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Development of an Adaptive Gripper Using Shape Memory Alloys for Industrial Robotics

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Abstract--- Industrial Robotic Grippers (IRG) with elasticity have significant advantages in grasping items with irregular shapes or fragility compared to conventional rigid gripping devices. The primary constraints of these systems are the diminished gripping force due to the characteristics of soft motors and the absence of variable rigidity in IRG devices, which restricts their applicability across a broader spectrum of uses. This article presents a soft gripper using Shape-Memory Alloy (SMA) technology, with three robotic digits that enable compliant gripping at moderate stiffness and secure holding with elevated rigidity. Each IRG finger (Fr) primarily included rigid components and two variable rigidity joints, affixed to the base at a predetermined angle. The paraffin, used as a variable rigidity substance in the joint, is thermally manipulated to alter the rigidity of the IRG Frs. Experimental results indicate that a single IRG Fr gets an estimated 18-fold increase in stiffness. Every finger, possessing two joints, proactively attains various postures by modulating the stiffness of the joints and activating the SMA wire. Utilizing these concepts, the gripper can grasp items of multiple forms and a wide range of weights, with the most significant gripping force enhanced to almost tenfold with adjustable stiffness connections. The final test is performed to verify the changing stiffness of the suggested soft grippers while grabbing an item.

Keywords--- Adaptive Gripper, Shape Memory Alloys, Industry, Robotics.

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I. Introduction

Shape Memory Alloy (SMA) (Kim et al., 2023) is a kind of intelligent material that experiences alterations in length, shrinking by approximately 4%, thereby producing a substantial resistive force during thermal activation. Unlike other alloys, this alloy's responsiveness to heat stimuli renders it intelligent. Various compositions of SMA include Ni-Ti alloy (Nitinol), Cu-Al-Ni alloy, Cu-Zn-Al alloy, Au-Cd alloy, Ni-Mn-Ga, and iron-based alloys. Only two composites have attained any degree of commercial utilization: Ni-Ti composites and copper-based composites (Li et al., 2023). SMA can respond to two distinct stimuli. The first is thermal stimulation, where a pre-stressed SMA cable (detwinned martensite) experiences a temperature increase to its designated heating temperatures (trained temperatures), allowing it to revert to its original shape (austenite) together with the associated stress. This phenomenon is referred to as the effect of shaping. This functionality is used for several position and angle monitoring control programs. The second factor is stress, whereby the stimulus at the optimal heating temperature functions analogous to a spring, allowing it to discharge substantial energy, resulting in an ideal option for damping and absorption.

The primary issue of Industrial Robotic Gripper (IRG) (Ivanov et al., 2024), a crucial component of soft robotic systems that communicate with surroundings and humans, is that its stiffness can't be significantly altered during the gripping process. Changing stiffness is a viable remedy to the limitations of soft grippers, significantly enhancing gripping ability. Sometimes, low-stiffness IRG devices efficiently absorb external impacts and ensure safe interactions when handling items in intricate settings (Lalegani Dezaki et al., 2024). They can automatically grasp irregular objects such as fruits. In some instances, while in a high rigidity condition, IRG devices can bear greater weights and preserve their shape when lifting large items such as bottles. The attributes have garnered significant interest from scientists in IRG devices with adjustable rigidity.

II. Background

Initially, SMA literature used proportional variables for system operation, but transitioned towards deploying nonlinear or hybrid regulators. The control strategies used in the SMA-based system primarily utilize linear controllers when the system requires just actuation without necessitating precision (Sohn et al., 2023). Complex structures, such as those using instruments in higher-order structures, need nonlinear controls to achieve optimal performance and effectiveness at elevated rates. Comprehensive knowledge of the intrinsic attributes has led to significant advancements in literary documentation and business growth.

Work on controlling position in SMAs has emerged in the past two decades, expanding across several domains, beginning with designing and implementing servo-type operations using SMA materials with diverse topologies and including various biasing components (Amin et al., 2021). The many facets of using the component to regulate location and force in robotic and haptic devices are also key factors.

Key considerations in constructing an SMA-based technology include determining the intended performance, the composition of the components, the structural configuration, and the biasing component (Fang et al., 2023). Despite SMA being a non-linear component, accounts indicate that the structure's response to output stays linear throughout operation. This process is executed utilizing an active influencing element, namely an antagonistic SMA mechanism, and the method to achieve linearity is established by selecting the inverse mechanical element (Xiong et al., 2021). The appropriate selection of influencing components sustains linearity in the reaction.

III. Method

Design

The suggested soft gripper's IRG fingers (Fr) are configured in a rectangular form, with two adjustable rigidity joints, as seen in Figure. 1(a). Each adjustable rigidity joint, measuring 55 mm in size, 20 mm in breadth, and 20 mm in width, is integrated into the rigid components to secure its place and prevent relative movement between the connection and the rigid elements. The joint next to the Fr is designated joint-1, whereas the subsequent joint is termed joint-2. The IRG Frs' rigid components are human phalanges and metacarpals. Two connections are positioned adjacent to the SMA wire inside the rigid sections, and the relative placements of the SMA and joints are demonstrated in Figure.1(b).

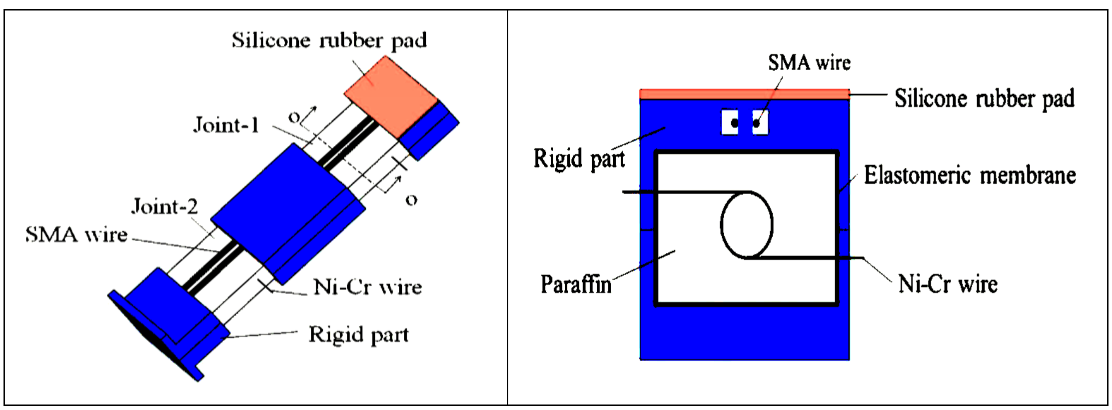

Figure 1: Proposed Design

At the room temperature, the paraffin exists in a state of solidification, rendering the joint rigid and inflexible, thereby allowing the IRG Fr to support external weights. Applying a voltage of 10 V to the Ni-Cr cable elevates the paraffin temperature, resulting in a phase transition to a liquid state, rendering the joint pliable and conforming. Additionally, the rigidity of each joint is independently adjusted by the activation of the corresponding Ni-Cr wire. Applying an electrical current of 6 V to the SMA wire at a weak point in the joint elevates temperatures to the Af, enabling the SMA wire to expand and generate a significant bending force on the joints of the IRG Frs. The persistent application of voltage to the actuating SMA wire sustains the bending of the IRG Frs until the liquefied paraffin reverts to its solid condition. The IRG Frs will maintain the distorted configurations with elevated rigidity. Once the joint stiffness diminishes due to the elastomeric membrane's rebounding pressure, the IRG Frs reverts to its previous straight position without activating the SMA cable.

Manufacturing

The suggested soft gripper comprises three IRG Frs characterized by adjustable stiffness and enhanced compliance. An IRG Fr has two elements: the varying rigidity joint and the rigid component. The soft gripper comprises five distinct materials: SMA wire, paraffin, Ni-Cr wire, rubberized silicone, etc. The actuation component utilizes SMA wire, drawing inspiration from pertinent studies. The adjustable stiffness joint, a crucial element of the IRG Fr, is constructed from silicone rubber, paraffin, and Ni-Cr wires. The rigidity of the joint is altered by heating the Ni-Cr wire immersed in the paraffin or by allowing the paraffin to cool naturally. The rigid component, constructed from PLA, links with the joint and functions as the basis. Three IRG Frs are affixed to the base at a designated angle.

The production of the soft gripper is efficiently achieved by 3D printing and shape depositing methods of manufacture. The construction process of an individual IRG Fr comprises

- Fabricate the elastomeric membranes' inferior section, measuring 2 mm in width, using a semi-closed two-part mould. All molds are produced by the 3D printer using 1.75 mm diameter.
- Forming the Ni-Cr wire into a coil to encapsulate it inside the elastomeric membranes and introducing fluid paraffin into them. It is essential to prevent the overflow of liquid petroleum.
- Pour the silicone material over the paraffin, which serves as the top layer of the elastomeric membranes for sealing, once the paraffin has cooled to a solid form. The following processes form a joint.
- Integrating the joint and rigid components produced by 3D printers, while incorporating SMA wire into the Frs.

IV. Results

The capacity to alter stiffness is a fundamental characteristic of this flexible grabber. The parameter stiffness architecture was manipulated to execute a sequential stiffness alteration to evaluate the gripper's capacity for stiffness variation. The movement of the Fr and the applied outside force are quantified. The degree of rigidity is determined from the gradient of the force versus movement graph. The actuator's results rigidity and its rigidity at the Fr's tip are defined independently. The observed stiffness fluctuation corresponds with the theoretical calculations. The adaptable gripper exhibited an end rigidity modification capacity ranging from 0.0071 to 0.061 N/mm, or a factor of 9.52. This is a significant improvement over the prior SMA variable rigidity architecture. The maximal rigidity of the SMA spring significantly exceeds that of the malleable grabber. The rigidity of the flexible grasping is restricted by the rigidity of the tendons and the soft Frs inside the gripper's cavity.

The flexibility gripper overcomes this constraint by using high-stiffness ligaments and rigid Frs; however, this compromises its communication capacity. In evaluating the application situations of adjustable stiffness bendable gripping devices, superior interaction capabilities were prioritized.

Studies exhibited the flexible grabber’s variable rigidity capacity and steady connection proficiency by manipulating diverse items. The carrying capacity of every Fr of the bendable grabber during the elevated rigidity mode is shown. All four weights utilized for the experiment are 50 g each.

It demonstrates the adaptable gripper's capability to grab things of various kinds and forms, including glass, frosting, plastics, fruits, and cardboard containers. A virtually empty tissue bag, characterized by minor stiffness, was used as the target to demonstrate the impact of the flexibility gripper's rigidity on object gripping. The flexible gripper operates in lower stiffness; the elastic gripper operates in higher stiffness. In these gripping studies, the Fr's movement remains consistent, meaning the number of rotations and the motor's torque stay unchanged.

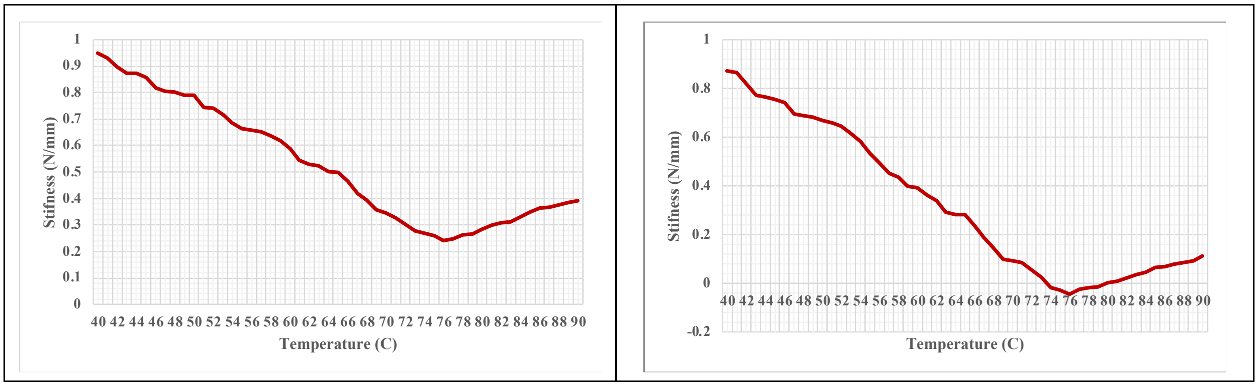

Figure 2: Stiffness analysis (a) Actuator (b) End of the Fr

This indicates that the Frs will converge on the exact location without a target. Analysis of the outcomes from the two gripping trials shown in Figure. 2(a) and (b) reveals that the lightweight mode of the flexible gripper more effectively conforms to the shape of the low stiffness item, hence minimizing the risk of damage. The optimal gripping stiffness for a specific target should exceed the minimal stiffness required to hold the target's mass. Insufficient stiffness fails to elevate the thing, while excessive stiffness harms the thing.

The article omits techniques for assessing the stiffness of things; yet, this presents no intractable obstacle. Numerous soft detectors are now under investigation to assist flexible grippers in determining the stiffness of items. The sensors will enhance the utility of adjustable rigidity flexible gripping devices.

V. Conclusion

This research presents an SMA-based IRG with variable rigidity capable of adaptable and resilient object grabbing. The soft gripper, consisting of three IRG Frs, integrates variable tension joints with rigid components, allowing soft changing and form retention capabilities. The paraffin offers an innovative approach for achieving a broad spectrum of variable rigidity in IRG. The soft gripper is effortlessly activated at reduced rigidity with greater adaptability and responsiveness. At elevated stiffness, the soft grabber can maintain steady postures to grab large items securely despite external disturbances. The IRG Frs have two primary characteristics: first, the rigidity of the soft grabber is substantially altered; second, the IRG Frs can modify their positions by adjusting the rigidity of the targeted joint and successively activating the SMA wires.

Experimental findings indicate that the suggested Fr's rigidity diminishes as the paraffin's internal temperature increases. The duration for altering the Fr's condition from high rigidity to low hardness was 70 seconds, whereas the duration for the opposite procedure was 380 seconds. The rigidity of the Frs is 0.25 N/mm at high rigidity and 0.01 N/mm at low rigidity, resulting in an 18-fold ratio. Three IRG Frs are integrated into the base to construct the soft grabber for seizing a stationary item, whereby the maximal grabbing force at elevated rigidity is about tenfold more than that at reduced rigidity.

The suggested IRG, integrating adaptable components, offers an innovative method for the gripping capabilities of soft manipulators, enhancing their compliance and efficacy in various grasping tasks. The use of SMA for actuators is predicated on their capacity for design and fabrication in small IRG systems. In contrast, the selection of paraffin for rigidity modulation is driven by its extensive stiffness range. A disadvantage of the suggested design that impacts how it's operated is the prolonged duration required to transition the connection from low rigidity to high rigidity, extending the time needed to grip items. The issue will be addressed and resolved by optimization and experimentation to efficiently reduce the time required for altering stiffness.

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