the processes from the project phase to the conclusion of the thesis and that the works I have benefited are from those shown in the References. (…/…/2023)

Sheikh Shahmeer HASSAN

Signature

FOREWORD

First, I would like to express my endless gratitude to God for being who I am right now and helping me to find patience, strength within myself to complete this thesis.

I would also like to thank my family not only for encouraging me to go abroad for a master's degree but also for teaching me to chase my dreams and never give up.

I feel very fortunate to have Dr. Öğr. Üyesi Rıza İLHAN as my supervisor and want to express my appreciation for guiding me within the whole research process in a patient and effective manner.

Finally, I would like to acknowledge the important contribution of Istanbul Aydin University to my life, not only from an academic perspective but helping to meet great people that inspire, challenge, support and motivate me.

Thank you all for your support and encouragement.

September, 2023 Sheikh Shahmeer HASSAN

PROVIDING TACTILE FEEDBACK TO A DRONE USER WHILE PICKING AN OBJECT

ABSTRACT

This research project presents the design, development, and evaluation of an innovative gripper system integrated with drones, offering advanced capabilities in object manipulation. The design and development of the gripper system follow 3D printing, sensor integration, and microcontroller coding, enabling a precise, secure, and efficient grasping mechanism. The gripper system incorporates an advanced control algorithm and integrates two distinct systems: the Remote Control System (RCS) and the Onboard System (OBS). These systems enable real-time data feedback and haptic-tactile sensations, enhancing the operator's control and perception during object manipulation. Tactile and data feedback from Force-Sensing Resistors (FSRs) and load cell is sent to RCS, which is a wearable wristband incorporating a Haptic Fingertip Device (HFD), a Friction Actuator Device (FAD), and a display module, providing the operator with valuable sensory information.

Extensive testing and research evaluation was conducted to assess the system's performance and capabilities. The gripper system demonstrated precise grip force control and weight sensing, as well as good adaptability to various object shapes, materials, and masses. This cost-effective innovation enhances the functionality of drones by providing accurate and efficient object handling capabilities. The integration of haptic and data feedback highlights its potential for enhancing drone operations. The results of this research contribute to advancing the field of drone technology, expanding the capabilities of robotic systems, and paving the way for future advancements in the domain of aerial manipulation.

Keywords: Aerial Robotics, Gripper System, Haptic Feedback, Data Feedback, Object Manipulations

BİR DRONE KULLANICISINA NESNE SEÇİMİ YAPARKEN DOKUNMATİK GERİ BİLDİRİM SAĞLAMAK

ÖZET

Bu araştırma projesi, dronlarla entegre edilmiş yenilikçi bir tutucu sisteminin tasarımını, geliştirilmesini ve değerlendirilmesini sunarak, nesne manipülasyonunda gelişmiş yetenekler sunmaktadır. Tutucu sisteminin tasarımı ve geliştirilmesi, hassas, güvenli ve verimli bir kavrama mekanizması sağlayan 3D baskı, sensör entegrasyonu ve mikrodenetleyici kodlamasını takip eder. Tutucu sistemi gelişmiş bir kontrol algoritması içerir ve iki ayrı sistemi entegre eder: Uzaktan Kumanda Sistemi (RCS) ve Yerleşik Sistem (OBS). Bu sistemler gerçek zamanlı veri geri bildirimi ve dokunsal-dokunsal duyumlar sağlayarak nesne manipülasyonu sırasında operatörün kontrolünü ve algılamasını geliştirir. Kuvvet Algılama Dirençlerinden (FSR'ler) ve yük hücresinden gelen dokunsal ve veri geri bildirimi, operatöre değerli duyusal bilgiler sağlayan bir Haptic Fingertip Device (HFD), bir Friction Actuator Device (FAD) ve bir ekran modülü içeren giyilebilir bir bileklik olan RCS'ye gönderilir.

Sistemin performansını ve yeteneklerini değerlendirmek için kapsamlı test ve değerlendirme yapılmıştır. Tutucu sistemi, hassas kavrama kuvveti kontrolü ve ağırlık algılamanın yanı sıra çeşitli nesne şekillerine, malzemelere ve kütlelere iyi uyum sağlama kabiliyeti gösterdi. Bu uygun maliyetli yenilik, doğru ve verimli nesne işleme yetenekleri sağlayarak dronların işlevselliğini geliştirir. Dokunsal ve veri geri bildiriminin entegrasyonu, drone operasyonlarını geliştirme potansiyelini vurgulamaktadır. Bu araştırmanın sonuçları, drone teknolojisi alanının ilerlemesine, robotik sistemlerin yeteneklerinin genişletilmesine ve hava manipülasyonu alanında gelecekteki gelişmelerin önünün açılmasına katkıda bulunmaktadır.

Anahtar Kelimeler: Hava Robotikleri, Tutucu Sistem, Dokunsal Geri Bildirim, Veri Geri Bildirimi, Nesne Manipülasyonları

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ABBREVIATIONS

3D	: Three Dimensional
AI	: Artificial Intelligence
ADC	: Analog to Digital Converter
DOF	: Degree of Freedom
FAA	: Federal Aviation Administration
FAD	: Friction Actuation Device
FSR	: Force Sensing Resistor
GPS	: Global Positioning System
HFD	: Haptic Fingetip Device
IDE	: Integrated Development Environment
LCD	: Liquid Crystal Display
NDTV	: New Dehli Television
OBS	: Onboard System
PWM	: Pulse Width Modulation
RCS	: Remote Control System
SETA	: Siyaset, Ekonomi ve Toplum Araştırmaları
TFT	:Thin Film Transistor
UAV	: Unmanned Aerial Vehicle
V-TOL	: Vertical Take-Off and Landing

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I. INTRODUCTION

Unmanned aerial vehicles (UAVs), or drones, are being developed and used for a wide range of applications. They are unmanned aircraft that can be remotely operated or flown autonomously using onboard computers and sensors (Gupta, 2013). Drones have evolved from their early use in World War I, when they were primarily used in military operations, to their current use in recent years with improvements in component miniaturisation and the integration of advanced sensors and control systems. With these advancements, drones are able to perform a wide range of tasks in diverse fields, including aerial photography, surveillance, delivery services, and agriculture (Mohsin, 2022). One of the most critical tasks for drones is object manipulation, which involves picking up and transporting objects. This ability greatly enhanced the functionality of drones and enabled them to perform a variety of tasks. The most prevalent are fixed-wing, multi-rotor, single-rotor, and fixed-wing hybrid V-TOL (vertical take-off and landing) aircraft (Tkac & Peter, 2019).

Figure 1. Types of drone

Source: (Tkac & Peter, 2019)

According to a report by the Federal Aviation Administration (FAA), the number of registered drones in the United States exceeded 1 million in 2020, and it is expected to grow even further in the coming years (FAA, 2019). The commercial use of drones has revolutionised various industries. In agriculture, drones equipped with imaging sensors and advanced algorithms can monitor crop health, optimise irrigation, and assess the effectiveness of fertilisation (Abioye, 2020). Drones have also found applications in logistical services, providing more cost-effective delivery of goods ((Škrinjar, 2018).

Furthermore, drones play a crucial role in rescue and emergency situations. They can be deployed for search and rescue missions in remote or hazardous environments, providing aerial surveillance, locating the whereabouts of the missing, and delivering supplies to disaster zones (Alsamhi, 2022). During natural catastrophes, drones equipped with thermal imaging cameras can help identify the heat signatures of survivors or locate hotspots in wildfires (Hossain, 2023). Drones capacity to access difficult-to-reach areas and collect real-time information has proven vital in emergency response circumstances.

A. Aerial Gripper System

A drone's gripper mechanism is one of its most significant accessories, enabling it to grab and carry items. The range of uses for drones has increased because of the introduction of gripper systems, notably in search and rescue missions. For instance, gripper-equipped drones can be used to pick up and deliver small items to patients in hard-to-reach areas, such as medication, water, or communication equipment (Nedungadı, 2019). Gripper systems can also be used to pick up and remove hazardous materials, such as explosives.

The design of gripper systems with more sophisticated functions is becoming more crucial as drone technology advances. Gripper systems that can provide tactile feedback, measure gripping force and weight, and communicate wirelessly with the drone are of great interest to researchers and industry experts. Such features will enable drones to perform challenging and complex tasks and to interact with the environment more efficiently.

Different gripper systems have been developed to improve their functionality in a variety of applications. These systems typically consist of a mechanical arm or gripper mechanism, a control system, and sensors for object manipulation (Follini, 2018). In many different industries, including production, inventory stocking, and manufacturing lines, gripper systems have been widely employed. Some common types of grippers are vacuum, mechanical, adhesive, magnetic, and pneumatic grippers, as shown in Figure 2.

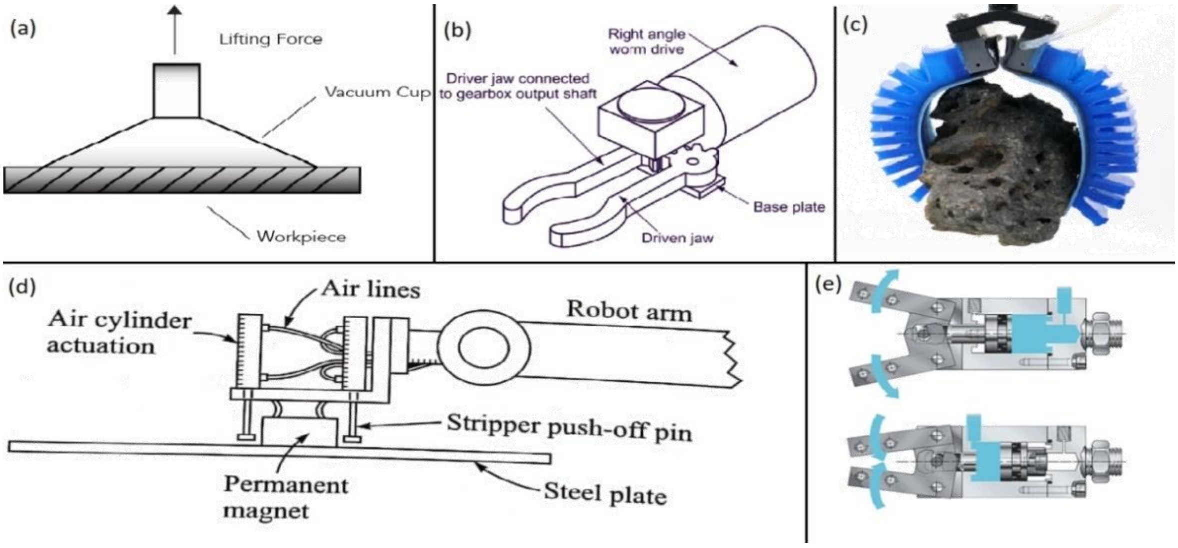


Figure 2. (a) Vacuum gripper, (b) Mechanical gripper, (c) Adhesive gripper , (d) Magnetic gripper , (e) Pneumatic gripper

Source: (KORANE, 2016)**,** (WORKBOOK, 2021), (Glick, 2018) (RAJA, 2022) and (TAMESON)

B. Haptic Feedback

Haptic feedback refers to the use of tactile sensations and forces to provide users with a sense of touch and physical interaction in human-machine interfaces (Jyothı & Krishnaiah, 2013). Haptic feedback enhances the overall user experience by providing a more immersive and realistic interaction. Haptic feedback has been applied to various robotics and drone systems to enhance their functionality and user experience.

In drone applications, haptic feedback can provide operators with a sense of touch and presence, improving situational awareness and enabling precise control during object interaction and navigation tasks (Chen, 2007). Haptic feedback has also found applications in training and simulation environments for drones and robotic systems. By providing realistic haptic sensations, users can practice and refine their skills in a safe and controlled setting (Lin, 2014). Some common haptic feedback mechanisms are vibrotactile, force feedback, actuation feedback, and friction feedback.

Vibrotactile motors are small actuators that generate vibrations to stimulate the sense of touch. (Lindeman, 2004). Force feedback devices provide users with the ability to perceive and manipulate virtual or remote objects by applying forces or resistive pressures. Actuation feedback devices use mechanisms such as pneumatic or electromagnetic systems to generate physical forces and motions that simulate object interactions (Dangxiao, 2019). Friction feedback devices can generate varying levels of friction or surface roughness to convey different surface properties or contact conditions (Culbertson, 2016).

C. Purpose and Significance of the Study

1. Overview of this thesis project

- **a.** The aim of the project is to design and develop a gripper system that can be attached to a drone for various applications.
- **b.** The gripper system will also be able to provide haptic feedback to the operator, allowing the operator to feel the manipulation and control it with more precision.
- **c.** The gripper system will be designed to provide real-time data feedback to the operator, allowing for precise control and manipulation of the gripped object.
- **d.** An onboard system (OBS) and a remote control system (RCS) will be developed for the gripper system and feedback system.
- **e.** After developing the gripper system, it will be incorporated into a drone.
- **f.** Some tests will be carried out to check the flexibility and adaptibility of the gripper system.
- **g.** A research questionnaire will be carried out to seek the opinions of experts and general participants.

2. Novelty of this thesis project

The primary intent of this project is to increase the vision and reliability of using aerial vehicles while picking force-sensitive objects, which may include explosives, animals, etc. This thesis focuses on constructing a drone that can carry light loads by integrating a control system for a gripping module with an on-board computer that can sense the gripping force and provide real-time haptic and data feedback to the observer. In addition, the observer can define the exerted force required to pick up the load. This invention can be a game changer in the modern era of drone systems.

In the literature, researchers have put in a lot of effort and highlighted the significance of deploying UAVs in lowering life-threatening dangers and increasing exposure to inaccessible areas. With this project, the idea is expanded upon, and a more sophisticated approach to addressing the significant threats is employed. The force-sensitive load pickups have a significant role in military conflicts, which can be readily handled by using our UAV system.

There are certain circumstances where it is very difficult to get there and save the objective. It is hard to search for and rescue a force-sensitive object in a circumstance like a volcanic eruption, but our system not only rescues the target but also reads the temperature condition and allows the user to define the gripping force to grasp the target with tactical feedback so the user can understand and act in the situation better.

The ability of drones to pick up objects has been limited by the lack of feedback systems that can provide information on the gripping force and weight of the objects being lifted. The development of a gripper system that can calculate the gripping force and weight of the object being lifted and provide haptic and data feedback would greatly enhance the capabilities of drones in a wide range of applications.

The purpose of this thesis project is to develop a mechanism through which, when a gripper is attached to a UAV and when it grasps and picks up an object, the user should be able to get tactile and data feedback for the gripping force and weight of the object. The system will be useful in various industries and applications, solely for carrying force-sensitive explosives or rescuing small animals.

D. Problem Statement

a. What are the key challenges and limitations of existing gripper systems for drones?

b. How can a gripper system be designed to provide accurate gripping force and lifted weight measurements?

c. What are the potential applications and benefits of integrating a gripper system with drones?

d. How can real-time data and haptic feedback be incorporated into the gripper system?

e. How will the gripper system be incorporated into a drone?

II. LITERATURE REVIEW AND RESEARCH OVERVIEW

The chapter begins with a thorough review of gripper design, examining the gripping mechanisms and their performance evaluation to understand the strengths and limitations of different designs. Following that, this chapter also explores the field of haptic feedback in grippers and drones, reviewing the literature on gripper haptic feedback and its use in drone systems. Furthermore, this chapter sets the foundation for the subsequent sections, which describe the proposed gripper system with feedback technology and its potential applications and benefits.

A. Gripper Systems for Drones: Prevıous Research

A gripper system typically consists of a gripping mechanism, a control system, and sensors that provide feedback on the object being grasped. The design of gripper systems for drones has garnered significant attention in recent years. In order to assess a generic gripper, a comparison of various UAV grippers with different designs will be made to ascertain the suggested gripper's capabilities. Several researchers have proposed different gripper designs to enable drones to perform object manipulation tasks. Some of the grippers for aerial graspers developed in earlier research can be observed in Figure 3.

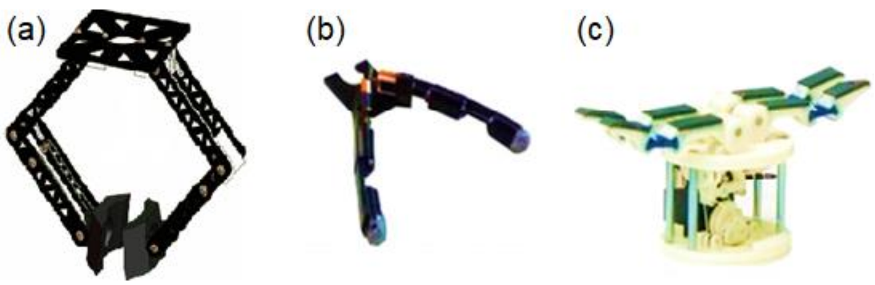


Figure 3. (a) 2 Finger Active Adaptive Gripper (b) Bioinspired 2 Finger Gripper (c) Yales Openhand Model T

Source: (Kruse & Bradley, 2018), (Zisimatos, 2014) and (Yales Openhand Project "Model T", 2019)

The performance evaluation of gripper systems for drones is crucial to assessing their effectiveness and identifying areas for improvement. Researchers conduct various trials and studies to assess the gripping capabilities, stability, precision, and endurance of different gripper designs. Performance parameters like grip force, slippage, and grasping success rate of objects are quantitatively measured. Additionally, qualitative assessment includes the ability to handle objects of various shapes, sizes, and weights. These evaluations provide insights into the benefits and drawbacks of different gripper systems and guide future advancements in the field.

Table 1 shows the comparison of the designs of aerial grippers in Figure 3. We examined the dexterity for each by comparing the degree of freedom (DOF) and number of fingers, whereas the payload capacity was compared by comparing the grasping force and weight of the model.

Table 1. Comparison of performance evaluation for grippers in Figure 3

Model	Weight (kg)	Grip Force (N)	Fingers	DOF	Dexterity	Payload Capacity
2 Fin. Active Adaptive	0.3	0.57	2	6	3	1.9
Bioinspired 2 Finger	0.04	-	2	4	2	-
Yales Model T	0.49	13	4	8	2	26.5

B. Haptic Feedback Systems in Grippers and Drones

1. Research on haptic feedback in grippers

In the context of grippers, haptic feedback refers to the tactile or force feedback provided to the user when interacting with objects. Many studies have explored various haptic feedback mechanisms in grippers; for instance, in a research paper by Chin (Chin, 2019), a soft gripper is developed for high- deformation haptic feedback, which can help the operator differentiate between soft vs. stiff objects and small vs. large objects by integrating an electric actuator and pressure and strain sensors. It is shown in Figure 4 (a).

In another study conducted by Salvietti (Salvietti, 2020), a wearable ring is developed that controls the gripper's opening and closing and provides feedback on the tightness of the grip. With the utilization of this ring, the speed of completion of gripper action and grasp tightness improved. It is shown in Figure 4 (b). The integration of haptic feedback in grippers has shown promising results in improving object manipulation, grasp stability, and user control.

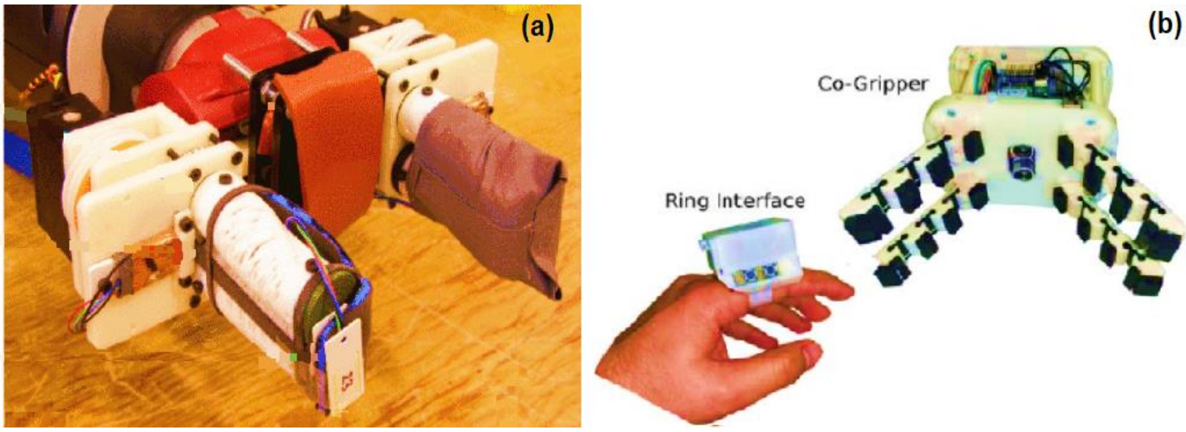


Figure 4. Gripper with Haptic Feedbacks (a) High deformation haptic feedback (b) Grasping tightness feedback

Source: (Chin, 2019) and (Salvietti, 2020)

2. Research on haptic feedback in drones

Haptic feedback has also been investigated in the context of drone systems to enhance the interaction between drones and human operators. Numerous studies have explored the use of haptic feedback for the drone's motion, environmental conditions, or proximity to objects. For instance, in research done by Lee (Lee & Ho-Yu, 2023), they developed a hand-held wearable device as shown in Figure 5 (a). This device can control the motion of the drone by gesture recognition and provide obstacle information for the direction of the drone's motion by providing vibration feedback for avoiding collision. Another study conducted by Duan (Duan, 2018) found that users can perform teleoperation drones with hand gestures and identify the object of interest through tactile feedback, as shown in Figure 5 (b).

Feedback technologies like these can enhance situational awareness, improve intuitive control, and simplify cognitive workload. Most research on haptic feedback in drone systems has been used to assist with teleoperation, object recognition, tracking, and collision avoidance. Furthermore, haptic feedback provides real-time information about the drone's interactions with the environment, enabling users to adjust their actions and responses accordingly.

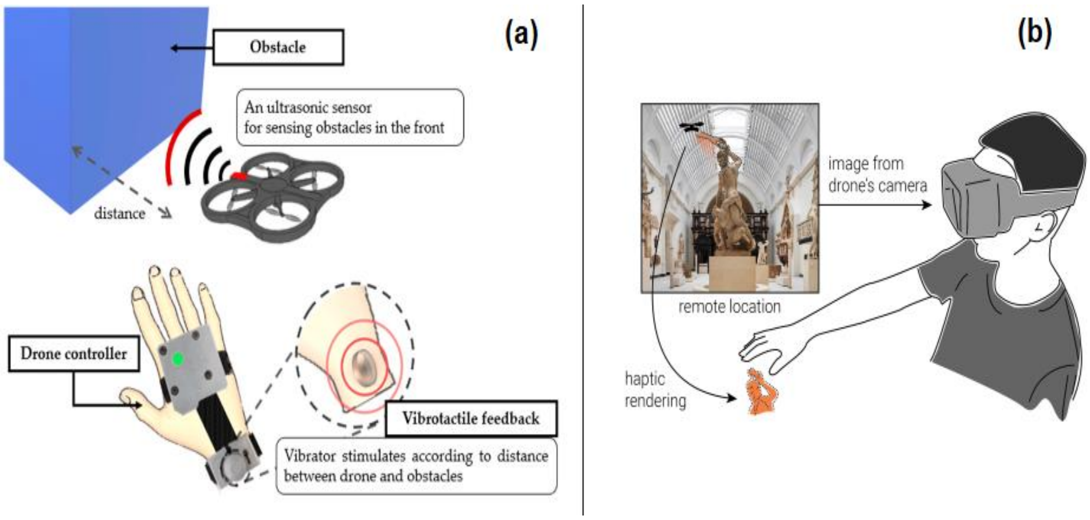


Figure 5. Drone technologies with different Haptic Feedback systems, (a) Controlling motion of drone through hand gesture and obstacle information through vibrotactile feedback (b) Teleoperation of drone by hand gesture and identification of object through tactile feedback

Source: (Lee & Ho-Yu, 2023) and (Duan, 2018)

C. Proposed Gripper with Feedback Technology

The gripper system designed for this thesis project is a two-finger mechanical gripper that aims to provide an effective way of grasping an object. The system is designed to be lightweight, easy to attach to any drone, and capable of providing accurate data on the weight and gripping force of the object being lifted.

The gripper system is composed of various components that work together to provide the desired functionality. The actuator is the primary component that controls the gripping action of the system. This actuator is controlled by the user through the RCS to provide a particular gripping force depending on the lifted object. This will be connected to the OBS.

OBS and RCS both have a microcontroller, which is an essential component of the gripper system. Both microcontrollers are interfaced via Bluetooth modules, and they are responsible for transferring commands and feedback between the OBS and RCS. These microcontrollers play a crucial role in ensuring that the user has complete control over the system and receives accurate data on the weight and gripping force of the object being lifted.

The gripping force of the system is measured using two force-sensitive resistor (FSR) sensors that are suspended at each end of the gripper's finger. FSR sensors are used to calculate the gripping force and provide real-time feedback to the user. The load cell is another crucial component of the gripper system that is used to accurately calculate the weight of the object being lifted and provide real-time feedback to the user.

The RCS receives data from the OBS through Bluetooth communication. The FSR data and load cell data are transmitted wirelessly and displayed on a thin-film transistor (TFT) liquid crystal display (LCD) screen. This display provides real-time feedback on the gripping force, weight of the lifted object, and gripper angle rotation as controlled by the user.

A finger wearable device is developed to provide tactile feedback of gripping force calculated by FSR sensors through vibration. Whereas for load cells, an SG90 linear actuator is developed, which linearly actuates against the skin of the user, providing friction feedback. The details regarding the design of the gripper and the details of the feedback will be discussed in Chapter III.

D. Potential Application of the Proposed Gripping Technology

The gripper system has a wide range of potential applications in various industries, particularly those that involve tasks that require precision, control, and the ability to lift and move objects. The system's ability to provide tactical feedback and calculate gripping force and weight makes it a valuable tool in many applications. For instance, in the military and defence sectors, the gripper system can be utilized for carrying force-sensitive explosives to a safer location in warzones, thus minimizing the risk of casualties and damages.

In addition, the gripper system can also be utilized in search and rescue missions, particularly for rescuing small animals. In the past, drones have been used for the transportation of food to animals in disaster-stricken areas or remote habitats where access by traditional means is challenging (Ivosevıc, 2015). But the use of drones in animal rescue and transportation is not common, but in some cases in recent times, it has been seen that animals have been rescued by using a UAV. However, all the incidents were not performed using professional equipment.

According to a New Dehli Television (NDTV) report from 2018, a man used a drone to save a puppy. The puppy was trapped in an open drain. It took him six hours to put together the improvised UAV by attaching a robotic arm with artificial intelligence (AI) control to a large drone. But he succeeded in rescuing the animal safely out of the drain (PANT, 2018). Cases like this are, however, not very common, so a gripping system like ours could prove useful for doing so due to the availability of real-time data and haptic feedback. It will be able to provide promising results in terms of efficiency, speed, and safety, minimizing human intervention and potential harm to the animals.

Figure 6. AI-controlled drone gripper used in rescuing a puppy

Source: (PANT, 2018)

One potential application for the gripper system is in the field of construction. The system could be used to lift and move heavy building materials, such as steel beams or concrete blocks, with greater precision and control than traditional methods. This would not only make the construction process more efficient but also increase worker safety by reducing the risk of injury from manual lifting.

Figure 7. Drone in Construction

Source: (ARCWEB, 2023)

Another potential application for the gripper system is in the agriculture industry. The system could be used to pick and sort fruits and vegetables, reducing the need for manual labour and increasing efficiency (GEERT, 2020). Additionally, the system's ability to calculate weight could be useful in ensuring that the correct amount of produce is being harvested and transported.

Figure 8. Drone Harvesting in Agriculture

Source: (GEERT, 2020)

The gripper system also has potential applications in the search and rescue industry. The system could be used to lift and move heavy debris, such as fallen trees or collapsed buildings, to help rescue workers gain access to areas where victims may be trapped. Additionally, the system's ability to provide real-time feedback could be useful in identifying the presence of survivors or hazardous materials in the area.

Figure 9. Drone in Search and Rescue

Source: (STONOR, 2019)

Another potential application for the gripper system is in the transportation of hazardous materials. The system's ability to calculate gripping force could be used to ensure that containers carrying hazardous materials are securely fastened and will not come loose during transport. Additionally, the system's ability to provide tactical feedback could be useful in identifying any leaks or spills that may occur during transport.

These are just a few examples of the potential applications for the gripper system. The system's versatility and precision make it a valuable tool in a wide range of industries and applications. As technology continues to advance and drones become more common, it is likely that the use of gripper systems such as this one will become increasingly prevalent.

III. SYSTEM DESIGN, DESCRIPTION & INTEGRATION

This chapter aims to provide a detailed description of the system developed for the two-fingered gripper using microcontrollers, HC-05 Bluetooth modules, Force Sensing Resistor (FSR) sensors, a servo motor, a load cell, a potentiometer, a vibrotactile motor, and an SG90 linear actuator. The chapter will discuss the description and methodology of each component and its interconnection to provide a functional prototype. The discussion will include the rationale behind choosing specific components and their use in the system. The gripper system includes several components that work together to provide a controlled grip on an object and feedback. The Arduino UNO microcontrollers were chosen as the main processing unit. The HC-05 Bluetooth modules were used to establish communication between the remote control unit and the onboard Arduino.

The FSR sensors were selected to measure the grasping force applied by the gripper fingers, and the 1kg load cell was used to measure the weight of the gripped object. The MG995 servo motor was chosen as the actuator to drive the finger movement of the gripper, while the potentiometer was used to control the movement of the servo motors remotely. The system also includes an LED screen to display the measured data in real-time, providing data feedback to the user. Whereas for the tactile feedback, a Haptic Fingertip Device (HFD) and an SG90 linear actuator, referred to as a Friction Haptic Device (FAD), are used for the FSR and load cell.

A. 3D Modelling

1. Gripper system

The drone grasping process is done using a gripper system that works on a servo-driven two-finger mechanism. Through the opening and closing of its gripper fingers, it enables the drone to manipulate the object. The design of the gripper system involves careful consideration of its components and their functionality.

The CAD (Computer Aided Design) model of the gripper system was designed using SolidWorks software, which offered a detailed representation of its components and their spatial arrangement. The model includes precise dimensions, geometries, and interconnections between the various parts. It was utilized to 3D print the gripper components as well as act as a visual representation of the gripper system, enabling the assessment of its design and functionality. The design of the gripper system assembled with its components can be observed in Figure 10.

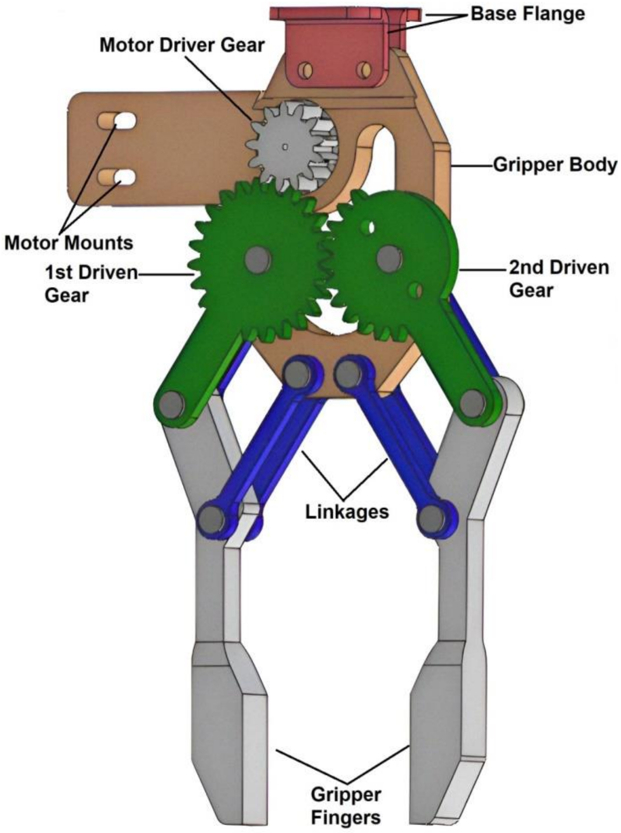


Figure 10. CAD Model of Gripper System

The design of the gripper involves several components that work together to achieve the desired gripping action. The geometrical drawing of this gripper system is provided in Appendix 1. The central servo motor serves as the driving force for the gripper mechanism. As the servo motor rotates, the driven gears engage and drive the gripper fingers through the linkages, enabling them to grip objects. The overall function of the gripper system depends on the synchronization of all the components working together. The design ensures precise and controlled gripping action.

For better division of torque, we connected the motor driver gear to one of the gripper fingers and made the other finger dependent. We directly linked the motor gear to the 1st driven gear attached to the left finger of the gripper. Figure 11 depicts the force distribution in a robotic gripper with two different kinds of gear arrangements. In case (a), each finger receives an equal distribution of torque, whereas in case (b), the whole torque is delivered to one finger, causing the other finger to rotate as well. Thus, without division, torque is supplied in this manner to each finger. We have used the second case in our gripper system.

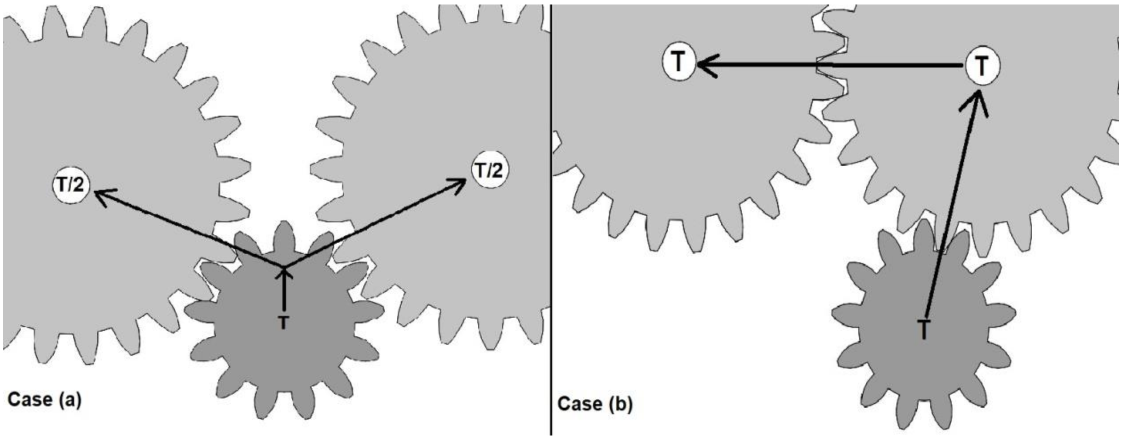


Figure 11. Torque districbution diagram for (a) Equal divsion and (b) Equal transmission

2. SG90 linear actuator

The SG90 linear actuator is used for providing tactile feedback based on load cell readings. It is integrated into the Remote Control System (RCS). It is referred to as the Friction Actuation Device (FAD), which gives friction feedback as well as displacement estimation for weight lifted by the gripper system. Further details of its workings and methodology will be discussed in later sections. The design of this actuator is discussed in this section.

The SG90 linear actuator is designed to create a mechanism that allows linear movement based on the rotational motion generated by the SG90 servo motor. It is designed to provide controlled forward and backward movement, which generates tactile feedback in the form of friction on the user's skin. It consists of several components carefully designed for their specific functions. Figure 12 depicts the design of the SG90 linear actuator. The dimentional drawing of this SG90 linear actuator is discussed in Appendix 1.

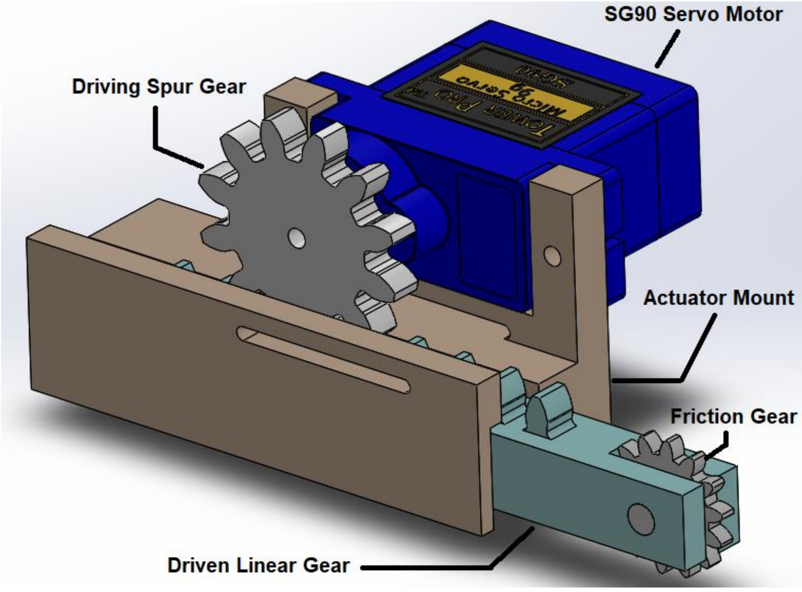


Figure 12. CAD Model of SG90 Linear Actuator

B. System Description:

1. Microcontroller and bluetooth for OBS and RCS

The system utilizes a microcontroller and Bluetooth technology on each Onboard System (OBS) and Remote Control System (RCS) to facilitate communication and control between them. In this project, we chose the Arduino UNO, which serves as the central control unit for both systems. It is responsible for processing input signals, controlling various components, and coordinating the overall functionality of the OBS and RCS.

Each Arduino has an HC05 Bluetooth module, which helps them interface with each other for wireless communication. The interfacing of both Arduinos involves a simple process. First, each Arduino UNO is configured with a HC05 Bluetooth module, which is done by accessing the AT Command Mode of the HC05 module. The two HC05 modules are paired in master/slave configuration using the Bind command through AT Command Mode. After interlinking the Arduinos, one is placed with the gripper system on OBS, while the other is used as a remote control device on RCS. The onboard HC05 is set in master configuration, whereas the remote control HC05 is set in slave device configuration. The circuit schematic of the master and slave systems is available in Appendix 2.

2. Onboard system (OBS):

The Onboard System (OBS) consists of the gripper system, microcontroller box, and power supply. Several components and sensors work together to provide the required functionality of the OBS. To ensure a compact and organized setup, the OBS components, including the Arduino UNO, HC05 Bluetooth module, and HX711 load cell amplifier, are enclosed in a protective box, which allows easy installation and integration onto the drone's frame alongside the gripper system. The main components attached to the OBS are as follows:

a. Gripper system:

A 3D-printed two-finger mechanical design of the gripper mechanism employed in this research prioritizes simplicity and adaptability. Figure 13 shows the gripper system with all components integrated into the OBS system.

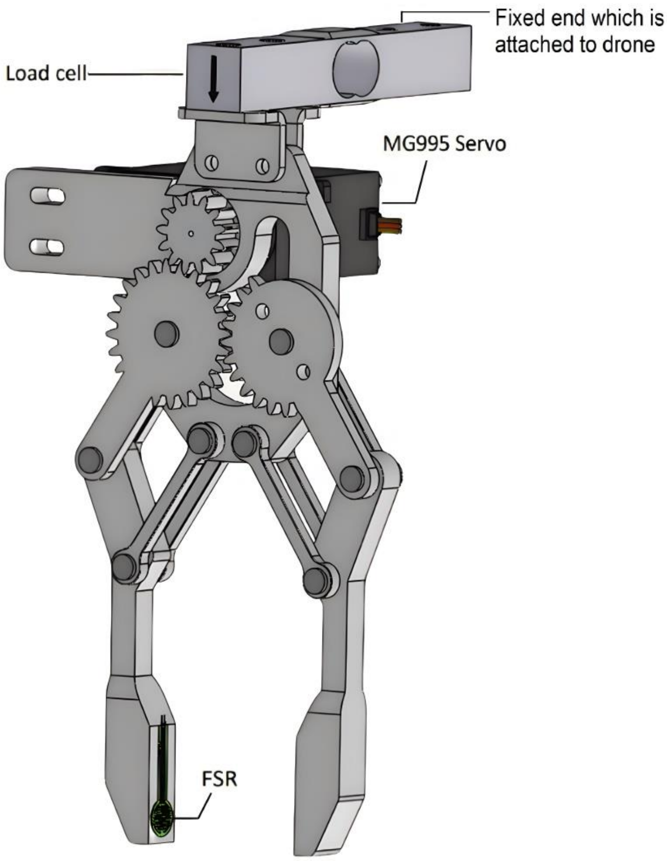


Figure 13. Onboard Gripper System

As illustrated by Figures 14 (a) and (b), the maximum jaw opening of the gripper is 61.37 mm, which means that the maximum width or diameter of the object that can be grasped by this gripper is 61.37 mm. And the maximum vertical length when the jaws are closed is 150.32 mm, which means that there should be a clearance of 150.32 mm between the drone base and the ground when it is at rest.

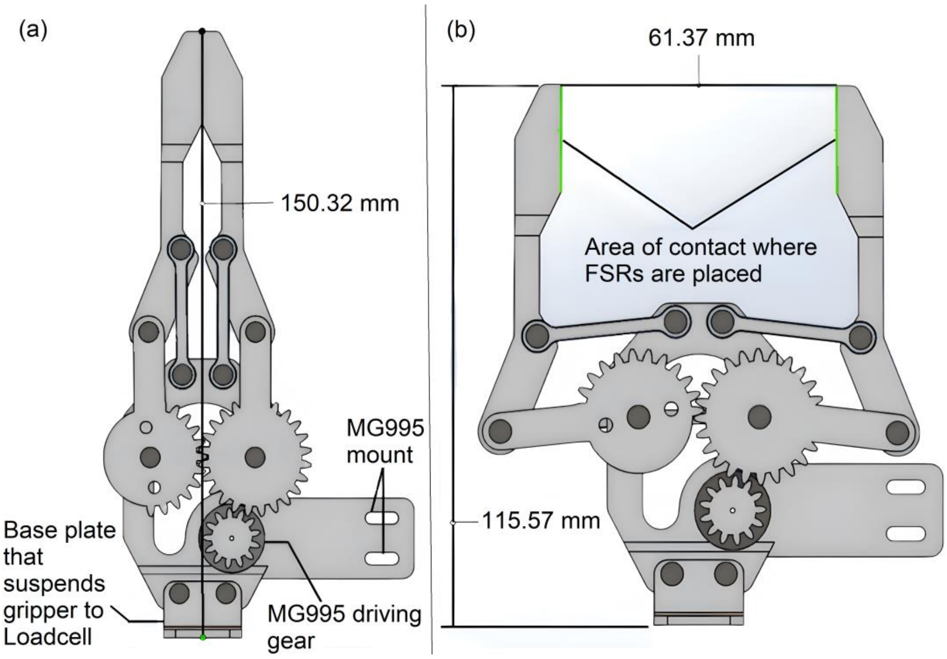


Figure 14. (a) Max vertical length of th egripper (b) Max jaw opening of gripper

b. MG995 servo motor

A spur gear is attached to the central shaft of the servo motor, known as the motor driver gear, as shown in Figure 15 (a). The two-fingered gripper system has two driven gears mounted to the gripper body. To drive these gears for grasping operation, 1st driven gear is mated with the motor driver gear, whereas the 2nd driven gear has a dependent rotation with 1st driven gear, as shown in Figure 15 (b). The rotation of the servo motor causes the gears to rotate, resulting in the fingers either opening or closing, depending on the direction of rotation. The linkages ensure that the fingers move in unison and exert consistent force, allowing for precise gripping and releasing actions. Calibrating the servo motor with the gripper system involved adjusting the mechanical linkage between the motor and the fingers to ensure that they moved in synchronization with the desired amount of force. A circuit schematic of a servo motor with Arduino is available in Appendix 2.

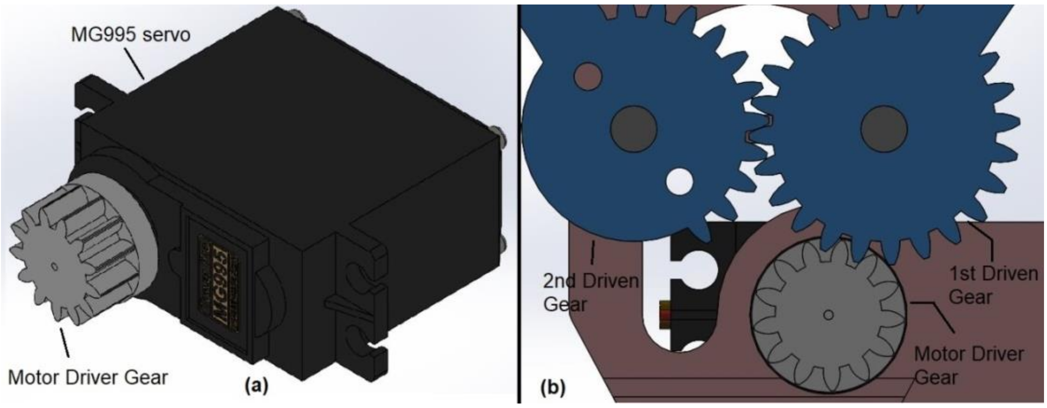


Figure 15. Servo driving gripper action (a) Motor Driver Gear attached to central shaft of MG995 (b) Gear Mating between Driver and Driven Gears

c. Force-sensing resistors (FSRs)

In our system, we have used two 0.2-inch-diameter FSRs attached to each gripping finger of the gripper system, as shown in Figure 16, with the help of thin foam double tape. Proper placement and alignment of the FSRs were ensured to measure accurate gripping force and provide precise control of that gripping force.

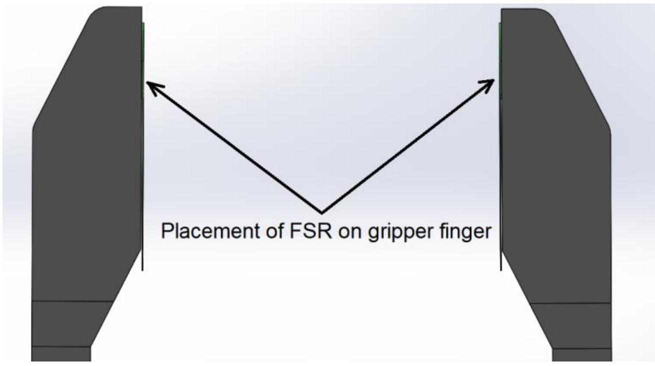


Figure 16. Placing FSRs on our Gripper system

FSRs measure the gripping force applied by the fingers and are connected to the onboard Arduino in a voltage divider configuration with a fixed resistor (10 kΩ) to create a voltage proportional to the applied force. A circuit schematic for the configuration of the FSR and Arduino is available in Appendix 2.

d. Load cell

In this project, we used a 1-kg strain gauge-based binocular bending beam load cell. The selection of the load cell was based on the range of force that needed to be measured and the method of suspension with the gripper system. Additionally, the size and shape of the load cell were also taken into consideration to ensure that it would fit within the constraints of the gripper design. Figure 17 shows that the gripper system is attached to the free end of the load cell from the down side of the load cell with the help of base flanges, and the fixed end of the load cell can be attached to the drone from the top side of the load cell.

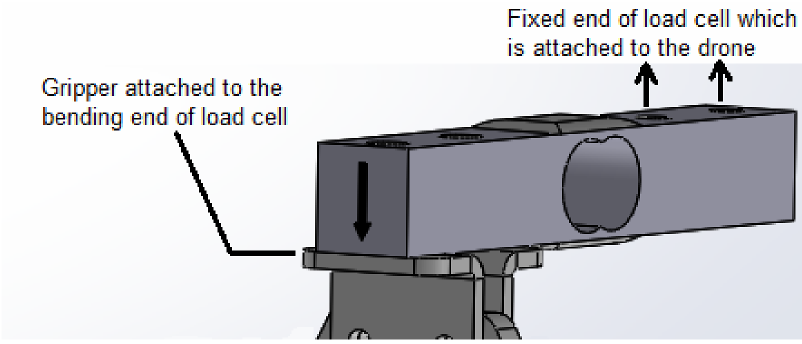


Figure 17. Placement of Load cell

The wiring of the load cell is done with the onboard Arduino UNO in such a way that when the object is grabbed and lifted, the deformation in the strain gauge is measured and transmitted to the HX711 amplifier, which converts the electrical signal to a digital signal that could be read by the Arduino, which calculates the weight data. The wiring was done according to the datasheet provided by the manufacturer (available in Appendix 2), and the code was written to calibrate the load cell and convert the raw data into weight readings.

3. Remote control system (RCS)

The remote control system (RCS) allows the user to operate and monitor the on-board gripper system from a distance while flying the drone. RCS offers intuitive control and a user-friendly interface, making it easier to receive tactical data and haptic-tactile feedback. RCS interacts with the drone gripper system with the help of an Arduino and various other components, which are discussed in this section.

a. Wearable wristband

The wrist wearable band is intended to be the main interface for receiving data feedback, providing tactile feedback, and controlling gripper action. The wristband consists of a box-like container that houses the RCS Arduino Uno and HC05 Bluetooth module. On the outside of the box, a 1.8" TFT LCD (for displaying data feedback) and a 50 kΩ potentiometer (for controlling gripper action) are placed. This container is positioned on the inner side of the wrist, while the SG90 linear actuator, which provides tactile feedback for the load cell, is placed on the outer side of the wrist. The wristband is secured to the user's wrist using elastic straps. Additionally, a haptic fingertip device (HFD) is used to provide feedback for the force resistive sensors (FSRs). The design of the wristband ensures convenient placement for easy access and visibility during drone operations. Figure 18 shows the wristband developed that works as the remote control system (RCS).

Figure 18. Wearable wristband working as RCS

b. Potentiometer for controlling gripper action

We have used a 50k ohm potentiometer on RCS as a control for the gripper system on OBS. When the operator rotates the potentiometer, the voltage level on the pin changes, which is read by the microcontroller. The microcontroller then maps this voltage level to a corresponding rotatory angle for the servo motor. Then this rotatory angle is sent to the onboard Arduino, which controls the servo motor. This results in the opening and closing of the gripper. The circuit schematic for a potentiometer with Arduino is available in Appendix 2.

c. Linear resonant actuator (LRA) for FSR feedback

To provide haptic-tactile feedback for the gripping force measured by the FSRs, a vibrotactile motor is employed on the RCS. The selection of an appropriate vibrotactile motor is crucial to ensuring accurate and discernible feedback. We chose a Linear Resonance Actuator (LRA) that offers a wide range of vibration frequencies and is compatible with the system. LRA is integrated into a finger cot, and this device is referred to as the Haptic Fingertip Device (HFD), as shown in Figure 19.

Figure 19. Haptic Fingertip Device (HFD) for Vibrotactile feedback

LRA is connected to the RCS Arduino through a vibration motor module, which helps to control its vibration frequency based on the gripping force value obtained from the average FSR value. By wearing the HFD on their finger, the user can experience haptic vibration sensations that correlate with the gripping force exerted by the gripper. The circuit schematic is available in Appendix 2.

d. SG90 Linear Actuator for Load Cell Feedback

The wristband incorporates a custom-made device called the Friction Actuator Device (FAD) to provide haptic-tactile feedback based on the weight determined by the load cell. The FAD consists of an SG90 linear actuator that converts circular motion into linear motion using a linear gear. At one end of the linear gear, a spur gear is attached, creating friction as it slides against the user's skin, as shown in figure 20.

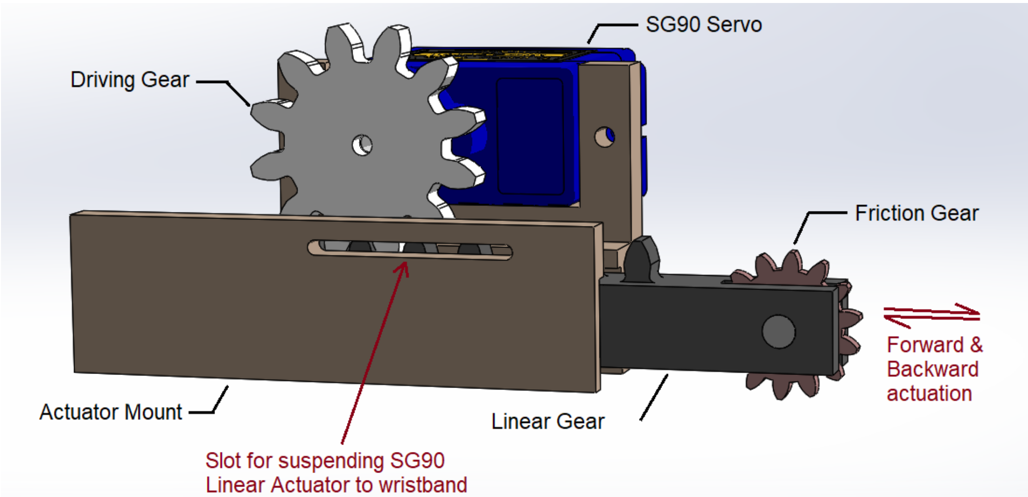


Figure 20. Haptic Fingertip Device (HFD) for Vibrotactile feedback

The linear actuation of the gear is carefully calibrated according to the measured weight values, ensuring precise feedback proportional to the weight. Using a 1 kg load cell, the linear actuator is designed to produce a displacement of 27 mm when lifting 1 kg. Figure 21 illustrates the displacement calibration for various weights, with a calculated displacement factor of 0.027 mm/gram.

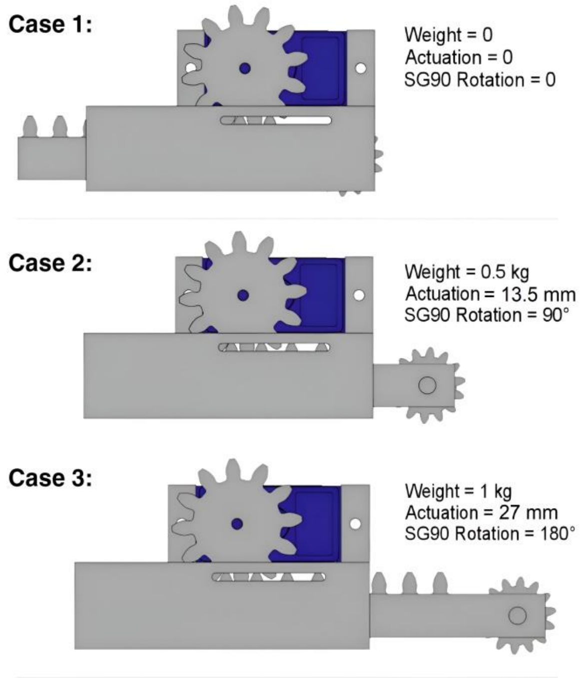


Figure 21. Actuation of FAD for Friction Feedback at different Loads

In this way, the friction generates a tactile sensation, simulating the interaction with objects and enhancing the user's perception of the weight being lifted by the gripper. The displacement calibration further contributes to an intuitive tactile feedback experience, as the user can gauge the weight being lifted by observing the displacement of the gear against their skin. FAD is connected to the remote control Arduino and controlled based on the weight values obtained from the onboard load cell. A control algorithm is implemented to calculate the displacement of the linear gear based on the weight, and the actuator is driven accordingly.

Incorporating haptic-tactile feedback through the vibrotactile motor and the SG90 linear actuator enhances the user's perception and interaction with the gripper system. It provides real-time feedback on the gripping force and weight, allowing users to have a more intuitive and immersive experience during drone operations. The circuit schematic for FAD with RCS Arduino is available in Appendix 2.

e. TFT LCD for data feedback

In this project, a 1.8-inch TFT LCD screen is used to display data collected by RCS sent from OBS, as shown in Figure 22. This display module provides a user-friendly interface that enhances the overall user experience and allows the operator quick and easy interpretation of the data, facilitating informed decision-making during object manipulation.

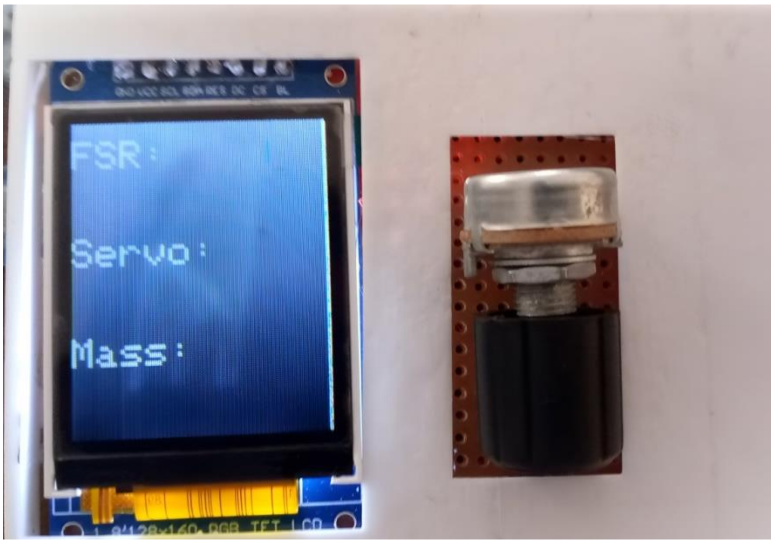


Figure 22. Display Module on Wristband

The force resistive sensor (FSR) data and load cell data are transmitted wirelessly from OBS to RCS and displayed on an LCD screen. This display provides real-time feedback on the gripping force, weight of the lifted object, and gripper angle rotation as controlled by the user through the potentiometer. The LCD serves as a visual interface that enables the user to monitor the operation. The detailed circuit diagram is available in Appendix 2.

C. System Integration and Calibration

The integration of OBS and RCS is done by coding their microcontrollers using the Arduino Integrated Development Environment (IDE). First, all the circuitry was done carefully by calibrating and interfacing sensors and actuators on both systems, then each microcontroller was attached to the computer, and then a code was developed for each system to work in proper synchronization as needed. All the circuits are provided in Appendix 2.

The code and algorithm implemented in the OBS and RCS microcontrollers are necessary for coordination in the operation of the gripper system and ensuring proper functionality. The IDE codes for OBS and RCS are available in Appendix 3.

The OBS code begins by including the required libraries for software serial communication, servo motor control, and the HX711 load cell amplifier. The relevant variables and pin assignments are then defined. The main loop function first reads the received value of the potentiometer from RCS and maps its value to the servo motor for gripper action. Then, it reads the FSR and load cell values and sends them to the RCS.

The RCS code incorporates several libraries for software serial communication, LCD display, and SG90 servo motor control. It begins by specifying the pins for various components. Within the main loop function, the code reads the value of the potentiometer, which is then mapped and transmitted to the OBS system via Bluetooth. This potentiometer value controls the angle of the servo on OBS, thereby influencing the behaviour of the gripper system. Then, the RCS system receives data from the OBS, including the servo angle, FSR value, and mass reading, which are subsequently displayed on the LCD screen.

The RCS code utilizes mapping functions to translate input values into appropriate control and feedback ranges. These mappings involve mathematical calculations to scale the input values to the desired output ranges. For instance, the potentiometer value is mapped from the analog input range (0–1023) to the servo motor angle range (0–180). This mapping enables precise control of the servo motor, determining the angle of the gripper system. Similarly, the FSR value is mapped to a pulse-width modulation (PWM) value for the vibration motor, enabling tactile feedback. The mapping function scales the FSR value from the range of 0-255 to the 0-255 PWM range for controlling the intensity of vibration, which means the HFD generates custom vibrational frequencies within the range of 0-255 Hz corresponding to different gripping force values within the range of 0-255 due to the values mapping within this range. The mass reading received from the OBS system also undergoes mathematical modelling and mapping to the SG90 servo motor. The load cell measures a mass value between 0-1000 grams and maps it for the SG90 linear actuator to provide actuation between 0-27 mm.

These mathematical mapping techniques ensure accurate and precise control of the system components and provide relevant feedback based on the sensor readings. In summary, the code and algorithm in both the OBS and RCS systems involve data acquisition, mapping, and control processes. The potentiometer value is mapped to the servo motor on OBS for gripper action. The FSR value is mapped to HFD tactile feedback, whereas the load cell value is mapped to FAD tactile feedback. Additionally, the received values are displayed on the LCD display, providing visual feedback to the user. The logic flow chart of the whole system can be observed in Figure 23.

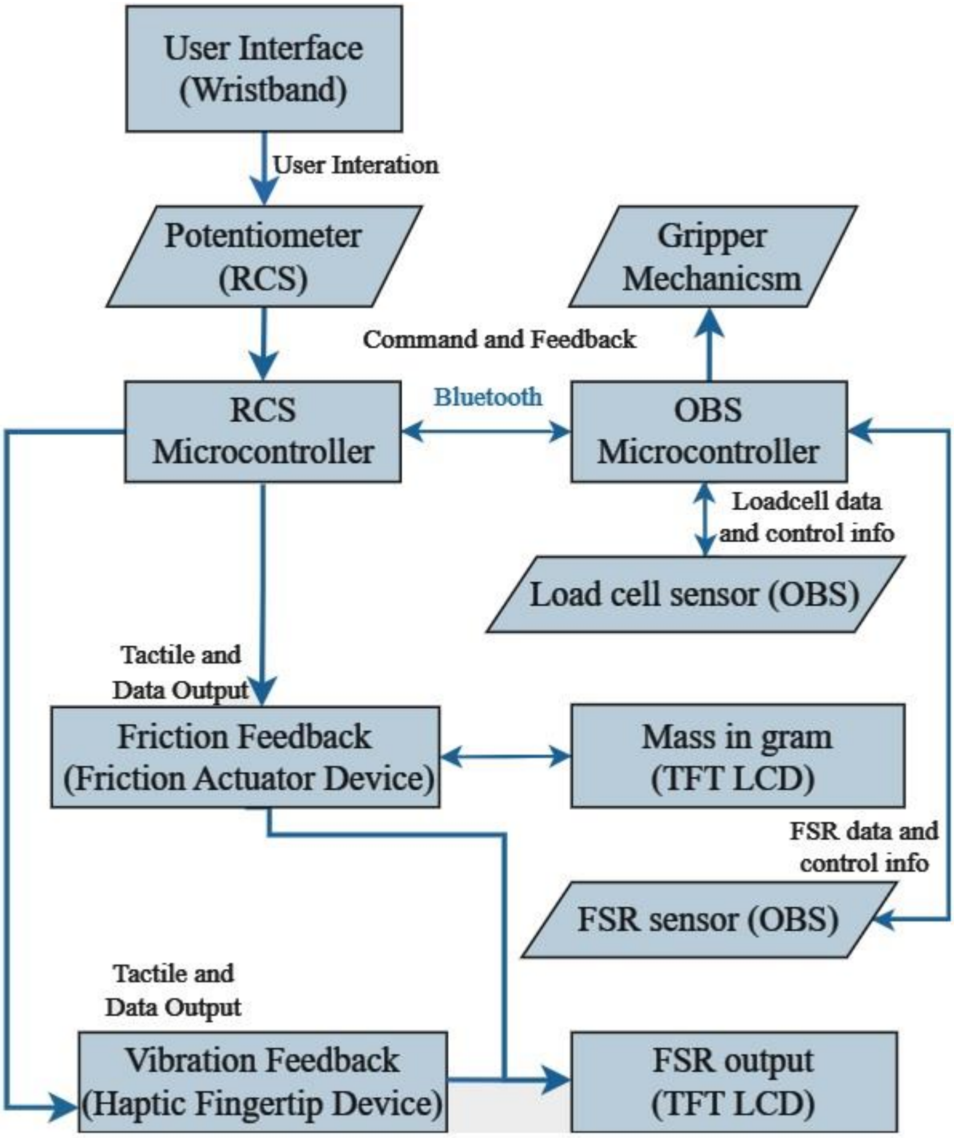


Figure 23. Control operation diagram of the Gripper system

IV. TESTING, EVALUATION AND RESULTS

The testing and evaluation phase is an essential step of this research process, allowing for the assessment and validation of the gripper system's performance, functionality, and capabilities. This chapter presents a comprehensive summary of the evaluation and testing procedures conducted to assess the effectiveness of the gripper system. The system's gripping force, weight sensing and control, overall performance in terms of dexterity and payload capacity, and comparison with existing models are addressed in detail.

The objectives of this chapter are twofold. First, it aims to assess the gripper system's performance in terms of a variety of factors, such as gripping force, weight, and performance analysis. By conducting systematic tests and analyses, the chapter seeks to provide quantitative and qualitative insights into the system's capabilities and limitations. Secondly, the chapter aims to present the results and findings of the evaluation and testing phases, facilitating a comprehensive understanding of the gripper system's performance and potential.

Through a detailed examination of the evaluation and testing process, this chapter intends to contribute to a comprehensive understanding of the gripper system's performance by shedding light on the capabilities and limitations of the developed gripper system.

A. Gripping Test

The purpose of the gripping test is to assess the effectiveness of the gripper system while performing the grasping operation. This test phase involved manually placing objects within the gripper without attaching it to the drone. The objective was to assess the system's gripping capabilities and its ability to adjust the gripping force based on variations in the shape, weight, and material of the objects. Real-time data feedback and haptic-tactile feedback were provided to enhance the user's experience and gather valuable insights.

In this test, three cases were examined to check the gripper system's potential to securely grasp objects of various shapes, masses, and materials. The primary focus was to determine the system's gripping performance and its adaptability to different object types. Table 2 shows the values observed on the display module on the wristband for each case as well as the calculated tactile feedback for the system.

Table 2. Results of Case 1, Case 2 and Case 3

Cases	FSR value	Mass	Servo angle (degree)	HFD custom vibration frequency (Hz)	FAD calculated actuation (mm)
1	156	94	69	156	2.565
2	181	419	69	181	11.367
3	176	780	72	176	21.2

1. Case 1:

In the first case, the gripper system successfully grasped a lemon, which represented a soft and circular object. The lemon, with a pre-measured mass of 94.6 grams, was placed within the gripper. The gripper applied an appropriate amount of gripping force to securely hold the lemon, ensuring it did not slip during the grasping process. The real-time data feedback was displayed on the LCD.

To enhance the user's sensory experience, the Haptic Feedback Device (HFD) provided tactile feedback by vibrating at a custom frequency corresponding to the FSR value. This haptic-tactile feedback simulated the sensation of gripping and lifting the lemon. Additionally, the Friction Actuator Device (FAD) exhibited a measured actuation value of 2.5 mm based on the mass (94 grams), while the calculated actuation value for the actual mass was 2.565 mm. Figure 24 depicts how Case 1 was carried out.

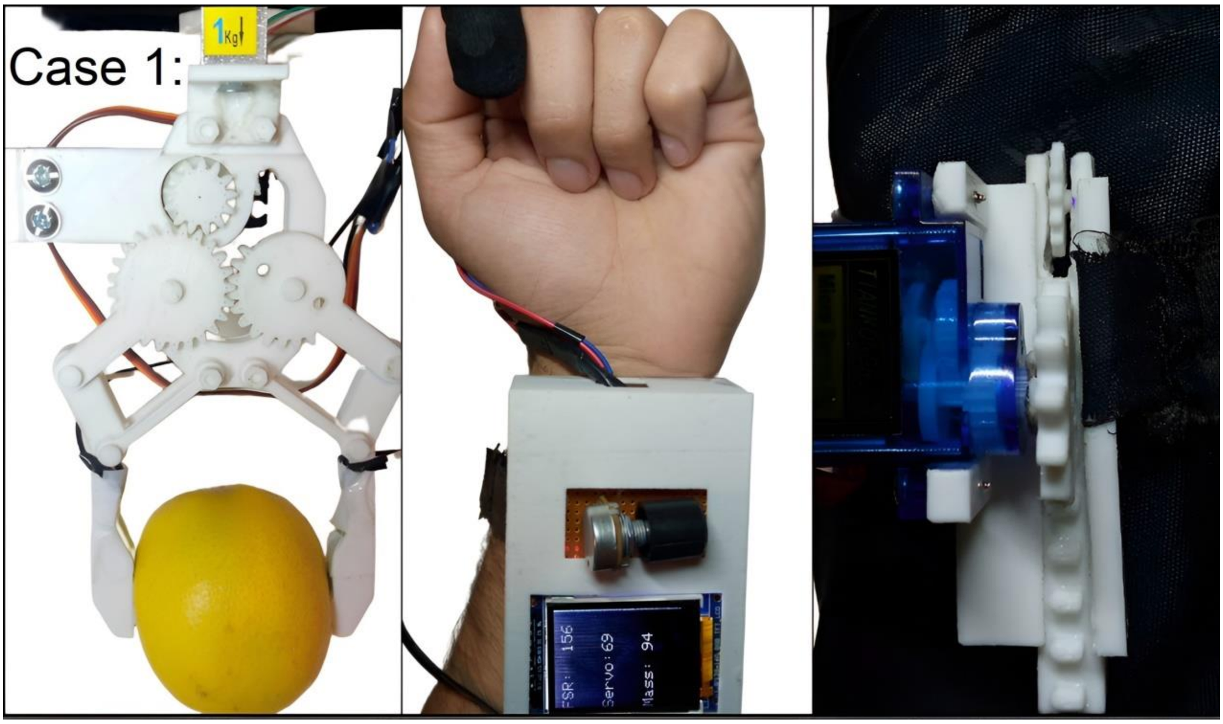


Figure 24. Feedback for Case 1

2. Case 2:

In the second case, the gripper system was tested with a rectangular box, introducing a different shape and challenging the system's adaptability. The box had a pre-measured mass of 421 grams, making it heavier than the lemon. Despite the change in object shape, the gripper system efficiently grasped the rectangular box. It adjusted the gripping force based on the FSR value to securely hold the object in place.

The user received haptic-tactile feedback through the HFD, enhancing the gripping experience. The HFD vibrated at a custom frequency of 181 Hz, providing sensory feedback. Additionally, the FAD exhibited a measured actuation value of 11.3 mm based on the mass (419 grams), while the calculated actuation value for the given mass was 11.367 mm. Figure 25 shows the feedback observed by the user.

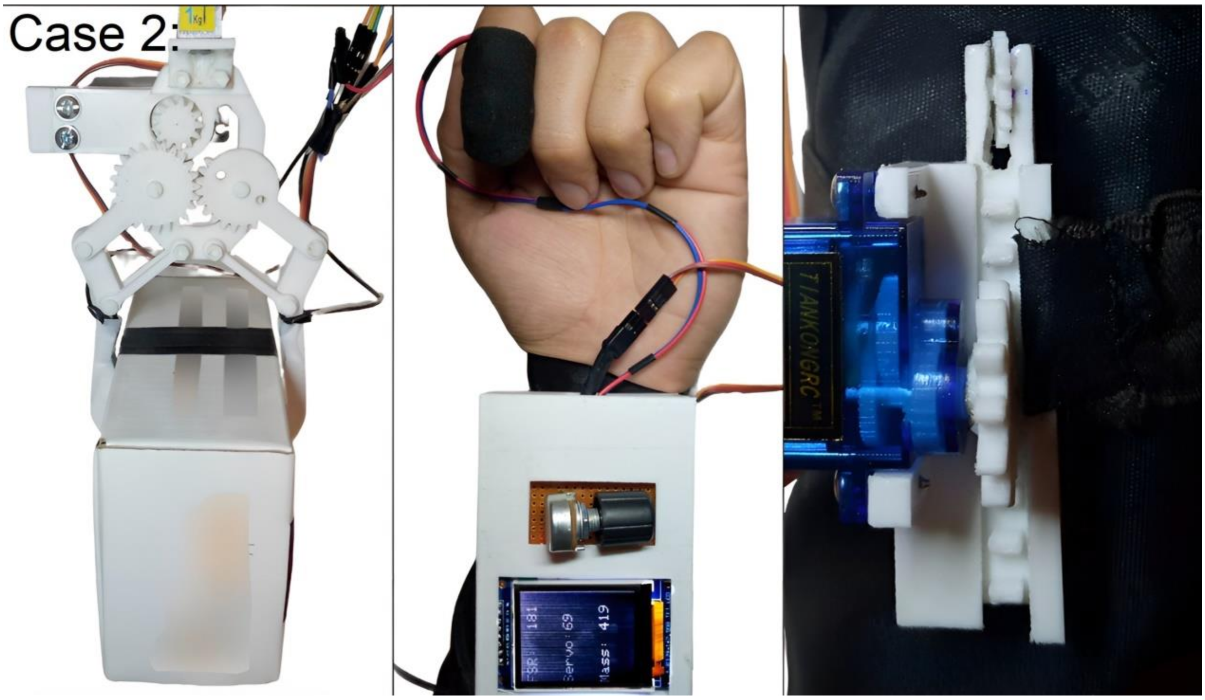


Figure 25. Feedback for Case 2

3. Case 3:

The third case aimed to determine the gripper system's maximum payload capacity. A rectangular box with the same shape as in the previous case was used, but its mass was increased up to a value at which the gripper could be able to firmly hold the load. The box had a maximum pre-measured mass of 784.5 grams, challenging the system's gripping force and control. The real-time feedback observed by the user can be seen in Figure 26.

Despite the increased weight, the gripper system successfully grasped the heavier box. It adjusted the gripping force based on the FSR value to ensure a secure hold. The user received haptic-tactile feedback, enhancing the sensation of lifting the heavier object. The HFD vibrated at a custom frequency of 176 Hz, providing sensory feedback. Additionally, the FAD exhibited a measured actuation value of 21 mm based on the mass (780 grams), while the calculated actuation value for the given mass was 21.2 mm.

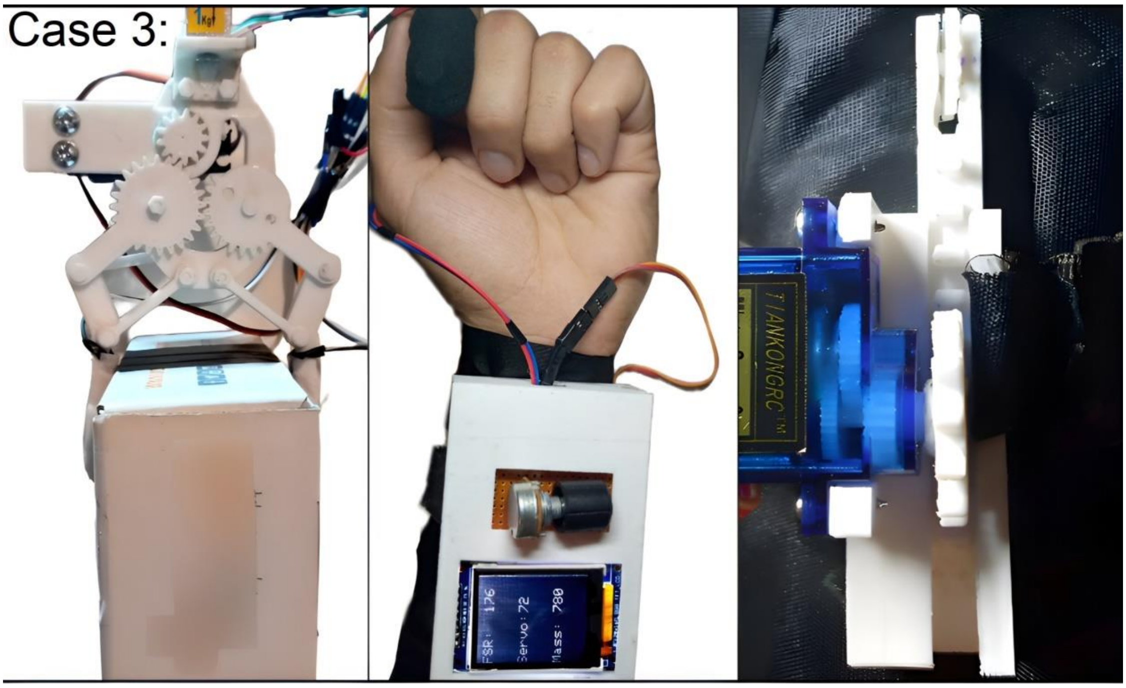


Figure 26. Feedback for Case 3

4. Results and Observations from the Gripping Test:

The gripping test gave profound insight into the functionality and capability of the gripper system. The gripper system showed high accuracy throughout the test in adjusting the gripping force based on the object's weight. The calculated actuation values for the given masses closely matched the measured actuation values, showcasing the system's precise gripping force control. The Friction Actuator Device (FAD) actuation accuracy percentage consistently exceeded 99%, affirming the reliability and precision of the gripper system (99.15% in case 1, 99.4% in case 2, and 99.1% in case 3).

Furthermore, the system showcased its adaptability to objects of different shapes, weights, and materials. It successfully grasped a soft and circular lemon, efficiently adjusted its grip to securely hold a rectangular box, and effectively handled an increased weight with a heavier box. The gripper system's ability to adapt to various object types demonstrated its versatility in real-world applications that require precise gripping and manipulation capabilities. The Haptic Fingertip Device (HFD) provided vibrotactile feedback that enhanced the user's experience during the gripping process. It simulated the sensation of gripping the objects, providing an immersive tactile experience.

Overall, the results and observations from the gripping test indicate that the gripper system performed exceptionally well in terms of accuracy. High accuracy ensures reliable and precise gripping force control, making the system suitable for a wide range of applications where accurate object manipulation is necessary.

B. Gripper System Integration on Drone

As a pivotal phase of this research, the successful integration of the gripper system with the drone unlocks new possibilities for object manipulation and enhances the drone's functionality. The precisely designed gripper system was now ready to be suspended from the drone.

The DJI Phantom 3 Standard drone, renowned for its stability and ease of use, provided an ideal platform for this integration. Its default weight balancing methodology, combining the battery and camera gimbal, was studied and adhered to, ensuring that the gripper system's attachment maintains the drone's equilibrium during flight. The gripper system and its components were harmoniously integrated into the drone's structure without compromising the drone's stability or safety.

1. Attachment of Gripper System to DJI Phantom 3 Standard

To integrate the gripper system with the DJI Phantom 3 Standard drone, the first step involved removing the camera gimbal from the drone's underside, as shown in Figure 27 (a). The camera gimbal is a standard component of the DJI Phantom 3 Standard used for stabilising and capturing aerial footage. Its removal was necessary to create space and provide a stable platform for attaching the gripper system.

To ensure a precise and reliable attachment, a 3D-printed part was designed with the same geometry as the gimbal's support structure. This custom part served as the mounting platform for the gripper system. The load cell, an essential component for weight sensing, was securely screwed to this 3D-printed part. One end of the load cell was attached to the drone, while the other end effectively suspended the rest of the gripper system, as shown in Figure 27 (b).

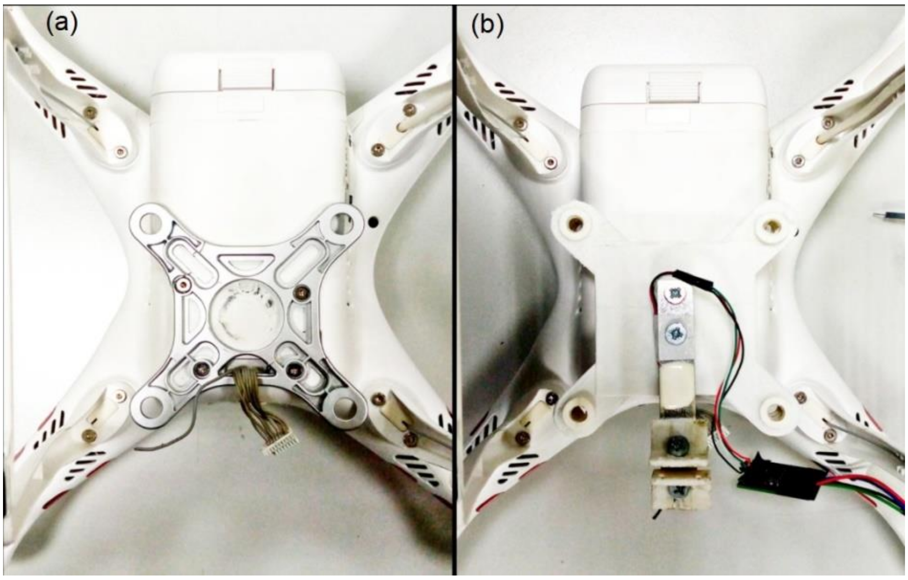


Figure 27. (a) Gimbal removed from underside of DJI Phantom 3 drone (b) 3D part attached to drone which suspends Loadcell and rest of gripper system

Once the load cell and gripper system were securely attached, the onboard microcontroller and power supply, responsible for controlling the gripper system and processing real-time data feedback, were suspended on the top of the drone using a combination of adhesive tape and a velcro band, as shown in figure 28. The thoughtful design and arrangement of the suspension system allowed for proper weight distribution, preventing any interference with the drone's maneuverability and flight performance.

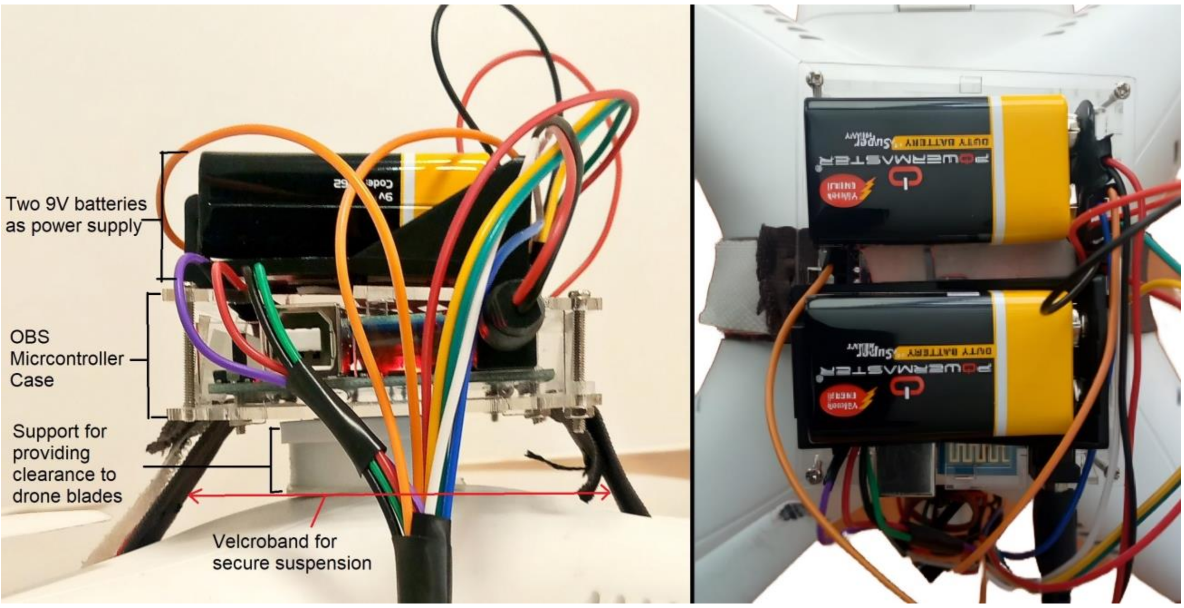


Figure 28. Attachment of OBS Microcontroller on Drone

2. Weight Balancing Methodology

To ensure stable flight performance and manoeuvrability, the weight balancing of the integrated gripper system with the DJI Phantom 3 Standard drone was essential. The default weight balancing methodology of the DJI Phantom 3 Standard involved the combination of the drone's battery and camera gimbal, which maintained the drone's centre of gravity and stability during flight, as shown in figure 29 (a). With the introduction of the gripper system, it was important to carefully distribute the additional weight of the gripper and its components.

To achieve the proper weight distribution, a 3D-printed support with the rest of the system suspended on it was positioned exactly like the default gimbal placement by the manufacturer. As shown in figure 29 (b), the gripper system was placed opposite the battery, which counterbalanced the mass, whereas the microcontroller and power supply were placed on top of the drone, preventing any potential disruption to the drone's flight dynamics. By considering the weight of the gripper, the load cell, and other components, a balanced distribution was achieved, minimising any impact on the drone's flight dynamics.

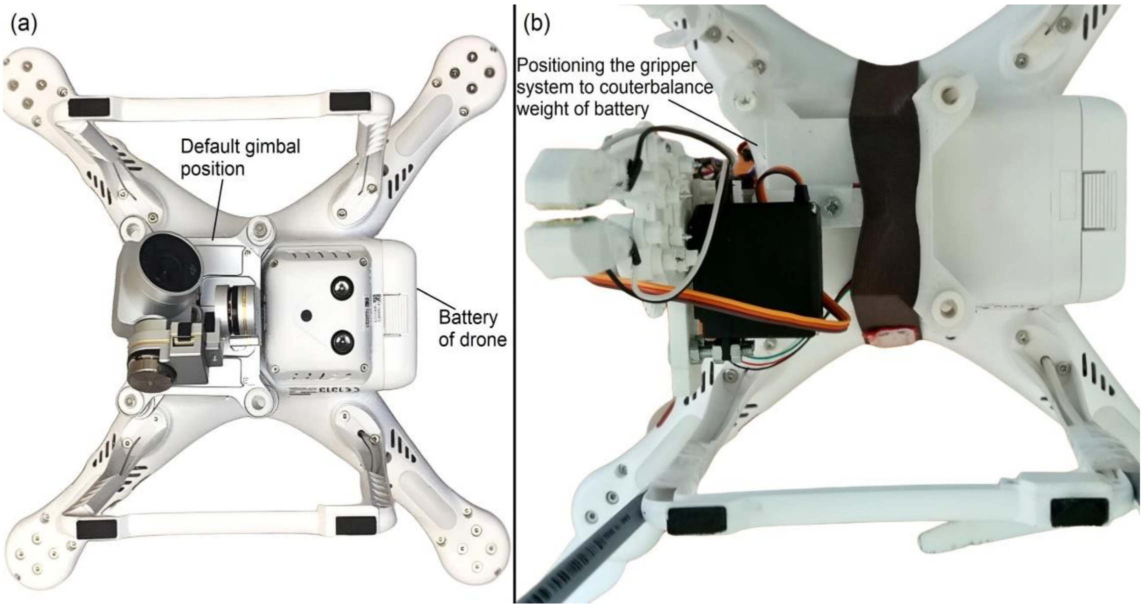


Figure 29. (a) Default position of gimbal (b) Positioning of gripper system likewise default

Theoretically, the installation of the gripper system did not significantly affect the drone's default weight distribution, according to a comparison between the weight balancing methodology with the integrated gripper system and the drone's default configuration. Calculations were used to ensure that the drone's centre of gravity stayed within allowable bounds by carefully positioning the gripper system in a balanced mechanism. A full representation of the gripper system attached to the drone can be observed in Figure 30.

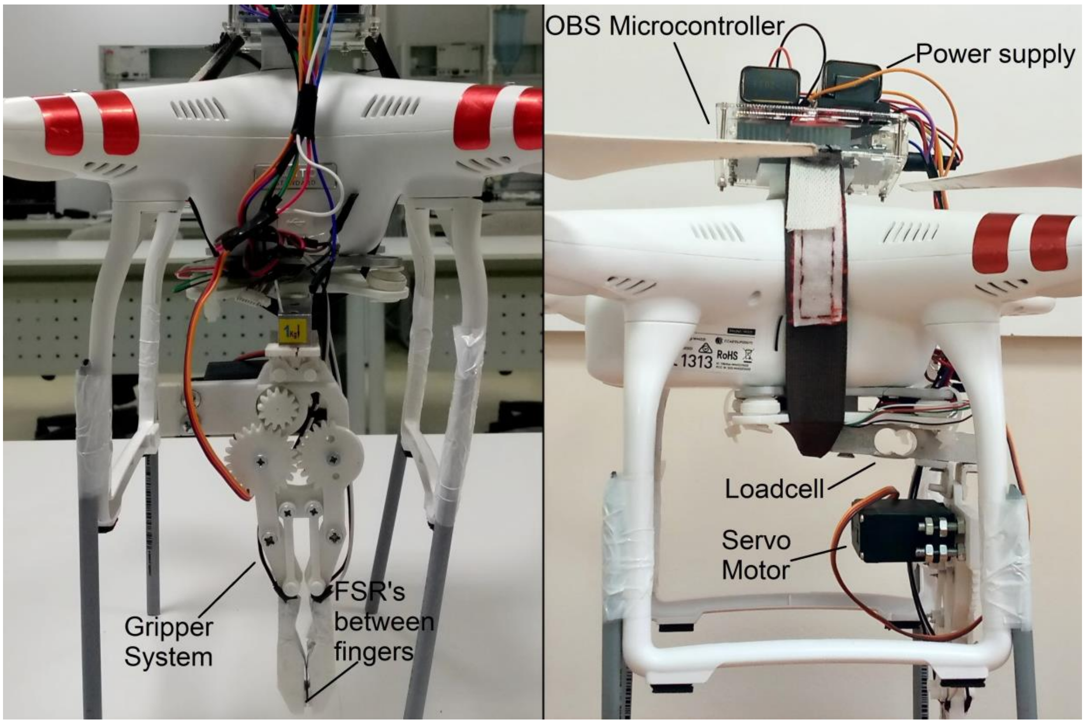


Figure 30. Gripper system attached to the drone

As previously stated, it is critical to emphasize that the drone's stability and performance were not evaluated through actual flight due to the prevailing restrictions. However, the research and theoretical analysis indicate that the proposed weight balancing approach aligns with the manufacturer's default methodology, aiming to keep the drone stable and performing well in flight.

3. Integration Challenges and Solutions

The integration of the gripper system with the DJI Phantom 3 Standard drone offered a number of technological obstacles that necessitated the development of novel solutions. A significant challenge was precisely attaching the gripper device without affecting the structural integrity of the drone. In order to address this, we tried integrating the gripper similar to how the gimbal was attached by default.

Safety and stability during drone operation were paramount concerns throughout the integration process. The potential risk of any instability or detachment during flight necessitated thorough testing and reinforcement of the gripper system's attachment points.

It is essential to acknowledge that practical flight testing was not performed due to flight restrictions. Therefore, while the integration challenges were addressed with innovative solutions, the actual stability and safety performance of the drone with the integrated gripper system remain to be confirmed through practical flight testing under controlled and permissible conditions.

While practical flight testing was not feasible at this stage, the theoretical design and integration process laid the foundation for further research during aerial manipulation. However, a comprehensive research questionnaire was conducted to gather feedback from experts and potential users. This questionnaire aimed to assess the perceived stability and safety of the gripper system's integration with the drone. Participants were asked to evaluate the design and attachment of the gripper system as well as the weight-balancing methodology. The research questionnaire is discussed in the next section.

C. Research Questionnaire:

The research questionnaire was meticulously crafted to gather valuable insights and feedback from potential users in various fields. The questionnaire aimed to assess the perceived usefulness, effectiveness, and practicality of the developed gripper system integrated with a drone. Participants were asked to evaluate various aspects of the gripper system, including its gripping performance, adaptability, tactical data feedback, haptic-tactile sensations, integration, and potential safety concerns when attached to the drone.

A Likert scale was given to the participants after they tested and observed the system. This form contained eight questions, which were enough to evaluate the system. A scale from one to five was provided, with one meaning the most negative evaluation and five meaning the most positive evaluation. Figure 31 shows the experimental evaluation of the system by participants.

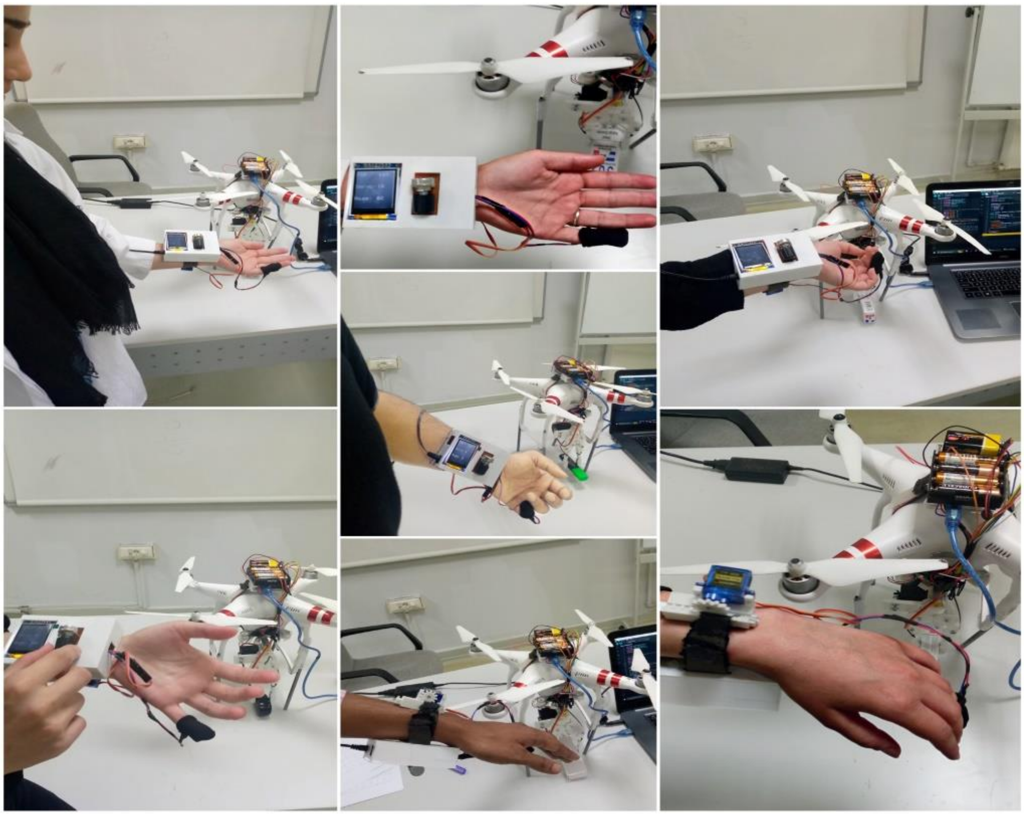


Figure 31. Participants testing the system

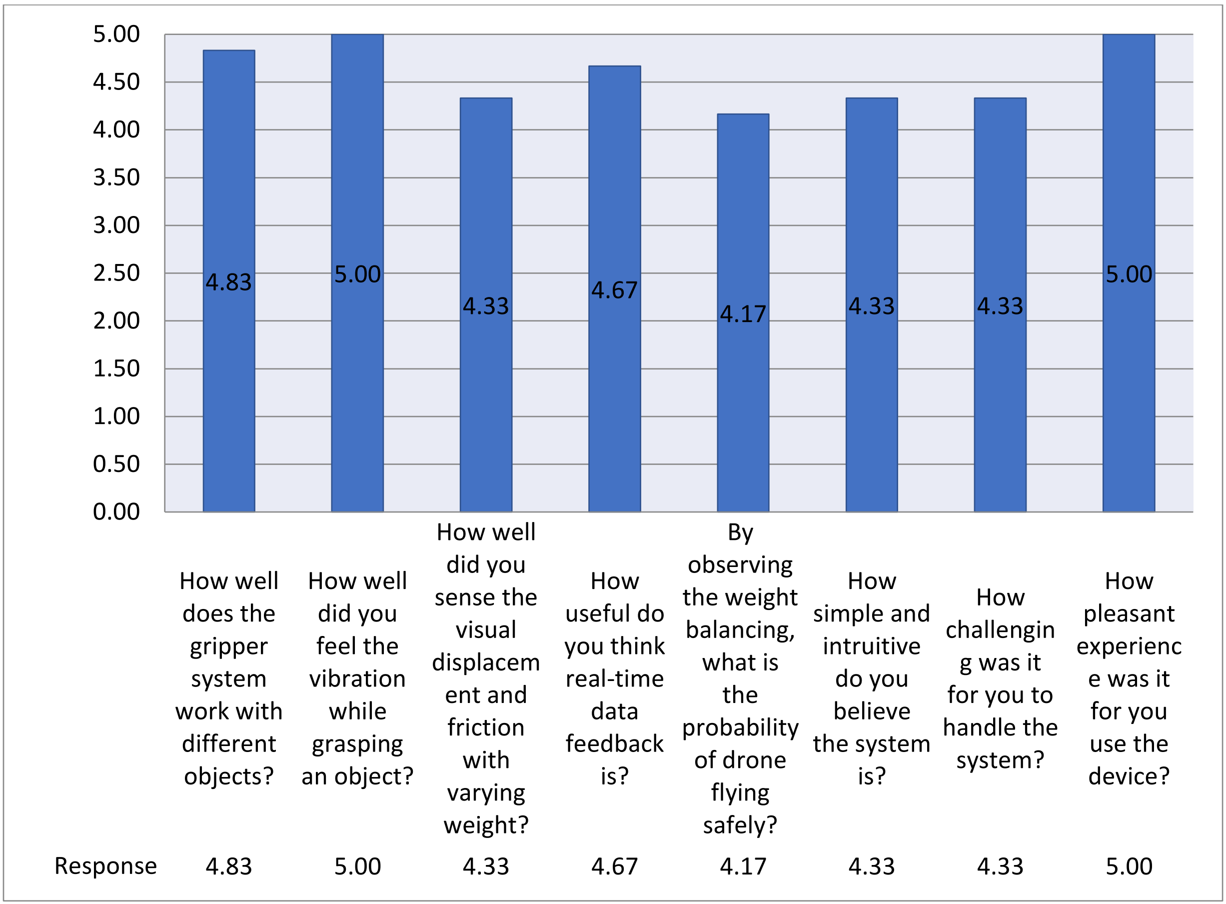
1. Key areas of inquiry:

Participants were asked to evaluate the gripping performance of the system based on its adaptability to different objects. They were asked to evaluate the vibrotactile feedback while grasping an object and the sense of visual displacement according to weight while simultaneously feeling friction on their wrist. Feedback on the effectiveness and usefulness of real-time data feedback provided by the gripper system during object manipulation was requested. Feedback regarding the perceived safety and stability of the drone during potential future operations with the attached gripper system Participants evaluated the simplicity and independence of the project and asked how much training you actually need as an amateur to be able to perform the operation. At last, they evaluated, on a certain scale, how pleasant it was to use the device.

2. Data Analysis and Insights:

The collected data from the research questionnaire was subjected to rigorous analysis to extract meaningful insights. Qualitative and quantitative analysis methods were employed to interpret participants' responses, providing a comprehensive evaluation of the gripper system's performance, usability, and integration aspects.

Table 3. Evaluation of the Research Questionnaire



3. Contributions to Research:

The research questionnaire played a vital role in gathering user feedback and expert opinions, allowing for a more comprehensive evaluation of the developed gripper system. The insights gained from the questionnaire contribute to a deeper understanding of the system's potential applications, limitations, and scope for further improvements. The data collected through the research questionnaire provides valuable feedback from potential users and experts, further reinforcing the practicality and significance of the gripper system's integration with drones. The user-driven evaluation and expert opinions shed light on the system's strengths and areas for refinement, aiding in the continuous improvement and future development of aerial manipulation technologies.

D. Performance Evaluation

1. Gripping force analysis:

Gripping force is an essential parameter in assessing the effectiveness and reliability of a gripper system in this research. In this section, FSRs are mathematically calibrated to provide force in Newton. FSRs are strategically placed within the gripper to measure the force applied when an object is grasped. The FSR sensor detects changes in pressure and converts them into a corresponding electrical signal that increases or decreases the resistance, which is manipulated by the microcontroller to give out an FSR value. This value can be converted into force in Newton using a mathematical model, which is discussed in this section.

The mathematical model involves establishing a relationship between the FSR output voltage and the FSR resistance. Calibration experiments are conducted to determine the conversion factors and coefficients. Figure 32 below shows the relationship of force with resistance and conductance. When no force is applied, the sensor has a high resistance (> 10 MegaOhms (MΩ) in our case), but as the force is applied, the resistance of the sensor decreases. Similarly, when we consider the conductance (inverse of resistance), it increases linearly as the force is increased.

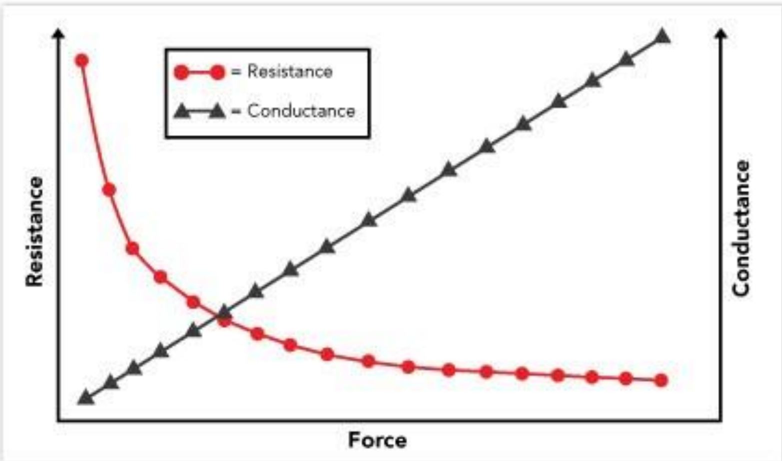


Figure 32. Relation of Force with Resistance and Conductance

Source: (TEKSCAN, 2019)

Thanks to ADA (ADA, 2012), they have already conducted calibration experiments and provided a mathematical model that uses the conversion of FSR voltage to FSR resistance based on the principles of linear resistivity. When pressure is applied to the FSR, the Arduino reads an analog value (0–255, in our case). This FSR value (FSR_{val}) is mapped to the input voltage V_{cc} (0–5000 mV in our case). The value of the voltage we get by mapping or linear interpolation is the FSR output voltage (V_o). Then further FSR resistance is calculated using the FSR output voltage, from which FSR conductance is calculated. This FSR conductance is further manipulated to get force in Newton. The step-by-step mathematical modelling is as follows:

a. Read the FSR analog value (FSR_{val}) using Arduino.

b. Now, calculate the FSR output voltage (V_o). This can be done by mapping or linear interpolation:

$$Vo = \frac{(FSR_{val} - Min\ FSR_{val}) * (Max\ Voltage - Min\ Voltage)}{Max\ FSR_{val} - Min\ FSR_{val}} + Min\ FSR_{val}$$

- Min FSR val is the lower limit of the analog range of FSR = 0
- Max FSR val is the upper limit of the analog range = 255
- Min Voltage is the lower limit of the voltage range = 0 V
- Max Voltage is the upper limit of the voltage range = V_{cc} = 5000 mV

So, by substituting these values into the expression we get,

$$V_o = \frac{FSR_{val} * 5000}{255}$$

c. Now after we get the FSR voltage output, we calculate the FSR resistance (R_{FSR}) by following relation:

$$R_{FSR} = (V_{cc} - V_o)\frac{R_{pull\ down}}{V_o}$$

- $R_{pull\ down}$ is the of the pull-down resistor with a value = 10,000 ohm

d. To get a more precise value of force in Newton (F) because of the linear relation between force and conductance, we convert the FSR resistance (R_{FSR}) to the FSR conductance (C_{FSR}) by following relation:

$$C_{FSR} = \frac{1000000}{R_{FSR}}$$

e. Now we can approximate the force (F) but there are two cases:

- If the conductance of FSR is less than 1000, i.e. C_{FSR} <= 1000:

$$F = \frac{C_{FSR}}{80}$$

- If the conductance of FSR is greater than 1000, i.e. C_{FSR} > 1000:

$$F = \frac{C_{FSR} - 1000}{30}$$

In this way, the force in Newton can be approximated through the FSR reading. This mathematical expression can be used to approximate the force in Newtons, but there is a limitation. The linear interpolation used in this modelling assumes a linear relationship between the FSR value and the output voltage. However, it's a simplified approximation and may not provide highly precise results.

The accuracy of the calculated force values also relies on the calibration and characteristics of the specific FSR sensor being used. To verify the validity of the proposed mathematical model, we did a test by applying known forces to an FSR and getting its FSR value. Then, these forces and their corresponding FSR values were used to draw a graph on Excel, and a linear equation was obtained as given below.

$$F\ (Force\ in\ Newton) = 0.0253(FSR) - 1.8078$$

Now the values of FSR obtained in the Gripping Test in Section B of this chapter were used to verify the mathematical model through this equation. Table 4 below shows the values of gripping force in Newtons as calculated by the developed mathematical model and the verifying equation.

Table 4. Values calculated for FSR values in Gripping Test cases

Case #	FSR value	Force in Newton by model	Force in newton by verifying equation
1	156	1.955	2.139
2	181	3.057	2.863
3	176	2.785	2.645

Thus, the values we get from the mathematical model in Newton are very close to the values obtained from the verifying equation developed. So the mathematical model proposed can be a good approximation for calculating force in Newtons for the obtained FSR values. It should be noted that the developed mathematical model uses some equations provided in the data sheet of the sensor used in this project. And the values of the coefficients may differ due to the different sensor specifications.

2. Weight sensing and control:

The weight-sensing capability of the gripper system relies on a load cell. Before taking weight measurements, a calibration process is carried out to ensure accurate and reliable readings. During this calibration process, a calibration factor (m) is measured. Once this calibration factor is calculated, we can use it in the code to measure the exact weight in grams from the load cell.

As we know, the load cell is connected to an HX711 amplifier, which converts its reading into an electrical signal, which is then read by the microcontroller. This HX711 works as an analog-to-digital converter (ADC). The ADC value it gives out to the microcontroller is referred to as the load cell reading, which is converted into actual weight values, providing quantitative data for weight sensing and control analysis. The mathematical model that is used to convert the ADC value utilizes a linear fit calibration method. The process involves the following steps:

a. Zero Load Calibration: With no load applied (X1 = 0 g), a measurement is taken, and the corresponding ADC value from the HX711 is recorded as Y1.

b. Known Load Calibration: A known load is applied, such as 500 g (X2 = 500 g), and another measurement is taken, noting down the ADC value from the HX711 as Y2.

c. Calculation of Calibration Factor: The calibration factor (m) represents the weight in grams per ADC code and allows for the conversion of ADC values to weight measurements. The calibration factor (m) is calculated using the formula:

$$m = \frac{X2 - X1}{Y2 - Y1}$$

d. Offset Determination: Since Y1 corresponds to the no-load condition, it becomes the offset value (c) in the calibration equation.

So the calibration process is carried out in this way; this process provides us with the calibration factor (m) and the offset value (c). Once these coefficients are carefully calculated, we can proceed with the direct conversion of the ADC value to the accurate weight value. The values of calibration factor (m) and offset value (c) in our case are 931 and 0. Now the accurate mass in grams (g) can be calculated using the following equation:

$$W = (ADC\ value * m) - c$$

By substituting the values of coefficients calculated in our system. The final expression for our system for mass in grams is as follow:

$$W = 931 * ADC\ value$$

The accuracy and precision of the weight sensing capability of the gripper system are evaluated by comparing the measured weight values with known weights. This analysis assesses the closeness of the measured weights to the actual weights, ensuring the accuracy of the system's weight measurements. The accuracy analysis is carried out for the mass values we got for all three cases in the Gripping Test in Section B. Table 5 below shows the mass values of the grasped objects that we got from the system in all three cases of the Gripping Test and compares them with the actual weight of the grasped objects.

Table 5. Accuracy of weight sensing

Case #	Measured value (g)	Actual value (g)	Accuracy %
1	94	94.6	97.6
2	419	421.3	98.6
3	780	784.5	98.2

The measured weight shows an exceptional accuracy in all three cases affirming the reliability and precision of the system

V. CONCLUSION

The design, development, and assessment of a robotic gripper system for UAV applications were the main topics of this work. The objective of the study was to address the necessity for an efficient gripper system that could safely grasp and manipulate a subject in real-life situations. We performed comprehensive testing and assessment throughout the research process in order to assess the efficacy and performance of the developed gripper system.

The thesis aimed to develop an efficient gripper system that could be integrated with drones with advanced functionalities. During the object manipulation, the system provided haptic-tactile feedback to the operator, enabling precise manipulation and control. Additionally, the system was designed to offer real-time data feedback to the operator, facilitating better grasping of the object. This is achieved through the development of an Onboard System (OBS) and a Remote Control System (RCS) specifically customized for the gripper system and its feedback mechanisms.

The research questions that guided this project focused on identifying the challenges and limitations of existing features of gripper systems, designing a gripper system with precise measurements of lifted weight and gripping force, exploring potential uses and benefits of integrating gripper systems with drones, and incorporating real-time data and haptic feedback into the gripper system.

Several significant discoveries and insights were made through the study and experiments carried out, including:

1. The developed gripper system demonstrated remarkable gripping performance and adaptability across various objects and factors. It exhibited precise gripping force control, accurately adjusting the gripping force based on the object's weight. This precision was achieved through well-written and constructed code for the microcontroller on both the remote control system (RCS) and the onboard system (OBS).

2. The integration of haptic feedback into the gripper system enhanced the operator's tactile experience during the gripping process. By simulating the sensations of vibration and friction, the haptic feedback device provided a realistic and immersive tactile experience.
3. A Haptic Fingertip Device (HFD) is developed for FSR feedback with vibrotactile sensation, whereas for loadcell feedback, a Friction Actuator Device (FAD) is developed, which provides an actuated friction sensation on the user's skin.
4. The real-time data feedback feature of the gripper system facilitated precise control and manipulation of the gripped objects. The operator received valuable information, such as gripping force, servo angle, and object weight, through the display module, enabling them to make informed decisions during operation.
5. The gripping test provided valuable insights into the gripper system's performance and flexibility across various objects and scenarios. The system demonstrated good precision in adjusting the gripping force based on object size, shape, and weight, enabling secure grasping. The system showcased its adaptability to objects of different shapes, weights, and materials, proving its versatility in practical applications.
6. The research questionnaire collected feedback from different participants after they tested and examined the system. The result of the questionnaire depicted a very good result, as the feedback from users after testing the device was positive.
7. Performance analysis revealed that the gripper system exhibited a high level of accuracy in terms of gripping force control and weight sensing. The calculated values closely matched the measured values, indicating a precise and calibrated system.
8. The gripper system demonstrated a maximum payload capacity of 784.5 grams and a maximum gripping force of 3.057 Newtons determined during the "Gripping Test", which ensured a secure hold on objects.

In conclusion, the conducted research successfully developed and assessed a robotic gripper system for drones that showed good gripping performance, adaptability to various objects, precise gripping force control, and reliable weight sensing capabilities. Furthermore, the integration of haptic feedback and real-time data feedback contributed to an enhanced user experience and improved operational efficiency. These findings highlight the significance of the developed gripper system in enabling UAVs to perform complex object manipulation tasks effectively and precisely.

Overall, this research significantly advances UAV capabilities and opens up a new pathway for the incorporation of robotic gripper systems in aerial robotics, providing enhanced functionality that broadens the potential applications of UAV technology, such as animal search and rescue operations, warzone assistance tools, agricultural automation, and industrial automation. Its features and capabilities open doors for better and more advanced object manipulation in drone-based systems.

The insights gained from this research can guide future advancements in gripper systems for drones and contribute to the ongoing progress in the field of robotics and automation.

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APPENDICES

A. Appendix 1

1. Gripper System

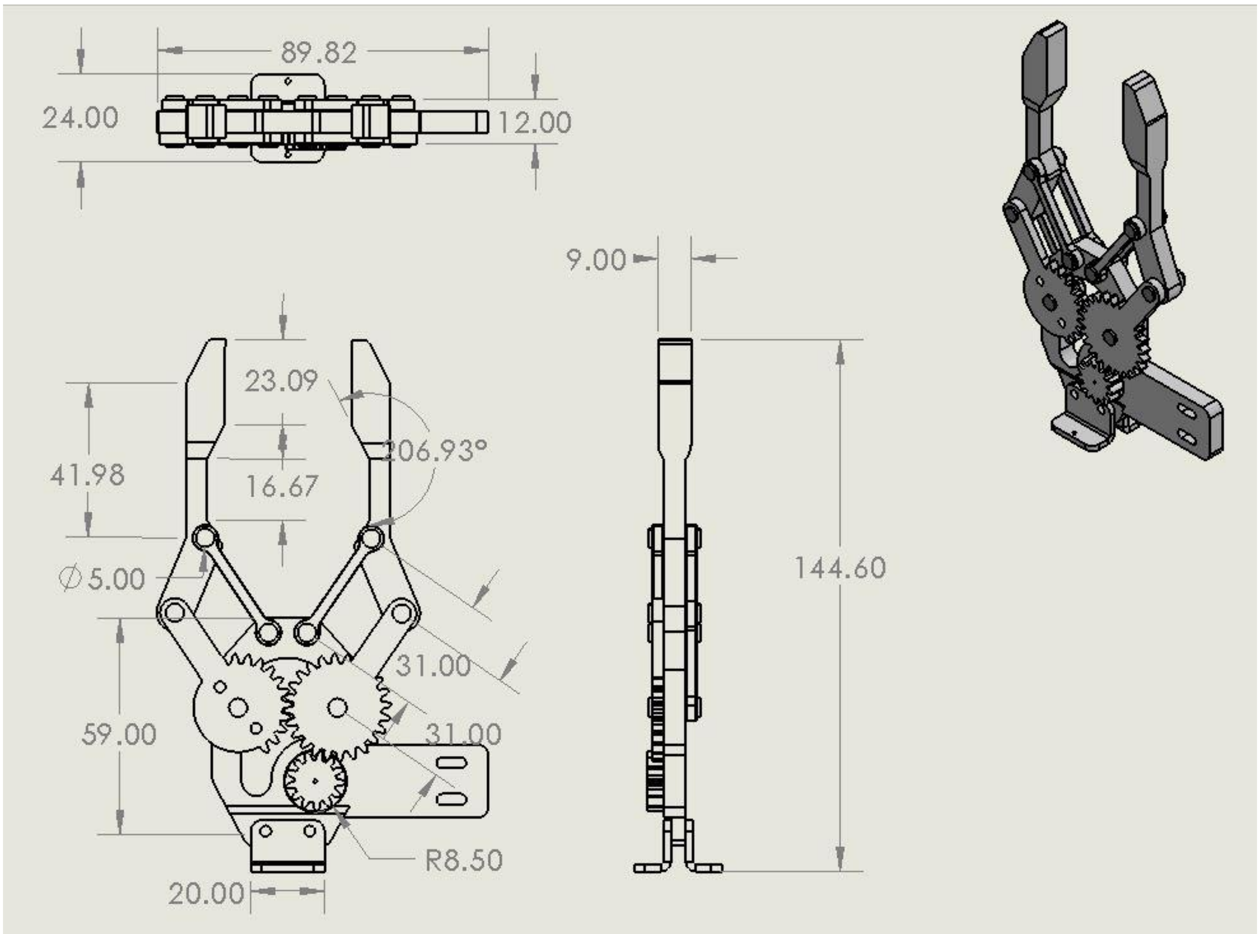

Figure 33. Technical Drawing of Gripper System (All dimentions are in mm)

2. **Technical Drawing of SG90 linear actuator (All the dimensions mentioned are in millimeters (mm))**

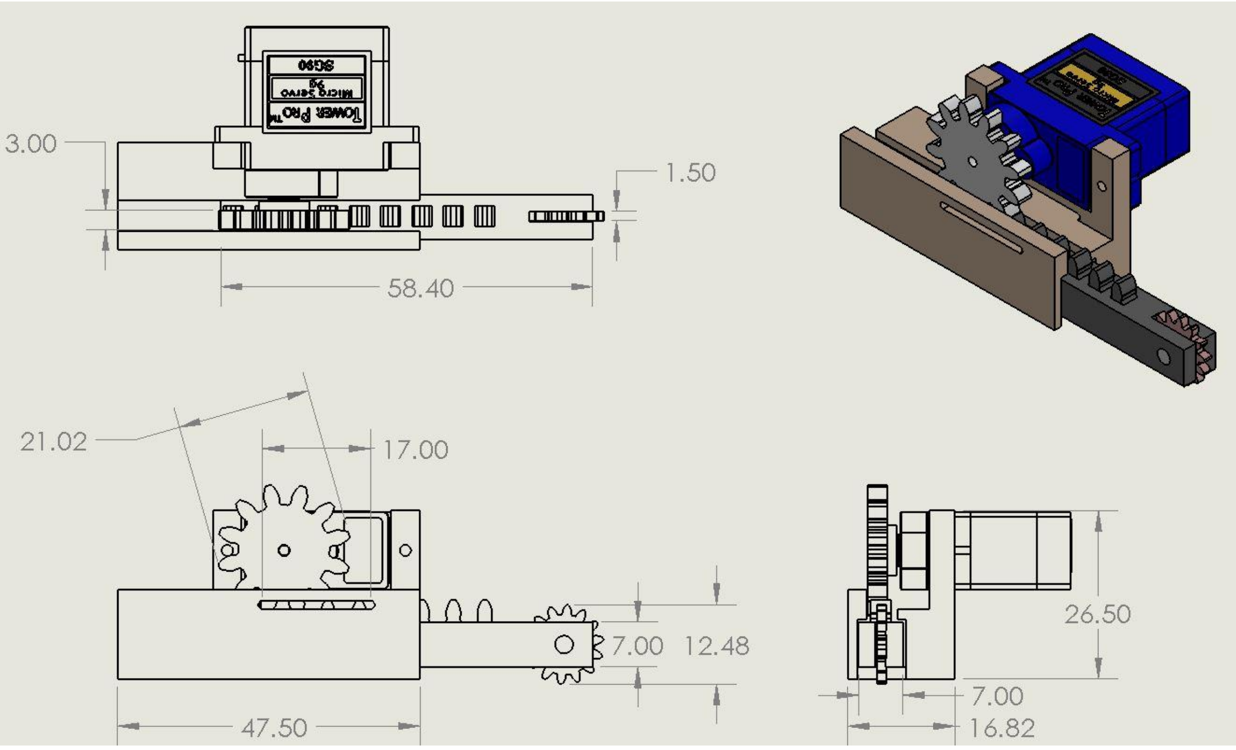

Figure 34. Technical Drawing of SG90 linear actuator (All the dimensions mentioned are in millimeters (mm))

B. Appendix 2

1. Master and slave system

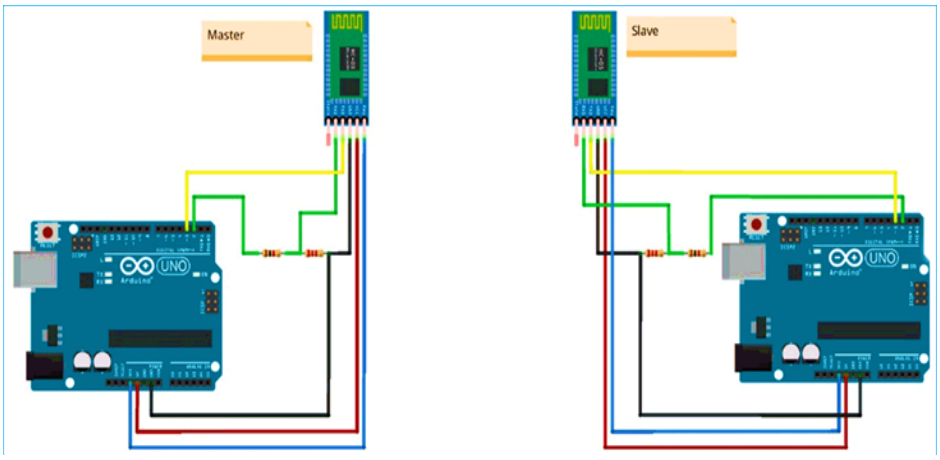

Figure 35. Circuit schematic of master and slave system

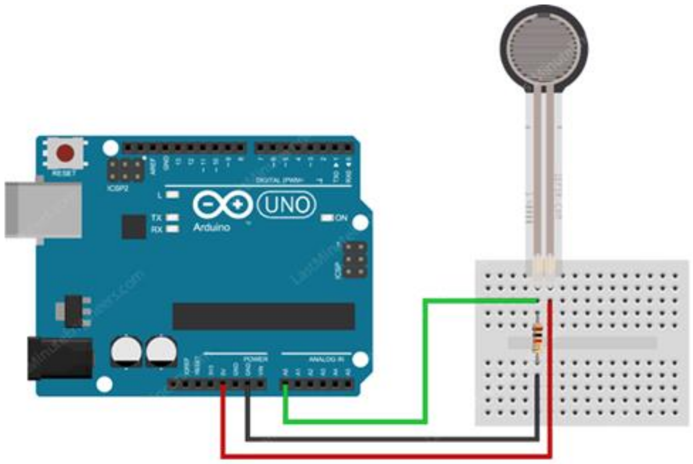

Figure 36. Circuit schematic for configuration of FSR and Arduino

2. Load cell with Arduino using HX711 amplifier module

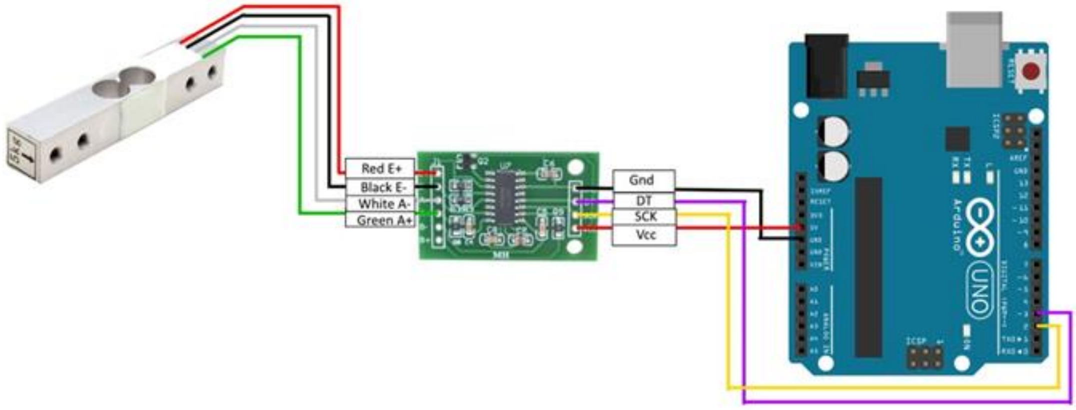

Figure 37. Circuit schematic of load cell with Arduino with HX711 amplifier

3. Servo motor with Arduino

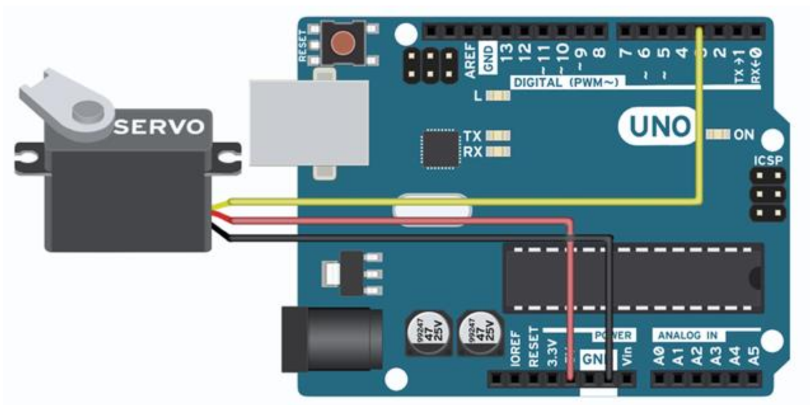

Figure 38. Circuit schematic of Servo motor with Arduino

4. Potentiometer with RCS Arduino

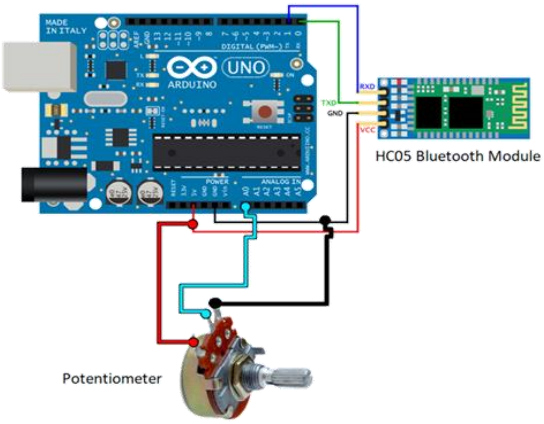

Figure 39. Circuitry of Potentiometer with RCS Arduino

5. Circuit schematic of LRA with Arduino

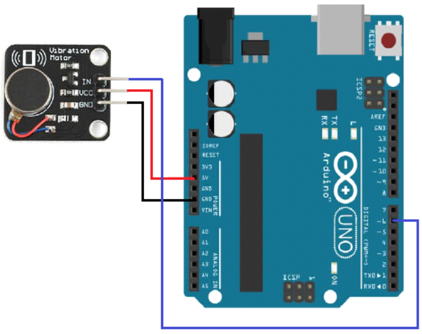

Figure 40. Circuit schematic of LRA with Arduino

6. Circuit schematic of FAD with Arduino

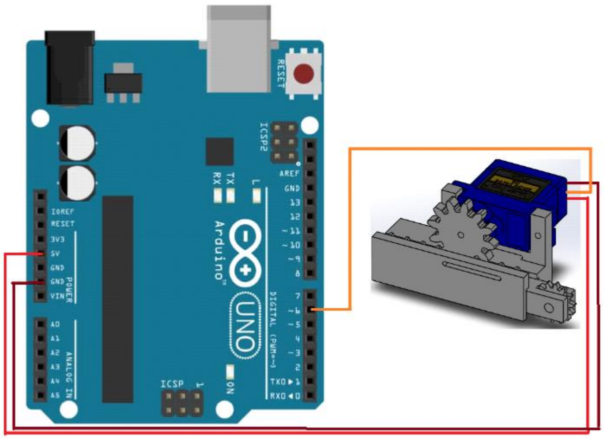

Figure 41. Circuit schematic of FAD with Arduino

7. Circuit schematic of TFT LCD with Arduino

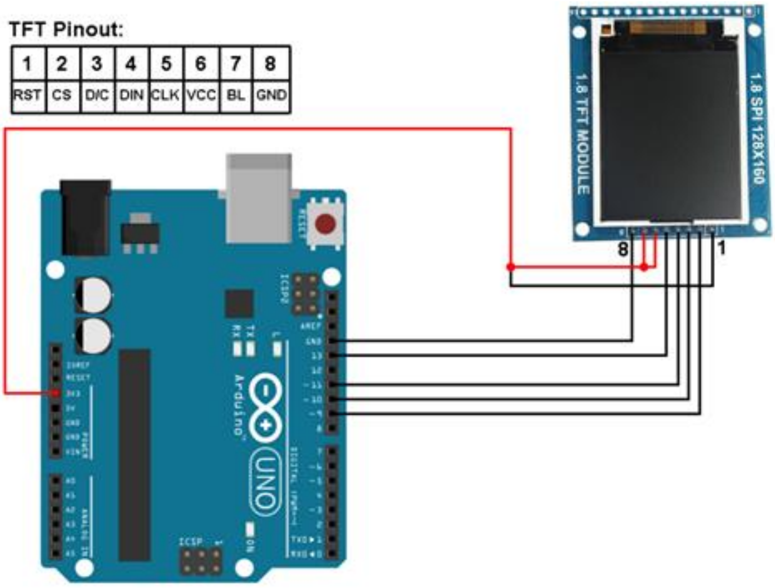

Figure 42. Circuit schematic of TFT LCD with Arduino

9. Onboard System (OBS):

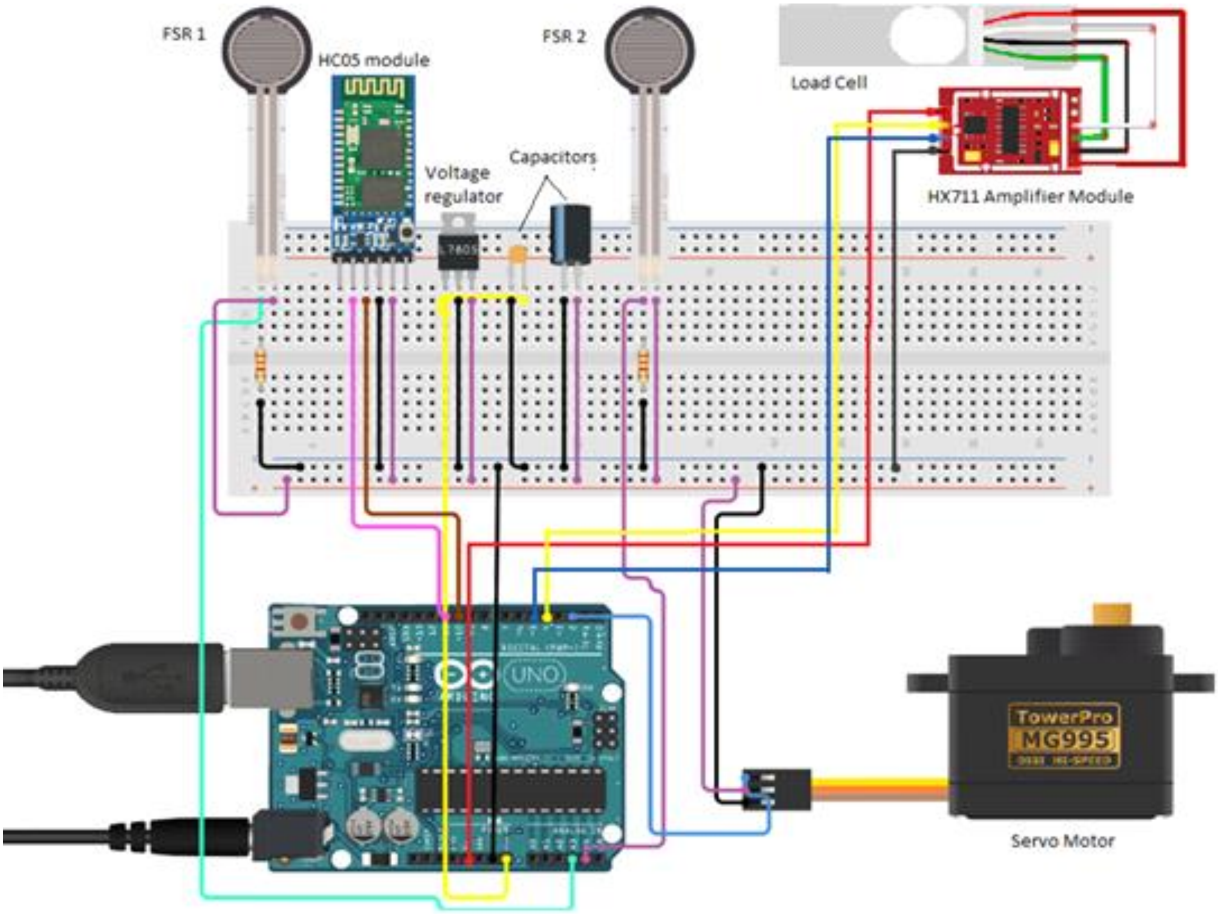

Figure 43. Overall circuitry of OBS

10. Remote Control System (RCS):

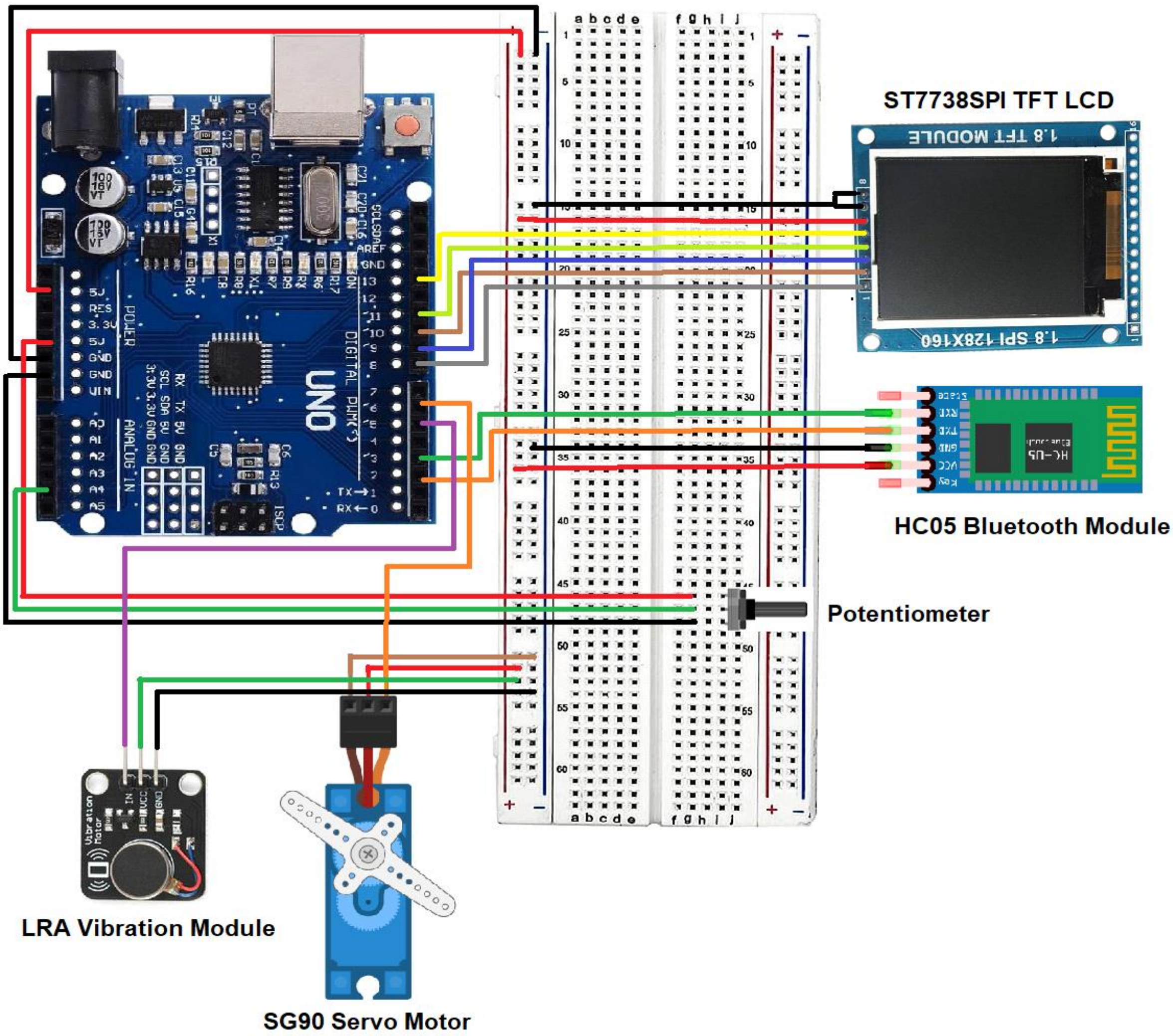

Figure 44. Overall circuitry of RCS

C. Appendix 3

1. Code of OBS

```
#include <SoftwareSerial.h>

#include <Servo.h>

#include <HX711.h>

SoftwareSerial BTSerial(3, 2); // RX | TX

Servo servo1;
```

```
int servoVal = 0;
int fsrPin1 = A1;
int fsrPin2 = A2;
float fsrVal1, fsrVal2, fsrVal11, fsrVal22, avgFsrVal, avgFsrVal2, mass;
HX711 scale;
const int loadCellDataPin = 8;
const int loadCellClockPin = 9;
const int numReadings = 5; // Number of readings to average


void setup() {
  servo1.attach(6);
  scale.begin(loadCellDataPin, loadCellClockPin);
  scale.set_scale(931); // set calibration factor
  scale.tare(); // reset the scale to 0
  BTSerial.begin(9600);
}
void loop() {
  if (BTSerial.available()) {
    int potMapped = BTSerial.read();
    int servoVal = map(potMapped, 0, 255, 0, 180);
    servo1.write(servoVal);
    fsrVal11 = analogRead(fsrPin1);
    fsrVal1 = map(fsrVal11, 0, 1000, 0, 255);
    fsrVal22 = analogRead(fsrPin2);
    fsrVal2 = map(fsrVal22, 0, 1000, 0, 255);
```

```
    avgFsrVal = (fsrVal1 + fsrVal2) / 2.0;
    float loadCellAvg = 0.0;
    loadCellAvg += scale.get_units();
    delay(10);
    mass = map(loadCellAvg, 0, 1000, 0, 255);
    BTSerial.write(servoVal); // send servo angle data back to slave module
    BTSerial.write(avgFsrVal); // send FSR sensor value to slave module
    BTSerial.write(mass); // send weight value to slave module }
  delay(200);
}
```

2. Code of RCS

```
#include <SoftwareSerial.h>
#include <Adafruit_GFX.h>
#include <Adafruit_ST7735.h>
#include <SPI.h>
#include <Servo.h>
// Pin definitions for Arduino Uno and LCD module
#define TFT_CS   10
#define TFT_RST  8
#define TFT_DC   9
#define LCD_SDA  11
#define LCD_SCL  13
// Initialize the ST7735 library with hardware SPI
Adafruit_ST7735 tft = Adafruit_ST7735(TFT_CS, TFT_DC, TFT_RST);
SoftwareSerial BTSerial(3, 2); // RX | TX
```

```
int potPin = A4;
int vibPin = 5; // PWM pin for the vibration motor
Servo sg90;  // Initialize the SG90 motor object
int sg90Pin = 6 ;  // PWM pin for the SG90 motor
int sg90Angle = 0;  // Initial angle for the SG90 motor
int avgmass = 0;
int massReadings = 30; // number of potentiometer readings to average
int potVal, vibVal, mass, servoVal, massTotal;

void setup() {
  //Initialize serial communication
  BTSerial.begin(9600);
  Serial.begin(9600);
  // Initialize pins for vibration motor and servo SG90
  pinMode(vibPin, OUTPUT);
  sg90.attach(sg90Pin);  // Attach the SG90 motor to the PWM pin
  // Initialize LCD display
  tft.initR(INITR_BLACKTAB);
  tft.fillScreen(ST7735_BLACK);
  tft.setTextColor(ST7735_WHITE);
  tft.setTextSize(2);
  tft.setCursor(2, 10);
  tft.println("FSR: ");
  tft.setCursor(2, 60);
  tft.println("Servo: ");
```

```
  tft.setCursor(2, 110);
  tft.println("Mass: ");
}
void loop() {
  // Read and send potentiometer value to master module's servo motor
  int potVal = analogRead(potPin);
  int potMapped = map(potVal, 0, 1023, 0, 255);
  BTSerial.write(potMapped);
  delay(80); // Add a small delay to allow the Bluetooth communication to finish
  if (BTSerial.available() >= 2) { // Only read the values if all 3 are available
    int servoVal = BTSerial.read();
    int avgFsrVal = BTSerial.read();
    int mass = BTSerial.read();
    int Mass_gram = map(mass, 0, 255, 0, 1000);
    massTotal += mass;
  if (massReadings == 0) {
      int avgmass = massTotal / 30; // Calculate average
    // Control the SG90 motor based on the Loadcell value received
      sg90Angle = map(Mass_gram, 0, 1000, 0, 180);  // Map Loadcell value to SG90
motor angle
      sg90.write(sg90Angle);
      massTotal = 0;
      massReadings = 0; // Reset the number of readings
    } else {
      massReadings--; }
    Serial.print("Servo angle: ");
```

```
    Serial.print(servoVal);
    Serial.print(" FSR value: ");
    Serial.print(avgFsrVal);
    Serial.print(" Mass: ");
    Serial.println(Mass_gram);
    // Clear previous FSR and weight values on LCD
    tft.fillRect(76, 10, 40, 20, ST7735_BLACK);
    tft.fillRect(76, 60, 60, 20, ST7735_BLACK);
    tft.fillRect(76, 110, 80, 20, ST7735_BLACK);
    // Display FSR and weight values on LCD
    tft.setCursor(76, 10);
    tft.print(avgFsrVal);
    tft.setCursor(76, 60);
    tft.print(servoVal);
    tft.setCursor(76, 110);
    tft.print(Mass_gram);
    // Control the vibration motor based on the FSR value received
    int vibVal = map(avgFsrVal, 0, 255, 0, 255); // Map FSR value to PWM value for vibration motor
    analogWrite(vibPin, vibVal); }
  delay(200); // A small delay to allow the servo to move and vibration motor to settle
}
```

RESUME

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EDUCATION

Master of Science in Mechanical Enigneering

Istanbul Aydin University (İstanbul Aydın Üniversitesi) [09/2021-09/2023]

Final Grades (Final Notları): 3.81/4.00

Master of Science in Mechanical Enigneering

Cyprus International University (Uluslarararası Kıbrıs Üniversitesi) [09/20-06/2021]

Final Grades (Final Notları): 3.85/4.00

Bachelor of Engineering in Mechanical Enigneering

Air University (Air Üniversitesi) [08/2016-08/2020]

Final Grades (Final Notları): 2.96/4.00