Design of a Low-cost Haptic Feedback for Industrial Underwater Gripper

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Abstract: The increasing complexity of deep underwater tasks such as sample collection and maintenance of subsea infrastructure necessitates advanced technological solutions. Despite significant progress in underwater robotic grippers' design and operational capabilities, one pivotal area that requires further exploration is how to provide operators with a sense of the objects being handled. This research addresses the abovementioned challenge by presenting an innovative, low-cost approach to incorporate load cell technology into underwater grippers. It is focused on the integration of the load cell, the challenges of underwater force measurement, and the accuracy of the force readings obtained. The system is designed with the potential for future integration with a haptic feedback glove, although these aspects are not fully implemented in the current work. This paper presents the system architecture, load cell integration, calibration process, and performance evaluations in laboratory underwater conditions. The system is validated by measuring the gripping forces applied to various objects, including a steel rod, a cuboid, and a soft ball. The results demonstrate the feasibility and accuracy of force measurements in underwater manipulation tasks, laying the groundwork for future enhancements in underwater robotic control and operator feedback.

1. Introduction

The exploration and manipulation of deep underwater environments present unique challenges that necessitate advanced technological solutions. Remotely Operated Vehicles (ROVs) have emerged as crucial tools in this domain, particularly in industries such as oil and gas, offshore wind farms, and marine research [1]. These unmanned submersible vehicles, tethered to surface vessels via cables for power and control, enable the execution of complex tasks in environments inhospitable for human divers [2].

ROVs are equipped with sophisticated manipulators – robotic arms that allow for intricate operations such as cutting, welding, lifting, and object handling. These manipulators, whether electrically or hydraulically powered, are controlled remotely by operators using joysticks and other interface technologies. The end-effectors of these manipulators, often in the form of grippers, serve as the primary means of interaction with the underwater environment [3].

However, despite significant advancements in underwater robotics, a critical limitation persists: the lack of tactile feedback in most current systems. This deficiency hampers the precision and effectiveness of underwater operations, particularly in scenarios where visual feedback is limited or unreliable [4].

1.1. The Challenge of Underwater Force Sensing

Force sensing is crucial because of its effectiveness in underwater environments, outperforming alternative feedback technologies like visual feedback, which is often hindered by turbidity or low light [5], and audio feedback, which is complicated by sound propagation and noise [6].

The integration of force sensors into underwater grippers presents a formidable challenge as it demands completely waterproof sensors capable of withstanding high pressures while maintaining sensitivity and accuracy in underwater conditions [7]. These requirements pose significant obstacles to the development and deployment of sensitive instrumentation. Moreover, designing the gripper structure to seamlessly accommodate the force sensors without compromising functionality or efficiency further complicates their integration.

1.2. Research Objective and Novelty

This research presents an innovative, low-cost approach to incorporating load cell technology into underwater grippers, enhancing their sensing functionality without compromising operational effectiveness. It emphasizes the importance of force reading from the load cell to improve operational effectiveness.

The novelty of the approach lies in its cost-effectiveness and adaptability to existing systems. This low-cost integration of load cell technology enhances sensing functionality without compromising operational effectiveness, facilitating scalability for its integration into various systems. This scalability is essential for applications where multiple units or installations with low costs are required. The presented integrated system was mounted on a UR10e robot and tested underwater scenarios in laboratory conditions as shown in Figure 1.

Fig. 1. Haptic Gripper mounted on UR10e Cobot for lab testing

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1.3. Paper Structure

The paper is structured as follows: Section 2 reviews recent advancements in underwater gripper design and functionality. Section 3 presents the methodology, including the proposed haptic input system, embedded system design, and calibration. The mechanical design considerations and force sensor integration are discussed in Section 4. Section 5 describes the experimental setup, while the results of lab trials are provided in Section 6. Finally, Section 7 concludes the paper with a summary of key findings and suggestions for future research directions.

2. Literature Review

The exploration of underwater environments demands robotic systems capable of delicate and precise interactions with a variety of objects. This section reviews some key recent advancements in the design and functionality of underwater grippers, highlighting the diversity and innovation in this rapidly evolving field.

2.1. Design Innovations

Recent trends in underwater gripper design show a shift from mechanically robust systems to bio-inspired soft robotics. Picardi et al. [8] and Galloway et al. [9] lead this movement with tendon-driven and soft robotic technologies, offering flexibility and adaptability. These designs excel in conforming to irregular objects and interacting delicately with marine life but often involve costly materials and complex manufacturing. In contrast, traditional approaches by Bemfica et al. [10] and Zhang et al. [11] focus on mechanical precision with three-fingered and parallel grippers, prioritizing reliability and strength in structured environments.

Parallel grippers stand out for their cost-effectiveness and easy manufacturing [12], making them a practical choice for various operations where budget constraints are a concern.

2.2. Actuation Mechanisms

The choice of actuation mechanism ultimately depends on the specific requirements of the underwater task, operating depth, required grip strength, and environmental considerations.

Cable-driven systems, like those discussed by Picardi et al. [8], offer a high force-to-weight ratio suitable for deep-sea tasks but have limited range and potential for wear over time.

Electric servos, explored by Palli et al. [13], provide precise control and integration ease with digital systems, albeit with waterproofing challenges at depth and lower force compared to hydraulic systems.

Soft actuators, emphasized by Herrero-Pérez and Martínez-Barberá [14] and Cianchetti et al. [15], offer gentle gripping ideal for delicate objects, though with lower gripping force than rigid actuators.

This research has opted for an electrical actuator to drive the gripper mechanism. This choice allows for accurate position control and easy integration with other digital systems, facilitating the initial force feedback experiments.

2.3. Depth Capabilities

Operational depth significantly impacts underwater gripper design. Bemfica et al. [10] developed a system operational up to 100 meters, suitable for near-surface tasks. Galloway et al. [9] tested their gripper beyond 300 meters, highlighting deep-sea exploration potential. These advancements broaden underwater robotics' scope for research in once-inaccessible areas.

In this paper, the tests are conducted under controlled laboratory conditions to simulate underwater environments without considering the effects of extreme depth. This approach allows us to focus on fundamental aspects of force sensing and gripper performance in submerged conditions, providing a foundation for future deep-water adaptations. The controlled environment testing enables precise calibration and performance evaluation of the force sensing system, which is critical for ensuring accuracy and reliability in various underwater applications, regardless of depth.

2.4. Sensory Feedback Integration

Sensory feedback mechanisms are crucial for enhancing underwater grippers' functionality and autonomy. Bemfica et al. [10] integrated force/tactile sensors for real-time grasping feedback, enabling nuanced manipulation. Their three-fingered design required multiple sensors per finger and isolation for underwater use, increasing cost and complexity.

While this trend towards intelligent, responsive grippers aligns with current research objectives, there's a growing need for more cost-effective and streamlined sensory integration. Future designs should balance advanced functionality with practical implementation, potentially leading to wider adoption in various underwater applications.

2.5. Degrees of Freedom

The degrees of freedom (DoF) in a gripper dictates its versatility and efficacy in complex underwater tasks. Studies such as that by Meng et al. [16], with their HEU Hand II showcasing 9 DoFs, illustrated the trend towards more articulated systems capable of sophisticated manipulation tasks. This is further echoed in the modular design of Barbieri et al. [17], where the configurability allows for varying DoF, demonstrating that the field' moves towards adaptable and multifunctional designs.

In contrast to these highly articulated designs, this project utilized a parallel gripper, which typically has 2 DoFs. Fewer moving parts generally leads to increased durability, which is crucial in underwater environments.

3. Methodology

3.1. Haptic Input

In this research, it has been focused on force feedback, which provides resistance or force, simulating the feeling of manipulating real objects. This choice was made due to its suitability for underwater applications and its potential to

Table 1 Comparison Between Different Haptic Feedback Technologies

Technology	Energy Consumption	Level of Feedback	Overall Size	Response Time	Cost	Disadvantages
Vibrotactile	Low	High	Small	Slow	Low	Vibration strength varies; high latency for desired force
Electrotactile	Low	Low	Small	Fast	Medium	Skin conductivity changes affect feedback; limited durability
Thermal	High	High	Small	Slow	High	High energy consumption; slow response time
Ultrasonic Tactile	High	Low	Medium	Medium	High	Low force perception; varying user experience
Force Feedback	High	High	Large	Fast	Medium	Bulky actuators; high energy consumption

significantly enhance operator control and object manipulation precision [4].

Table 1 presents a comparison of different types of haptic feedback, highlighting the advantages and limitations of each in the context of underwater robotics.

Our future plan involves a system converting load cell force readings into haptic feedback. The load cell integrated into the gripper measures the forces applied during object manipulation, The processed signals from the readings will be sent to a wearable glove equipped with a motor. This motor will be connected to one finger of the glove, providing the operator with haptic feedback. The operator will feel varying levels of force feedback on their finger, corresponding to the forces experienced by the gripper underwater.

3.2. Embedded System

To achieve the proposed goal of integrating force feedback, an Arduino-based low-cost system utilizing a load cell for force measurement has been developed. The core components of the embedded system include:

- Arduino Mega 2560: It was chosen due to its high processing capabilities and multiple I/O pins, suitable for the focused application. It costs about £40.
- HX711 Module: A 24-bit analogue-to-digital converter (ADC) is specifically designed for weigh scales and industrial control applications with load cells. It offers a programmable gain of 128 or 64, suitable for different load cell configurations with the cost about £10.
- Load Cell: A waterproof 20 KN sensor capable of operating underwater was employed. This load cell was crucial for measuring force during the pick-and-place testing process. It costs around £1000.

The system connections are illustrated in Figure 2, showing the integration of the load cell with the Arduino board via the HX711 module.

3.3. Calibration

Accurate calibration of the load cell is essential for ensuring precise force measurements. For this setup, a 100g standard weight is selected to obtain an appropriate sensor response.

The calibration factor "C_n" is adjusted by using the deviation observed during preliminary tests. The new calibration factor was calculated using the following formula, which has been adjusted via the direct proportional criteria:

$$C_n = C_c\left(\frac{W_a}{W_m}\right) \qquad (1)$$

The Current Calibration Factor "C_c" refers to the pre-set or previously determined calibration factor, Actual Weight "W_a" is the known weight (100g in this case), and Measured Weight "W_m" is the reading obtained from the scale (76g in this case).

After updating the calibration factor, a series of test measurements were performed to confirm the load cell's accuracy. If discrepancies persisted, then the calibration process was repeated, adjusting the factor iteratively until the desired accuracy was achieved.

The calibration code is available on Github repository, and Figure 3 shows the output of the load cell after successful calibration.

4. Mechanical Design

The mechanical design of the haptic-enabled underwater gripper was focused on seamlessly integrating a force sensor while maintaining the gripper's functionality and structural integrity. This section details the design objectives,

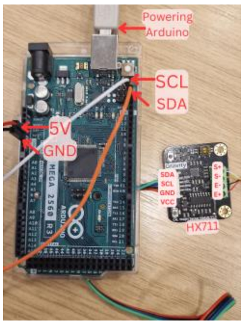
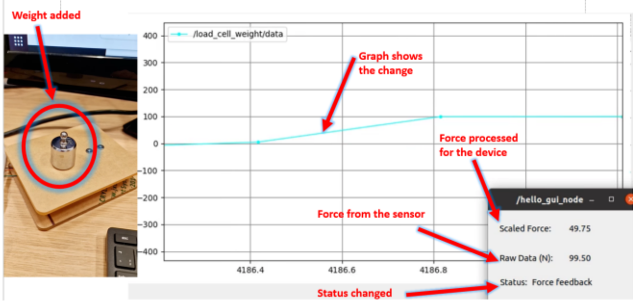
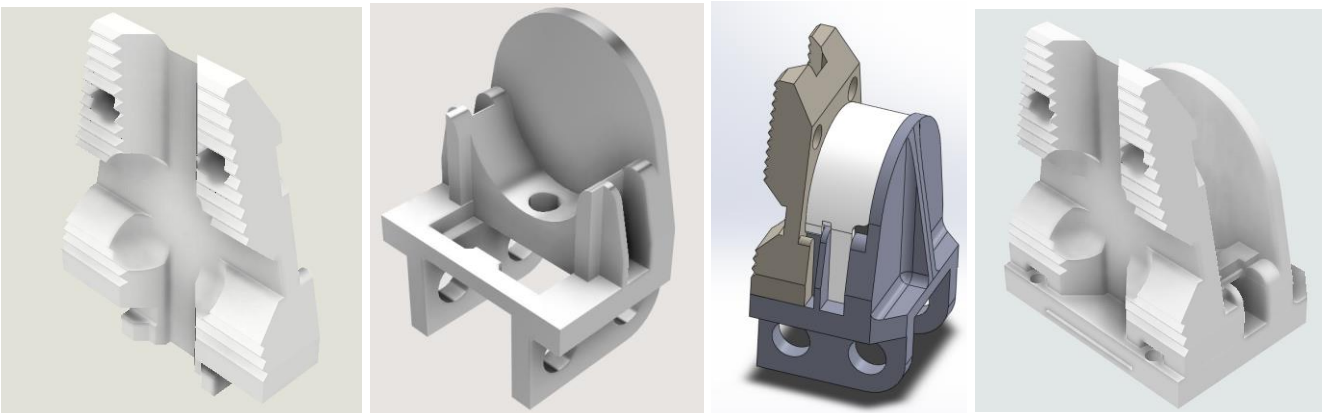


Fig. 2. *Connections of HX711 with load cell*



Scaled Force: 49.75
Raw Data (N): 99.50
Status: Force feedback

Fig. 3. *Calibration of load cell*



(a) Movable front of the jaw (b) Modified base of the Gripper (c) Assembled Jaw (d) Fixed modified jaw

Fig. 4. *Design of the modified gripper with force sensor integration*

the evolution of the gripper design, and the final configuration of the prototype.

4.1. Design Objectives

The primary objectives of mechanical design were:

1. Integration of a pancake-shaped force sensor (load cell) into the gripper jaw for accurate force measurement during object manipulation.
2. Preservation of the gripper's waterproof capabilities without additional protective measures.
3. Maintenance of the gripper's structural integrity and compatibility with existing systems.
4. Minimization of design complexity to ensure reliability and ease of manufacturing.

4.2. Sensor Integration

The chosen force sensor, a waterproof pancake-shaped load cell, was specifically selected for its ability to measure forces applied perpendicular to its surface. This design feature aligns well with the gripping action, allowing for precise force feedback during object manipulation.

The inherent waterproof nature of the selected sensor eliminated the need for additional waterproofing measures, simplifying the overall design and enhancing the gripper's reliability in underwater environments.

4.3. Design Evolution

The design process involved the following two main iterations, each addressing specific challenges and improvements:

The initial design split the gripper into two main components: Movable Jaw (Figure 4a), designed to move linearly when it is subjected to a normal force, creating the necessary clearance to contact the sensor probe and transmit the force; Stationary Base (Figure 4b) served as the foundation for the sensor and provided structural support.

A sensor cover was designed to protect the load cell and provide support for the jaw. A 1.5mm gap was maintained between the front jaw and the sensor to ensure effective force transmission (Figure 4c).

In the second version, shown in Figure 4d, the significant modifications were made to enhance reliability: The front of the jaw was fixed to the base, reducing modularity but improving the overall stability.

This design change impeded the jaw's movement from the bottom, resulting in lower sensor readings when the contact was made with the base. To maximize sensor response, the contact should be made at the top of the jaw face.

4.4. Material Selection and Manufacturing

The gripper components were fabricated using 3D printing technology, allowing for rapid prototyping and iterative design improvements. The 3D printed prototype was used to test the underwater performance in laboratory conditions. Figure 5 shows the manufactured 3D-printed gripper prototype.

Through addressing design constraints, the modified gripper balances force measurement accuracy, waterproofing, and structural integrity. This integration boosts functionality and reliability, improving object manipulation with precise force feedback for underwater control and monitoring.

5. Experimental Setup

5.1. Parallel Gripper Integration

To simulate ROV conditions, the fabricated gripper was mounted on a Robotiq parallel gripper, attached to a UR10e robot (Cobot) arm. The UR10e was selected for its precision, human-friendly interaction, and payload capacity, with a maximum safe handling weight of 10kg. The tests were

Fig. 5. *3D printed gripper*

conducted in a small water-filled container, where the gripper performed pick-and-place tasks. This setup allowed us to evaluate the gripper's submerged performance and force measurement accuracy, providing insights into its potential real-world underwater applications.

5.2. Test Objects

To evaluate the gripper's performance across a range of scenarios, three distinct objects were selected for the experiments:

- Steel Rod: Representing a rigid, cylindrical object common in underwater industrial environments.
- Cuboid: Simulating a geometric shape with flat surfaces and defined edges.
- Soft Ball: Mimicking a deformable object to test the gripper's ability to handle delicate items.

These objects, shown in Figure 6, were chosen to represent a diverse range of sizes, shapes, and material properties commonly encountered in real-world underwater manipulation tasks.

5.3. Load Cell

Two types of load cells were utilized to test the main objective of the project. The first load cell was the single point weight beam. This is a commercially available off-the-shelf sensor. It is a strain gauge-based load cell that operates on the principle of measuring the deformation of strain gauges in response to the applied forces. This Load Cell provided a cost-effective and readily available option for initial testing and calibration of the gripper prototype.

For the advanced stages of the project, the shear pancake was chosen as the primary load cell. This load cell provides a balance between price and performance, making it suitable for embedded force sensing applications. Based on the compression load cell design, it was selected due to its compact size and ability to read large force values. The selection of this Load Cell has ensured reliable and precise force measurement throughout the experimental phase of the project.

6. Results

The experiments, designed to verify the system's performance, involved four phases: object picking, lifting, descending, and gripper opening (Figure 7). The gripper demonstrated exceptional performance across all the tests, achieving a 100% success rate with no instances of object dropping. This high reliability suggests the design is robust and suitable for a wide range of underwater tasks.

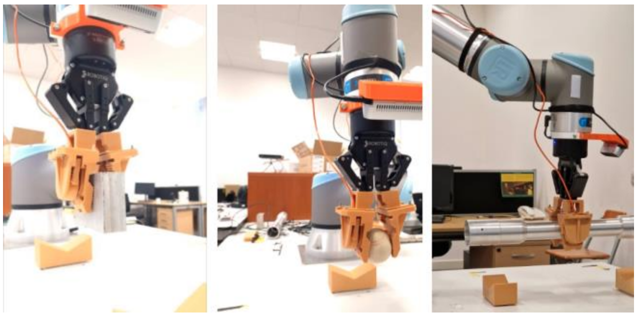


Fig. 6. *Objects used for the experiments*

Force measurements showed remarkable consistency, with small standard deviations (59.5, 48.0, and 41.0) across multiple trials for each object type (Table 2). The gripper successfully handled various shapes and materials (steel rod, cuboid, soft ball), demonstrating its versatility. This consistent force feedback is a strong indicator of the system's reliable performance, crucial for providing accurate haptic feedback to operators.

The low-cost approach proved highly effective. Using off-the-shelf components and 3D-printed parts, The achieved performance can be comparable to more expensive systems at a fraction of the cost. The total material cost, including the Arduino board and 3D-printed components, was under £60, with only the waterproof load cell costing £1000. This represents a significant cost reduction compared to commercial underwater force-sensing systems. The obtained results are promising when they are compared to similar studies, such as Galloway et al. [9], as the proposed design in this study can provide a lower cost force measurement system crucial for developing accurate haptic feedback systems.

Table 2 Performance of the modified Gripper of picking objects of various sizes five times

Object	Average force reading (N)	Standard Deviation	Percentage Success
Rod	760	59.5	100%
Cuboid	1190	48.0	100%
Ball	1540	41.0	100%

Despite these results, the current study has some limitations. The tests were only conducted in the controlled laboratory conditions, which can not fully represent real-world underwater challenges. Only three object types were tested, so more tests using the broader range objects with varying textures, sizes, and weights would provide more comprehensive data. Additionally, as the haptic feedback system is still in the lab-research and development stage, effectiveness of force feedback on operator performance could not been tested.

7. Conclusion

This study has demonstrated the successful development and testing of a low-cost, force-sensing feedback underwater gripper with potential for haptic feedback integration. The proposed approach can offer a viable alternative to more expensive systems while providing crucial force measurement capabilities. The gripper's consistent performance and reliable force measurements highlight its potential for enhancing underwater manipulation tasks across various off sea industries, including oil and gas, marine research, and offshore wind farms.

This work builds upon previous research in underwater robotics but sets itself apart through its focus on low-cost solutions and potential for haptic feedback. This addresses a crucial need in the industry for more accessible and advanced underwater manipulation technologies. Future work will focus on implementing the proposed haptic feedback system, conducting field trials, and exploring additional sensory feedback integration, etc.

In conclusion, this research represents a significant step towards more accessible, capable, and intuitive underwater robotic systems, paving the way for the next generation of underwater manipulation technologies.

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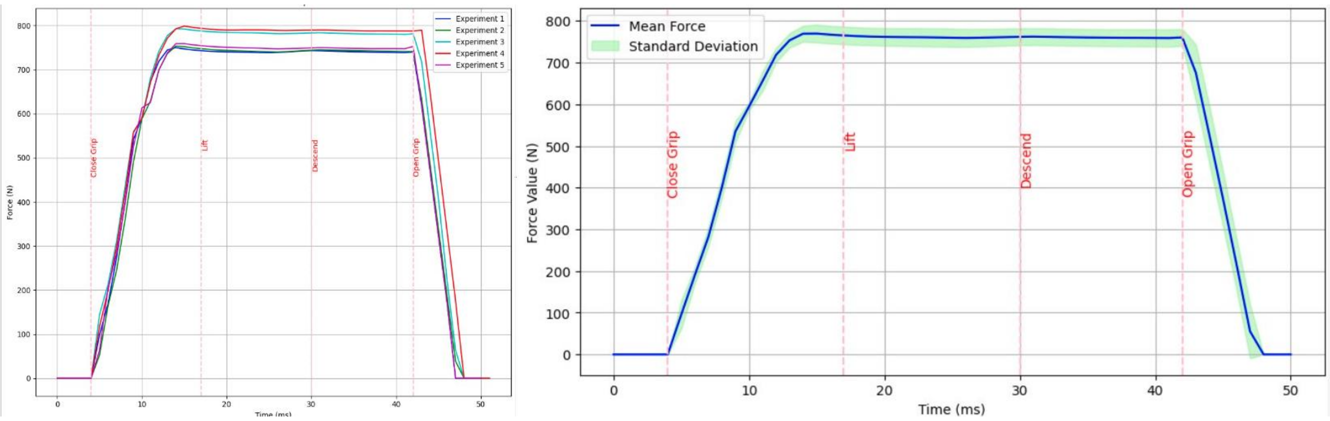
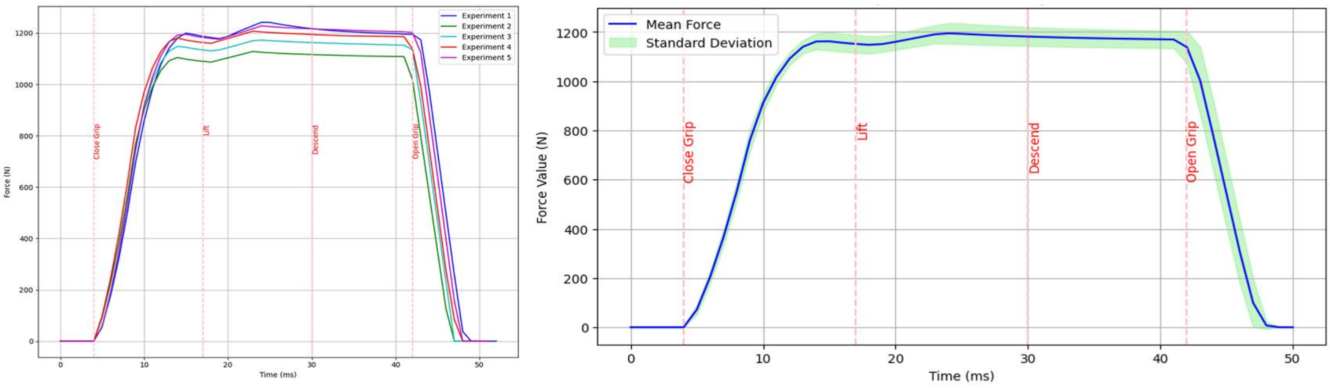
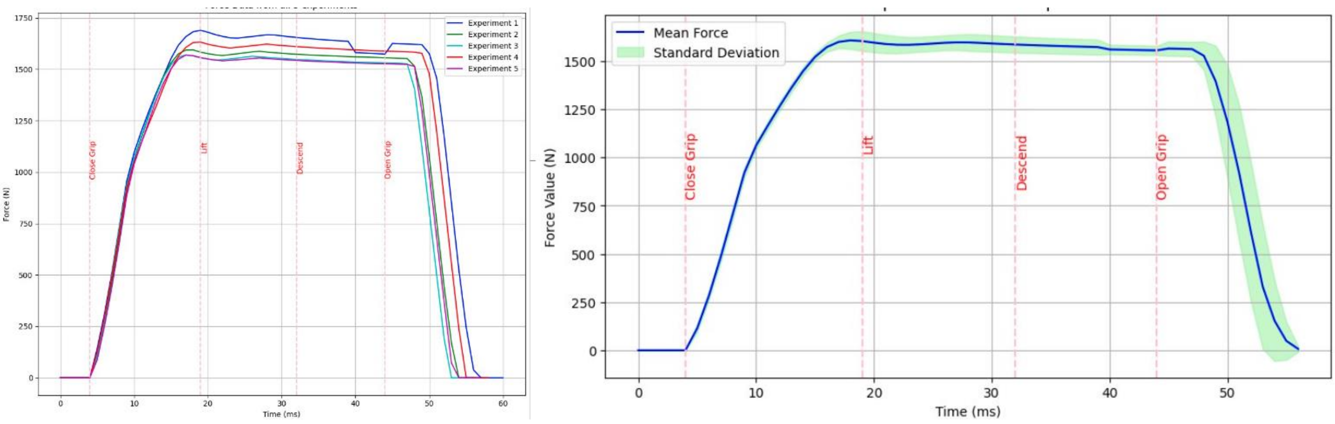


(a) Load cell measurements while holding aluminium rod



(b) Load cell measurements while holding aluminium cuboid



(c) Load cell measurements while holding soft ball

Fig. 7. *Performance of sensor for different objects*

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