Robotic Food Handling Utilizing Temperature Dependent Variable-Stiffness Material

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Abstract

This paper presents a robotic end-effector that addresses challenges of automated robotic food handling. We utilize a variable stiffness fabric on the finger surfaces of the gripper. Depending on its temperature, the finger stiffness changes to tackle grasping food items with different physical characteristics. Hard objects can be grasped with the hard mode of the finger while a fragile object can be safely grasped with the soft mode. This gripper design was validated empirically through force and object-grasping experiments.

Keywords: robotic end-effector, food picking, variable stiffness, temperature dependence

1. Introduction

Within industry, the adoption of robotic automation is driven by the promise of heightened efficiency and the reduction of laborious, repetitive tasks that can exert both mental and physical strain on humans [1]. The food industry is a continuous source of opportunities for advancements in automation. Successful automated food handling can improve product quality and production rates [2], however, is a challenge due to inherent inconsistencies in food size, texture, and delicacy [3]. The automated processes may take significant time or fail to adjust for these variances. This paper addresses these challenges by utilizing a compact, mechanically simple design that takes advantage of the dynamic control of its applied force and stiffness variability. The adjustable compliance of the device's material is used in combination with force feedback sensors to successfully eliminate the chance of bruising that pinching or other enclosing end-effectors can cause [2]. Force feedback or tactile sensors are commonly used in industrial robotics [4], allowing the design to remain industry compatible. The goal of this paper is to demonstrate the potential of utilizing this material to handle items requiring different amounts of applied force by only altering the temperature exposed to the gripper - eliminating the need for extensive or challenging control procedures required by other soft robotic grippers [5]. We attached the variable stiffness material to the finger surface of a two-fingered gripper and the compliancy increases as the temperature becomes higher. We demonstrate the gripper can successfully adapt to grasping a variety of food materials by changing the finger stiffness according to the stiffness properties of food. The effectiveness of the proposed gripper is verified by experimental results.

2. Related Work

Food items that are heavy, slippery, fragile, or have a minimal-height profile commonly experience grasping difficulties with currently proposed gripper designs [6], [7]. This gripper is compatible with objects having these attributes that other developed variable-stiffness general grippers are not [8]. The design proposed by A. Pettersson et al. utilizing magnetorheological fluid [9] also maintains a secure grasp through a gripper with high and adaptable compliance. However, an improvement this paper introduces is the compactness of the design — a crucial attribute for practical deployment in confined spaces [10]. Other grippers that grasp food items by the side surfaces require the object's size to be predetermined [10]. The paper by G. Endo et al. [11] required the height of the samples to be known and constant. Food items can vary in size and shape even between samples of the same food, different apples for example, and this requirement limits the success and robustness of the gripper. The design proposed in this paper eliminates that requirement through its dynamic force application and compatibility with force feedback implementation. The gripper by R. Maruyama et al. [12] was successful in handling fragile and soft food items but required predetermination of the required force to apply to obtain a successful grasp. The design of this gripper allowed for more innate tolerance in this aspect, allowing it to work with food items not encountered previously.

3. Design

The goal of the design was to achieve both simplicity and effectiveness. Simple mechanical design minimizes the risk of contamination during usage due to component separation [10] and the gripper's achieved compactness, increases the ease of adoption in practical scenarios [10]. Relying on the variability of the gripper's compliance from temperature exposure as the means of adapting the force application decreases the requirement for precise mechanical human adjustments thus not requiring an upskill in labour [13].

3.1. *Concept*

The robotic end-effector incorporates a variable stiffness fabric as its primary functional component and is the main contributor to the gripper's low mechanical complexity. This fabric exhibits temperature-dependent properties, becoming more flexible as the temperature rises and stiffer as it decreases. When controlled, this dynamic behaviour can be used to handle objects with different structural integrities. Explicitly, the end-effector can be subjected to higher temperatures when the target for transportation is fragile or soft as the fabric would apply less force while in this more compliant state. Likewise, when the fabric stiffens when exposed to lower temperatures, the gripper can exert greater force, making it suitable for firmly grasping rigid food items. This ultimately allows for a secure hold and movement without causing deformation or damage to samples in both scenarios.

Between grasps, warm temperature can be applied to return the fabric to its neutral position. This methodology of subjecting the gripper to warm temperature after each grasp will be applied during the experiments used in this paper and can be seen in the flow chart of Fig. 1.

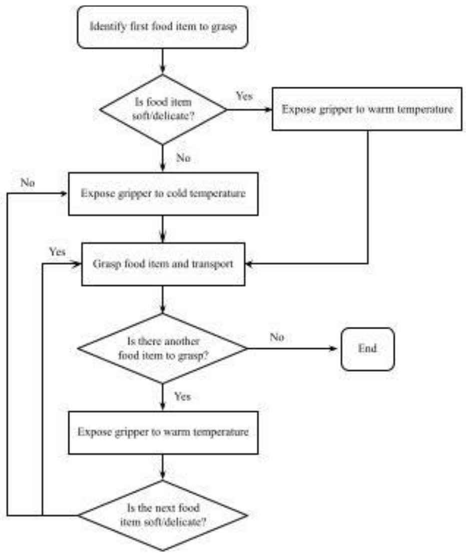

Fig. 1. Decision flow chart when picking an item.

3.2. *Implementation*

The base structure of the gripper was created through CAD software and was 3D printed (Fig. 2) with the fabric attached via sewing. Aside from providing a strong foundation, the base material is inconsequential to the functioning of the gripper. It can thus be substituted for a hygienic material such as stainless steel [14].

Fig. 2. Gripper physical implementation and CAD model: (A) Front Profile, (B) Three Quarter Profile, and (C) CAD side profile of gripper (i) 73.7°, (ii) 20.5mm, and (iii)2mm.

An essential feature of the gripper base is the curved nature at the bottom which guides the fabric beneath the item and provides support to the bottom when the gripper encloses it. This creates a secure position between the fabric and the food item and prevents the item from slipping through the bottom during transportation. To prevent the loss of the curved formation (Fig.2.B), the fabric was attached to the base while exposed to warm temperature. This was a method of pre-tensing the fabric to ensure the curved position remains taut as the fabric's innate stiffness is reduced at higher temperatures.

The 2mm between the bottom face and the fabric (Fig. 2.C.iii) enables effective grasping of items with narrow height profiles. The angle of the stem and the radius of the inner curvature of the base are 16.3° and 11mm respectively. These values were chosen to minimize the gap between the hands of the gripper and maximize the amount of fabric held vertically. Minimizing the gap between the hands increased the minimum width of food items that could demonstrate the enclosing property of the gripper i.e. in Fig. 2.C.ii. Maximizing the amount of vertical fabric increases the area that applies uniform force along the side of an object. Future design iterations will investigate methods of allowing these dimensions to be variable, increasing the versatility of the gripper.

4. Experiments

The first experiment executed was a force gauge experiment to observe the force applied to the fabric depending on displacement and fabric temperature. The second was a set of demonstrative experiments to display the success of the gripper in a variety of arrangements and sample types. Water was selected as the stimulus medium as it possesses a high heat capacity, meaning it requires a relatively high amount of energy to change its temperature by one degree [15]. This ensured it maintained at a considerably stable temperature throughout the execution of an experiment sequence.

4.1. *Force gauge experiment*

The force gauge experiment was conducted with the gripper to analyze the force applied to an object over time under two temperatures and at three final displacement positions. Specifically, 30°C and 67°C, and 10mm, 20mm, and 30mm respectively. The experiment setup consisted of the force gauge sensor mounted onto a cart of a linear motion apparatus with a blocking cart positioned at the desired displacement away from the force gauge's starting position (Fig. 3). To depict the behaviour throughout the different segments of a standard pick-and-place operation, the carts were:

- manually moved the same velocity until the final displacement to mimic the initial grasping,
- maintained its position for approximately 10 seconds to simulate the effect the gripper would have during the time required for transportation,
- and then released, as if the object has arrived at its final location.

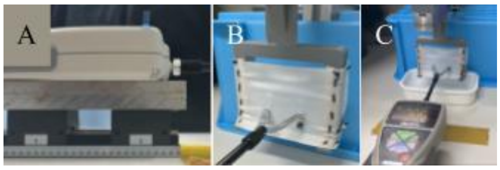

Fig. 3. Force gauge experimental set-up: (A) gauge cart and displacement blocker cart on track, (B) gripper and gauge prong, and (C) entire force gauge setup.

4.2. *Food picking experiment*

The goal was to showcase and verify the final design's practical ability to handle a variety of characteristics - heavy, slippery, fragile, brittle, flat, and rigid. Accordingly, corresponding food items were used during testing as seen in Table 1 and Fig. 4.

Table 1. Food Item Characteristics and Water Temperature Assignment

Item	Characteristics	Water Temperature
A	Heavy – 66 g	Hot
B	Hard, non-uniform vertical profile	Cold
C	Malleable, slippery plastic surface	Hot
D	Soft, narrow	Hot
E	Fragile	Hot
F	Hard, spherical	Cold
G	Brittle	Hot
H	Hard, narrow – 12.95 mm	Cold

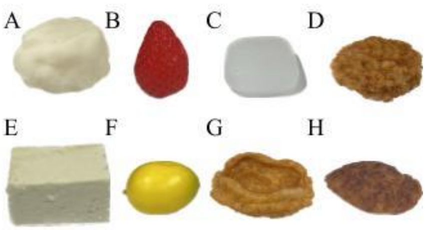

Fig. 4. Experimental food items.

The gripper was exposed to temperatures depending on whether the physical properties of the target object are better suited for greater or weaker applied force during grasping. Each food item was tested individually on the platform as well as in more complicated combinations including multiple items on the platform grasped in continual sequence and objects in a stacked formation (Fig. 5). A successful grasp is defined in this paper by moving a sample from its initial to final location without causing damage or the item slipping mid task.

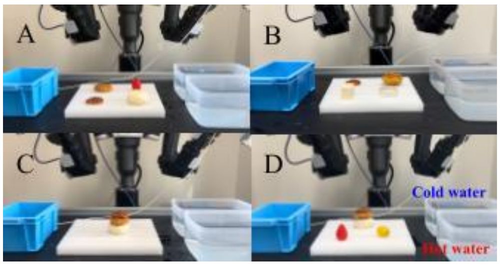

Fig. 5. Experiment arrangements: (A) Sequential (B) sequential (C) stacked, and (D) combined stacked and sequential.

The gripper was attached to an industrial robot and integrated with software that controlled grasp planning and execution while employing a depth camera for the identification of item locations. The gripper's linear actuator operates using force feedback to determine when an adequate clamping width has been achieved.

5. Results

5.1. *Force gauge*

The results are seen in Table 2 and Fig. 6 for each final displacement value, the fabric exposed to the cooler temperature applied more force compared to when exposed to a higher temperature. This confirms the premise of the gripper i.e. force applied increases as the temperature of operation decreases and vice versa.

Table 2. Force Gauge Experiment Key Values

Displacement	Max Force	Plateaued Force	Velocity
Hot Temperature - 67°C			
10 mm	0.6 N	0.4N	1.429 mm/s
20 mm	1.8 N	1.3 N	1.818 mm/s
30 mm	3.8 N	2.8 N	1.887 mm/s
Cold Temperature - 30°C			
10 mm	2.8 N	0.7 N	1.613 mm/s
20 mm	6.5 N	2.5 N	1.538 mm/s
30 mm	9.6 N	3.8 N	1.657 mm/s

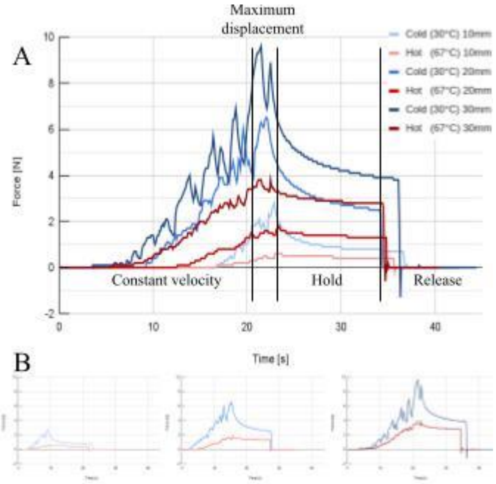

Fig. 6. Results of the force gauge experiment plotted: (A) all displacements and (B) each displacement individually.

The constant velocity of the gripper movement meant that time and displacement differed by a constant factor. Therefore, while accounting for this factor, modelled relationships with respect to time can proxy relationships with respect to displacement. The constant velocity portion of the experiment was isolated and time vs. force - or equivalently displacement vs. force - was analyzed using both linear and second-order polynomial models. A strong second-order polynomial relationship was determined between the displacement of the gripper and the force applied as seen with the R-squared values in Table 3. In future work, an analytical model will be formalized to depict the force a sample will experience depending on the item's width (i.e. the gripper displacement) and considering the temperature.

Table 3. Force Gauge Experiment Model Performance

Displacement	Linear Model	Polynomial Model
Hot Temperature - 67°C		
10 mm	0.909	0.927
20 mm	0.971	0.971
30 mm	0.969	0.983
Cold Temperature - 30°C		
10 mm	0.931	0.932
20 mm	0.957	0.962
30 mm	0.888	0.936

When the final displacement is achieved, the force quickly decreases and then plateaus. This is ideal as there is no prolonged period of unnecessary high force applied after the fabric has molded to the shape of the target. As seen in Table 2, there is a directly proportional relationship between this plateaued value and the displacement of the gripper and an inversely proportional relationship between the force and temperature. Given that in practice, the displacement of fabric - i.e. a target's width - is immutable, plateaued force can be controlled with temperature. The relationship between this plateaued force, the temperature of the fabric, and the final displacement value can be further investigated to optimize and formalize the temperature used for various targets with different ideal handling requirements.

5.2. *Food picking*

The gripper was successful in grasping and transporting each food sample from its respective initial positions to their final destinations. Fig. 7 shows the end-effector gripping pose for each food item from Fig. 4 and Fig. 8 shows the gripper throughout experiment D from Fig. 5.

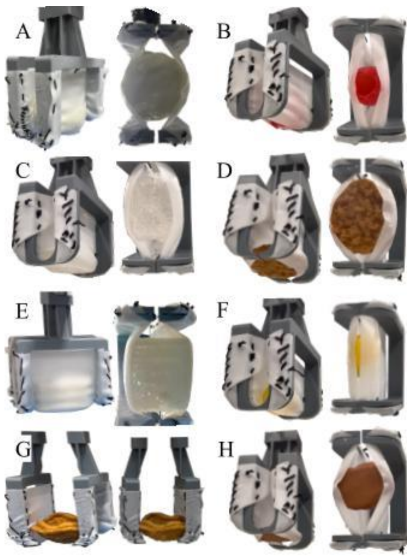

Fig. 7. Gripping snapshots of each food item.

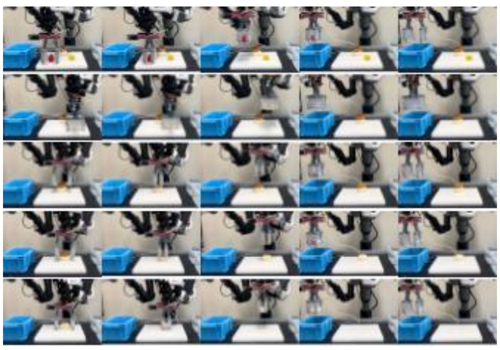

Fig. 8. Snapshots during the execution of experiment D.

Unsuccessful grasping attempts were seen with samples with widths comparable to the maximum open position width of the gripper and with the samples in experiments with. These failures can be attributed to incorrect positioning of the gripper prior to closure. This could be corrected by further developing the method of identifying the desired initial location through the calibration matrix of the software. Additionally, the gripper can be modified to have a bigger difference in the open position width of the gripper compared to the size of the samples to have larger tolerance limits to account for the margin of error between generated and desired locations.

6. Conclusion

The robotic gripper proposed in this paper was designed to utilize its variable stiffness property to successfully grasp food samples with commonly difficult-to-handle features without causing damage and while maintaining mechanical simplicity and compactness. This concept was formed on the basis that allowing the material of the gripper to do the bulk of adapting to the shape and delicacy of a given sample permits the gripper to be functional without human intervention or immediate control. The gripper's variable force application was validated in a force gauge experiment conducted under two temperature conditions and at three displacement values, confirming the viability of our design concept. The practical capabilities of the gripper were demonstrated experimentally with the gripper performing food-picking sequences involving a diverse range of items, each possessing distinct properties and arranged in both sequential and stacked configurations.

In future developments, enhancing the gripper's versatility could involve the implementation of variable width and height dimensions to accommodate an even broader range of items. Moreover, expanding the range of temperatures utilized for more customized force applications can be investigated for more tailored handling of samples.

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