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Development of a Robotic Manipulator for Grasping Deformable Objects: A Case Study

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Abstract
The manipulation of deformable objects without inflicting damage is a critical requirement in automating fish processing. This work details the development of a pneumatically actuated soft robotic manipulator designed for use in combination with a Stäubli TX2-60 arm. Key objectives included minimization of weight, integration into an existing system, hygienic design, and slip-free grasping of fish. Through iterative prototyping, a gripper is fabricated using 3D-printed carbon fiber-reinforced polylactic acid (PLA) and Festo DHAS-120 adaptive fingers. The final design incorporates four finger pairs and structural reinforcements to optimize stability and contact area. Testing confirmed that the prototype, successfully grasps fish without damage while adhering to payload and environmental constraints. These results validate the efficacy of soft robotic structures for gentle, hygienic automation in the food industry.

I. Introduction

The utilization of automation through robotic solutions has been increasing for an extended period and with it, there has been a surge in the pursuit of suitable robotic manipulators. Manipulation can be broadly categorized into two distinct types: non-prehensile, such as pushing or sliding, and prehensile with the aim to grasp an object [1]. A notable challenge in the realm of prehensile manipulation pertains to deformable objects, which are generally considered more complex to manipulate, in contrast to rigid objects [2].
However, in a variety of applications, the successful grasping of deformable objects has the highest priority. One of the applications in question pertains to the domain of food processing, where preventing damage to the handled goods is a primary objective [3]. This also applies to the fish processing industry, where a pivotal step in the processing chain is the safe and reliable transfer from one machine to the next. The utilization of a robotic arm is imperative for the execution of this procedure. To ascertain an adequate manipulation solution, it is necessary to consider multiple factors. Firstly, the solution is mounted to a robotic arm. This implies a weight limitation as to not exceed robot limits. Secondly, the solution must accommodate fish of variable sizes. In this work, fish with a length between 350 mm and 550 mm and a weight between 2900 g and 3300 g, are utilized. The upper weight limit is derived from the typical fish for this task and the robot limits.
Additionally, the solution must ensure adequate compliance to maximize the effective contact area and distribute pressure evenly to prevent slippage of the fish. Furthermore, it is imperative that the fish is protected from any potential harm inflicted by the manipulator. To integrate the solution into a functional pipeline, it must be controllable via a Programmable Logic Controller (PLC). Furthermore, for future applications, the

solution should adhere to the principles of hygienic design [4].
In this paper, these factors are taken into account in order to develop a robotic manipulator for fish handling.

II. Methods and Materials

This work build on [5], where a soft robotic gripper for fish handling is proposed and a preliminary prototype presented, but without considering the constraints imposed here. To adhere to these restrictions, an optimized lightweight design is developed through iterative prototyping and integrated into the existing environemnt.

II.I. Integration into Existing Environment

One quintessential requirement is the integration of the manipulator into an existing environment. This environment, depicted in figure 1, features a Stäubli TX2-60 robotic arm, a conveyor belt, and a camera setup. The management and control of all components is facilitated by a Siemens PLC. The manipulator is attached to the TX2-60's flange with the objective of amplifying the effective workspace. The TX2-60 robotic arm is equipped with pneumatic valves and electrical lines [6]. Consequently, the employment of either a pneumatically or an electrically operated manipulator is logically coherent. As previously stated in section I, a future focus will be on the hygienic design aspect. In light of these considerations, the utilization of a pneumatically actuated manipulator is recommended as this approach circumvents the necessity for electric motors within the manipulator that do not adhere to the specific ingress protection (IP) [7] class rating.
This method additionally facilitates the integration into the existing environment by accessing the interface through the integrated TX2-60. It is important to note

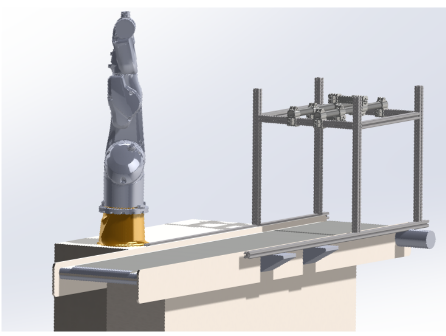

Figure 1: This illustration presents a 3D reconstruction of the environment, encompassing the Stäubli TX2-60, the conveyor belt, and the camera mounting rig. This visual is a screencapture of the rebuild created in the 3D modeling software SolidWorks.

that the maximum payload capacity of the TX2-60 is 4.5 kg [6]. The manipulator's weight must be minimized to optimize the effective payload for the fish. As indicated by the specifications enumerated in section I and the prevailing environmental constraints, the maximum allowable manipulator weight is estimated to range from approximately 1200 g to 1600 g.

II.II. Development Process and Hardware Components

An iterative design process is employed, whereby prototypes are created, tested, and refined based on performance and compliance with the established constraints. The design process commences with the generation of conceptual sketches and 3D models utilizing the software SolidWorks. In [5] the conclusion that soft robotic structures are particularly well-suited for the grasping of fish is drawn. The soft robotic structure exhibits the capability to conform to the shape of the constrained object, thereby ensuring the distribution of pressure is uniform, minimizing potential damage, and maximizing grip. The utilization of existing components in prototyping is a strategic measure that aims to minimize development time and cost. For this application, the Festo DHAS-120 Adaptive Gripper Finger is selected as the preferred soft robotic structure [8]. The DHAS fingers can enclose objects with a maximum diameter of 120 mm [8] and are designed to adapt to various object shapes and sizes, rendering them suitable for grasping deformable objects such as fish. The fingers are mounted onto a custom-designed manipulator structure. To comply with the weight limitations imposed by the robotic arm and to further optimize the manipulator's weight, 3D printing is employed for the fabrication of the manipulator components. It allows for rapid prototyping and experimentation with diverse design concepts. Polylactic acid (PLA) is selected due to its accessibility and ease of use in 3D printing. The final design prototypes are printed using a carbon fiber-reinforced PLA (PLA-CF) to enhance strength while maintaining a low weight. Through the identification of flaws in early prototypes, as detailed in section III.I, the design is refined.

III. Results and Discussion

This section delineates the results obtained from the development and testing of the robotic manipulator. Additionally, it will examine the technical specifications of the final prototype and explore potential applications. The iterations are presented in chronological order to highlight the reasoning behind each change.
The development process culminates in a manipulator prototype that successfully meets constraints while achieving reliable performance in grasping deformable objects.

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III.I. Initial Prototype and Composition

Given the distribution of attention across multiple constraints, the initial prototype must encompass numerous facets. The selection of pneumatic actuation offers the advantage of seamless integration into the existing environment. Conversely, this approach imposes constraints on the available design freedom, necessitating the incorporation of a pneumatic cylinder within the structural framework.

The design incorporates a main plate that serves to house the pneumatic cylinder, in addition to the TX2-60 flange mount. The pneumatic cylinder is affixed to a sliding component that exhibits linear motion when actuated. Moreover, a side plate serves to stabilize the structure and provide a mounting point for the rotating Festo DHAS-120 finger brackets. Upon actuation of the pneumatic cylinder, the sliding part moves forward, exerting an outward force on the finger brackets and opening the manipulator. Actuating the cylinder in the opposite direction results in the retraction of the sliding part, thereby leading to the closure of manipulator.

A 3D-printed version of the gripper is assembled, and preliminary manual tests are conducted. However, the initial testing phase has exposed the initial prototype's deficiencies. The primary concern pertains to the instability exhibited by the sliding component. An unwanted rotation occurs when the fingers are actuated, leading to an uneven grip on the object.

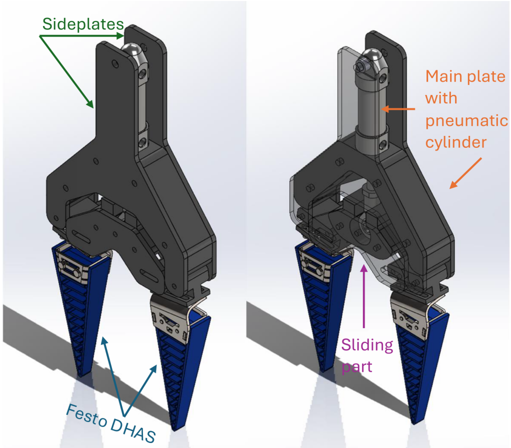

Figure 2: The second iteration of the prototype incorporates a main plate with pneumatic cylinder, two side plates, a sliding part, and two finger brackets with attached DHAS fingers. This is a screencapture of the 3D model, created in SolidWorks.

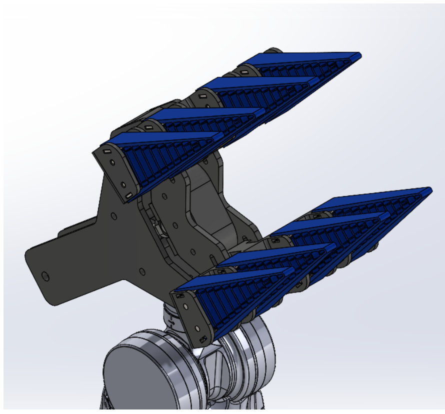

Figure 3: The final prototype is shown here mounted to the TX2-60's flange. It is equipped with four pairs of Festo DHAS-120 Adaptive Gripper Fingers, designed to optimize the contact area during grasping operations. The visual is a screencapture of a 3D model created in SolidWorks.

III.II. Refinements and Final Prototype

In order to remediate the observed issues with stability in the initial prototype, refinements have been implemented in the design. The most substantial modification entails the incorporation of an additional side plate, thereby augmenting the overall stability of the sliding component. This modification effectively mitigates the unwanted rotation, thereby ensuring a more secure and consistent grip on the object.

Figure 2 illustrates the refined design of the prototype that features a weight of 1300 g. A thorough testing process has led to the identification of a persisting issue. This issue pertains to the area of contact of the manipulator. It has been observed that the contact area provided by one pair of DHAS-120 fingers is inadequate in preventing slipping out of the manipulator and bending of the object during grasping. To address this, the number of DHAS-120 fingers is increased from one pair to four pairs. This final prototype also eliminates an error in the integrity of the finger mounting brackets identified in testing. The fingers are mounted directly to the 3D-printed part instead of the manufacturer-provided mounting plate. This modification has been demonstrated to enhance the overall stability of the fingers during operation.

In the final stage of prototype assembly, the utilization of 3D-printed parts made from PLA-CF is employed to ensure strength while minimizing weight. Figure 3 illustrates the final design of the prototype. The final prototype has been engineered to a weight of just over 1700 g.

III.III. Application Test and Verdict

The subsequent stage in the sequence of events is the execution of a test of the manipulator prototype to ascertain its performance when integrated into the existing environment. For this, the manipulator is mounted onto the TX2-60 robotic arm and pneumatically actuated at a pressure of 600 kPa. In total, over one hundred grasping attempts are performed. The tests are performed in accordance with the general ethical and economical principles. Due to the scope of the feasiblity study and the

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proportionality, three individual fish are used for these experiments. The grasping procedure is developed and perfected for these fish through more than fifty graps. After optimization, almost the same number of optimized grasps are performed.
The fish are taken from the middle of the expected cohort in accordance to their weight and size proportions as specified in section I. No conclusions can be drawn about the boundaries of the cohort and no statistics can be collected. In figure 4, the final prototype can be seen attached to the TX2-60 robotic arm, grasping a fish without causing any visible damage. Damage assessment is performed by checking for deep grooves or pressure marks on the fish skin after each run. This is done in parallel to the visual checks performed for human fish handling. This demonstrates a successful application test which serves to validate the design choices made throughout the development process and highlights the manipulator's potential for applications in domains requiring the handling of deformable objects such as fish processing.
With this application, all initially set targets are met, with the exception of the weight constraint. However, the achieved weight of 1700 g for the manipulator prototype still allows for effective operation within the payload limits of the TX2-60 robotic arm. A trade-off between weight and functionality is made here, as an earlier prototype with a weight of 1300 g exhibited instability issues. During the testing phase, the TX2-60 operated at a rate of about 80% of its limits in speed and acceleration. However, it must be acknowledged that the TX2-60 may not be able to operate at maximum dynamics.

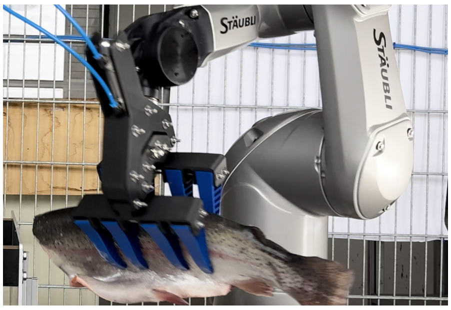

Figure 4: The manipulator is shown here grasping a fish. The grasping position is deliberately chosen; however, this goes beyond the scope of this work.

IV. Conclusion

The present development of a prehensile robotic manipulator for deformable objects demonstrates the potential of robotic automation solutions for delicate tasks. The imposed constraints necessitated a careful balance between functionality and design limitations. The manipulator prototype's demonstration of full functionality signifies its potential for future utilization in fish processing applications and establishes a foundation for future advancements.
Subsequent steps include further experimental testing and optimizing the manipulator's weight while ensuring functionality, for example, through the replacement of screws with 3D-printed clips.

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Author's statement

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