Vibrotactile Communication for Bilateral Haptic Cooperation with Soft Grippers

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***Abstract*— Collaborative robots are designed to share the workspace with a human operator. Several collaborative robotic arms are currently available on the market as the results of extensive researches on robot safety and on the simplification of robot programming. However, in several collaborative tasks the end-effector of the robot is the part that mainly interacts with the operator. In this work, we present a cooperative gripper system composed of a soft gripper and a wearable interface. The soft gripper, called CoGripper, has been design so to guarantee a safe interaction giving the possibility to the operator to reconfigure the device according to the object to be grasped. The wearable interface can be used to control the open/close motion of the gripper as well as to provide the user with a feedback, obtained through a vibrotactile motor, about important parameters measured by the gripper, e.g., the grasp tightness. The outcome is a bilateral haptic collaboration where human and robot bidirectionally communicate through the interface. The interaction with the system results extremely intuitive and simple. We performed two user studies to prove the effectiveness of bilateral haptic collaboration involving ten subjects. Results confirm that the use of the interface reduces the time to accomplish a cooperative task and also allows a better control of the grasp tightness.**

I. INTRODUCTION

The concept of bilateral haptic collaboration introduced in this work goes beyond the simple communication of intention or posture detection. The interface we propose can be used both to control the robotic gripper motion and to haptically display information related to the task that are measured by the robot. As a paradigmatic example, we propose the collaborative gripper system reported in Fig. 1. A ring-shaped interface can be used to control open/close motion of a collaborative gripper through two embedded switches. The ring embeds also a vibrotactile motor that may be used to feedback the grasp tightness measured by the gripper. We also consider the case where the gripper autonomously detects the presence of an object through a proximity sensor embedded in its palm and the ring interface is used to display the acknowledge of a gripper status, i.e., of the start closing motion and the reaching of a predefined level of grasp tightness. We report on two user studies to investigate both usage of the interface. In the first, we evaluated whether the presence of haptic feedback from the gripper would reduce the time to complete a collaborative hand over task and better regulate the grasp tightness. In the second study, we evaluate the perceived system usability when the interface is used to recognize action of the gripper. The rest of the paper is organized as follows. In Section II the collaborative gripper system proposed in this work is described in detail. In Section III the two user studies and their relative results are reported. In Section IV conclusion and future work are outlined.

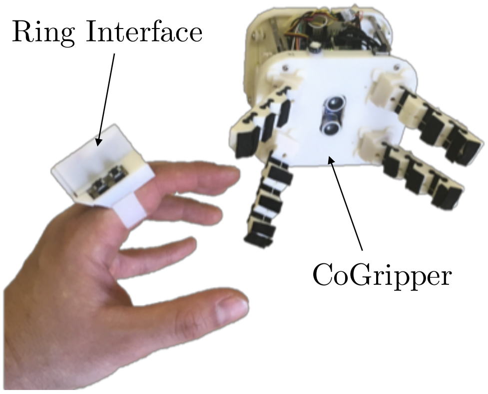

Fig. 1. The Co-Gripper and its ring-shaped interface. The ring provides vibrotactile haptic feedback about the grasp information coming from the gripper.

II. THE COLLABORATIVE GRIPPER SYSTEM

In this section, we recall the main features of the CoGripper, a soft tendon driven modular gripper that has been designed following the guidelines reported in [1] and we introduce a novel ring-shaped interface to control it. With respect to its preliminary version, the novel system includes

- a sonar sensor installed in the gripper palm to detect the proximity of an object to grasp;
- a completely redesigned ring-shaped interface embedded with a vibrotactile motor that enables bilateral haptic collaboration;
- a novel Bluetooth communication protocol between the interface and the gripper allowing a bilateral data flow.

A. The CoGripper

Exploiting compliance with underactuated compliant hands is an active research branch for the design of novel robotic end-effectors [2]. Different soft grippers examples are available in literature, see e.g., the Yale OpenHand Project [3], the 3-Finger Adaptive Robot Gripper [4], the Jamming Gripper [5], and the underactuated grippers presented in [6]. The CoGripper is an intrinsically-compliant, modular, underactuated and cable driven gripper. It has four soft finger

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connected to a palm. The CAD model of the gripper is shown in Fig. 2, whereas the 3D printed prototype is reported in Fig. 1. Each finger has a modular structure where each module consists of a rigid 3D printed link realized in ABS (Acrylonitrile Butadiene Styrene, ABSPlus, Stratasys, USA) and a 3D printed thermoplastic polyurethane part (Lulzbot, USA) that acts as the flexible joint. Following the approach presented in [7], it is possible to regulate the stiffness of the flexible joints so to design the closing trajectory of each finger. In [1] this feature was used to obtain different behaviours for the two pair of fingers in the gripper. In this version, all the four fingers have the same closing trajectory designed for power grasps.

The modules can be connected sliding the thermoplastic polyurethane part in the ABS part easing the assembling process and avoiding screws or passive elements to combine the modules. This also allows to quickly add/remove modules so to regulate the length of the fingers according to the desired task. For the presented work, the fingers contain four modules. A tendon cable realized with polyethylene (Dyneema fiber, Japan) is passed through the holes in the rigid links and is used to achieve the tendon driven actuation. Tendon wires are attached on one side to the fingertips and on the other to the differential mechanism which in turn is connected to a pulley rigidly attached to the actuator shaft. Two Dynamixel MX-28T (Robotis, South Korea) are used for the actuation. Each motor is in charge of the motion of a pair of fingers. A differential mechanism [3] is embedded on the gripper base so to adapt fingers' configurations to the specific geometric features of the grasped object. Thanks to the differential mechanism, if one of the fingers contacts an object, the other one can continue its closure motion until a firm grasp is achieved. 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 actuators have a maximum torque of 3.1 Nm and a maximum angular speed of 684 deg/s. The fingers are connected to the palm of the gripper through a dovetail joint that allows complete rotation of the fingers along the direction perpendicular to the palm plane. The operator can passively orient the finger according to the shape of the object to be grasped. Passive orientation is also useful during grasping since the fingers tend to passively reorient themselves during closure motion. In the proposed version of the CoGripper, an ultrasonic (HC-SR04) sensor module is installed in the middle of the palm, see Fig. 2. The sonar sensor provides a detection range from 2 to 40 cm. The sensor functions on the concept of ultrasonic waves, the transmitter sends a burst of ultrasonic waves, when the waves encounter an object these are reflected back and received by the receiver. The receiver convert the ultrasonic waves into electrical signal to be read by the main controller. The distance is calculated by measuring the time difference between sending a signal and receiving its echo. The sensor can detect when an object enters in a predefined grasping area, and can provide the information to the main controller triggering a closure of the gripper.

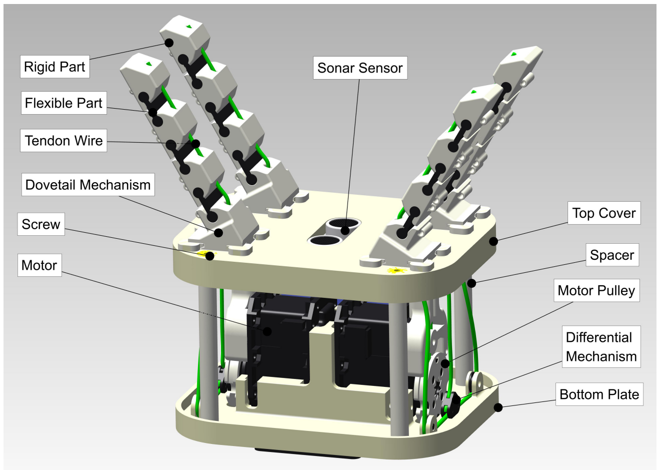

Fig. 2. The Co-Gripper: A wireless underactuated tendon-driven gripper with four flexible fingers composed of three soft-rigid modules each. Modules can be assembled with different stiffness values at flexible joint level, obtained changing 3D-printer parameters during manufacturing.

The main technical features of the Co-Gripper and its actuation system are summarized in Table I. Experimental evaluation of the payload and the maximum horizontal resistive force reported in the table are detailed in [1].

The overall weight of the CoGripper is 480 g and it can resist forces up to 4.75 kg. The main technical features and material/geometric parameters of the soft modular gripper are summarized in Table I. The gripper embed a battery and can be used completely wireless. This allows the gripper to be used also together with passive supports.

B. The wearable interface

The control interface of the Co-Gripper is based on a remote ring, whose CAD exploded view is shown in Fig. 3. The proposed prototype is shown in Fig. 1. The ring configuration has been chosen to obtain an interface highly wearable and portable [8]. The ring is realized in ABS material and it is designed so to comfortably adapt to different finger's sizes. The remote ring consists of a very compact structure containing all the electronics on board. It has two push buttons currently being used to control the actuation/ different modes of actuation of the gripper. Ring controller (ATtiny45) receives the activation signals from the push buttons and wirelessly transmit them to the actuator main controller, which in turns control the motion of the gripper according to the high level control strategies summarised in Table II. Bluetooth (RN42-i/RM) module is used to transmit and receive all the relevant information. A coin type shaftless vibratory motor (Precision drive, USA) with a diameter of 10 mm is also installed in the ring, which is perfect for non audible indicators. A reduced dimensions Li-Ion 3.7V rechargeable battery is used to power up the remote ring.

The Arbotix-M controller (Robotis, South Korea) is used to control Dynamixel actuators of the soft gripper. This

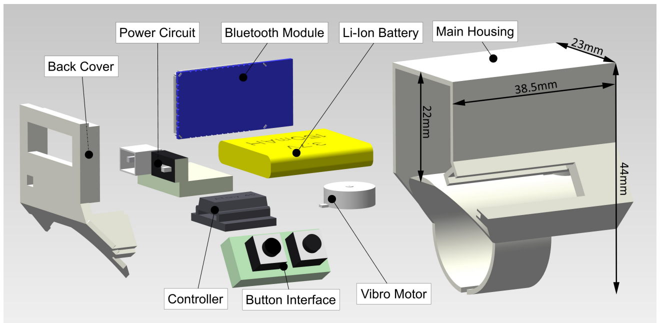

Fig. 3. CAD exploded view of the remote ring interface for the Co-Gripper.

control solution for Dynamixel motors incorporates an AVR microcontroller, a socket for a XBee wireless radio (being used for bluetooth module) and the motor driver. The wireless communication between the remote ring and the gripper controller is realized through the bluetooth modules.

The soft gripper can be operated in two different modes both involving the four fingers. In the first mode, the remote ring is used to control the activation of the gripper. The user can use a push button to activate the flexion of the gripper. When the flexion motion is initiated the gripper starts to close, as soon as all the fingers of the gripper establish a contact with the object the gripper starts exerting force on the object, which is achieved by increasing the torque of the actuators. The user can stop any further closure of the fingers at any moment by pressing the same push button again. The remote ring provides a feedback to the user, relevant to the force exerted on the object, in the form of vibrations. The frequency of vibratory feedback increases proportional to increase in torque, this is achieved by decreasing the period of active vibration. The user perceive this change and can better understand the amount of force being exerted on the object. With a single click of the second push button extension of the gripper is activated.

The gripper can also work in self-closing mode where the user can benefit from the automatic sonar detection. As soon as the object arrives in the predefined graspable window, a single burst of vibration is provided and the gripper automatically initiate flexion with a predefined torque value. When the motor torques reaches the predefined torque value the gripper automatically stops the flexion motion and a double vibration is provided to the user. The extension of the gripper can be achieved by the push button. The automatic sonar detection can be enabled and disabled by providing a trigger signal of both push buttons having a signal length greater than 2 sec. In sonar disable mode the user can also re-orient the fingers in different configuration as per the size and shape of the object. The user can switch between these two modes by simultaneously pressing both push buttons installed on the ring interface for a duration lasting less than 1.5 sec.

III. USER STUDIES

TABLE I

TECHNICAL FEATURES OF THE CO-GRIPPER.

Technical Features	
Weight (including motors)	480 g
Max. actuator torque	3.1 Nm @ 12 V
Max. current	2.8 A @ 12 V
Continuous operating time	3.5 h @stall torque
Max. operating angles	300 deg, endless turn
Max. non-loaded velocity	684 deg/s
Dimension of Gripper	130 mm x105 mm x 85 mm
Max. payload	4.75 kg
Max. horizontal resistive force	64.0 N @(cylinder diameter 95 mm)

Material Parameters	**Flexible Part**	**Stiff Part**
Modulus of elasticity (E)	15.2 MPa	40 MPa
Shore Hardness	85A	70D
Density	1200 kg/m^3	1070 kg/m^3
Module Geometric Par.		
width	25 mm	23 mm
length	23 mm	30 mm
height	3.5 mm	15 mm

TABLE II

FINITE STATE MACHINE FOR PUSH BUTTONS (PB)

Trigger signals	**Associated actions**
Both PB (signal length $<$ 1.5 sec	Mode change (Ring mode or self closing mode and vice versa)
Both PB (signal length $>$ 2 sec	Sonar Mode ON/OFF
Four–fingers mode	
Sensor Detection	flexion
Single trigger (right PB)	flexion/stop
Single trigger (left PB)	extension

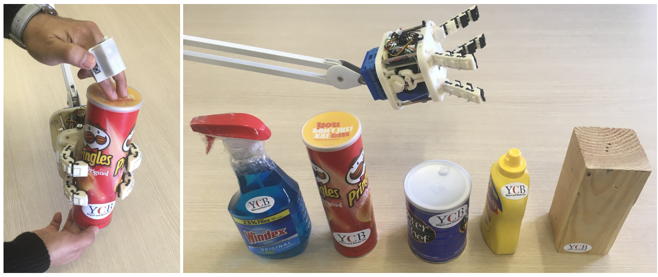
(a) (b)

Fig. 4. User study on ring-controlled mode. (a) shows how objects were hand over to the gripper. The thumb of the left hand is used to control the gripper. (b) The five objects used for the study. From the left: a cleaner bottle ($\sim$ 1 kg), a chips tube ($\sim$ 200 g), a coffee jar ($\sim$ 400 g), a mustard bottle ($\sim$ 600 g) and a wood block ($\sim$ 800 g).

One of the main goals of this work is to introduce the concept of bilateral haptic cooperation as a novel paradigm for human-robot interaction. The wearable haptic interface plays a major role since it allows both to control the gripper and to perceive robot action through the vibrotactile feedback. We conducted a user study involving ten subjects (four females, average age 28.3 years) to prove the effectiveness of bilateral haptic cooperation. In the following, we describe the two user studies and we report the results. Each study focuses on a different modality of use of the interface.

A. *Ring-Controlled mode*

In this study, the open/close motion of the gripper is controlled by the user through the two buttons available in the ring. More specifically, the left button is used for opening the fingers, whereas the right button is used for closing. It is possible to stop the motion by pressing again the same button. Both motors are equally controlled resulting in the motion of all the four fingers. The goal of this study is to test whether a feedback signal proportional to the force exerted by the gripper on the grasped object can improve the gripper usage. To this aim, user perceives a vibration on the ring interface that is proportional to the torque exerted by the servomotors. The torque is measured through the control board of the servomotors. The average torque between the two motor is computed and then mapped into a value of pulse frequency (period of active vibration) for the vibromotor and send to the interface via Bluetooth. According to the results reported in Sec. II, the torque values are mapped into a range of pulse frequency going from 2 to 10 Hz.

The participants were asked to hand over five objects to the CoGripper. The CoGripper was fixed to a passive support, see Fig. 4-(a). The five objects were selected among those available on the YCB set [9] and are shown in Fig 4-(b). The objects were selected so to have different weights starting from about 200 g of the chips tube to the kilogram of the cleaner bottle. Participants were instructed to use the ring to start the closing motion and to stop the motion as soon as they felt confident about the grasp stability. Closing velocity of the motors was set to 8 mm/s to provide enough time to the user to recognize a torque variation. For each object the hand over task was repeated for six times. Haptic feedback was randomly provided for half of the times. In total, each subject performed 30 hand over grasps, 15 of them being provided with the haptic feedback. We compared the torque of the motors reached for each object with and without the force feedback. Results are reported in Fig. 5. As expected, lighter objects required less torque to be grasped. For all the objects, the torque commanded, with feedback activated, resulted lower. A paired T-test analysis [10] revealed statistically significant difference between the average torques obtained with tactile feedback and with no feedback condition ($p < 0.001$) for each object.

We also considered the time to achieve each single grasp. As the user initiates closing motion of the gripper, a timer is activated and runs until the motion of the gripper is stopped. Average completion times for each object are reported in Fig. 6. As expected, lighter objects were grasped more quickly. A paired T-test analysis revealed statistically significant difference between the average time needed to grasp an object with tactile feedback and with no feedback condition ($p < 0.001$) for each object.

B. *Self-closing mode*

In this second experiment, we evaluated the possibility to use the interface to inform the user about the status of the gripper. When self-closing mode is selected, the gripper autonomously detect the presence of an object in the grasping area and start to close the finger. The presence of the object is detected through the sonar sensor, as soon as the object arrives at a distance of 3 cm from the palm, flexion of the fingers is automatically activated. At the start of the flexion, the user is informed with a vibration burst lasting for 1 s. The object grasp is then tightened until motor torques reached the predefined value of 2 Nm. Once the torque limit is reached, another vibration lasting for 2 s is provided to the user through the wearable interface. For this study, it was not possible to measure the completion time or the torque considering feedback and no feedback conditions. So we decided to ask the participants to perform 5 hand over grasp of the coffee jar using the system. Then we asked the participants to answer the ten questions of the system

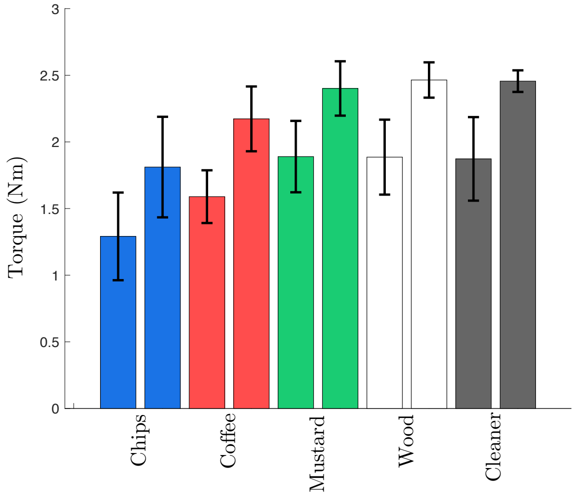

Fig. 5. Motor torque. Means and standard deviations of the commanded motor torque are plotted for the two conditions (feedback of the grasp tightness and no feedback) for the five considered objects..

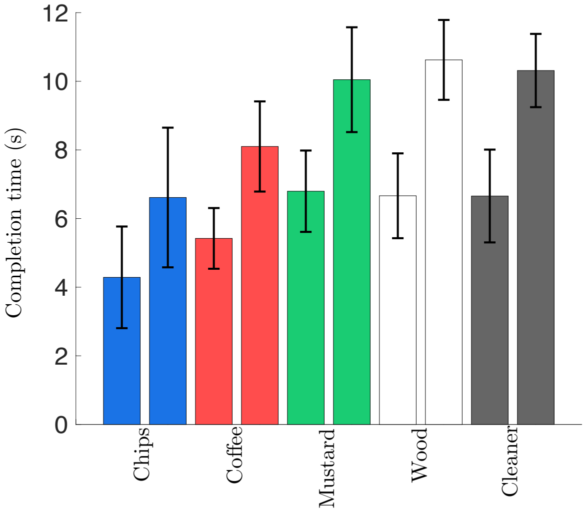

Fig. 6. Completion time. Means and standard deviations are plotted for the two considered conditions (feedback of the grasp tightness and no feedback, respectively) for the five considered objects.

TABLE III

ITEMS OF THE SYSTEM USABILITY SCALE

I think that I would like to use this system frequently
I found the system unnecessarily complex
I thought the system was easy to use
I think that I would need the support of a technical person to be able to use this system
I found the various functions in this system were well integrated
I thought there was too much inconsistency in this system
I would imagine that most people would learn to use this system very quickly
I found the system very cumbersome to use
I felt very confident using the system
I needed to learn a lot of things before I could get going with this system

usability scale (SUS) [11]. The SUS is used to evaluate the subjective assessments of usability. SUS yields a single number that represents 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 III. SUS scores ranges from 0 to 100. Details on how to compute the final mark can be found in [11]. The bilateral haptic collaborative system got an average score of 97.25 with a standard deviation of 4.15.

IV. CONCLUSIONS

This paper presents a novel system including a Co-gripper having a sonar sensor to detect the proximity of the object and new remote ring shaped interface embedded with a vibrotactile motor for bilateral haptic collaboration. This paper sheds light on the importance of communication between the worker and a robot. We carried out two user studies emphasizing on the importance of haptic feedback during human robot collaboration, where a user is provided with a continuous as well as discrete vibration feedback pertaining to the gripping force and state of the gripper respectively. This novel interface is a first step towards bridging a communication gap between human and robot. Currently, we are evaluating different kinds of acknowledgement that can be of great importance in a working scenario. Another important feature that we are embedding in the interface is a design of tactile buttons with haptic cues e.g. different sizes, different roughness etc, for better user recognition. As a future work we are planning to make the re-configuration of the gripper automatic providing the user with an ease to reconfigure the gripper using the same remote ring interface.

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