

# Multi-Modal Sensing for Grasping and Human-Robot Interaction

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**Abstract**—To enable precise grasping and control in complex environments, robotic manipulation increasingly relies on the integration of multiple sensory modalities. This paper introduces an advanced multi-modal sensor that combines a refined matrix of optoelectronic elements with an inertial measurement unit in a compact design. The improved tactile resolution provides reliable force feedback, allowing for delicate and controlled handling of fragile or perishable objects. A novel approach has been proposed that utilizes the multi-modal sensing capabilities of our sensor suite to integrate data from optoelectronic elements and an inertial measurement unit (IMU) to enhance robustness and precision of manipulation. The designed sensor integrated into a Robotiq 3-fingers adaptive gripper influences advanced sensor fusion techniques to optimize the performance of deployed Proportional-Integral (PI) control for accurate positioning of fingers, enabling precise grasping. Furthermore, the innovative contribution of our work is the enhancement of Human-Robot Interaction (HRI) capabilities, in which the gripper adeptly responds to external forces exerted by the human in either longitudinal or lateral directions, thereby facilitating the controlled release or holding of objects. Hence, this manner develops safety and collaboration in distributed workstations. The experimental results of our system validate its effectiveness in handling delicate objects, and the study aligns with the premise of human-friendly robots by prioritizing insightful interaction and adaptive control.

## I. INTRODUCTION

The developments in robotic grasping in recent years have significantly emphasized the need for intelligent manipulations in industrial automation, particularly in applications relating to delicate or deformable objects. The ability of a robotic gripper to securely grasp and manipulate soft and hard objects is essential to improve efficiency in automated food processing. In addition, the integration of a human-friendly interaction mechanism is also essential to work in a collaborative environment. The primary contributions of this work include:

- development of an extended multi-modal sensor with a high-resolution tactile matrix for improved object perception;
- integration of the sensor within the Robotiq 3-finger adaptive gripper to improve grasping capabilities for different objects, as presented in Fig. 1;
- implementation of a PI controller for precise finger position regulation based on tactile feedback.
- implementation of an HRI-based control strategy that allows intuitive release mechanisms based on force direction;
- experimental validation of the system.

The literature presents numerous solutions based on two classifications of sensors. The first approach engages a



Fig. 1. Gripper demonstrating its adaptability by securely holding a soft ball, a hard ball, and a water bottle in both horizontal and lateral orientations

continuous deformable medium between the receptors and the contact, allowing a few receptors to interpolate the data among themselves. The second approach introduces an array of tactile receptors or independent elements that allow the identification of exact contact locations. Various transduction technologies, such as optoelectronic [1], magnetic [2], [3], resistive [4], [5], and capacitive [6], [7], can be employed with both sensor-based approaches, depending on factors like weight, size, compatibility, and the specific task at hand. Historically, a significant number of relevant articles have been published on tactile sensing. Optoelectronic-based sensors typically exhibit faster response times and greater durability, making them suitable for advanced applications in robotics. Also, achieving robust and adaptive manipulation requires a deep understanding of the interaction between the robot's gripper and the objects to handle [8],[9]. Traditional grippers rarely lack the sensitivity and dynamic response required for effective and efficient handling [10], especially in environments where human-robot collaboration is needed. To address the challenges, an extended multi-modal sensor has been presented with an enhanced matrix of optoelectronic components, designed to improve the sensing resolution and spatial accuracy, resulting in an enhanced gripper's ability to perceive and respond to external forces. This newly developed sensor with high-resolution force and mapping feedback is integrated into the 3-finger adaptive gripper for improved grasping performance, enabling it to differentiate between soft and hard objects while adjusting the grip strength accordingly.

Multi-modal sensors integrate multiple sensing capabilities within a single device, enabling the collection of varied and corresponding data streams. This type of sensor has a thorough understanding of the environment and objects, which improves robot interaction and manipulation capabilities [1]. Integrating several sensing modalities into a miniature unit reduces space and weight, which is fundamental for

confined-dimensional applications. The fusion of data from numerous modalities leads to more precise and consistent measurements, improved accuracy, and reduced noise [11]. The multi-modal sensor utilized in this study incorporates an Inertial Measurement Unit (IMU) alongside other advanced tactile sensing technology. The IMU plays a vital role in obtaining high-precision measurements of the acceleration to avoid slippage. Using innovative sensor fusion techniques, data from the gyroscope combined with an accelerometer, equipped in IMU enhances the accuracy and stability of pose estimation. A variety of grippers are commonly developed in robotic automation tasks, including pick-and-place operations and part assembly[12]. In particular, electrically actuated adaptive grippers are preferred to simple pneumatic-based grippers, especially in a collaborative environment [13]. Recent advances in adaptive and soft gripper research have gained significant momentum in both academic and industrial sectors, resulting in the introduction of commercial adaptive and soft grippers by companies such as RobotiQ [14]. Grippers, commonly known as mechanical hands, exhibit improved agility through a larger number of degrees of freedom (DOF), illustrating inspiration from the human hand, which consists of 35 muscles and 47 joints [15]. Although an increase in DOF allows for more complicated movements, it also results in larger weight, more complex designs, and the need for advanced control systems [16]. In contrast, simple grippers with a single DOF are lightweight and easy to design and control, but are limited to gripping only one fixed shape. Recently, some adaptive grippers featuring under-actuation have been introduced, such as the Robotiq 3-finger adaptive gripper.

To ensure the optimal force distribution for different types of objects, the PI control strategy has been incorporated for precise positioning adjustment of the gripper’s fingers. This closed-loop control improves stability and minimizes overshoot, allowing the gripper to be more reliable in handling delicate and fragile items without exerting unnecessary force. The PI controller constantly regulates the position of the finger based on real-time sensor feedback, improving grasp precision and compliance.

An innovative aspect of this work is the gripper’s context-aware response to human interaction. Gripper differentiates between the pulling force along the longitudinal axis (resisting release) and lateral axis (allowing release) when a user attempts to remove the grasped object. This selective response enhances safety and perception in collaborative tasks, a significant requirement for human-friendly robotics. The application focuses on handling and emphasizes the system’s relevance to industries involving moderate and adaptive manipulation. By merging advanced tactile sensing, adaptive control, and human-robot interaction features, this research contributes to the development of robots that can operate seamlessly alongside humans while maintaining efficiency and reliability. This paper is organized as follows. Section 2 provides an overview of the design and architecture of the enhanced multi-modal sensor. Section 3 describes the Control Strategy. Section 4 demonstrates human-robot interaction

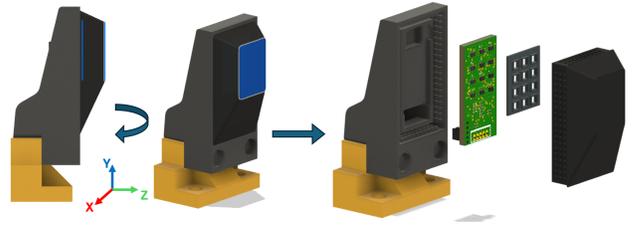


Fig. 2. CAD of an assembled sensor (left) and exploded view with all components (right)

in a collaborative environment. Finally, Section 5 discusses the broader implications of this research, highlighting its potential impact on future technologies.

## II. SENSOR DESIGN

A multilayered PCB design featuring a micro-controller, a  $4 \times 3$  array of optoelectronic photo reflectors, referred to as “taxels”, which consist of LED and photo-transistor pairs arranged in a matrix configuration beneath a deformable layer, and an Inertial Measurement Unit (IMU) to enhance the capabilities of the multi-modal sensor. An exploded CAD model of the multi-modal sensor, showing all components, is illustrated in Fig. 2. Mechanical parts, such as the grid and PCB adapter to integrate the sensor on the gripper, have been designed and produced by ABS plastic using 3D printing. The deformable pad, made of silicone, was created using high-precision ABS-printed molds. The primary function of the sensor is to convert contact data into measurable deformations using optical components. The LEDs emit light that reflects off the underside of the deformable layer, and the photo-transistors measure the reflected signals. These signals vary according to the degree of deformation affected by external contact, creating a tactile map that can help assess the shape of grasped objects or reconstruct external forces. The IMU continuously provides data that can be utilized to estimate the pose of an object, prevent slippage, and measure the temperature of grasped objects. The sensor comprises a six-layer PCB with dimensions of  $(12.65 \times 25.9)$  mm, having an array of 12 taxels ( $4 \times 3$ ) manufactured by New Japan Radio with code NJL5912R soldered to the top layer along with some resistors presented in Fig. 3. The bottom layer consists of analog buffers using low-power operational amplifiers (ADA4691), connectors, adjustable current source (LT3092), inertial measurement unit IMU (LSM6DSV16X) and a microcontroller (PIC16F19155) with adequate number of 12-bit A/D channels for acquisition of tactile signals that digitizes the buffered outputs to enhance the signal-to-noise ratio and facilitates firmware development. The LEDs of the optoelectronic elements connected in series are powered by 1 mA from the adjustable current channel, connected to the 24 V external power supply. The photo-transistors are powered up by the 3.3 V derived from a DC/DC converter, which is connected to a 5 V external power source. The signals from the photo-transistor are transmitted to the OP-Amp based buffers, which subsequently feed into the analog-

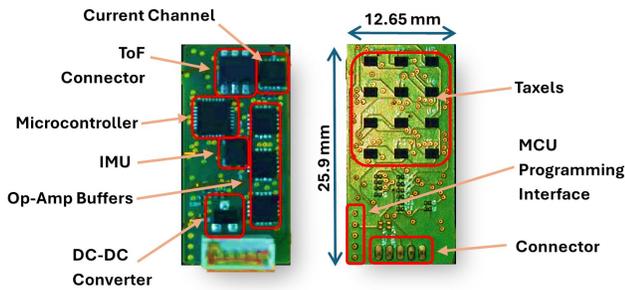


Fig. 3. Multi-modal sensor PCB: bottom (left) and top (right) views.

to-digital (AD) channels of the microcontroller. The IMU integrated on PCB offers a 3-axis gyroscope, accelerometer, and temperature sensor, with on-board processing capabilities, is also powered by a 3.3V source and communicates with microcontroller using the I2C communication protocol. and the sensor utilizes the UART serial communication protocol to communicate with the main PC as illustrated in the block diagram shown in Fig. 4. The deformable pad is the fundamental part of this sensor that can be realized in distinctive shapes depending on the application, i.e., if the objective is the recognition of features for manipulation of small objects compared to the size of the pad, then a flat surface pad can be employed [17]. Otherwise, the dome-shaped deformable pad can be used to reconstruct the information about contact forces and torques for manipulation, by employing a trained neural network to tactile map signals, reported in [18]. The sensor presented reports a flat surface pad with a polygonal shape resembling a frustum, as illustrated in the Fig. 2. The highlighted section of the pad is particularly designed to encompass only the optoelectronic components, thus enhancing the overall functionality and effectiveness of the sensor. This proposed design not only optimizes the performance of the optoelectronic elements but also influences a streamlined aesthetic, ensuring that the sensor remains compact and effective in its application.

The pad is realized from silicone, selected for its low hysteresis and good elastic properties compared to other deformable materials, with the underside revealing black

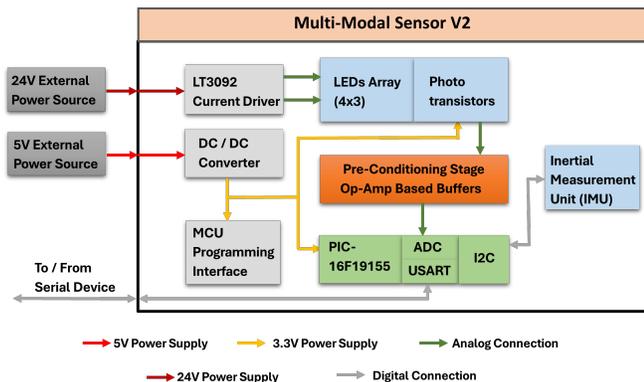


Fig. 4. Architecture of power and communication flow within sensor

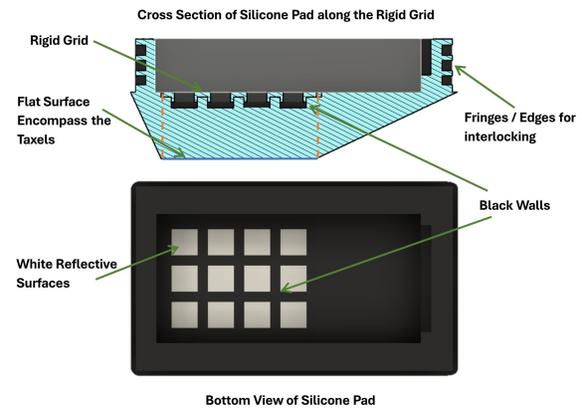


Fig. 5. Fingertip detailed cross-section (top) and a bottom view of pad (bottom).

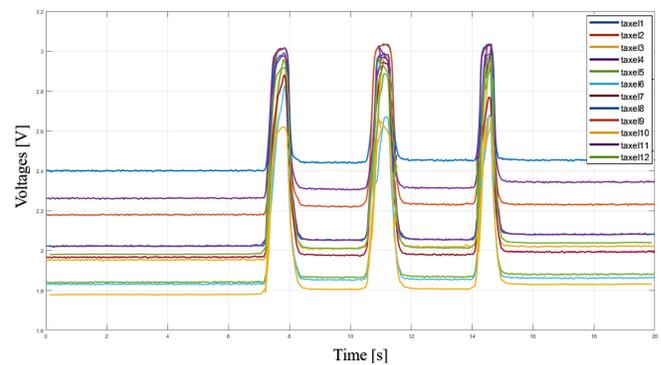


Fig. 6. Signals from the 12 taxels, with three distinct peaks upon contact.

walls to optically isolate the taxels. while white surfaces are placed in front of the optical components to maximize reflectivity presented in Fig. 5.

A rigid grid is positioned between the PCB and the pad to ensure the operation of the optoelectronic components within a monotonic range. The design ensures that the distance from the reflective surface to the photo-reflector does not reduce below  $500\mu\text{m}$ . The grid is manufactured with black ABS plastic using 3D printing technology, achieving a precision of approximately  $\pm 100\mu\text{m}$ , and the choice of black color is intentional to avoid unwanted lateral reflections. The tactile sensor directly measures the voltage signals (presented in Fig. 6) that are subsequently converted into force values. This conversion is calibrated using reference values obtained from a load cell (referring to the Fig. 7), ensuring accurate force measurements during grasping tasks. The experiment was designed to study the correlation between the sum of voltages recorded by a tactile sensor integrated into a Robotiq gripper with minimum velocity and the corresponding force applied to a load cell. The objective was to recognize the variation of voltage readings corresponds to the force exerted, which is important for applications in robotic manipulation and feedback control. The proportionality observed in both graphs in Fig. 7 presents a strong relationship between tactile voltages [V] and force [N] over 5 s. The maximum voltages

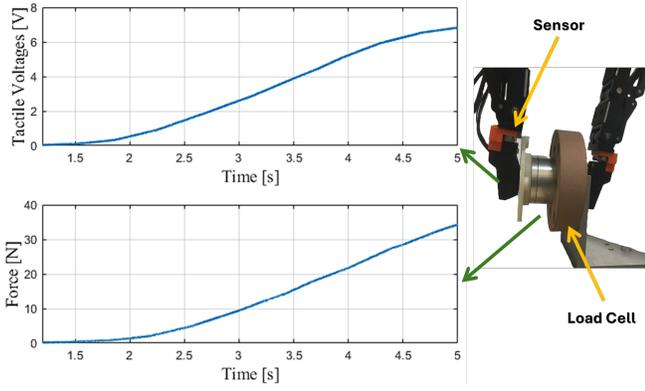


Fig. 7. Relationship between the sum of voltages measured and the force measured by the load cell

that can vary for tactile sensor range from 0 V to 6.8 V, and the corresponding measured force has a range of about 0 N to 34 N, highlighting the dynamic relationship between tactile sensing and applied force. Simultaneously, these trends suggest that as the force applied to the sensor increases, there is also an increase in the tactile voltage readings, demonstrating the sensor's effectiveness in capturing tactile stimuli.

### III. CONTROL ARCHITECTURE

To ensure the precise and responsive manipulation of the objects, the control architecture is designed for the position control of the 3 fingers of the adaptive gripper. The architecture employs a Proportional-Integral (PI) control strategy that efficiently minimizes steady-state error, avoids slower response, and enhances the stability of the system. The motivation to implement this control strategy is to guarantee a desired consistent response under varying conditions. The control system is structured around a feedback loop that constantly observes the position of the gripper fingers and regulates the control input accordingly. The main components of the control architecture include the multi-modal sensor, the PI controller, and the actuators interface.

The multi-modal sensor is an essential component of the control architecture, providing real-time feedback on the position and orientation of the gripper fingers. Sensor data is processed to obtain relevant position information, which is then fed back to the PI controller for real-time adjustments, as illustrated in Fig. 8. The PI controller is implemented to control the position of the gripper fingers based on

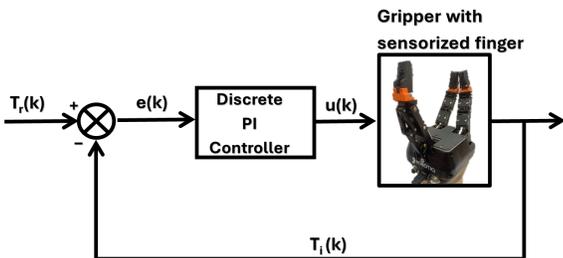


Fig. 8. Control scheme based on sensorized fingers.

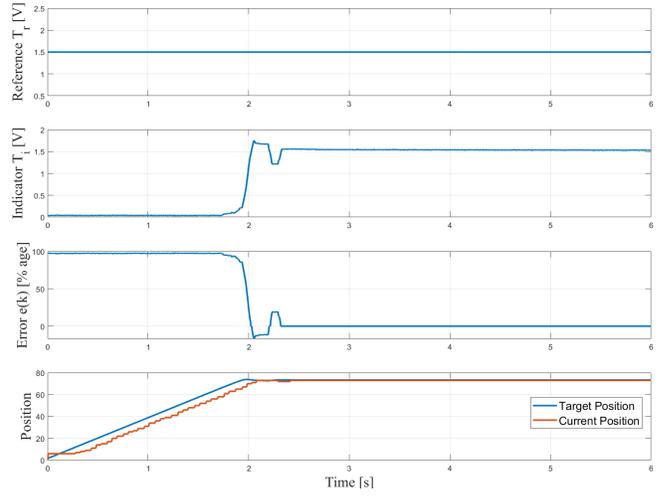


Fig. 9. Experimental validation for PI control of real gripper fingers

the feedback sensed from the multi-modal sensor. The PI controller, implemented in discrete time, can be expressed as:

$$u[k] = u[k - 1] + K_p(e[k] - e[k - 1]) + K_i e[k] \tau_s \quad (1)$$

where:

- $u[k]$  is the control output at discrete time step  $k$  (discrete). This is the control signal used to adjust the finger position.
- $e[k]$  is the error signal at discrete time step  $k$ . It is defined as the difference between the reference signal  $T_r[k]$  and the measured tactile indicator  $T_i[k]$ :

$$e[k] = T_r[k] - T_i[k]$$

- $T_i[k]$  is the tactile indicator computed as the sum of all voltages acquired from  $\text{taxel}_i$ , with  $i = 1, \dots, 12$ .
- $K_p$  is the proportional gain. This parameter determines the reaction of the controller to the current error.
- $K_i$  is the integral gain. This parameter determines the reaction based on the accumulation of past errors. It helps eliminate steady-state errors.
- $\tau_s$  is the sampling time used to discretize the controller.

The PI controller processes the error signal to generate the control output, written in the gripper register to regulate the finger position. The process repeats, creating a continuous feedback loop that maintains the desired position. Figure 9 presents a comprehensive overview of the performance of the Proportional-Integral (PI) control system during an experiment, with  $K_p = 1.0$ ,  $K_i = 0.06$  and  $\tau_s = 0.002$  s. The first subplot reports the reference value, which is equal to 1.5 V, set for the control system. The second subplot exhibits the measured tactile indicator throughout the experiment. This signal represents the actual output of the system in response to the control input, allowing a comparison of the system with the reference value. Initially, the tactile indicator is zero since the fingertip is not in contact with anything, the percentage error (third subplot) is the maximum, and the gripper starts to close. When an object comes in contact

with the sensor attached to the finger, the tactile indicator rapidly increases to about 1.65 V, and then, in about 0.33 s, it settles to the target value. The percentage error clearly converges to zero after the transient phase, demonstrating the effectiveness of the PI control. The fourth subplot shows the position of the gripper fingers throughout the experiment, providing information on the physical response of the system as it attempts to reach the reference value. Target position and current position lines converge, indicating that the system achieves the desired position within about 2 s. Hence, the sensor signal and the position of the fingers are stabilized, demonstrating good performance and reliability of the control system. Collectively, these results illustrate the successful implementation of the PI control strategy, highlighting its ability to achieve a desired grasped force related to the value of tactile indicator reference. This control mode has been used for the grasping of several objects as the ones reported in Fig. 1.

#### IV. HUMAN ROBOT INTERACTION

In the domain of human-robot interaction, the integration of advanced sensory feedback mechanisms is essential to improve the performance and safety of robotic systems and the comfort of humans. The tactile sensing capability of the multi-modal sensor plays a pivotal role in this collaboration, enabling the gripper to adaptively react to the forces exerted by objects or humans during manipulation.

The centroid calculation of the force distribution is a significant component of the tactile sensor integrated into the robotic gripper, as it provides essential information about the distribution of forces exerted on the gripper's fingers during manipulation. Hence, the robotic system can make informed decisions about how to adjust its grip, ensuring stability and control during interactions with various objects.

The approach presented in [19] is exploited to compute the **centroid coordinates** of the tactile map. Centroid represents an estimation of the application point of the contact force. When an object is grasped, the centroid coordinates take on an initial value. If after grasping, an additional external force is applied to the object, the centroid coordinates move accordingly to the force direction, and a different interaction modality can be implemented on the basis of centroid measurement. The centroid coordinates are estimated as

$$C_x = \frac{\sum_{i=1}^{12} v_i x_i}{\sum_{i=1}^{12} v_i}, \quad C_y = \frac{\sum_{i=1}^{12} v_i y_i}{\sum_{i=1}^{12} v_i} \quad (2)$$

where:

- $C_x$  is the  $x$ -coordinate of the centroid (in mm)
- $C_y$  is the  $y$ -coordinate of the centroid (in mm)
- $x_i$  is the physical  $x$ -position of  $i$ -th taxel (in mm)
- $y_i$  is the physical  $y$ -position of  $i$ -th taxel (in mm)
- $v_i$  is the voltage variation measured by the  $i$ -th taxel

The centroid coordinates can be continuously estimated using the physical data of the sensor, reported in Fig. 10 in combination with the acquired voltages. Figure 10 shows the distribution of the  $4 \times 3$  array of tactile elements, with a

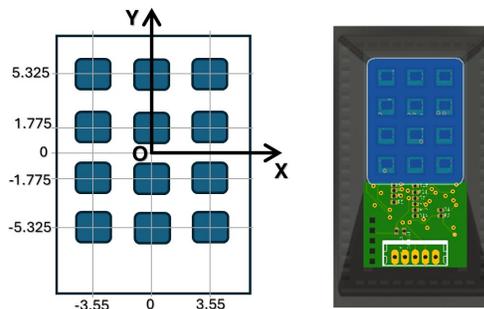


Fig. 10. Physical positions of taxels with respect to sensor reference frame (left) and with respect to the whole fingertip (right).

spatial resolution equal to 3.55 mm. The estimated centroid has been exploited to implement the following human-robot interaction strategy. After grasping an object, if a user pulls the object along any axis, the system can detect a significant change in the centroid position relative to the gripper's grip. In our case, the system has been programmed to release the object if an external force is applied along the  $y$ -axis, in particular if the centroid shows a shift along the  $y$ -axis greater than 0.3 mm. On the other hand, if the user pushes or pulls the object along the  $x$ -axis, the gripper will continue to hold the object. Figure 11 shows a frame sequence for two different objects, where in the first phase an interaction is applied along the  $x$ -axis and then a second interaction is applied along the  $y$ -axis.

The graphs presented in Fig. 12 validate the experimental results. The first graph illustrates the tactile voltage values collected when the gripper successfully engages with the object using Proportional-Integral (PI) control. Each line represents the voltage value from individual taxels. The second graph presents the  $C_x$  centroid coordinate before and after the object is grasped. It also includes vertical red lines that indicate the regions where centroid values shift due to applied pull or push forces along the  $x$ -axis. It demonstrates that the gripper effectively maintains its hold on the object during this phase. The third graph displays the  $C_y$  centroid coordinate, which includes two red lines that highlight the timing when the centroid shifts along the  $y$ -axis. This lateral shift ultimately results in the controlled release of the object.

Finally, the fourth graph depicts the position of the gripper fingers throughout the experiment. In particular, the graph line of position at about 28 s experiences a sharp decline, indicating that the gripper fingers reach their maximum open position. These graphs collectively validate the effectiveness of the human-robot interaction algorithm implemented.

#### V. CONCLUSION AND FUTURE WORK

In this study, an advanced multi-modal sensor integrated with the Robotiq 3-Finger Adaptive Gripper has been presented, significantly enhancing its capability to grasp delicate objects. This integration is also significant for effective manipulation within human-robot collaborative environments, where the ability to handle multiple objects with care is

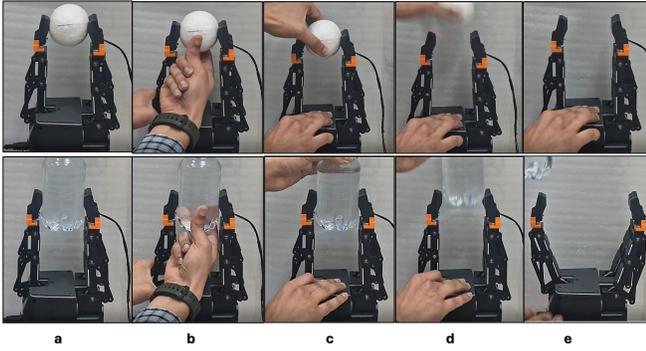


Fig. 11. From grasp to release: (a) object grasping, (b) pulling along  $x$ -axis, (c) transitioning to  $y$ -axis, (d) object releasing along  $y$  direction.

essential. Our experimental validation demonstrates the effectiveness of the proposed sensing system in achieving secure and adaptable grasping, which is further supported by the implementation of a Proportional-Integral (PI) control strategy. This strategy ensures precise finger positioning, allowing for a more responsive interaction with objects of varying shapes and fragility. Moreover, our innovative approach to human-robot interaction dynamics encourages a safer and more cooperative environment. By prioritizing human-friendly interaction protocols, the advancement for more intuitive and effective collaboration between humans and robots has been pursued, which is essential in applications ranging from industrial automation to assistive robotics.

Looking forward, there are several promising possibilities for future work. One key area is the utilization of Inertial Measurement Units (IMUs) for enhanced pose estimation. By integrating IMU data, the accuracy of the gripper's spatial awareness and its ability to adapt to dynamic environments can be improved. This capability will be particularly beneficial in conditions where the robot must interact with moving objects. Additionally, advanced algorithms for slippage avoidance during grasping are aimed to be explored. By leveraging the data from our multi-modal sensor system, we can develop predictive models that anticipate slippage events

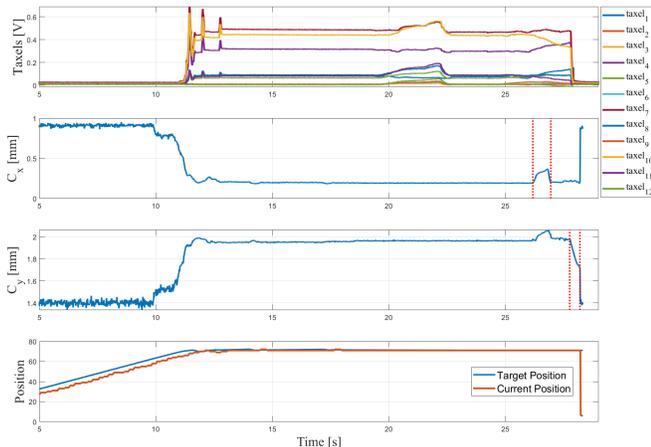


Fig. 12. Gripper performance during human-robot interaction

and adjust the gripper's force and positioning in real-time. This will not only enhance the reliability of the grasping process but also contribute to the overall safety of human-robot interactions.

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