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A Compact, Cable-driven, Activatable Soft Wrist with Six Degrees of Freedom for Assembly Tasks

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***Abstract*— Physical softness has been proposed to absorb impacts when establishing contact with a robot or its workpiece, to relax control requirements and improve performance in assembly and insertion tasks. Previous work has focused on special end effector solutions for isolated tasks, such as the peg-in-hole task. However, as many robot tasks require the precision of rigid robots, and their performance would degrade when simply adding compliance, it has been difficult to take advantage of physical softness in real applications. A wrist that could switch between soft and rigid modes could solve this problem, but actuators with sufficient strength for this state transition would increase the size and weight of the module and decrease the payload of the robot. To solve this problem, we propose a novel design of a soft module consisting of a cable-driven mechanism, which allows the robot end effector to change between soft and rigid mode while being very compact and light. The module effectively combines the advantages of soft and rigid robots, and can be retrofitted to existing robots and grippers while preserving the characteristics of the robotic system. We evaluate the effectiveness of our proposed design through experiments modeling assembly tasks, and investigate design parameters quantitatively.**

I. INTRODUCTION

Human-like manipulation ability has long been a main goal of robotics research. As such, the behavior of humans in solving manipulation and assembly tasks has been a consistent source of inspiration for robot design [1]. When performing assembly tasks, humans bring objects into contact softly and effortlessly maintain their contact using our in-built compliant actuators and complex force control. However, contacts with the environment still pose large difficulties for current rigid robots [2], so that contact is avoided or simplified whenever possible. It stands to reason that softness would help robots perform more smoothly and human-like, for example by reducing the impact of the collision between two parts and compensating for hand pose errors [3]. Softness in robots can be realized either by passively compliant, soft mechanisms, or active compliance control.

Active compliance control involves the use of force/torque control methods to control the force robots exert on the environment and contact. These methods typically require

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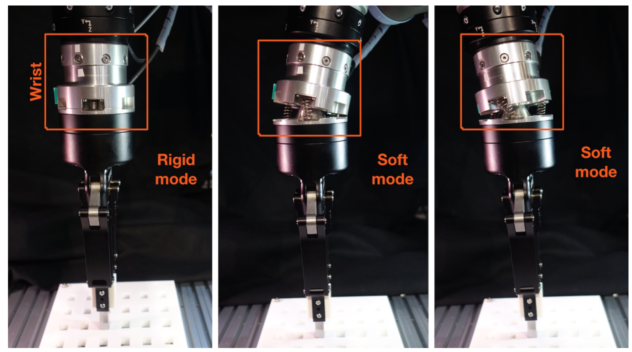

Fig. 1. A prototype of the proposed wrist design with six passively compliant degrees of freedom, in rigid and soft mode. Rigid mode has no compliance but high precision (left). Soft mode has physical compliance and error compensation for assembly tasks (middle and right). These pictures demonstrate the flexibility during a peg-in-hole task.

additional sensing modalities such as force/torque sensors, acceleration sensors, and additional motor encoders, as well as a high-frequency controller [4]. Thus, actively controlled robot systems tend to be more complex and expensive.

By contrast, robots with physically soft parts absorb impacts and inherently react quickly to force changes, even if the controller's accuracy and frequency are low [15]. Thus, the complexity and cost of a robot with physical compliance can be lower than that of a rigid robot reproducing similar levels of softness through active control.

A number of robotic arms with soft parts have been proposed, such as Rethink Robotics' Sawyer [16] using series elastic actuators, or the Shadow Dexterous Hand [17] using wire-based underactuated joints. These robots implement softness in different locations, such as the arm, wrist, hand, or fingers. Among these possible placements, we surmise that the level of the wrist has a number of highly desirable properties. First, the wrist flange is a standard interface in numerous robots, allowing a soft wrist module to be easily integrated into existing systems. Second, the closer to the robot base (the earlier in the kinematic chain) softness is added, the more likely it is to be at odds with the position control accuracy of the motors driving the robot, as it requires the joints not only to function as power train components, but also to provide physical softness, thus causing them to become more complex and expensive [18]. Third, compliance at the finger level has a limited stroke, and the implementation can be complex due to space constraints. By contrast, a compliant wrist can have a long stroke of multiple mm, which should be sufficient to compensate and

TABLE I

COMPARISONS BETWEEN EXISTING DESIGNS AND OUR PROPOSAL.[1]

Article	Type	Dimension [mm]	Stroke(x-y) [mm]	Stroke(z) [mm]	Stroke($R_x R_y$) [deg]	Rigid Lock	Application
[5]	RCC(5DoF)	-	-	-	-	-	Vertical peg-in-hole
[6]	RCC(5DoF)	$\phi 235 \times 86$	±4.6	5.1	-	-	Vertical peg-in-hole
[7]	RCC(5DoF)	-	-	-	-	-	Vertical peg-in-hole, pick&place
[8]	6DoF	-	-	-	-	-	Edge tracking, Insertion
[9]	6DoF	$\phi 107.95 \times 76.2$	-	-	-	-	-
[10]	6DoF	$\phi 70 \times 64$	-	-	-	-	Vertical peg-in-hole
[11]	6DoF	$\phi 210$	-	-	-	-	Vertical/Horizontal Chamferless Peg-in-hole
[12]	6DoF	-	±1	10	±1.63	✓	Vertical peg-in-hole
[13]	5DoF	-	±1.7–2.2	-	±0.3–1.1	✓	Vertical/Horizontal peg-in-hole
[14]	3DoF	$\phi 165 \times 86$	-	-	-	-	Surface exploration
Ours	6DoF	$\phi 75 \times 60$	±6.35	11	±8	✓	Approach, picking, and peg-in-hole

absorb larger errors and impacts.

Making a compact soft module is not trivial. The soft wrist proposed in [8] is large, as it used six joints for its six passive degrees of freedom (DoF), resulting in a large number of individual parts. Based on these considerations, and the design paradigm of separating functions into independent components [19], we chose to pursue a compact robot wrist module.

The main contribution of this paper is the proposal and evaluation of a novel soft robot wrist design which offers:

- a compact size and low weight, as no actuator is contained in the wrist,
- six-DoF passive compliance using a spring array allowing up to ca. 10 mm deflection, and
- a locking function to switch between the soft and rigid state using a wire-driven mechanism.

The appearance and behavior can be seen in Figs. 1 and 3.

The rest of this paper is structured as follows. We summarize related work in Section II, propose our wrist in Section III, describe our experiments using a robot equipped with the wrist in Section IV, and conclude our results in Section VI.

II. RELATED WORKS

There are two main paradigms to realize softness or compliant behaviors in robots: active compliance, and passive compliance using physical softness. Below, we provide a brief overview of related works on the latter.

Wang et al. compared active and passive compliance in mechanical assembly tasks by robots [20], providing evidence for the intuition that the physical response of passive compliance is faster than using sensory feedback in active compliance. While there are many types of passive compliance such as jamming hands [21], compliant wrists [5], continuous arms [22], and soft arms [18], Laferriere et al. [14] posit that compliant wrists have the advantage of being retrofittable to existing robot arms and hands, as well as versatile, as the dexterity of existing grippers can continue to be used. Thus, we focus on physical softness implemented on the robot wrist.

Many researches have shown that wrist compliance is effective in automatic assembly tasks including the peg-in-hole insertion task. Advantages of passive compliance such as the relaxation of geometric uncertainties in the part position, protection from damage caused by impact forces, and reduction of jamming or wedging were evaluated in [5], [11], [23].

While various mechanism designs have been investigated, remote center compliance (RCC), which shifts the center of compliance towards the tip of the peg is the most significant [5]–[7]. While the mechanism is simple enough to fit into a compact wrist, the stroke is short, allowing only small positioning errors and absorbing little impact if any, so that the robot needs to approach the hole very carefully to avoid fast collisions. Solutions with more degrees of freedom are proposed in [8]–[12], [18].

Among compact soft module mechanisms, cable-driven [24]–[26] and spring-based structures [27], [28] have been shown to be effective. Drawing inspiration from these works, we also use a spring arrangement inside our wrist design, which contributes to making it simple and compact. [29] gives a comprehensive survey of locking mechanisms, which we have considered for switching between the rigid and soft mode. [12] proposed a soft wrist with a mode switch using an air-spring based locking mechanism. However, their design requires a large number of parts which are hard to miniaturize, such as pneumatic actuators, and thus require a significant amount of space. Robotic wrist solutions with similar mechanisms are commercially available [13]. We note that the range of motion is limited.

In contrast to their work, a cable-driven mechanism that achieves rigidity through tension was proposed in [30]. However, since there is no latch or lock mechanism and it relies only on tension, the lock would likely be imperfect, especially under large loads.

Our design is similar to their work, in that it features a cable-based mode switch and an internal pin, and the actuator is outside the wrist, thus removing it from the payload and providing a light and compact solution. To the best of our knowledge, this paper is the first to use a cable-based mode switch to realize complete rigidity as well as softness in the

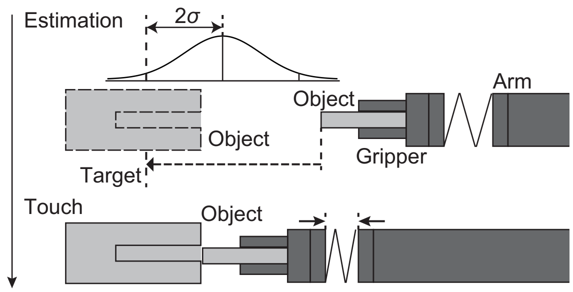

Fig. 2. A scenario where a gripper approaches an object with an uncertain position.

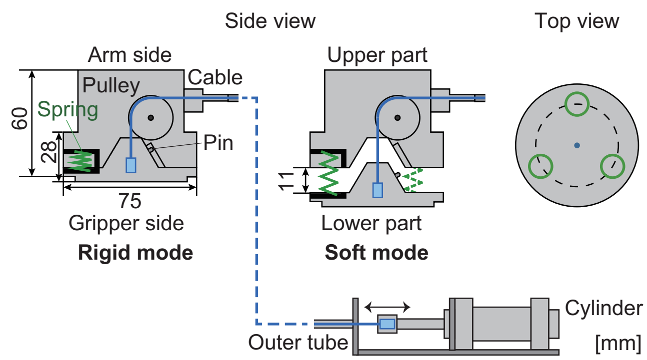

Fig. 3. The design of the wrist. As only a spring and cable are part of the wrist, and the actuator is external, the solution is compact.

wrist.

The design variables of the mechanism's size, weight and dimensions, and its number of DoF and range of movement are at odds. Considering this, we believe that our design achieves a new best compromise, with a high level of overall performance. The comparison between existing methods and our work is shown in Table I [1].

III. Design

In this section, we first explain the design goals and requirements for the soft wrist module, and then how we implemented them in our prototype.

A. Requirements

Since the wrist is to be used with an industrial robot arm for mechanical assembly tasks, we use the parts from the World Robot Summit Assembly Challenge [31] as a reference and set the maximum payload to 2 kg. There are a number of desired properties, which are described in the following subsections.

1) Compactness and six degree-of-freedoms deformation capability: In mechanical assembly tasks, robots often need to move the gripper in constrained spaces and access parts from different directions. Thus, the wrist of the robot should be compact so as to avoid reducing the workspace of the robot, and no wider than the 80 mm diameter of our robot's flange.

We assumed that the robot equipped with the wrist will control the position of the gripper based on noisy measurements, and that impact forces on the gripper may occur in various directions. Therefore, the wrist should be able to move passively in any direction. Let the position of the target-part surface x_{surf} follow a normal distribution $\mathcal{N}(\mu, \sigma)$ (Fig. 2), as the observed target position has an uncertainty, and let the tip position of grasped object be $x_{\mathrm{grip}}(> x)$. If the target is located within the range 2σ, i.e. $|x_{\mathrm{surf}} - \mu| < 2\sigma$, and the grasped object moves to the position $x_{\mathrm{grip}} = \mu - 2\sigma$, then the grasped object will make contact with the target surface with a probability of 0.98, i.e. $\int_{-2\sigma}^{\infty} p(x)dx \fallingdotseq 0.98$, where $p(x)$ is a Gaussian probability density function. In this way, we designed the movable range and set the maximum displacement no shorter than 4σ. From the observation on measurement precision, we obtained $\sigma \fallingdotseq 2\,[\mathrm{mm}]$, so the movable range of the wrist requires at least 8 mm in X, Y, and Z direction, including passive rotation to allow parallel displacement.

2) Switching between rigid and soft modes: While obots have to move quickly in industrial practice to minimize cycle time, fast motions require high accelerations, which cause undesired vibrations if the wrist is used in soft mode. Thus, it is advantageous for the wrist to switch between the modes depending on the task: it should be rigid during quick motions, and soft when performing assembly tasks that require compliance. We also require that the wrist returns to a known position when switching to rigid mode.

B. Design

To make our design compact and light, we manufactured an upper and lower part from aluminium, and connected them using three helical springs that provide compliance, as shown in Fig. 3. The upper part is attached to the end of the robot arm[2] and the lower part to the gripper. The springs are arranged on a circle, enabling passive six-DoF movements of the lower part of the wrist.

Instead of embedding an actuator inside the wrist, which would increase its weight and size, we placed a pneumatic cylinder (CM2B40-100Z, SMC) nearby the robot, which activates the wrist via a cable wire that is connected to the lower part, passes through the upper part via a pulley, and pulls the two parts together when the cylinder is activated, thus locking the wrist in rigid mode. The stroke of the cable is 11 mm and the length and width of the cylinder are 254 mm and 42.5 mm, respectively. The cable runs through the outer tube between the cylinder and the wrist. The cylinder is back-drivable and force-controlled, which compensates for uncertainties, change in the wire's length and friction inside the cable, and thus allows for very simple control.

[1]Note: Physical softness may cause minor, unexpected displacement in any direction. For the purpose of this comparison, this is not regarded as free motion.

[2]We placed a force-torque sensor between the arm and the wrist to measure the contact forces.

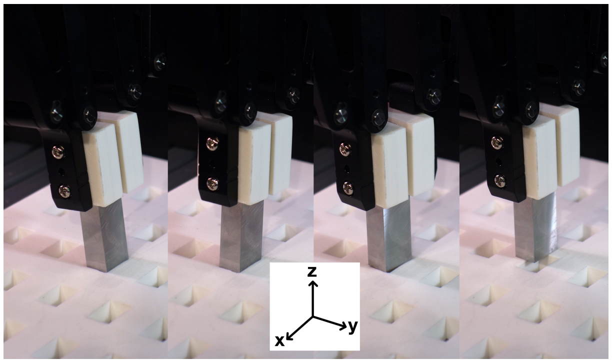

Fig. 4. Experimental setup for the peg-in-hole task with coordinate frame. The gripper holds the peg near the hole with different offsets. Left-to-right: θ_X, θ_Y, θ_Z, $XandY$

The center of the two parts is designed such that the wrist is re-centered when the parts are pulled together, using a conic taper and pin.

IV. Experiments and Results

A. Setup

To evaluate the proposed design, we used a UR5 robot arm equipped with our wrist, a force-torque sensor (FT 300, Robotiq Inc.) between the arm and the wrist, and a gripper (2F-85/140, Robotiq Inc.) on the other end of the wrist. An external desktop computer was connected to the robot via Robot Operating System (ROS) and sent position commands and scripts to be executed on the robot controller, e.g. to move until a force is encountered.

The gripper was equipped with 3D printed fingertips that enclose the grasped peg to avoid slippage. The total length from the robot wrist to the tip of the gripper tips was about 29 cm when the soft wrist was attached to the robot, and about 21.5 cm when our wrist was not mounted ("rigid mode").

We performed two series of experiments to show the effectiveness of the proposed design: an Approach experiment, to show the shock absorption capability compared to a rigid robot, and a Peg-In-Hole experiment to show the error compensation capability. To evaluate the effect of the spring stiffness and opening width (the distance between the two solid parts of the wrist unit, as shown in Fig. 5) on task performance and residual forces, we performed the experiments at three different spring stiffnesses (0.94, 1.45 and 2.2 N/mm; "soft", "medium" and "strong") and wrist opening widths (15, 6 and 1 mm).

B. Approach task

This experiment modelled the robot's approach of a hole with a peg until it detects a contact. Conventional rigid robots need to proceed very slowly when approaching an object, to avoid causing high forces, protective stops or damage upon collision. We hypothesized that the soft mode of our wrist would decrease the impact of the collision, and thus enable higher approach speeds and reduce the force acting on the joints.

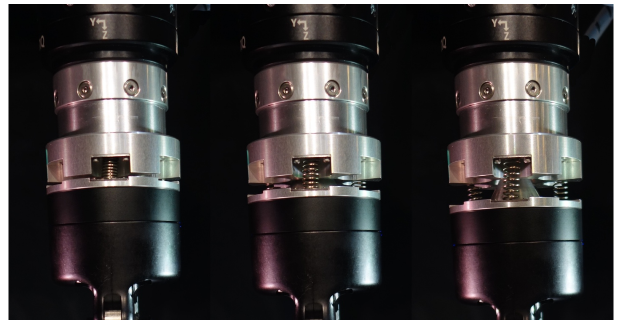

Fig. 5. Evaluated wrist opening widths. A larger opening width corresponds to a greater range of motion. Left-to-right: 1 mm, 6 mm, 15 mm

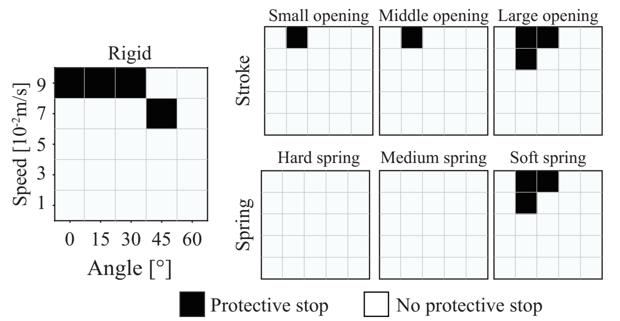

Fig. 6. Protective stop occurrences when colliding a rigid object at different speeds and angles, for different spring stiffnesses and wrist opening widths.

To investigate this, we moved the robot downward from about 0.1 m height a horizontal surface, so that it makes contact with the table surface at about 0.3 m distance from the robot base and 0.01 m height, which was detected by the force-torque sensor at the robot wrist. After the robot stops, we recorded the force at the wrist, the robot position and if a protective stop had occurred due to the collision. Note that this means that the recorded force is a lower bound, and the maximum contact force might be higher than the one recorded in this experiment. We changed the posture of the gripper and its movement speed as shown in Fig. 4, so that the angle of impact on the tip of the gripper would vary between 0° and 60° at a 15° interval.

The contact forces after making contact at different movement speeds for different spring stiffnesses and opening widths are shown in Fig. 8 and the approach success rate in Fig. 6. The results show that the soft wrist decreases the contact forces substantially, especially at higher speeds, and also decreases the number of protective stops at higher speeds. When using the soft wrist, protective stops only occurred when there was a pre-existing contact of the top and bottom part of the unit due to gravity and low spring stiffness. For appropriately chosen spring stiffnesses, or when the unit is in vertical orientation, protective stops are avoided entirely.

In summary, the results show that a robot equipped with the soft wrist can approach into contact at faster than without, and the soft wrist significantly reduces the contact force upon collision.

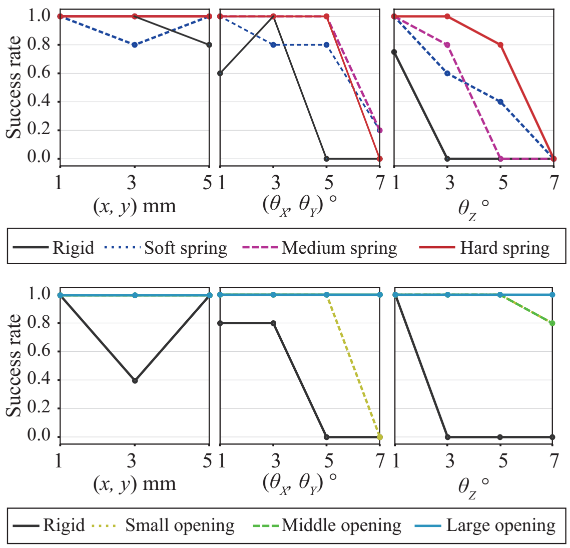

Fig. 7. Success rates for peg-in hole insertions using different spring stiffnesses and wrist opening widths.

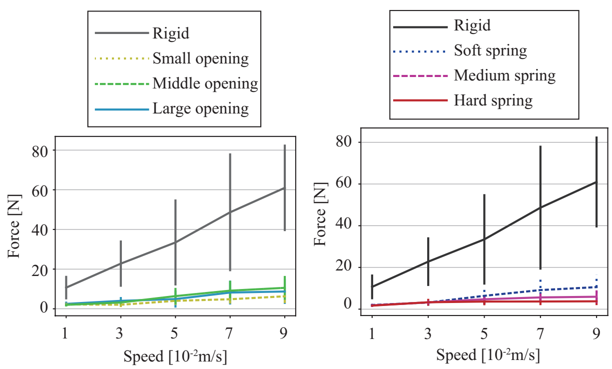

Fig. 8. The forces measured by the force-torque sensor after collision with an object, for different spring stiffnesses and object widths.

C. Peg-in-hole task

In this experiment, we evaluated the effect of the soft wrist on the performance of the peg-in-hole task when affected by positioning errors. The robot inserted a stainless steel rectangular pin with 10 mm x 15 mm side length and 80 mm length[3] into a rectangular hole (nylon 3D print) which was fixed to the table. The clearance was evaluated manually to be under 0.1 mm.

We simulated measurement noise by positioning the gripper at different offsets relative to the center and axis of the hole. The x and y offsets were $0, 1, 3, 5, 7$ mm and the angle offsets $\theta = 0, 1, 3, 5, 7\,°$. The angle offsets were evaluated separately and applied to the x, y and z axis.

After positioning the gripper in front of the hole and adding the offset, we initiated the insertion routine. For the soft modes, this consisted of a spiral helix motion with $r = 3\,[\mathrm{mm}]$. For the rigid case, we first performed a spiral motion to find the hole, based on a script supplied by the gripper manufacturer. After the spiral motion, we assume the robot is at the hole and insert the peg using a custom routine that applies a force, and moves 1 mm back and forth in the x or y axis when the peg is stuck.

[3]15 µm tolerance

We took care to use insertion strategies that make the modes relatively comparable and which would run at similar speeds, but would not disadvantage one method disproportionately. As is recommended for comparisons with baselines, we spent roughly equal time tuning the for the best possible performance within our insertion task.

After the routine, we checked if the insertion was successful (i.e. the peg was inserted deeper than 1 cm) and if a protective stop occurred during execution. The robot performed the task five times in each condition, while we recorded the number of successes, failures and protective stops.

As Fig. 7 shows, the success rates for our soft wrist are significantly higher as the positioning errors increase. With growing angle misalignment, the compensating effect of physical softness is especially pronounced. Starting from only 3 and 5 degrees of x/y- and z-angular offset respectively, the robot fails to insert the peg without the soft wrist.

For purely translational errors, the success rate is high even without the wrist, as the spiral search for the hole succeeds relatively often, which is likely due to the clean geometry around the hole. However, in preliminary experiments using a circular peg and a bearing, the spiral search was much less reliable, as the ridges around the hole make the force signal noisier. The main causes of failure in rigid mode were protective stops during the spiral search motion, or misperceptions when the gripper had entered the hole without the force sensor detecting it.

We observed that with larger wrist opening widths, the larger range of motion of the wrist affects the success rate favorably, as seen in Fig. 7, but that even at the smallest opening width it has a significantly positive effect. This is related to the fact that the cylinder controlling the opening width can extend under sufficient force, so that high forces can cause the wrist to extend further than the small opening width would imply.

V. Discussion

The results of our experiments show the significant benefits gained from a soft wrist mode. As hypothesized, it allows both precise position control, as well as soft control and error compensation.

When approaching an object with the wrist in soft mode, the contact force is significantly reduced, allowing both faster approach speeds and softer interactions between objects, which allows reduced cycle times, safer motions and lower risk of damaging parts during collisions. We also showed that the softness can be used when picking up thin objects, or during bin-picking, to avoid collisions and compensate for positioning uncertainty.

A limitation of our results is that the same strategies for e.g. peg-in-hole tasks cannot be applied to both hard and soft wrists, thus making the comparison difficult. We alleviated this by spending roughly equal amounts of time on tuning the parameters for each mode to the task, so that one would not be significantly more polished that the other.

A point of consideration in our current prototype is that it only allows a binary transition between rigid and soft. This is sufficient for a range of tasks, considering that the stiffness of the springs can be changed as well. However, it would be advantageous to be able to control the stiffness continuously, and to be able to change it during task execution, thus allowing more dexterous manipulation even with simple grippers. We will consider this feature in future versions of our design. Furthermore, we will investigate learning-based control approaches to fully exploit the wrist's potential.

VI. CONCLUSIONS

In this paper, we have proposed a novel design for a soft wrist for assembly tasks, and investigated the effectiveness of physical softness for robotic assembly tasks. By using an external actuator and a wire-driven mechanism, rather than internal power sources or power train components, our proposed wrist design is compact and can be installed between existing robot arms and grippers. We show experimentally that the large and passive six-DoF compliance and locking function has a positive effect on approach, picking, and peg-in-hole tasks, increasing the possible approach speeds, as well as reducing protective stops and the force exerted. We also show that spring stiffness and wrist opening width affect the performance, which needs to be taken into consideration when designing a soft wrist. We conclude that physical softness can be a low-cost alternative for active compliance based on high-frequency sensors and controllers, thus simplifying the control component. We are currently exploring learning approaches for control as we believe that such methods are a promising research direction with the potential to fully exploit the benefits of our soft wrist, and generate simple and adaptive controllers.

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