Bachelor Project

Czech Technical University in Prague

F3

Faculty of Electrical Engineering
Department of Cybernetics

# Measuring Buoy and a Mechanism for Its Deployment by an Unmanned Aerial Vehicle

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Study program: Cybernetics and Robotics
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# BACHELOR‘S THESIS ASSIGNMENT

## I. Personal and study details

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## II. Bachelor’s thesis details

Bachelor’s thesis title in English:

**Measuring Buoy and a Mechanism for Its Deployment by an Unmanned Aerial Vehicle**

Bachelor’s thesis title in Czech:

**Měřící bójka a mechanismus pro její vyzvednutí bezpilotní helikoptérou**

Guidelines:

1. Get familiar with the most relevant approaches for object manipulation and evaluation of water properties.
2. Design mechanical solution for the manipulator, ensure compatibility with the T650 drone and water resistance.
3. Design mechanical solution for the measuring buoy, include onboard computer and sensors for localization and water attributes.
4. Propose an algorithm for the onboard computer of the UAV to control the manipulator. Make sure the solution is compatible with ROS and MRS UAV system.
5. Evaluate proposed solution, the performance of the manipulator and functionality of the buoy.
6. (optional) Implement a method for the onboard computer of the buoy to gather the sensory data and to communicate with the UAV. Make sure the solution is compatible with ROS and MRS UAV system.
7. (optional) Perform the practical experiment.

Bibliography / sources:


[1] Heřt, Daniel, et al. "MRS Modular UAV Hardware Platforms for Supporting Research in Real-World Outdoor and Indoor Environments", 2022
[2] Ruggiero, Fabio, et al. "Aerial Manipulation: A Literature Review", 2018
[3] N. A. Cloete, et al. "Design of Smart Sensors for Real-Time Water Quality Monitoring", 2016
[4] Anis Koubaa, "Robot Operating System (ROS), The Complete Reference (Volume 3)", 2018
[5] Báča, Tomáš, et al. "The MRS UAV System: Pushing the Frontiers of Reproducible Research, Real-world Deployment, and Education with Autonomous Unmanned Aerial Vehicles", 2021


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Date of bachelor’s thesis assignment: **03.02.2023** Deadline for bachelor thesis submission: **26.05.2023**

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|---|---|---|
| Supervisor’s signature | Head of department’s signature | Dean’s signature |

## III. Assignment receipt

The student acknowledges that the bachelor's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor's thesis, the author must state the names of consultants and include a list of references.

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Date of assignment receipt

Student's signature

② Acknowledgements

I would like to express my sincere thanks to all those who have supported me during the completion of this Bachelor's thesis.

First and foremost, I am deeply grateful to my supervisors Martin Šrámek and supervisor-specialist Pavel Stoudek for their guidance, expertise, and invaluable support throughout the entire thesis process. Their insightful feedback and encouragement have been instrumental in shaping this work.

I am also grateful to my friends, family, and fellow students who provided support, encouragement, and fruitful discussions during this journey.

## Declaration

I declare that the presented work was developed independently and that I have listed all sources of information used within it in accordance with the methodical instruction for observing the ethical principles in the preparation of university theses.

Prague, May, 2023

# Abstract

Unmanned aerial vehicles (UAVs) have gained popularity for various applications. One of the possible applications of drones is retrieving buoys from the water surface. Traditional buoy retrieval methods can be dangerous, time-consuming, and costly. In this thesis, we present a comprehensive system for measuring water properties and retrieving buoys using a UAV. The system consists of a custom-designed measuring buoy equipped with sensors and localization capabilities, and a specially modified Tarot T650 drone with an aerial manipulator. The manipulator, controlled by an on-board computer using ROS and the MRS UAV system, enables successful buoy grasping and retrieval. The entire system has been successfully tested under real-world conditions. The experimental results hold great potential for practical applications.



**Keywords:** measuring buoy, unmanned aerial vehicle, manipulator

**Supervisor:** Ing. Martin Šrámek



# Abstrakt

Bezpilotní letecká vozidla (UAV) získala v poslední době na popularitě v různých aplikacích. Jednou z nich může být vyzvedávání bójek z vodní hladiny. Tradiční metody vyzvedávání bójek mohou být nebezpečné, časově náročné a nákladné. V této práci představujeme systém skládající se z měřící bójky a mechanismu pro její vyzvednutí pomocí UAV. Systém se skládá z měřící bojky vybavené senzory pro lokalizaci a měření vodních parametrů a speciálně upraveného dronu Tarot T650 s robotickým manipulátorem. Manipulátor je ovládaný palubním počítačem pomocí ROS a MRS UAV systému, což umožňuje úspěšné uchopení a vyzvednutí bójky. Celý systém byl úspěšně otestován v reálných podmínkách. Výsledky experimentů slibují velký potenciál pro využití v praktických aplikacích.



**Klíčová slova:** měřící bójka, bezpilotní dron, manipulátor


**Překlad názvu:** Měřící bójka a mechanismus pro její vyzvednutí bezpilotní helikoptérou

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# Chapter 1

# Introduction

Unmanned aerial vehicles (UAVs) are becoming increasingly popular for a wide range of applications, including agriculture, environmental monitoring, delivery, and search and rescue operations. In particular, UAVs have proven themselves in tasks that require flexibility, mobility, and the ability to operate in difficult environments. One application of UAVs could be retrieval of buoys from the water surface.

Buoys are commonly used in marine research and waterway maintenance to mark positions, measure water conditions, and provide navigation aids. However, retrieving buoys from water surfaces can be challenging, especially in remote or inaccessible locations. Traditional methods, such as using boats or divers, can be dangerous, time consuming, and costly. UAVs offer a potential solution as they can quickly and safely retrieve buoys from the water without the need for human intervention.

## 1.1 The aims of this work

In this Bachelor's thesis, we present a measuring buoy and a mechanism for its retrieval by an unmanned aerial vehicle. Our system consists of a custom-designed buoy that measures important water parameters. These parameters will be defined based on research and the availability of specific sensors. The buoy will also record and transmit its position.

The second part of our system is a buoy-catching mechanism that will be mounted on a specially modified Tarot T650 drone (depicted in Figures 1.1 and 1.2) created by Multi-robot systems group (MRS). This drone is modified to ensure safe flight over water and provide sufficient thrust to lift the buoy from the water.

**Figure 1.1:** Tarot T650 in flight

**Figure 1.2:** Tarot T650 on water

We demonstrate the effectiveness of our system through an experiment in which the UAV, controlled by human operator, successfully retrieves a buoy from the water surface. Our system shows potential for use in applications such as marine research and waterway maintenance.

## 1.2 The structure of this thesis

This Bachelor's thesis will be divided into the following chapters:

- **Chapter 2 - Related work:** This chapter provides a comprehensive overview of the existing literature and research related to UAV applications, manipulator design, and buoy systems. Establishes the context of the thesis and identifies the research gap that the study aims to address.
- **Chapter 3 - Manipulator design:** This chapter focuses on design and development of the aerial manipulator system. It discusses the selection of suitable components, the mechanical design considerations, and the integration of the manipulator with the UAV platform.
- **Chapter 4 - Buoy design:** This chapter focuses on detailed design and construction of a buoy that incorporates sensors to measure crucial water parameters. It covers the selection of sensor technologies, the design of the buoy structure, and the integration of the sensing capabilities. The goal is to create a reliable and accurate buoy that can provide essential data for water analysis.
- **Chapter 5 - Software:** In this chapter, we will take a look at all the written source code. This will include the program responsible for data collection and buoy localization, as well as the program for controlling the manipulator.
- **Chapter 6 - Evaluation:** This chapter presents the experimental setup and methodology used to evaluate the performance of the aerial manipulator system. The results of the evaluation provide insight into the system capabilities and highlight areas for improvement.
- **Chapter 7 - Conclusion:** This final chapter summarizes the key findings and contributions of the thesis. It provides a comprehensive

reflection on the effectiveness of the proposed aerial manipulator system for buoy retrieval and its potential impact on marine research and waterway maintenance.

# Chapter 2

# Related work

The goal of this literature review is to provide an overview of the state of the art in measuring buoy and UAV-based retrieval mechanisms. The review is divided into three main sections: the first section focuses on the characteristics and research findings related to measuring buoys and their usage in water quality measurement, the second section contains a brief overview of water quality measurement in general, and the last section focuses on the characteristics, challenges, and research findings related to aerial manipulation systems.

## 2.1 Buoy

In this part of Related work, we will take a look at buoys, more specifically at measuring buoys. A buoy is an object that floats in the water and can be used for many different tasks [1]. These tasks include navigation, marking underwater objects [2], military purposes [3], research, etc. Among research tasks, we can include measuring the properties of the surrounding environment.

### 2.1.1 Specific buoy solutions

This website [4] presents a commercial solution for measuring water quality and weather using measuring buoys. Their measuring station (depicted in Figure. 2.1) consists of a yellow floating cylinder that houses a data logger that collects data from sensors. Under this platform is located an instrument cage that usually contains sensors for water quality measurement. They are able to measure a large variety of water parameters, e.g. conductivity and total dissolved solids (TDS), dissolved oxygen (DO), pH, turbidity, and temperature. In addition, the buoy may have weather sensors and solar panels situated at the top of the platform.

**(a) :** CB-25 [5] **(b) :** CB-250 [6]

**Figure 2.1:** Diferent types of data Buoys by Nexsens technology

Authors of [7] designed a man portable buoy. Usually, buoy stabilization relies on its size. It is a common understanding, that larger buoys are comparatively easier to stabilize in open waters. Therefore, a significant challenge in creating this design was to achieve levels of stability similar to those of a traditional buoy while significantly reducing its footprint for easier transportation. This stability was achieved through the implementation of a special sliding mechanism. This mechanism is illustrated in Figure 2.2.

**Figure 2.2:** Man-portable buoy [7]

In [8], the authors focused on the structural design of a small buoy. They established a mathematical model and analyzed the influence of geometric size, average density, and system damping on its roll and pitch stability. They found that *for pillar buoys, increasing the average density of the buoy can improve its stability* [8].

## 2.2 Water quality measurment

According to [9], [10] and [11], there are numerous different water quality indexes (WQI) that are used around the world. Each WQI model uses different parameters to determine if the water is suitable for drinking. The most common parameters among all WQI models are temperature, acidity, dissolved oxygens (DO), fecal coliform concentration, and dissolved solids.

## 2.3 Aerial manipulation

In this part of the literature review, we will take a look at various types of aerial manipulation. Aerial manipulation is the art of manipulating objects while they are in the air, typically using drones, quadcopters, or other UAVs, equipped with a specialized device that is used for manipulation [12]. *The two most adopted solutions are either to mount a gripper or a multi-fingered hand directly on the aerial vehicle, e.g., a flying hand (FH) or to equip the UAV with one or more robotic arms, e.g., an unmanned aerial manipulator (UAM)* [13].

These two papers [13] and [14] present a literature review on aerial manipulation, covering topics such as aerial vehicles, manipulator mechanisms, modeling methods, estimation and control techniques, and suggestions for future research. These two papers served as important references for this section of the literature review.

Ollero et. al. provides a comprehensive analysis of the evolution and current trends in aerial robotic manipulation, including helicopters, multirotors, and thrust platforms equipped with various manipulators for physical interaction with the environment [15]. It discusses cooperative manipulation, multibody-actuated designs, advances in teleoperation, perception, and planning. The review concludes by presenting a vision of the future with the introduction of a new generation of aerial robotic manipulators.

Authors of [16] came to a surprising conclusion. Mounting the manipulating tool on the upper part of the quadrotor unmanned aerial vehicle (UAV) results in better stability compared to its lower attachment. However, they noted that placing a manipulative tool on the upper part of the drone may not always be possible.

### 2.3.1 Flying hand

The key challenges encountered when lifting a grasped object and transitioning into laden free-flight were analyzed by the authors in [17]. They were using Yale Aerial Manipulator equipped with the manipulator, based on the SDM (Shape Deposition Manufacturing) hand. This system is shown in Figure 2.3. The details of the original SDM hand are described in this paper [18].


**Figure 2.3:** Yale Aerial Manipulator with gripper and fixed gear [17]

In their research documented in [19], the authors center their focus on the mechanics, design, estimation, and control aspects of aerial grasping. They designed several lightweight, low-complexity grippers for quadrotors. They are using two methods for grasping objects: impactive and ingressive. According to [20] impactive grippers use solid jaws or fingers in contact with an object to produce the necessary grasping force while ingressive grippers depend on surface deformation, possibly penetration of the surface, to grasp the object.

The possibilities of capturing airborne targets in flight are explored in [21]. The authors designed lightweight gripper that is passively triggered. *The use of a passive triggering mechanism eliminates the need for sensors to detect and respond to contact with the target and allows the gripper to use stored potential energy for fast closure. It also avoids the weight and complexity of a system with sensors, actuators, and electronics.* [21]. This mechanism is shown in Figure 2.4

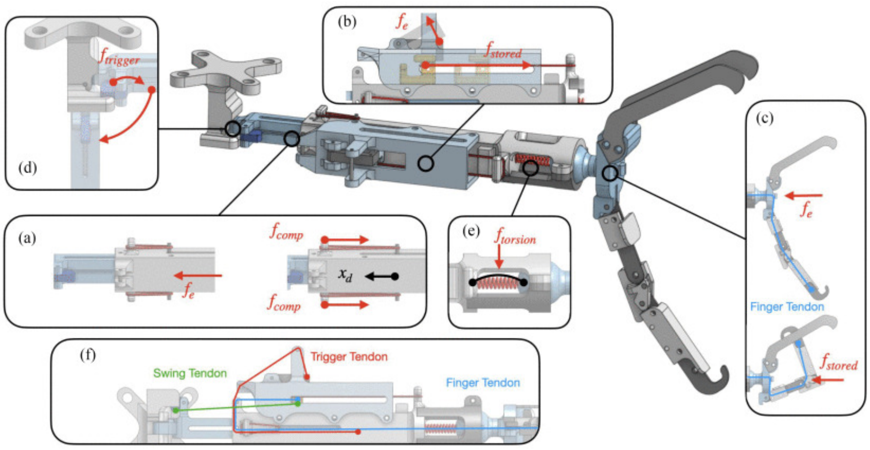



**Figure 2.4:** Passively-triggered gripper mechanism [21]

### 2.3.2 Unmanned aerial manipulator

The design and control of a lightweight robot manipulator with five degrees of freedom are introduced by Bellicoso et. al. in [22]. To minimize the destabilizing influence imposed by the manipulator on the UAV, the authors relocated the motors to the arm's base. This strategic adjustment ensures that the center of gravity remains close to the UAV body frame, thereby minimizing destabilization effects. This arm (Figure 2.5) is capable of folding itself to reduce air resistance during flight and facilitate landing.

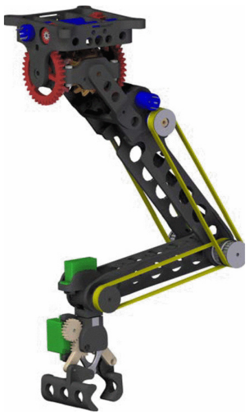


**Figure 2.5:** Pul5AR robot ARM (motors in blue, servos in green) [22]

The large format drone with dual robotic arms, introduced by PRODRONE [23], demonstrates versatile capabilities for a wide range of applications. This particular drone configuration exhibits the ability to transport cargo of varying shapes, manipulate cables by cutting them, activate switches, and deploy buoys that contribute to lifesaving endeavors. The visual representation of the drone design is shown in Figure 2.6.


**Figure 2.6:** Dual Robot Arm Large-Format Drone [24]

An in-depth examination of the design and control aspects of an outdoor-operable aerial manipulator based on a multirotor platform is presented in [25]. This platform features eight rotors and a large payload capacity to integrate a 7 degree of freedom arm along with necessary sensors and processing hardware. Experimental tests showcasing the performance of the controllers and the arm's object-tracking capabilities are also presented. Their solution is depicted in Figure 2.7.

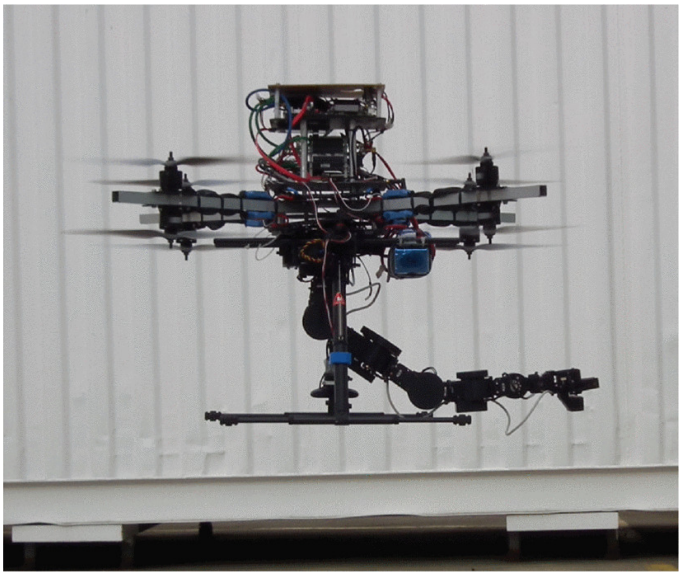


**Figure 2.7:** AMUSE Octoquad aerial platform with 7 DOF arm [25]

# Chapter 3

# Manipulator design

In this chapter, we will take a look at the mechanical design of the manipulator that will be connected to an unmanned aerial vehicle. Through process of acquainting ourselves with the problematic, we came to the conclusion that using a flying hand, rather than a complex unmanned aerial manipulator, would be sufficient for catching a buoy. The schematic diagram of the manipulator is depicted in Figure 3.1.

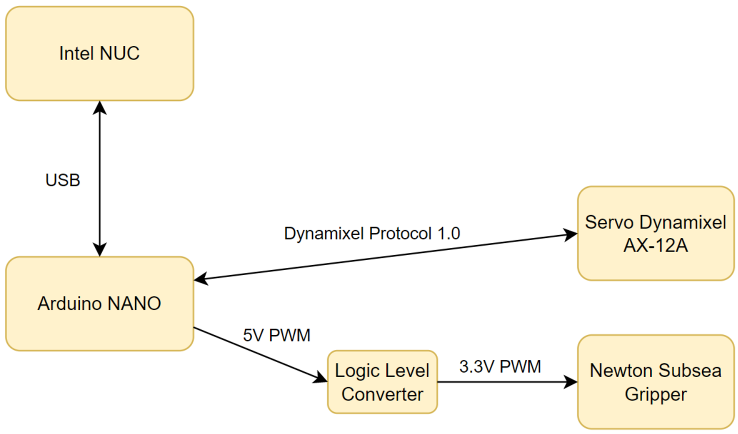



**Figure 3.1:** Schematic diagram of the manipulator

The entire arm will be controlled by a ROS node [26] on the UAV's computer through an Arduino Nano, which will ensure low-level communication with the servo and gripper. The ROS node running on the computer will use the *MRS_LLCP_ROS* [27] node to send and receive messages from the Arduino. Subsequently, the Arduino will process and evaluate these messages to initiate further actions. These actions include sending commands to the servo or gripper and obtaining information from the servo. Communication with the servo is done using the Dynamixel Protocol 1.0. Communication with the gripper is straightforward. The Arduino generates a 5 V PWM signal that is reduced to a 3.3 V PWM signal using a logic level converter. Based on the PWM signal, the gripper opens or closes. A more detailed description of the entire communication will be provided in Section 5.

## 3.1 Used components

When selecting components, we considered several important factors that were common to the majority of manipulators encountered during the literature review. The most significant factors are as follows:

- **Water resistance:** The components should be designed to withstand exposure to water without compromising their functionality. They should have appropriate waterproof or water-resistant properties to ensure reliable operation in wet environments.

- **Strength and Rigidity:** As the aerial manipulator will be subjected to dynamic forces during operation, the components should have high strength and rigidity to withstand these forces without deformation or failure. This ensures the reliability and durability of the system.

- **Lightweight:** The components should be lightweight to ensure that the overall weight of the aerial manipulator system is within the payload capacity of the UAV. This allows optimal flight performance and maneuverability.

- **Compatibility:** The components should be compatible with the UAV's existing systems and electronics for seamless integration. This ensures proper communication and coordination between the UAV and the aerial manipulator.

Based on these factors, we selected the following components, Arduino Nano, servo Dynamixel AX-12A and Newton Subsea Gripper.

### 3.1.1 Newton Subsea Gripper

The Newton subsea gripper was chosen for integration into the aerial manipulator design due to its specialized functionalities and compatibility with the project requirements. The robust construction and sealing properties of the gripper ensured reliable performance in water environments, making it well-suited for buoy retrieval from water. Its design featured strong gripping force and dexterity, enabling secure grasping and manipulation of buoys of varying sizes and shapes. Another reason for the selection was the possibility of easy replacement of the entire end effector of the gripper.

**Figure 3.2:** Newton subsea gripper [28]

### 3.1.2 Arduino Nano

The Arduino Nano [29] microcontroller board was selected as a crucial component in the design of the aerial manipulator due to its versatile features and suitability for project requirements. Its cost-effectiveness and widespread availability also contributed to its selection, making it a reliable and efficient choice for the aerial manipulator design. The compact form factor of the Arduino Nano allowed for seamless integration within the limited space constraints of the drone. Its wide range of input/output (I/O) pins enables the connection of the servo, gripper, and computer. Additionally, the Arduino Nano's open-source platform provided flexibility for programming and customization.

### 3.1.3 Servo Dynamixel AX-12A

The Dynamixel AX-12A [30] servo motor was a straightforward choice in the design of the aerial manipulator due to its exceptional performance. The AX-12A servo offers high torque output, precise position control, and smooth rotational movements, making it well-suited for manipulator joint actuation. Its robust build quality ensured durability and reliability, allowing extended operation in demanding environments. The intelligent features of the servos, such as built-in position and temperature feedback, facilitated accurate and safe manipulation tasks. Additionally, the servo's communication protocol and compatibility with popular development platforms simplified the integration and control of the manipulator within the overall system architecture. The combination of these attributes made the Dynamixel AX-12 servo an optimal choice to enable effective and precise actuation in the design of the aerial manipulator. This servo is depicted in Figure 3.3.


**Figure 3.3:** Robotis Dynamixel AX-12A [31]

### Dynamixel Protocol 1.0

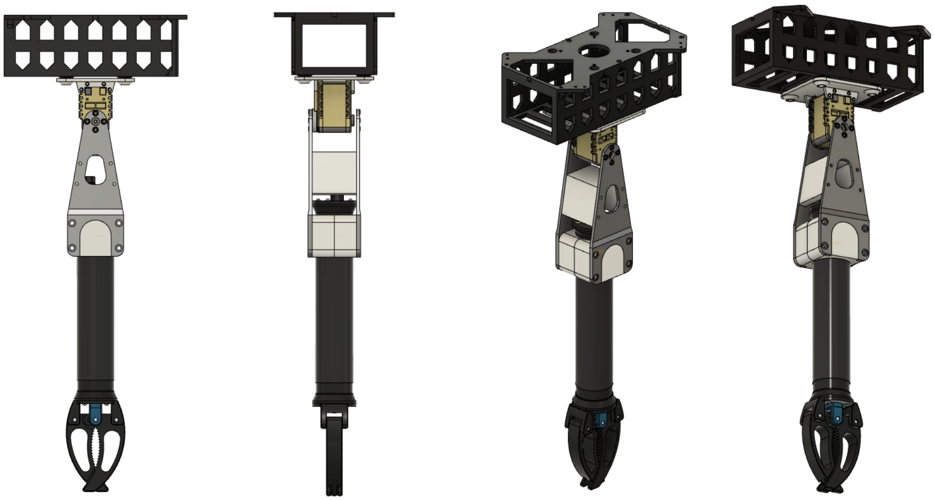
Dynamixel protocol 1.0 [32] uses half-duplex universal asynchronous receiver transmitter (UART) communication. The protocol was developed by Robotis specifically for their Dynamixel series of servomotors. It serves as a standardized interface for controlling and interacting with Dynamixel servos in various robotic applications. Protocol 1.0 offers a straightforward and efficient means of exchanging commands, data, and feedback between the host controller and the servos. The protocol allows for bidirectional communication, enabling real-time monitoring of servo status and the ability to modify control parameters on-the-fly. With its well-defined packet structure (shown in Table 3.1) and error checking mechanisms, the Dynamixel Protocol 1.0 ensures reliable and robust communication.

| Header1 | Header2 | Packet ID | Length | Instruction | Param 1 | ... | Param N | Checksum |
|---|---|---|---|---|---|---|---|---|
| 0xFF | 0xFF | Packet ID | Length | Instruction | Param 1 | ... | Param N | CHKSUM |

**Table 3.1:** Instruction packet [32]

## 3.2 Mechanical design

The mechanical design of the manipulator was designed using Autodesk Fusion 360 CAD software. All parts were designed for the additive manufacturing process, specifically FDM 3D printers. During the mechanical design process, priority was given to creating a manipulator that can be easily mounted to and detached from the drone to comply with the MRS hardware design standards presented in [33]. To simplify the landing and taking off process, we incorporated an additional rotary joint that enables retraction of the manipulator. This joint can also be used during buoy retrieval. In order to achieve uniform distribution of load among all motors, the manipulator was specifically designed to be mounted at the central point of the battery holder. The proposed manipulator design is illustrated in Figure 3.4.



**(a) :** Right view **(b) :** Front view **(c) :** Side view **(d) :** Side view

**Figure 3.4:** Manipulator design

The entire design of the manipulator consists of six printed parts and three purchased parts, which are mentioned in Section 3.1. Printed parts were processed after printing to eliminate inaccuracies caused by the printing process. Additionally, threaded inserts were inserted into some of the parts. Subsequently, these parts were assembled into the intended shape. During the design process, we focused on the weight and strength of the final design to ensure its suitability for retrieving buoys from the water surface. The real assembled manipulator is depicted in Figure 3.5.

**Figure 3.5:** Assembeled manipulator

# Chapter 4

# Buoy design

In this chapter, we will take a look at the mechanical design of the buoy.

## 4.1 Design Requirements

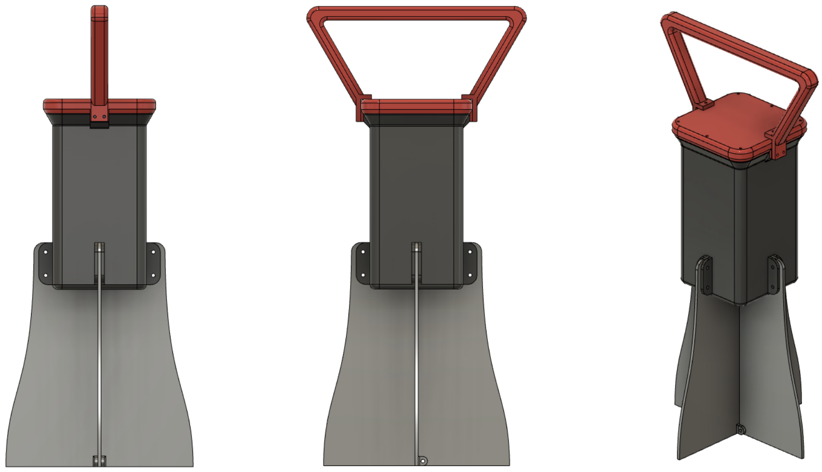
In this section, we will look at the requirements that the buoy should meet. Design requirements include these factors:

- **Buoy dimensions:** The primary objective of this buoy design is to create a lightweight and compact structure that can be easily handled by a UAV during retrieval operations.
- **Water and mechanical resistance:** The outer shell should be constructed from a durable, waterproof material that will provide protection against water intrusion and physical damage.
- **Buoyancy:** Ensure adequate buoyancy to support payload and instruments within the payload capacity of the UAV.
- **Visibility:** Enhance the visibility of the buoy through the use of high-visibility colors.
- **Compatibility:** Ensure compatibility between the buoy design and the UAV retrieval mechanism, taking into account factors such as size, shape, and weight distribution for successful retrieval.
- **Stability:** Ensure the buoy stability during retrieval operations, incorporating stabilizing mechanisms to minimize undesired drift or movement.

These design requirements will serve as guiding principles for the subsequent stages of buoy design and development, ensuring that the resulting buoy is well-suited for retrieval by an unmanned aerial vehicle.

## 4.2 Mechanical design

When designing the buoy, we took into account all the requirements specified in the previous Section 4.1. we have concluded that the buoy should weigh around 2 kg. At this weight, the drone should maintain sufficient lift for its stabilization and subsequent flight. Based on the findings from article [8], the buoy should have a density close to the density of water. This will ensure that the movement of the buoy caused by wind and propeller effects will be minimized. From this information can be concluded that the total volume of the buoy should be around 2 $dm^3$. All components during the buoy design process were designed to be 3D printable with minimal need for print supports. Based on all the specified requirements, the outer design depicted in Figure 4.1 was created.



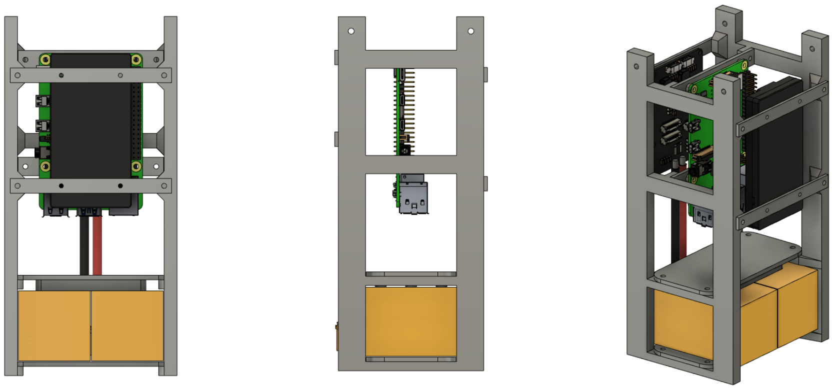
**(a) :** Right view **(b) :** Front view **(c) :** Side top view

**Figure 4.1:** Buoy design

This outer design can be divided into three functional parts. The first functional part can be considered the top handle, which is used for grasping by the drone. This grip is slightly larger than the buoy itself to facilitate the retrieval operation. Another functional part can be considered as the body of the buoy, including the lid. This body provides sufficient buoyancy for the entire buoy and protects all internal electrical components. The final functional part of this design is the stabilizing fins, which ensures the stability of the entire buoy during retrieval. Additional weights will be attached to this lower section to achieve the desired overall density and lower the center of gravity of the buoy. The lower center of gravity will also enhance stability. If necessary, all the designed components can be easily replaced with new ones.

In the following Figure 4.2, the internal design of the buoy is shown. This construction aims to secure the internal components of the buoy to prevent any damage. The components used will be described in detail in Section 4.3.

The batteries, being the heaviest components, are placed at the bottom to achieve a lower center of gravity. This design is also intended to be easily removable from the buoy. Easy removal from buoy facilitates the assembly of all internal components used and allows for convenient battery replacement.



**(a) :** Right view **(b) :** Front view **(c) :** Side top view

**Figure 4.2:** Internal buoy design

The insertion process is illustrated in Figure 4.3.

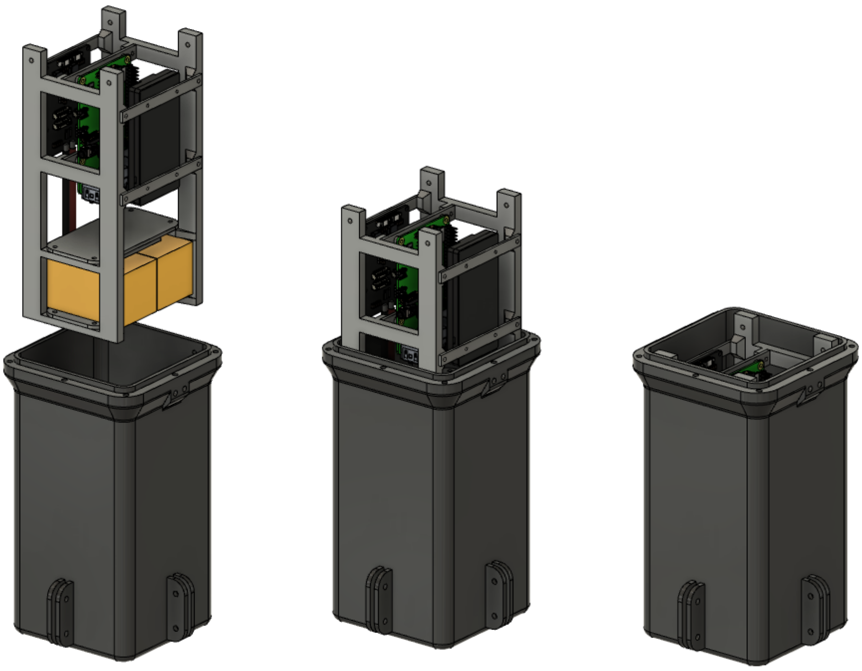


**Figure 4.3:** Insertion process

## 4.3 Used electronics components

In this section, we will take a look at the electronic components used. Electronic components were selected to meet all functional requirements of the buoy while keeping their dimensions as compact as possible. Another important factor in the selection process was the desired voltage and the amount of heat generated. In the following Figure 4.4, we can see the schematic diagram of the circuit. The individual components will be discussed in more detail in the following subsections.

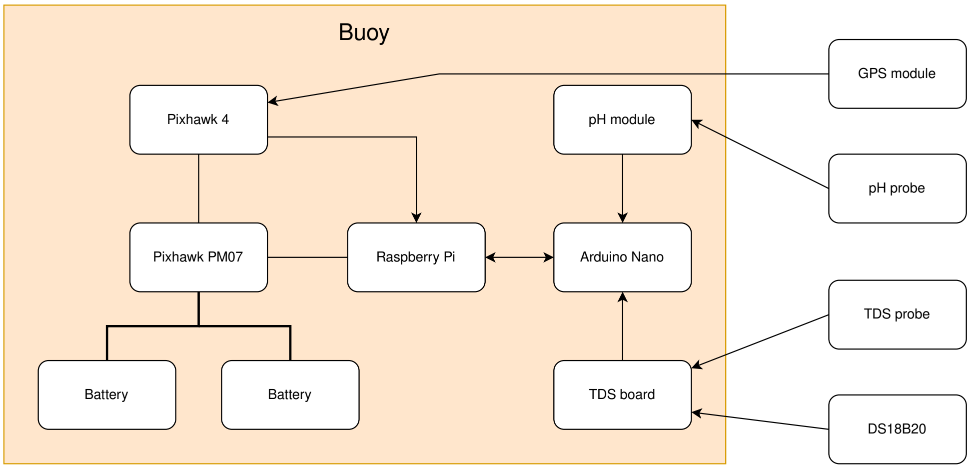



**Figure 4.4:** Electronic scheme

The arrows in this diagram represent the direction of communication. If there is just link without arrow between two blocks, it signifies only a power connection.

### 4.3.1 Raspberry Pi 4 model B 8GB

The selection of Raspberry Pi 4 as the main computer for the buoy was driven by several factors that make it a suitable choice for this application. The first and primary requirement that the computer had to meet was the ability to run Ubuntu 20.04 LTS with ROS Noetic and parts of the MRS UAV system. Another important factor that contributed to the selection of this computer was its low weight and compact dimensions, which were necessary due to the limited space within the buoy. Last but not least, Raspberry Pi boards are designed to be energy-efficient, consuming low power while providing significant computational capabilities. This feature is crucial for autonomous buoy systems, as it allows for prolonged operation using limited power sources and minimizes the need for frequent maintenance or power supply replacements.

Considering these factors, the selection of Raspberry Pi as the main computer for the buoy offers a compact, versatile, energy-efficient computing platform with sufficient software support, making it an ideal choice to enable the required functionalities and capabilities of the buoy system.

### 4.3.2 Pixhawk 4 and Pixhawk PM07

The decision to select Pixhawk 4 and Pixhawk Power Module 07 (PM07) for the buoy system was influenced by several factors. Mainly, the Pixhawk 4 is commonly used within the MRS group, indicating its reliability and suitability for applications. By choosing this module, compatibility with the existing MRS UAV system is ensured, enabling smooth integration and allowing for seamless communication between the buoy and the UAV. Also, Pixhawk 4 allows for the connection of the GPS module and subsequent transmission of position data to the drone. Additionally, Pixhawk PM07 offers the advantage of powering the entire buoy system, including Pixhawk 4, Raspberry Pi, and other components from batteries. This feature simplifies the power management aspect, eliminating the need for separate power sources and facilitating a more compact and efficient design.

### 4.3.3 Batteries

The most significant requirement for the batteries was their compatibility with the Pixhawk PM07 and their dimensions. Based on these requirements, we decided to choose Tattu R-Line 1800mAh 4S batteries. we used two of these batteries in parallel to ensure better weight distribution and longer endurance of the entire buoy on a single charge.

### 4.3.4 Sensors

Based on research, availability, and dimensions of the sensors, pH, total dissolved solids (TDS), and temperature sensors were chosen as good indicators of water quality for the buoy. The voltage requirements of the sensors were also an important consideration during their selection. The individual sensors are shown in Figures 4.8, 4.6 and 4.7

#### pH sensor

For pH measurement, this [34] probe was chosen. The probe measures pH in the range of 0 to 14 pH with an accuracy of ±0.2 pH.

The pH sensor was calibrated using two known pH solutions with defined pH values. The first solution possessed a pH of 4.01, while the second solution had a pH of 6.86. In each solution, we measured 10 values at the output of the analog-to-digital converter (ADC) in Arduino. In the first solution,an average of ADC reading was 704, while in the second solution, an average of ADC reading was 600. Using the measured values, I fitted a line with the equation

$$pH = -0.02740385 * ADC\_value + 23.30231. \tag{4.1}$$

In the last solution, which had a pH of 9.18, I measured a value of 511 at the output of the AD converter. The measured value corresponds to a pH of 9.30, with a difference of 0.12 from the actual pH value. This difference falls within the expected range of ±0.2 pH. Figure 4.5 illustrates the relationship between pH and the output of the AD converter.

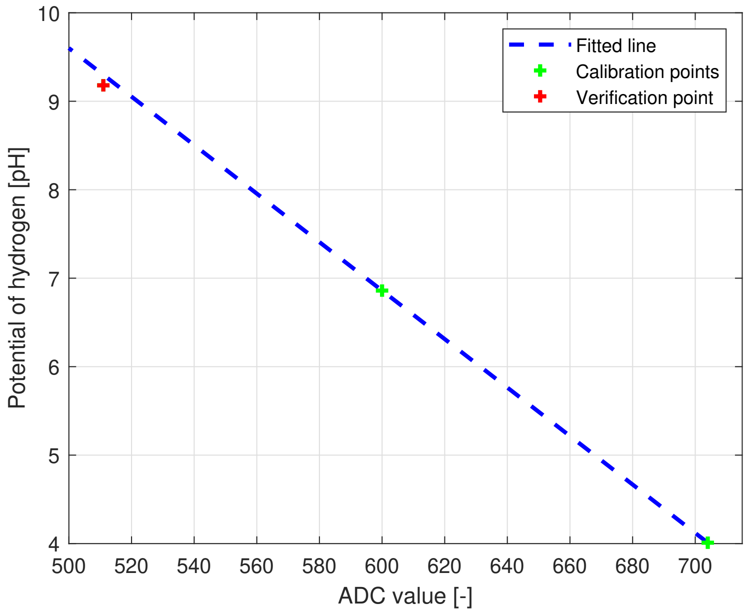



**Figure 4.5:** pH graph

**Figure 4.6:** pH probe [34]

**Figure 4.7:** TDS probe [35]

## TDS sensor

For TDS measurement, this [35] sensor was chosen. The sensor measures TDS in the range of 0 to 1000 ppm with a measurement accuracy of ±5% FS (full scale). The manufacturer specifies that the relationship between TDS (Total Dissolved Solids) in parts per million (ppm) and voltage is described by the equation:

$$y \approx 66.71x^3 - 127.93x^2 + 428.7x. \tag{4.2}$$

The calibration of this sensor was performed following the instructions provided on the manufacturer's webpage.

### Temperature sensor

The DS18B20 [36] sensor was selected for temperature measurement. The DS18B20 is a widely used and highly reliable digital temperature sensor that provides accurate temperature measurements. This sensor operates on a one-wire communication protocol, which simplifies the wiring and reduces the complexity of the buoy's wiring network.

**Figure 4.8:** DS18B20 temperature sensor [36]

## 4.4 Prototype construction

Given that all parts of the design were intended to be 3D printed, the construction process was relatively straightforward. All components were initially 3D printed and then further processed to compensate for any deficiencies arising from the 3D printing process. The PETG material (Polyethylene Terephthalate Glycol) was chosen for the printing process. The selection of PETG material for the buoy was driven by its convenient combination of durability and excellent water resistance [37], which ensures long-term functionality in harsh water environments. Selection of water resistant material is just the initial step, as water can still infiltrate between individual printing layers.

The next step involved ensuring the water resistance of the design. Waterproofing was achieved by applying a protective coating to all components that may come into contact with water in the future. The protective coating was applied in three layers, with each layer being applied one day apart to ensure a sufficient drying time. Additionally, a thin rubber sheet was adhered to the joint between the lid and the body to create a watertight seal at this junction. To enhance visibility on the water surface, the upper part of the buoy was colored red.

The final step involved the installation of sensors. The sensors were securely attached to pre-designated locations, and the cables were threaded through a hole in the lid, then this hole was sealed.

Figure 4.9 illustrates the internal assembly of the printed components along with the connected electronics. Figure 4.10 illustrates the complete assembly of the buoy.

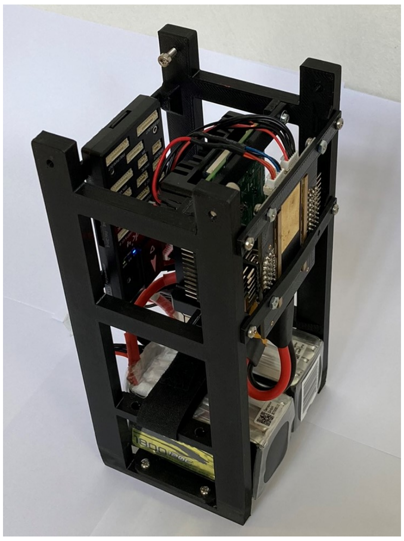


**Figure 4.9:** Internal part of buoy

**Figure 4.10:** Assembled buoy

# Chapter 5

# Software

In this chapter, we delve into the software aspects of our proposed system for the measuring buoy and its retrieval by an UAV. Software plays a vital role in enabling efficient control of the manipulator and buoy subsystems. This chapter aims to provide an overview of the software components and their functionalities within the manipulator and buoy sections, both of which are implemented with the Robot Operating System (ROS). For this reason, this chapter also includes a short section dedicated to ROS itself.

## 5.1 Robot Operating System

The Robot Operating System [38] (ROS) is a set of software libraries and tools widely used in robotics that provides a standardized platform for developing, integrating, and controlling robotic systems. In our system of measuring buoy and its retrieval by an unmanned aerial vehicle, both the manipulator and the buoy software are controlled using ROS.

### 5.1.1 Key Features of ROS

ROS offers key features that contribute to its popularity in robotics applications. It follows a modular architecture, allowing developers to build complex systems by integrating and reusing modular software components called "nodes" [26]. ROS facilitates communication among nodes through a publish-subscribe messaging system [39], promoting loose coupling and efficient data exchange. ROS also employs a package-based organization that simplifies software distribution and dependency management.

## 5.2 Manipulator Software

In this section, we focus on the software components and functionalities related to the manipulator. The manipulator software enables simple movements of the manipulator in the joint, simplifying the takeoff and landing process, while providing separate control over the gripper. Our manipulator software is divided into two main parts: the control ROS node and the Arduino Nano code, which will ensure low-level communication with the servo and gripper.

### 5.2.1 Drone ROS node

The control ROS node serves as the central control hub for the manipulator. Implemented within the ROS, this node coordinates the various tasks and functionalities involved in controlling the robotic arm. It acts as an intermediary between higher-level commands and the Arduino Nano, which is responsible for low-level servo and gripper control.

### 5.2.2 Manipulator Arduino code

The Arduino Nano is responsible for interfacing with the servo motors and gripper mechanism of the manipulator. It receives commands from the control ROS node and translates them into the appropriate signals to control the servo motors positions and the gripper's opening and closing actions.

Communication with the gripper is very straightforward. Arduino generates a PWM signal, and the gripper's behavior depends on the pulse length. When the pulse length is between 1530 $\mu$s and 1900 $\mu$s, the gripper opens. At a pulse length of 1500 $\mu$s, the gripper is in a neutral state, and when the pulse length is within the range of 1470 $\mu$s to 1100 $\mu$s, the gripper closes.

Since the Arduino Nano has only one serial line available and it is used for communication with the computer, the HalfDuplexSerial library [40] was utilized. This library enables the creation of software-based half-duplex serial communication on specific pins. This type of communication is necessary for interacting with the servo. To construct individual messages for the servo, the DynamixelArduino library [41] is used.

## 5.3 Buoy Software

The buoy software section centers around the software components responsible for the buoy's measurement and retrieval process within ROS. Our buoy software consists of two main parts: the Arduino code responsible for data collection and transmission, and a ROS node running on Raspberry Pi that handles data processing and publication to ROS topic.

### 5.3.1 Buoy ROS components

On the Raspberry Pi, we implement a ROS node that receives, processes, and publishes the measurement data collected from the buoy. This ROS node subscribes to the Arduino data stream and handles the incoming data packets. It extracts relevant information, performs additional processing if required, and publishes the processed data on a designated ROS topic.

For localization purposes, we used the *mavros* package [42]. The *mavros* package provides the necessary localization data for the UAV, allowing it to navigate and interact with the buoy. By integrating the *mavros* package into our buoy software, we ensure a reliable and precise localization mechanism for the UAV during the retrieval process.

### 5.3.2 Buoy Arduino code

The Arduino code, running on this board, collects data from sensors. The pH and TDS sensors provide analog voltage, which is then converted into corresponding pH and TDS values in Arduino. The temperature sensor provides data digitally, so there is no need for further processing. Once the data is collected and processed, the Arduino code is responsible for transmitting this information to the Raspberry Pi.

# Chapter 6

# Evaluation

To evaluate the performance of our buoy measurement system and its retrieval by an unmanned aerial vehicle, we performed a series of experimental evaluations. Initially, we performed the experiments in a controlled indoor environment. Subsequently, we verified the functionality of the entire system in natural conditions.

## 6.1 Manipulator evaluation

To evaluate the performance of the manipulator in our system, we conducted a series of experiments.

Before connecting the manipulator to the Arduino itself, we used an oscilloscope to verify that the expected control signal for the servo and gripper is present on the respective output pins of the Arduino.

Subsequently, we mounted the manipulator to the table and connected it to the Arduino. By sending various commands, we verified the communication with the servo and the gripper. During communication with the servo at a baud rate of 115200, packet losses occurred in approximately 20 % of the cases. Therefore, we reduced the baud rate to 57600, resulting in packet losses less than 1 %.

In the final test of the manipulator, we mounted it to the drone and examined the effect of its movement on flight performance. By observing, we concluded that the influence of manipulator movement on the stability and flight performance of the drone is negligible.

## 6.2 Waterproofing evaluation of the buoy

The waterproof integrity of the buoy was examined within controlled laboratory settings. Our criteria for determining its waterproof capability were that it should remain submerged in water for one hour without any water entering.

After the first experiment, we found around 200 ml of water inside the buoy. By rotating the buoy in the air, we identified the areas where water was entering and sealed them.

After conducting the second experiment, this time with the modified buoy, no trace of water was detected within the buoy, enabling us to confidently proclaim that the buoy is waterproof.

## 6.3 Buoy retrieving evaluation

The objective of the experiment was to assess the feasibility and effectiveness of using the manipulator arm to grasp and retrieve a buoy from the water surface. The experiment was conducted outdoors at the Orlík reservoir.

Under the control of the human operator, the UAV approached the buoy with precision and caution. The operator relied on visual feedback to maneuver the UAV into the desired position above the buoy. Once the UAV was properly aligned, the operator initiated the grasping action of the manipulator.

The manipulator successfully grasped the buoy, firmly securing it for retrieval. The buoy was safely lifted from the water surface, demonstrating the system's capability to retrieve the buoy using the manipulator arm under human guidance. However, by changing the end effector of the manipulator, it would be possible to achieve a faster and easier retrieval of the buoy. Based on this experiment, we proposed a larger end effector that should result in faster and simpler buoy lifting. This end effector is very similar to the original, but its size has been increased from 75 to 128 mm. The size comparison of these two end effectors is depicted in Figure 6.1.

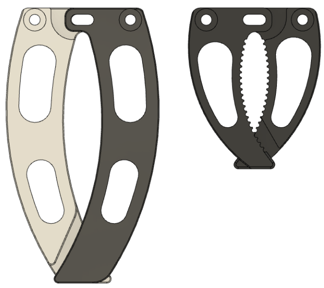
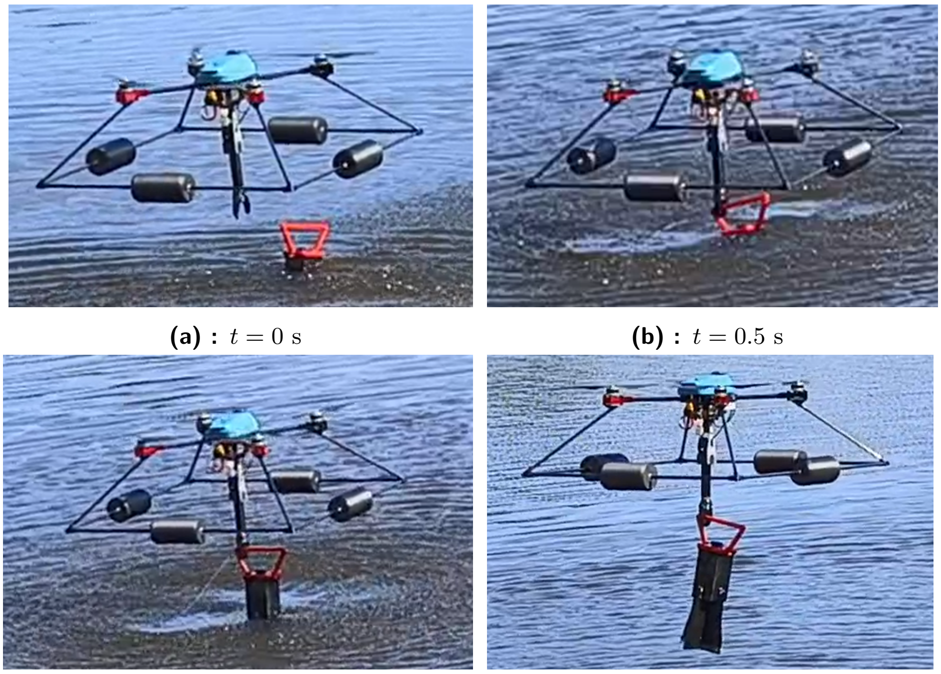


**Figure 6.1:** End effector size comparison

The success of the experiment signifies the potential of the system and the manipulator arm to be integrated into fully autonomous operations for buoy retrieval tasks. It showcases the effectiveness of the human-UAV collaboration, where the human operator's expertise and control combined with the capabilities of the manipulator enable successful retrieval of the buoy.

The entire process of lifting the buoy from the water is documented in Figures 6.2a to 6.2d.



(a) : $t = 0$ s
(b) : $t = 0.5$ s
(c) : $t = 1$ s
(d) : $t = 2$ s

**Figure 6.2:** Buoy catching process

# Chapter 7
# Conclusion

In this thesis, our primary objective was to develop a measuring buoy and a mechanism for its retrieval by a UAV. We began by familiarizing ourselves with the most relevant approaches for aerial manipulation, buoy solution, and evaluation of water properties. This foundational knowledge guided our subsequent design processes. We carefully designed mechanical solutions for the manipulator and measuring buoy, ensuring compatibility with the T650 drone, water resistance, and integration of necessary components such as sensors and localization systems.

To control the manipulator, we proposed an algorithm for the UAV onboard computer, taking advantage of the power and versatility of ROS and the MRS UAV system. This algorithm facilitated precise and coordinated movements of the manipulator, allowing for successful grasping and retrieval of the buoy.

Throughout the development process, we evaluated the performance of the manipulator, ensuring its reliability in reaching target positions and successfully grasping the buoys. We also implemented a method for the onboard computer of the buoy to gather sensory data and communicate with the UAV, further enhancing the system's capabilities.

The optional practical experiment provided a valuable opportunity to validate the effectiveness and practicality of the developed system. By conducting real world tests, we gained insight into the system's performance under realistic conditions and potential areas for improvement.

In conclusion, this thesis successfully addressed each guideline, resulting in a comprehensive system for measuring water properties and retrieving buoys using a UAV. The developed mechanical solutions, control algorithm, and evaluation process demonstrated the effectiveness, reliability, and potential of the system for practical applications.

Future work can focus on achieving full autonomy for this system, although it will be highly challenging. To accomplish full autonomy, an additional localization method that works together with GPS localization may be required. Furthermore, it will be necessary to design a drone path planning strategy that considers the buoy's potential movement.

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# Appendix A
# Attachment

Files provided on a CD:

```
BPthesis
├── hardware
│   ├── buoy_hw
│   └── manip_hw
└── software
    ├── buoy_data_collector
    │   ├── arduino_code
    │   ├── launch
    │   └── src
    └── manip_control
        ├── arduino_code
        ├── launch
        └── src
```