The Co-Gripper: a Wireless Cooperative Gripper for Safe Human Robot Interaction

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Abstract—In this paper, we introduce a set of guidelines for the design of grippers suitable for a safe human robot/interaction in cooperative tasks. Modularity, adaptability, robustness, intuitive control, limited weight are some of the key elements that could allow to effectively spread these devices in industrial and service applications. Following such guidelines, we present the prototype of the Co-Gripper: a robotic device for cooperative manipulation tasks with humans. The gripper is composed of two pairs of fingers, actuated with two motors, that can be controlled in a coordinated way or independently. Each finger has a modular underactuated structure, composed of three phalanges connected by passive joints. The gripper is wireless, so it can be easily connected both to the robotic arms and on passive structures. We designed a wearable wireless control interface composed of a ring and a bracelet allowing a simple and intuitive activation of the gripper without limiting human operator’s manipulation capabilities. We performed a set of tests to quantify gripper performance and to exploit its potentialities in human-robot cooperation tasks.

I. INTRODUCTION

Applicative scenarios envisaged in the Industry 4.0 framework present a closer cooperation between humans and robots. The automated solution will be spread not only in large productive realities but also in SME (small medium enterprises) \cite{1}. This new perspective effects also design requirements for robotic systems: from the maximization of the merely dynamical performance needed in a completely automated reality to more complex constraints necessary to assure a suitable level of adaptability to uncertainties, robustness, safety in the physical interaction with an unstructured environment and with humans \cite{2}. Most of the work on collaborative robots (cobots) and more in general on physical human robot interaction have focused on robotic arm design and control. This has led to a novel generation of collaborative robots that can safely interact with a human operator. Commercial examples of these new robots are the LBR iiwa (KUKA, Germany), the Sawyer (Rethink Robotics, USA) and the FRANKA (FRANKA EMKA, Germany), just to name a few. A concept common to these robots is the possibility to compliantly react to a collision, in opposition to the stiff behavior of classical industrial robots.

Exploiting compliance and environment constraints with underactuated compliant hands is also a lively research branch \cite{3} for robotic end-effectors. Remarkable examples of soft grippers are available in literature, e.g., the Yale OpenHand Project \cite{4}, the 3-Finger Adaptive Robot Gripper \cite{5}, the Jamming Gripper \cite{6}, the underactuated grippers presented in \cite{7}, etc. In all these works, however, the attention was mostly devoted to analysing hand/gripper manipulation capabilities and adaptability, rather than specifically evaluating the interaction with humans.

Although robot end-effectors are most of the time the part of the robot more proximal to the human partner in collaborative scenarios, only a few works have been dedicated to the design and the control of collaborative grippers. The Schunk Co-Act Gripper \cite{8} is an example of gripper designed for collaborative robotics, even if it still needs a complex system to be safe and can deal with a limited type of object’s geometries. Another example of a plug–and–play gripper is represented by the RG6 Collaborative Gripper \cite{9}, that however can be controlled only through the robotic arm interface thus limiting its applicability in many collaborative contests.

In this work, we present some design guidelines and propose a prototype of a soft–gripper explicitly devoted to an easy and safe interaction with human operators in cooperative tasks. The key ingredient of the soft-grippers is the intrinsic softness of the devices, i.e., their embodied ability to comply and adapt to features of the objects and of the environment.

The proposed device, that we named the Co-Gripper (see Fig. 1), is a wireless underactuated tendon-driven gripper, with four flexible fingers composed of three soft-rigid modules each. A wireless implementation allows to easily integrate the gripper both on actuated arms and on passive...
structures. Also, its control interface is extremely simple and can be used both in industrial and more general service application, without the need for specific knowledge or training for the user. Nevertheless, we managed to obtain suitable adaptability and robustness properties, thanks to a tendon based actuation and flexible finger structure, in which joint stiffness is evaluated according to the methodologies proposed in [10]. The gripper has been realized using rapid prototyping techniques, in which we can manage material’s mechanical properties by properly regulating 3D-printing parameters, and it can easily be reconfigured, due to its modular structure at a finger level.

The rest of the paper is organized as it follows. In Sec. II, design guidelines for collaborative soft-gripper are outlined. In Sec. III a prototype realized according to the proposed guidelines is presented and evaluated as well as the interface designed for its control. Sec. IV deals with the experiments performed to evaluate the proposed system and its usability, whereas in Sec. V conclusion and future work are outlined.

II. DESIGN GUIDELINES

In this section, we report the main design guidelines for the collaborative gripper. As we introduced in Sec. I, in this paper we delineate which are the main features of a novel generation of grippers explicitly designed to interact with a human operator. Together with the automation standards detailed in the ISO/TS 15066 [11] and more in general in the ISO/TS 10218 [12], [13], we identified four main principles that a co-gripper should have with respect to foster human robot cooperation: i) intrinsic safety and adaptability, ii) easy reconfigurability, iii) portability and iv) easy interface with the human operator. In the rest of the section, we detail how each of these principles impacts the human-robot cooperation.

A. Intrinsic safety and adaptability

Safety is a crucial aspect to take into account in workplaces where humans are directly assisted and supported by robots, improving product quality, productivity, and worker’s comfort. Using robots in an unstructured environment and in the presence of humans needs specific requirements in terms of sensory perception, mobility, dexterity, planning, and management of uncertainties and disturbances [14]. Robustness, adaptability, flexibility, and changeability of assembly processes, especially in an unstructured environment with human presence, need a close linkage between the worker and the robot: the human operator controls the process, while the robot provides support and assistance [15]. The whole robotic system should comply with the above mentioned issues, including the end-effector. In this view, an interesting solution can be sought in the novel generation of underactuated compliant hands that is growing in the robotics community in the last years, upgrading the preliminary attempts pioneered by Hirose et al., at the end of the seventies [16]. These devices are usually referred to as “soft hands” since they embed intrinsically passive compliant elements often at the joint level. Passive elements guarantee a safe interaction with the human co-worker. Moreover, compliant elements consent to store elastic energy, avoiding tendon slackness, to distribute forces over a large contact area, and to overcome the indeterminacy of configuration problem typical of an under-constrained mechanical system [17]. Finally, this type of underactuated hands has the desirable adaptability to shapes which allows them to easily perform grasps of several objects. Underactuation is usually implemented using differential and elastic elements that allow the motion of other joints to continue after contact occurs on a coupled link so that the hands can passively adapt to the shape of the grasped object [7]. Another advantage of passive adaptability is reduction of requirements on engineering the environment of the manufacturing facility since the passive adaptation to different object shapes is less demanding for accurate perception [18]. Such extended capabilities also lead to a reduced effort in programming the manipulation system enabling to drive the device with a reduced number of control parameters. Both of these factors significantly reduce set-up cost and shorten set-up times.

B. Easy reconfigurability

Human-robot collaborative environments are intended to be highly dynamic if compared with classic industrial production chain where specific areas are devoted to the production of a specific item. Such flexibility can be obtained if it is possible to quickly change the gripper configuration. Flexibility refers to the various types of operations that the machine can perform without requiring a prohibitive effort in switching from one operation to another [19]. Reconfigurable manufacturing system aims at achieving cost-effective and rapid system changes, as needed and when needed, by incorporating principles of modularity, integrability, flexibility, scalability, convertibility, and diagnosability [20]. When flexibility and reconfigurability concern grippers, this usually refers to devices that can rearrange the position and orientation of their fingers [21] or that can adapt the number of DoFs to the task at hand [22]. In Co-Grippers this reconfiguration should be easy to be performed by the human operator while performing a cooperative task.

C. Portability

The Co-Gripper envisaged in this paper is intrinsically safe thanks to the embedded passively compliant elements and thus does not need a complex perception system to detect human presence. This can also be exploited to use the gripper detached from a robotic arm. In Fig. 1, the co-gripper is attached to a passive arm support (in this case a simple table lamp support) and can be used by a worker without the necessity of a robotic arm. This can be possible if the gripper can be used in a completely wireless solution, i.e., if it has batteries for power supply on board. This solution opens interesting scenarios where the co-gripper can be used in a broader context than in manufacturing scenarios, e.g., by other types of workers such as plumbers, electrician, etc. The passive arm support and the portable co-gripper may be a valid support to hold pipes, pass cables, and so on. Within
an industrial environment, portability may also be exploited to use the gripper both as the end effector of a robotic arm to perform pick and place and other common operations, and together with a passive arm as an advanced third hand support system on the worker’s desk.

D. Ease of the interface

One of the characteristics of collaborative robots is their intuitive as an easy interface. Different solutions have been proposed to control grippers of collaborative robots that mainly involve displays or buttons embedded in the gripper themselves or in the supporting robotic arm, see as an example the interface proposed for the gripper of the Rethink Robotics Sawyer robot [23]. However, we do believe that co-grippers should also be used detached from a robotic arm. The portability requirements should be extended also to the interface, that should be light and easily wearable. Simple interfaces are sufficient to basic operative commands, like the opening and closure of gripper fingers. More complex, still wearable, interfaces could be adopted also to haptically render to the user specific operating conditions [24]. Moreover, the interface should require a minimal cognitive effort to be used by the operator and it must not prevent the user’s hand to perform a collaborative task.

III. THE CO-GRIPPER SYSTEM

In this section, we introduce the Co-Gripper, a soft tendon driven modular gripper that has been designed following the guidelines reported in Sec. II and a possible wearable interface to control it. The CAD model of the gripper is shown in Fig. 2, whereas the 3D printed prototype is reported in Fig. 4. Its overall weight is 480 g and, as we will detail later, it can resist forces up to 4.75 kg.

A. The Co-Gripper

The proposed device is intrinsically-compliant, modular, underactuated and cable driven. Each module consists of a rigid 3D printed link realized in ABS (Acrilonitrile Butadiene Styrene, ABSPlus, Stratasys, USA) and a 3D printed thermoplastic polyurethane part (Lulzbot, USA) that acts as the flexible joint. We selected polyurethane for soft parts because the high elongation of this material allows for repeated movement and impact without wear or cracking proving also an excellent vibration reduction.

The main technical features and material/geometric parameters of the soft modular gripper are summarized in Table I. The mechanical properties of 3D printed materials, as the polyurethane, depend on manufacturing processes and can be controlled. We exploited this property in [10] to design the stiffness of passive joints so to realize a robotic underactuated finger whose fingertips follows a given trajectory when the finger is actuated. This approach can easily be applied also to the co-gripper described in this paper, in which passive joints can be realized with stiffness values defined to obtain a given closure strategy, for example, suitable to grasp large objects or perform pinch grasp of small objects. The modules are connected by sliding the thermoplastic polyurethane part in the ABS part. This method makes the assembling process easy without using any screws or passive elements to combine the modules. The holes in the rigid links allow the passage of a cable (realized with polyethylene Dyneema fiber, Japan), which realizes the tendon driven actuation.

The device actuation is achieved by using two actuators and four tendons running in parallel through the modules of the fingers. The actuators are two Dynamixel MX-28T (Robotis, South Korea), each having a maximum torque of 3.1 Nm and a maximum angular speed of 684 deg/s. The main technical features of the Co-Gripper and its actuation system are summarized in Table I. Each actuator along with a differential mechanism [25] is used to control the motion of two fingers. The differential mechanism is necessary to adapt fingers’ configurations to the specific geometric features of the grasped object, if one of the fingers contacts the object or any surface, the other one can continue its closure motion until a firm grasp is achieved. In Sec. IV we will report some examples where the Co-Gripper is conforming to irregularly shaped objects. Tendon wires run through the fingers and are attached on one side to the fingertips and on the other to the differential mechanism which in turn is connected with a pulley rigidly attached to the actuator shaft. When the motor is actuated, the tendon wire is wound on the pulley reducing the length of the wire and producing the closure/flexion of connected fingers. The opening/extension of the fingers is achieved thanks to elastic force stored in the flexible parts of the modules.

The fingers are connected to the palm of the grippers through a Dovetail joint that allows to completely rotate the finger along the direction perpendicular to the palm plane. This feature can be exploited to reconfigure finger orientation according to the object to be grasped. Fig. 3 shows some of the possible fingers’ configurations. We named them perpendicular, parallel and circular configurations. In the first configuration, the fingers are perpendicular to the longest side of the gripper. The two pair of fingers are at the maximum distance, which allow grasping relatively big objects. Instead, the configuration where fingers are oriented parallel to the long edge of the palm can be exploited to grasp objects with a dimension much higher than the others, e.g., pipes. Finally, the circular configuration may be exploited for objects with a circular section. These three are only examples of the high number of the possible achievable configurations.

The combination of the modularity, possible finger trajectory design through stiffness and finger configurations meet the requirements for easy reconfigurability of the system. The soft structure and the tendon driven actuation satisfy the requirements for safety and adaptability.

B. The wearable interface

The control interface of the Co-Gripper is based on a remote ring, whose prototype is shown in Fig. 4. The ring configuration has been chosen to obtain an interface highly wearable and portable. The ring is realized in a flexible material which allows the ring to comfortably adapt to different finger’s sizes. It includes two push buttons to
remote control Co-Gripper motion. The user wears the remote ring on the index finger, its controller box housing is included in a bracelet that can be worn on the wrist, (see, Fig. 4). Ring controller receives the activation signals from the push buttons and sends them to the actuator’s controller through a wireless transmission, which in turn controls the motion of the gripper according to the high-level control strategy summarised in Table II.

The Arbotix-M controller (Robotis, South Korea) is used to control Dynamixel actuators of the soft gripper. This control solution for Dynamixel motors incorporates an AVR microcontroller, a socket for a XBee wireless radio and the motor driver. The wireless communication between the remote ring and the gripper controller is realized through the XBee modules.

The soft gripper can be operated in two different modes of operation: four finger mode and two finger mode depending on the nature of the task to be performed. In case of former, the four fingers are moved simultaneously to grasp relatively big size objects. The fingers can be oriented in different configurations depending on the size and shape of the object to grasp. In case of latter, the gripper has two different two fingers’ gripper configurations where each pair of the fingers is controlled separately enabling the grasp of multiple objects at the same time.

As a default condition, four–fingers mode is selected: when one of the push buttons is selected, the flexion/extension motion of all the four fingers is initiated. With a single button pressure, the user switch between the motion/stop of the fingers. When the fingers are stopped, two trigger signals within a time window of 1 s, switch the motion direction from flexion to extension and viceversa. Switching between the modes (four fingers and two fingers) can be achieved by pressing both push buttons simultaneously. The switch is possible at any state of the gripper. In two finger mode, the gripper behaves as two independent grippers that can be separately controlled. A LED on the board is used to provide a visual feedback of the selected modes of operation and activation of the trigger signal. The wireless communication and battery on-board together with the ring interface

<table>
<thead>
<tr>
<th>Technical Features</th>
<th>Flexible Part</th>
<th>Stiff Part</th>
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<tbody>
<tr>
<td>Material type</td>
<td>Thermoplastic polyurethane (TPU)</td>
<td>Acrylonitrile Butadiene Styrene (ABS)</td>
</tr>
<tr>
<td>Modulus of elasticity ($E$)</td>
<td>15.2 MPa</td>
<td>40 MPa</td>
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<tr>
<td>Shore Hardness</td>
<td>85 A</td>
<td>70 D</td>
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<tr>
<td>Density</td>
<td>1200 kg/m$^3$</td>
<td>1070 kg/m$^3$</td>
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<th>Geometric Parameters</th>
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<tr>
<td>width</td>
<td>25 mm</td>
</tr>
<tr>
<td>length</td>
<td>23 mm</td>
</tr>
<tr>
<td>height</td>
<td>3.5 mm</td>
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C. Performance characterization

The performance of the gripper was evaluated through a subset of the tests proposed in [26]. In particular, we measured the maximum payload and maximum horizontal grasp resistive force in the case of power grasp. The experimental setup is shown in Fig. 5. To compute the maximum payload of the gripper in power grasp configuration, a cylindrical object (diameter 95 mm, weight 130 g) was slowly pushed down by using a dynamometer’s bumper (Vernier, USA) as shown in Fig. 5-a. The maximum force was recorded when the object started to slip from the gripper. The maximum payload of the device is the sum of the grasp object’s weight and the force applied to the point of slippage. It was observed to be 46 N, which resulted in a maximum payload of 4.75 kg. To measure the maximum horizontal grasp resistive force, the gripper was fixed on the table and the hook of the dynamometer was attached to the object by using a small thread. The object was slowly pulled in the horizontal direction by using the hook of the dynamometer as shown in Fig. 5-b. It was observed that the gripper hold on to the object till 64 N. It is pertinent to mention that in all of the above summarized tests the gripper was actuated at the maximum motor torque, the results obtained are summarized in Table III.

IV. Experiments

We first evaluated the capability of the Co-Gripper to adapt to different shapes of objects. We selected 10 common objects with different shapes and we exploit the characteristic of our prototype to achieve stable grasps. Two fingers were assembled so to perform a pinch grasp by selecting the stiffness of the soft joints as reported in Sec. III. The obtained results with the relative chosen fingers’ configurations are reported in Fig. 6. After this evaluation of the device capabilities, we performed an evaluation of the whole system (gripper + interface).

Ten subjects (7 male, average age 28) tried the system wearing the ring interface on the non dominant hand to control open/close motion of the device. Four different objects were presented to the subjects (small cube, pipe, ball and electronic board, see Fig. 6). The subjects were instructed on the functioning of the ring interface and on the possible reconfiguration of the fingers, but no suggestions on fingers’ positioning according to the object shape were given. After the explanation of the system working principle, subjects were asked to grasp the objects with the device, open again the gripper fingers and put the objects back on the table. Each subject was left free to rearrange the orientation of the fingers to achieve the grasp. After the task was completed, subjects were asked to fill the System Usability Scale (SUS), a simple, ten-item scale giving a global view of subjective assessments of usability [27]. SUS yields a single number representing a composite measure of the overall usability of the system being studied. It is a Likert scale where it is possible to answer to each item with a mark ranging from 1 “strongly disagree” to 5 “strongly agree”. Items of the SUS are reported in Table IV. To calculate the SUS score, it necessary to sum the score contributions from each item. Each item’s score contribution ranges from 0 to 4. For items 1, 3, 5, 7, and 9 the score contribution is the scale position minus 1. For items 2, 4, 6, 8 and 10, the contribution is 5 minus the scale position. The sum of the scores is then multiplied by 2.5 to obtain the overall value of SU. SUS scores have a range of 0 to 100. The Co-Gripper used together with the ring interface got an average score of 92.25 with a standard deviation of 4.92. This result confirms how
Fig. 6. Possible grasps achieved with the Co-Gripper. a) two fingers in a pinch grasp configuration. b) grasping of small size objects achieved with the two fingers. c) each of the two finger grippers controlled separately so to achieve the grasps of two objects with the same gripper. d) grasp of big size objects achieved with a circular configuration. e) grasps obtained with the perpendicular configuration. f) grasps obtained with the parallel configuration.

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<tr>
<th>Table IV</th>
<th>Items of the System Usability Scale</th>
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<tr>
<td>I think that I would like to use this system frequently</td>
<td></td>
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<tr>
<td>I found the system unnecessarily complex</td>
<td></td>
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<tr>
<td>I thought the system was easy to use</td>
<td></td>
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<tr>
<td>I think that I would need the support of a technical person to be able to use this system</td>
<td></td>
</tr>
<tr>
<td>I found the various functions in this system were well integrated</td>
<td></td>
</tr>
<tr>
<td>I thought there was too much inconsistency in this system</td>
<td></td>
</tr>
<tr>
<td>I would imagine that most people would learn to use this system very quickly</td>
<td></td>
</tr>
<tr>
<td>I found the system very cumbersome to use</td>
<td></td>
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<tr>
<td>I felt very confident using the system</td>
<td></td>
</tr>
<tr>
<td>I needed to learn a lot of things before I could get going with this system</td>
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the system is easy to use also without a specific training. Note that 9 out of 10 subjects chose the circular configuration for the ball, 10 out of 10 chose the pinch grasp gripper for the small cube, 6 out of 10 used the perpendicular configuration both for the pipe and the cup, while the other 4 chose the parallel.

V. Conclusions

In this paper, we presented the design guidelines and a possible device realization of a soft collaborative gripper. Soft-manipulation technology imposes fewer requirements on engineering the environment of the manufacturing facility since the passive adaptation to different object shapes is less demanding for accurate perception. The extended capabilities also lead to a reduced effort in programming the manipulation system. Collaborative grippers inherently address aspects of safety, preparing robotic systems with the ability to forcefully interact with their environment while being safe in proximity to the human. This facilitates the co-manipulation applications making the soft-grippers ideal candidates for a possible technology transfer to the industry.

We are currently working on the gripper interface so to display to the user the grasp force measured on the gripper. We are also testing novel possible finger configurations so to enhance the possible gripper dexterity.

REFERENCES
