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Implementation of a Remote Center of Motion Robot Finger with Tactile Sensors in the Joints

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***Abstract*— Robot grippers and hands are commonly used to grasp various objects. However, for multi-link fingers, it is challenging to cover the joints with tactile sensors, which limits the safety and sensitivity of such fingers. In the current paper we use a remote center of motion (RCM) mechanism for the joints, which enables us to cover also the joints completely with soft and thick tactile sensors, in particular distributed 3-axis sensors. The RCM joints are implemented as 6-bars, and we evaluate their robustness in simulation. A real implementation of the gripper is tested by grasping various objects, and the resulting tactile sensor readings are presented.**

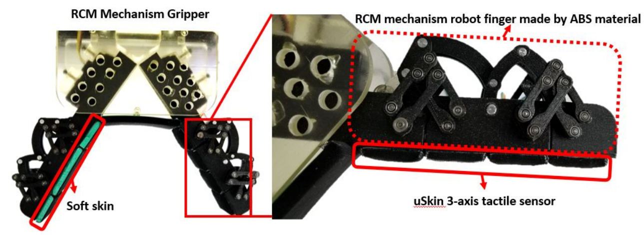

Fig. 1: Proposed RCM Mechanism Robot Finger with uSkin Tactile Sensor.

I. Introduction

Robotic grippers and hands are commonly used to grasp various objects. Multi-link fingers have the benefit of being able to wrap around the object, and thereby increase the contact surface, which reduces the required contact pressure and enables more delicate and dexterous grasping. Moreover, covering fingers with soft and sensitive skin is beneficial for sensitive grasping. While sensor solutions for soft skin exist, however, it is typically difficult to cover the joints with such sensors. Therefore, such fingers have substantial gaps in the soft and sensitive covers for the joints. Contacts in these areas can go unnoticed, no soft material cushions the fingers, and small objects can get squeezed in the joints.

Stretchable sensors could cover joints [1] [2], but existing stretchable skin sensors typically have limitations, in particular they cannot measure distributed force vectors, only distributed 1-axis forces, and including the digitization electronics in stretchable material is still challenging. Furthermore, to cover the palmar side of typical joints, which is the one typically in contact with the grasped object, the sensors have to be thin, which limits the softness that can be implemented.

In the past, our lab developed the uSkin sensors [3] [4], which can measure distributed 3-axis forces, and each 3-axis sensor already provides digital output, enabling to put many sensors on the same digital communication bus, vastly reducing the number of required cables to readout the sensor signals. uSkin is 4 mm thick and soft. However, uSkin is not stretchable.

Therefore, in previous work we introduced the concept of a remote center of motion (RCM) mechanism for the joints of a robotic gripper [5]. We furthermore implemented adaptive coupling of the RCM joints. In the current paper, for the first time, we implement tactile sensors that completely cover the palmar side of the finger. Overall, the gripper presented in this paper has the following benefits:

- The palmar side of one finger is completely covered with soft and sensitive skin. To the best of our knowledge, this is the first time this has been achieved. The softness aids the grasping of delicate objects, and it is guaranteed that soft material will be in contact with the grasped object, irrespective of the contact location on the palmar side of the finger. The sensors provide feedback about the contact with the object, again regardless of the contact location. Both softness and sensors enable safe and delicate grasping.
- Because also the joints are covered with the sensors, more information about the contact with the object is available, potentially benefiting machine learning approaches (for example for tactile object recognition) or aiding even just simple feedback control. The surface area, and therefore the potential contact and sensing area, does not get smaller when the finger flexes.
- The thickness of the skin that can be implemented with RCM joints has no principal limit. In our case, we implemented 4 mm thick uSkin, which provides distributed 3-axis measurements. Thereby, one finger, which has 2 joints and is about 90 mm long and 27 mm wide, provides 64 3-axis measurements.
- There is no risk of pinching or squeezing the grasped object in the joints between the finger segments when flexing the fingers.
- Adaptive joint coupling between the two joints in each finger is implemented. Therefore, only one actuator suffices, and the fingers wrap automatically around various object shapes.

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The rest of this paper is structured as follows. Section II presents related work on robot joints and tactile sensors. Section III introduces the gripper design, the control architecture, and shows results on the simulation of the gripper when loaded. Section IV presents grasping experiments with the real gripper. Section V draws conclusions and discusses possible future work.

II. Related Works

Many grippers and multifingered robots have been designed [6] [7], and they employ various actuation techniques. The actuators can be placed directly in the fingers or remotely in the palm or forearm. Various transmission techniques have been used, including tendons, linkages and cams, various gears, belts, twisted strings and flexible shafts. If the actuators are placed directly in the fingers, the actuator can be either in the joint [8] or in one of the links [3], and rotary or linear actuators can be used. Placing the actuator close to the joint increases the size and mass of the critical distal phalanges, but decreases the transmission chain complexity.

Underactuation is commonly employed, especially for the distal and proximal interphalangeal (DIP and PIP) joints, similar to humans. Underactuation in general creates challenges for dexterity, but has the benefit of passive shape adaptation. It can be achieved in various ways, for example with tendons or with linkage driven mechanisms, with or without springs. Underactuation is discussed for example in [9] [10] [11].

To realize ordinary revolute joints in robot hands, rotary bearings at the joints are used, and they function in a reliable and space efficient way. Furthermore, elastic elements like springs have been used as joints [12] [13]. Moreover, another type of non-revolute joint with contact-aided surfaces has been used [14] [15] [16] [17]. However, all these joints create challenges for the coverage with skin, as the surface area changes with the joint angle. It is not feasible to completely cover these joints with a thick, flat, continuous skin.

Regarding tactile sensors [18], thin tactile sensors exist and have been integrated for example in the Gifu hand [19], which could help to cover the hands with sensors without increasing the finger length. Furthermore, stretchable sensors exist [1] [2], and have been used to cover the joints of arms. However, even with thin, stretchable sensors it seems to be challenging to cover small finger joints [20]. Furthermore, thicker sensors like uSkin could provide more information such as distributed force vectors, and thicker soft material is beneficial for increased compliance even without tactile sensors.

Recently, there has been an increasing number of soft robotics grippers and hands [21] [22] [23], which unlike traditional robots do not have rigid links and defined joints, and therefore are highly compliant and have an excellent ability to passively adapt to the grasped object, making them an attractive choice for many applications. However, precise and strong manipulation is challenging with soft grippers, as well as the coverage with dense tactile sensors like uSkin.

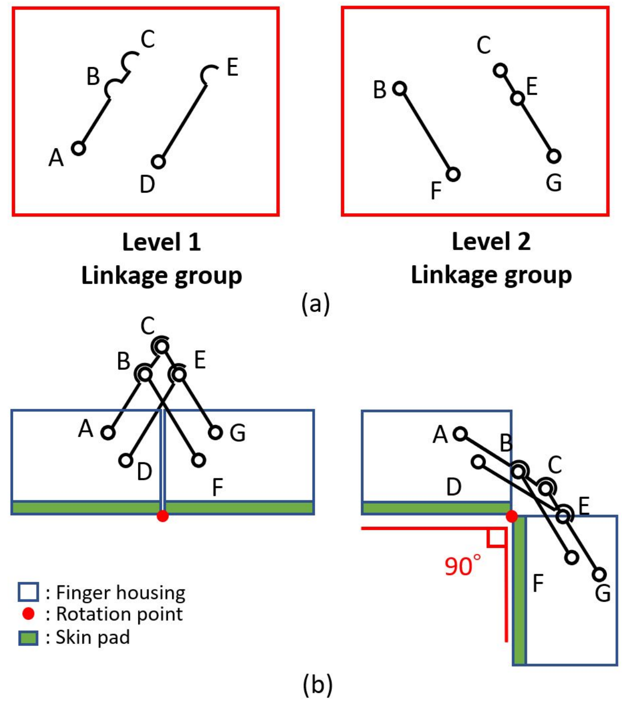

Fig. 2: RCM Mechanism

RCM mechanisms [24] can achieve pivot points outside the mechanical joint structure. They have been used for example for surgical needle-insertion devices [25] and for exoskeletons [26] [27], for which it is crucial that the exoskeleton's center of rotation matches the human's one. A straightforward method is to use a circular slider to implement a circular-prismatic joint [24], and the exoskeleton in [26] used a circuitous joint. Both these mechanisms use sliders, which are challenging to produce in a sturdy and space efficient way. Another way to implement an RCM mechanism is with a 6-bar [24] [27], which relies only on common rotary bearings. Using an RCM mechanism for robot fingers could achieve the benefits discussed in the introduction, but to the best of the authors' knowledge has previously not been used for robot hands or grippers.

III. Hardware Description and Simulation

This section will first describe the proposed robot finger design and the integration of the tactile sensors. Subsequently, we present the stress test simulation of the proposed joint mechanism.

A. Combination of Gripper and Tactile Sensor

The conceptual design of the joint can be seen in Fig. 2. Instead of a conventional robot finger, which has the rotation points located inside of the finger, implemented with revolute joints at the rotation points, the proposed design has the rotation point located outside the finger structure. The position of the rotation point was adjusted to the desired skin thickness. Therefore, in our case, the pivot point is 4 mm apart from the finger housing. This design allows the finger

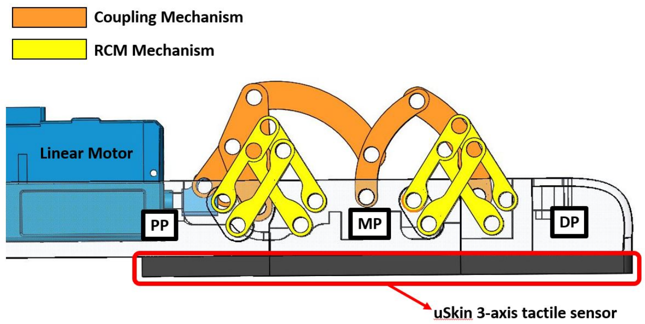

Fig. 3: Robot finger with RCM joints, a joint actuation coupling mechanism, and tactile sensors

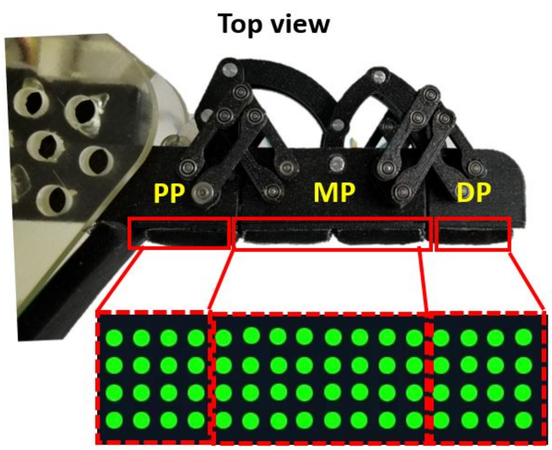

Fig. 4: Integration of tactile sensors in robot finger. Each green dot represents one 3-axis tactile sensor.

segments to rotate without creating a significant gap between the skin of each phalange. Fig. 2 shows the diagram of the 6-bar which implements the RCM mechanism in our finger.

Fig. 2(a) shows the links attached to the two separate phalanges. Letters A-G represent rotary joints of the linkage. In both groups you can see the letters B, C, and E, as they represent the same joint, as shown in Fig. 2(b). The left side of Fig. 2(b) shows the extended state, and the right side shows the flexed one. The linkage includes 6 links, which are A-C, D-E, B-F, C-G, A-D and F-G. A-D and F-G are formed by the housings of the corresponding phalanges. Furthermore, there are 7 joints in the mechanism. Thus, the mobility equals to 1, proving that each of the 6-bar mechanisms forms 1 DOF. The red dot shows the location of the virtual joint corresponding to this 1 DOF.

We place two 6-bar mechanisms in each finger, one for each finger joint (DIP and PIP), enabling 2 DOF for each finger, see Fig. 3. Two more 6-bar mechanisms are placed in parallel to the first two, on the other side of the finger, which does not influence the number of DOF of the finger, but increases the structural stiffness. Furthermore, adaptive joint coupling is implemented, as shown in orange in Fig. 3 and described in our previous paper [5].

For this paper, we integrated skin sensors on the palmar

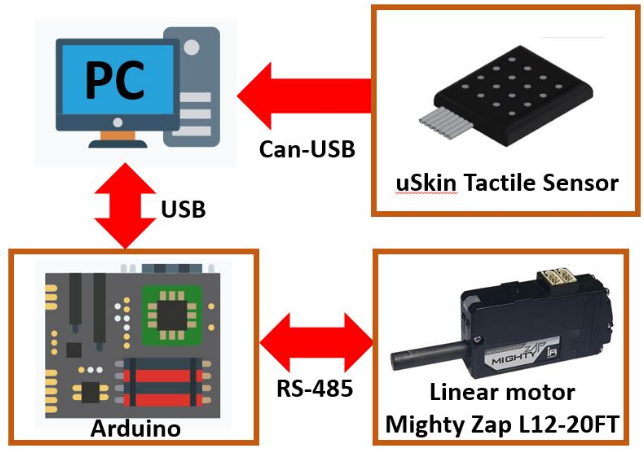

Fig. 5: Flow chart of the actuation and sensor system

side of one finger. In particular we integrated four flat uSkin modules [3]. Due to the joint mechanism, the sensors modules can be placed directly next to each other, and the complete palmar side of the finger is covered with skin sensors, as can be seen in Fig. 4. In particular, 4 uSkin modules are used to cover the finger. The distal phalange (DP) and proximal phalange (DP) have one module installed each, while the medial phalange (MP) has 2 modules. Each uSkin module includes 16 3-axis tactile sensors in an area of 26.6 mm $\times$ 22.40 mm. The sensors are soft (but not bendable due the integration of a rigid PCB) and the sensor surface is gecko tape. Each uSkin module provides digital output via an I2C connection. Other specifications can be found in Table I. Section IV will present the sensor readings visualization when the gripper is grasping various objections.

B. Architecture of the system

This section introduces the communication configuration of the gripper actuation and the tactile sensor system, as shown in Fig. 5.

- Tactile skin sensors: The output of each sensor module is digital via I2C. One custom, small-sized microcontroller is used for each sensor module. The microcontrollers are daisy chained and provide output via the CAN protocol. One of the 4 microcontrollers is connected to a PC via a CAN-USB converter.
- Linear motor: A linear motor from iR Robot (Mighty Zap, L12-20F-3) is used. Every finger is equipped with

TABLE I: Specifications of distributed 3-axis sensors

Sensor per module	16 sensors
Peak Efficiency Point	Each individual sensor measures 3-axis(x,y,z)
Size	4.7 x4.7 mm center to center distance, 4mm thick
Max shear force	430 gf
Max normal force	1800 gf
Resolution shear force	0.1 gf
Resolution normal force	1 gf

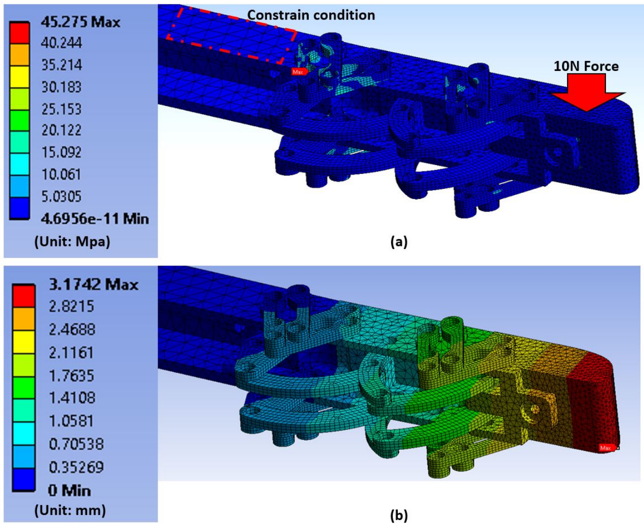

Fig. 6: Simulation of shear force applied on robot finger: (a) equivalent stress test, (b) deformation test

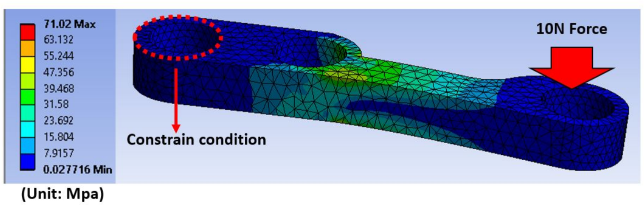

Fig. 7: Equivalent stress test on single part of 6-bar mechanism

one motor for independent actuation. An Arduino Due is used to control the motors via RS-485. The Arduino Due is connected to the PC via USB.

C. Simulation of RCM mechanism and it's material

The 6-bar mechanism enables the integration of tactile sensors at the joints. However, the mechanism also has downsides, in particular it includes 4 relatively thin bars, which could limit the achievable stiffness of the finger. Therefore, in this section we investigate the robustness of the finger.

As an improvement compared to our previous design [5], in the current paper we use 3D-printed ABS plastic, which is stronger than the previously used 3D-printed Keyence Agilista AR-M2 material.

ANSYS is used to simulate the situation in which the gripper is grasping a 2 kg heavy object from the side. As the gripper has 2 fingers, 10 N shear force is applied to the simulated finger, with the material setting being ABS. Fig. 6(a) shows the equivalent stress test when applying 10 N shear force at the fingertip area. The restraint condition is on the proximal phalange, as this part is fixed to the sturdy gripper housing. It can be seen that most of the stress accumulated in the 6-bar linkages. The maximum observable stress is around 10 MPa (10 N/mm2), which is lower than the maximum stress that ABS material can stand (about

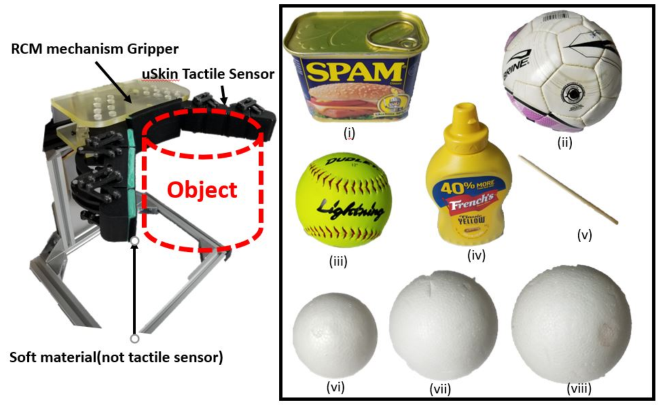

Fig. 8: Evaluation method and objects for grasping task: (i) SPAM can, (ii) volleyball, (iii) baseball, (iv) mustard bottle, (v) chopstick, (vi) D70mm ball, (vii) D100mm ball, (viii) D120mm ball

46 MPa). Therefore, the whole structure still remains solid and secure.[1] Fig. 6(b) presents the deformation test, again while applying 10 N shear force. Respective to the blue zone, the red area is deformed (shifted) by around 3.1 mm. Even though the finger is deformed, it still remains intact according to results from Fig. 6(a).

According to the results from Fig. 6, and as expected, the bars are the weakest parts of the whole finger. Therefore, we perform another evaluation for one bar specifically. The result is shown in Fig 7. While in the previous test the load of 10 N was distributed over several parts, and therefore each part had to withstand less than 10 N, in this test 10 N was applied to only one bar. As can be seen from the yellow-green area in Fig 7, a tensile stress of around 42 MPa occurred in the middle of the part. As a material property of ABS material, its tensile strength is 46 MPa, which means that also in this case the part can keep its structural integrity.

IV. Grasping Experiment and Result

In this experiment, the actual gripper grasps 8 kind of objects (Fig. 8). The corresponding uSkin measurements were recorded, and are shown in Fig. 9. 64 3-axis measurement were taken, corresponding to 4 uSkin modules, as explained above. For the visualization, the size of a green dot corresponds to normal force, and the displacement in x- and y-direction corresponds to the shear forces. The chopstick was pushed against the finger to show the response to thin objects. In general, even if the contact occurred at a joint, the uSkin sensors registered the contact.

V. Conclusion and Future Work

This paper presented an RCM joint mechanism which enables to integrate skin sensors at the joints. Because also the joints are covered with sensors, no contact goes unnoticed, and overall more information about the contact with the object is available. Adaptive joint coupling was

[1] ANSYS indicates that the maximum stress is 45.275 MPa, but the area is too small to be observable, and even that would be below 46 MPa.

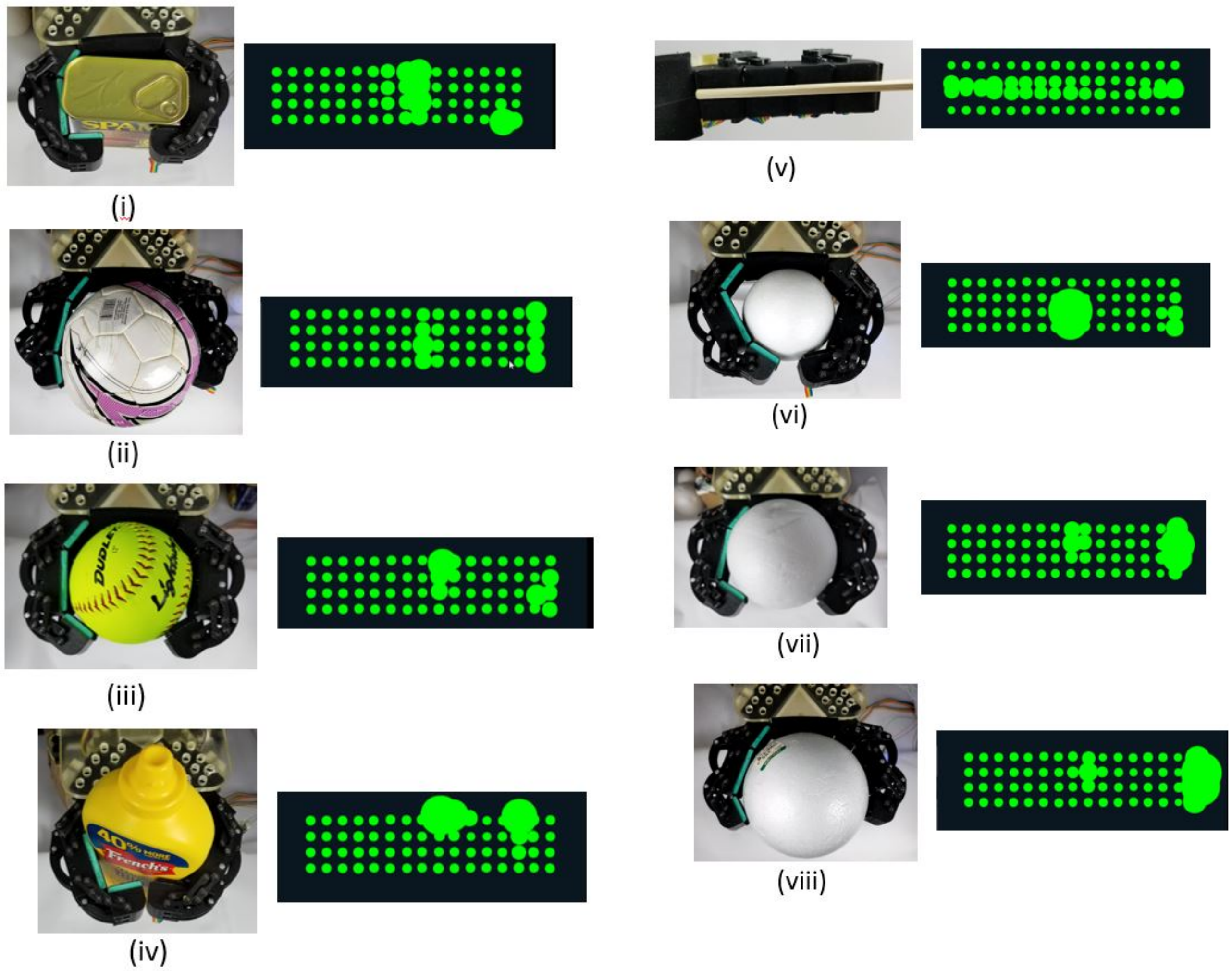

Fig. 9: Grasping different objects with visualization: (i) SPAM can, (ii) volleyball, (iii) baseball, (iv) mustard bottle, (v) chopstick, (vi) D70mm ball, (vii) D100mm ball, (viii) D120mm ball

also implemented, as already discussed in our previous publication [5]. The robot grasped 8 different objects, and the resulting sensor activation was visualized.

A potential downside is reduced structural stiffness due to the RCM linkage. Shear forces of 10 N acting on one finger were studied in simulation, and while the finger deformed by 3.1 mm, it remained within its tensile strength.

Another potential downside is that the robot finger kinematics are different to human fingers, in particular, the finger surface does not get shorter as the finger flexes, and therefore grasping small objects between the distal and proximal phalange is not possible. Nevertheless, we could demonstrate that the hand could grasp various objects. Indeed, we assume that less shear force on the object gets produced, as the finger segments are not shortening as they are grasping the object.

Moreover, continuous coverage of the sides and backsides of the fingers is not possible with our method. Overall, however, we believe that the downsides are not prohibitive for a wide array of applications.

In future work we will use metal instead of the 3D printed material, reduce the size of the fingers, and create an anthropomorphic multi-fingered robot hand with RCM joints.

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