A Low-cost Sensor Glove with Vibrotactile Feedback and Multiple Finger Joint and Hand Motion Sensing for Human-Robot Interaction

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***Abstract*— Sensor gloves are widely adopted input devices for several kinds of human-robot interaction applications. Existing glove concepts differ in features and design, but include limitations concerning the captured finger kinematics, position/orientation sensing, wireless operation, and especially economical issues. This paper presents the DAGLOVE which addresses the mentioned limitations with a low-cost design (ca. 300 €). This new sensor glove allows separate measurements of proximal and distal finger joint motions as well as position/orientation detection with an inertial measurement unit (IMU). Those sensors and tactile feedback induced by coin vibration motors at the fingertips are integrated within a wireless, easy-to-use, and open-source system. The design and implementation of hardware and software as well as proof-of-concept experiments are presented. An experimental evaluation of the sensing capabilities shows that proximal and distal finger motions can be acquired separately and that hand position/orientation can be tracked. Further, teleoperation of the iCub humanoid robot is investigated as an exemplary application to highlight the potential of the extended low-cost glove in human-robot interaction.**

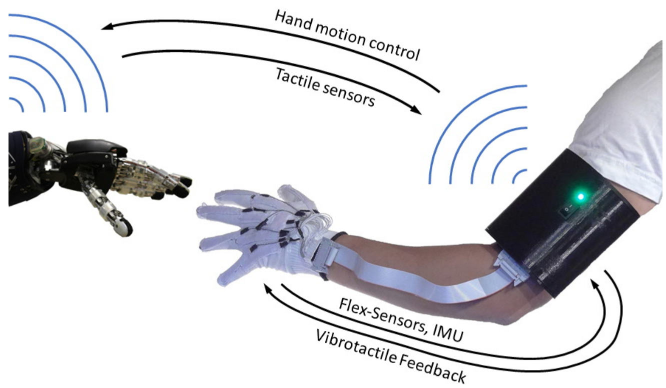

Fig. 1. The low-cost sensor glove can be used for teleoperation of complex robots with five finger hands such as the iCub humanoid (shown in the picture). If the robot hand exhibits sensors, vibrotactile feedback can be provided to the operator through motors at the fingertips.

I. INTRODUCTION

Sensor gloves have various uses in robotics and human-robot interaction such as learning manipulation tasks from human demonstrations [1], [2], [3], rehabilitation [4], or investigations of psychological issues [5]. In manipulation, the transformation from human to robot motions is an important issue since these usually do not match perfectly, e.g., due to kinematic differences. A possible solution for this issue is active learning which relies on mapping from human to robot kinematics [6], [7], [8]. Alternately, the operator directly controls the robot hand through an instantaneous mapping from sensor glove measurements to control actions in passive approaches [2], [9]. Considering the latter class of techniques, human operators can adapt and compensate for limitations of the robot and kinematic mapping errors.

Providing additional degrees of freedom should lead to better use of complex robots such as the humanoid robot iCub [3], [10] (see Figure 1). Furthermore, vibrotactile feedback could improve human-robot interaction by giving the user a feeling of ownership [11]. Yet, potential benefits depend on the application: for instance, a combined degree of freedom per finger might be sufficient in certain rehabilitation robots [12], while additional ones could improve exploring body schema integration [5], [13] and can be crucial in hand exoskeletons [14].

In contrast to commercial and rather high-priced data gloves such as the Cyberglove [15], many low-cost gloves do not provide more than one degree of freedom (DoF) per finger, e.g., [10], [13], [16]. Besides resistive sensors [10], [13], marker-based motion capturing [17], optical linear encoders [18], or stretch sensors [19] are used to track finger motions. While the glove from [18] provides additional DoFs, it lacks other important features such as hand position/orientation acquisition. The glove introduced in [20] provides a wireless interface to the host but only five DoFs. Although combining more DoFs and hand position/orientation sensing, the DJ Handschuh [21] is limited to a single finger. Alternative approaches to motion acquisition rely on external tracking of the human hand by fusing visual and gyroscope data [22] or using marker-based measurement [23]. The majority of gloves does not provide vibrotactile feedback. One system that implements feedback and combines it with the other features discussed above, is the VR Data Glove [24]. This glove aims at virtual reality applications and only exhibits a single degree of freedom per finger. An alternative feedback implementation is found in

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007–2013) under grant agreement #600716 (CoDyCo).

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the Hands Omni Glove [25] which generates contact forces by inflatable bladders but uses external motion capturing.

As no low-cost glove combines multi-DoF finger tracking, vibrotactile feedback, hand position/orientation detection and wireless interfacing, this paper suggests the DAGLOVE. The DAGLOVE is based on the open-source and low-cost sensor glove described in [10], [13]. It extends the existing concept to provide the mentioned features and makes use of electronic components that are affordable and that simplify the development. The hardware design of the new DAGLOVE is presented based on a brief description of the preliminary glove in Section II before data acquisition and software design are given in Section III. Beyond presenting the improved glove design, the paper qualitatively demonstrates the basic functionality of fingers and hand motion measurements in Section IV. To show the benefits of extended kinematic sensing with the glove, it is shown how the additional degrees of freedom can be exploited in teleoperation of the iCub humanoid robot. The results of the paper are concluded in Section V.

II. GLOVE DESIGN

In the following sections, the design of the preliminary glove and the re-designed DAGLOVE are described. Key features of the DAGLOVE are the consideration of interphalangeal (IP) and metacarpophalangeal (MCP) joint flexion of the index, middle, ring, and pinky fingers as well as metacarpophalangeal I (MCP I) and carpometacarpal (CMC) joint flexion of the thumb (see Figure 2).

A. Preliminary glove

The preliminary glove used a single 4.5 inch flex sensor per finger to measure flexion and extension [10], [13]. The orientation of the hand and its position in space were acquired by a marker-based motion tracking system in [10]. For this purpose, reflecting markers were fixed on the back of the glove and captured by multiple infrared cameras installed in the laboratory. Coin vibration motors (Solarbotics VPM2) were attached to the fingertips to provide vibrotactile feedback that can be controlled based on tactile or pressure sensors of the teleoperated robotic hand. In [10], the feedback was implemented to be proportional to the contact forces occurring at the robotic fingertips and thereby inform the user during grasping. A microcontroller-board (ARDUINO MEGA 2560) read the sensor values and communicated with a host computer. To exchange sensor and feedback data, an USB/COM-Port interface connects the Universal Series Bus (USB) of the host with the Serial Port (COM) of the microcontroller.

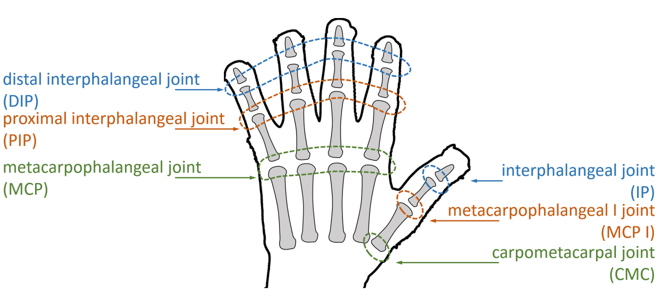

Fig. 2. Overview of the human hand articulations [26].

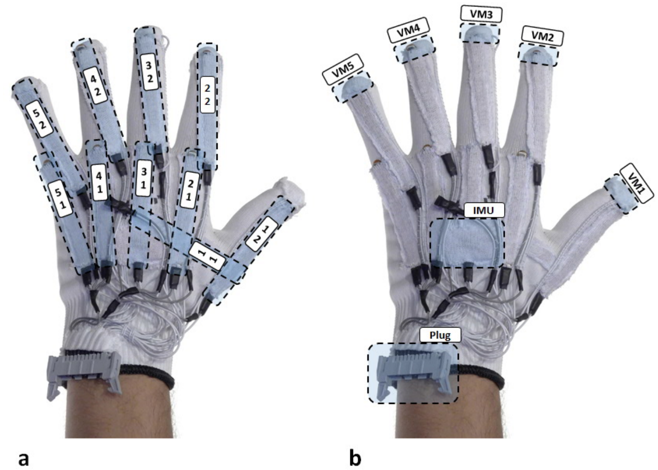

Fig. 3. Component placement: **a** Placement of the ten flex sensors. Sensor denominations $\frac{X}{Y}$, while X stands for the finger number (1=thumb, 2=index, 3=middle, 4=ring and 5=pinky) and Y stands for the sensor number on each finger (thumb: 1=CMC&MCP I and 2=IP; other fingers: 1=MCP and 2=PIP&DIP). **b** Location of the five vibration motors (VM), the inertial measurement unit (IMU) and the plug of the glove.

B. Requirements and redesign

The objectives of re-design of the preliminary glove resulting in the new DAGLOVE are:

- Sensing complex motions
- Improvement of position/orientation sensing
- System integration
- Extended motion possibilities and improved ergonomics (e.g., through wireless transmission)

For this purpose, the new DAGLOVE uses ten flex sensors, the visual motion tracking is replaced by an inertial measurement unit (IMU), the position of the vibration motors is optimized and the electronics as well as the software are completely redesigned as presented subsequently.

1) Sensing complex motion: Ten 2.2 inch flex sensors from SPECTRASYMBOL are implemented as depicted in Figure 3. This facilitates the detection of more complex motion-tasks and the acquisition of different joint motions separately. Since flexion and extension of the distal and proximal interphalangeal joints are coupled in the human hand [27], [28], it is sufficient to use one flex sensor placed on the upper part of the finger. The second flex sensor is placed at the lower part of the finger to measure the flexion and extension of the metacarpophalangeal joint. At the thumb, flexion of the interphalangeal joint is measured by

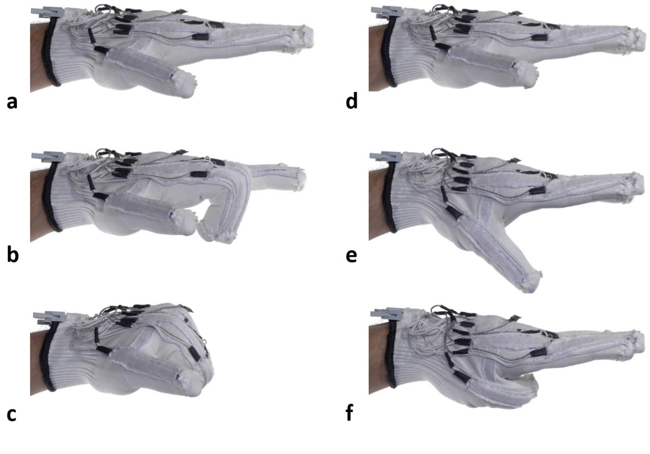

Fig. 4. Exemplary motion sequences exploiting the degrees of freedom of the glove: **a** Starting position. **b** Flexion of the PIP and DIP joints of the index and middle finger. **c** Flexion of the PIP, DIP and MCP joints of the index, middle, ring and pinky finger. **d** Starting position. **e** Flexion of the CMC joint of the thumb. **f** Flexion of the IP and MCP I joints of the thumb.

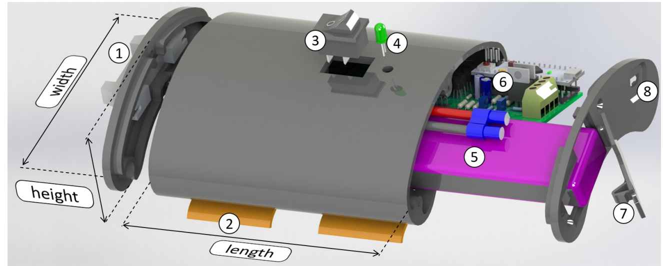

Fig. 5. Exploded view of the electronic box with its components. **1** Connector for the flat ribbon cable. **2** Elastic band. **3** ON/OFF-button. **4** Power-LED. **5** Exchangeable battery-pack. **6** Circuit board including the ARDUINO MICRO, BLUETOOTH-transmitter, analog multiplexer (MUX) and voltage regulation. **7** Cover for the battery-pack. **8** Micro-USB-Port. **length** 130 mm. **width** 120 mm. **height** 50 mm.

a single flex sensor. A second flex sensor detects the coupled flexion and opposition movement of the metacarpophangeal I and carpometacarpal joints exploiting their dependency discussed in [29].

The additional degrees of freedom are acquired to meet the requirement of facilitating more complex movements given above. Examples of hand motions that present movements which exploit the additional degrees of freedom are illustrated in Figure 4. A critical requirement is that the motion of each joint must be sensed isolated from the movement of the other joints. This is realized by placing the flex sensors as shown in Figure 3a.

To fix the flex sensors and allow them to move along the finger axis but not orthogonal to it, they slid into small pockets that are sewed on the top of the glove. The sensors are fixed at the side of their electronic connection pins and their motion is guided by the pocket. The guidance and fixation of the sensors with these elastic pockets prevents the sensors from being damaged during different finger movements.

2) Position- and orientation-sensing: The DAGLOVE further includes an IMU with nine degrees of freedom to acquire hand motions and orientation. For this purpose a INVENSENSE MPU-9150-chip, which includes a 3-axis accelerometer, a 3-axis gyroscope, and a 3-axis digital compass (magnetometer) is implemented. To break out all required pins of the MPU-9150 to standard 0.1 inch spaced headers, a breakout version of this chip from SPARKFUN (SPARKFUN 9 DEGREES OF FREEDOM BREAKOUT - MPU-9150) is used. The board has an I^2C-interface and is centered on the back of the hand as it is shown in Figure 3b.

3) System integration and ergonomic aspects: The system is designed as a standalone, easy-to-use, untethered, and integrated solution which includes two main parts, i.e., sensory glove and electronic box. The glove is connected to the electronic box with a flexible flat ribbon cable to avoid disturbing the user. The connector of the electronic box is shown in Figure 5. If the cable is unplugged, the glove can easily be put on or off without any mechanical disturbances. The connector of the glove is shown in Figure 3b. The electronic box includes the circuit board and an exchangeable and rechargeable battery pack. The box with its components is illustrated in Figure 5. The circuit board and its functionality are presented in Section III. The electronic box can be connected to an external PC over a BLUETOOTH-interface and together with its battery pack, the sensory glove allows an easy-to-use wireless operation. Due to its special shape and low weight, the 3D-printed box can be attached to the upper arm of the user with elastic bands. The compact design of the different components and the wireless connection allow a high flexibility to use this low-cost sensory glove in different operation and motion scenarios.

Further improvements are made regarding the fixation of the vibration motors to the glove. They are sewed on the glove at the tip of the fingertips, as close as possible to the fingernails. These new positions provide a more compact fixation, give the user a better feeling in the fingertips and do not disturb the user while grasping objects.

III. DATA ACQUISITION

In this section, the implemented electronic hardware as well as the firmware that controls and monitors the whole glove system are presented.

A. Glove electronic implementation

The whole system is controlled and monitored by an ARDUINO MICRO-board which is chosen for its small size and overall good compatibility. On the one hand, it reads all the data from the sensors and streams it to the host computer, as it is illustrated in Figure 6. On the other hand, it can get a command line from that device which defines the intensity of the vibrotactile feedback of each finger. The connection to the microcontroller can either be implemented over its own

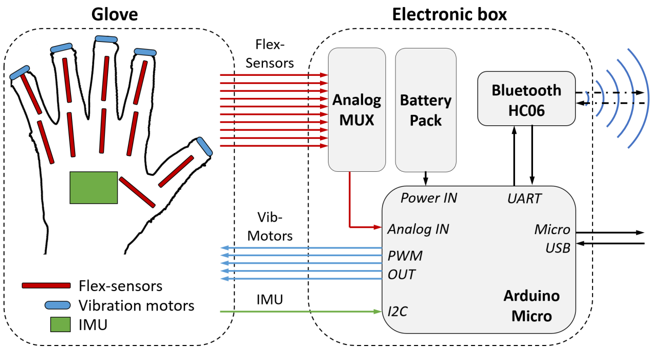

Fig. 6. Simplified block diagram of the electronic implementation.

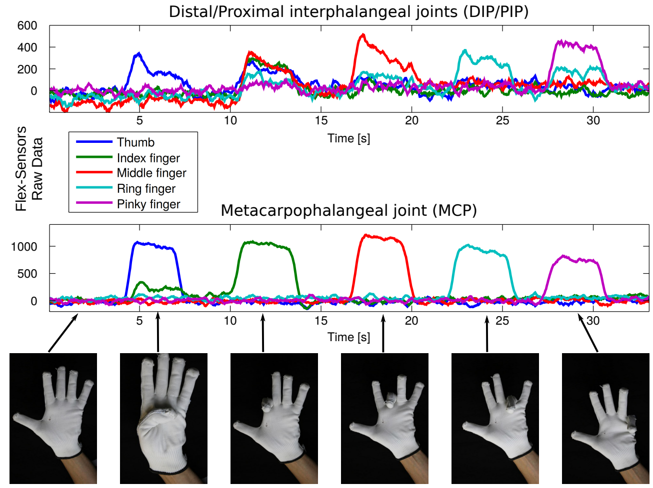

Fig. 7. Example of raw data recorded for both MCP and IP joints with the flex sensors for various hand poses (each color correspond to a different finger). The flexion of the different fingers is visible from the data.

Micro-USB-Port or via BLUETOOTH. The BLUETOOTH-connection is provided by an additional transceiver module (AUKRU HC-06) connected to the UART-serial-interface of the ARDUINO MICRO. The IMU is connected to the microcontroller through a serial I^2C-interface. The intensity of the vibrotactile feedback depends on the frequency and amplitude of the corresponding vibration motor. The frequency, as well as the amplitude, is directly proportional to the motor input voltage and can be varied in a range of 50 Hz to 220 Hz, respectively 1.2 N to 2.4 N. For this purpose, the input voltage is regulated by an amplified pulse width modulation (PWM) signal of the microcontroller-board. The microcontroller includes 20 digital inputs and outputs of which 7 can be used as PWM outputs and 12 as analog inputs. The sensory glove needs five PWM outputs (vibration motors), four serial-port pins (IMU and BLUETOOTH-module) and 11 analog inputs (monitoring the battery-level and 10 flex sensors). As three of the analog inputs have to be used as PWM outputs, the remaining nine analog pins are insufficient to read out all the flex sensors. That is the reason why a 16-channel analog multiplexer (MUX) (CD74HC4067) is used in a breakout-board version from SPARKFUN. This multiplexer allows to read 16 analog channels using a single analog input (and five additional digital outputs) on the ARDUINO-board. The exchangeable battery-pack with 2400 mA h provides enough power for a constant operation of at least five hours. Figure 6 gives a block diagram of the system, its components, and interfaces.

B. Glove software interfaces

The software is written in the ARDUINO IDE using additional libraries in C++. The measured values from the IMU are read using modified versions of the open source libraries published on GITHUB[1]. Due to the analog multiplexer (MUX), it is possible to read the values from each flex sensor subsequently with one analog input only. Then the microcontroller checks for feedback-intensities coming from an external device in the form of a string command, e.g., from tactile sensors at the operated robots finger tips. The command line can be detected on any serial-communication-port, either on the Micro-USB-Port or over the BLUETOOTH-connection. Subsequently, the values are extracted from this command line and the vibration motors are controlled by a PWM-output that is proportional to these values. In addition to that, the software monitors the actual battery level. Finally it writes a string command with all the values of the flex sensors, the IMU, the actual battery level and some control data (actual time stamp and feedback intensities). This string is either sent over the Micro-USB-Port or the BLUETOOTH-connection with a baudrate of 115 200 bit/s. The main software loop runs with a frequency of 25 Hz. The glove software interface, as well as detailed information about the hardware implementation are freely available at `https://github.com/TUDarmstadtPWeber/DAGlove`.

IV. EXPERIMENTAL EVALUATION

As a first proof-of-concept of the design and functionality of the DAGLOVE, its capabilities and the performance of its sensors are demonstrated. Moreover, a first application in teleoperation that benefits from the separation of DIP/PIP and MCP joints is presented.

A. Sensor capabilities

In the following sections, the functionality of the sensors are presented by collecting the measured values from the flex sensors, as well as the IMU for exemplary finger and hand movements.

1) Finger Sensors: This experiment demonstrates that the placement of the sensors is appropriate to collect valuable information about the flexion of the single phalanges. To reduce the measurement noise of the flex sensors, a simple moving average filter $\hat{x}_t = \frac{1}{n}\sum_{i=0}^{n-1} x_{t-i}$ with a window $n = 10$ is applied. More advanced filtering techniques including

[1] `https://github.com/sparkfun/MPU-9150_Breakout`

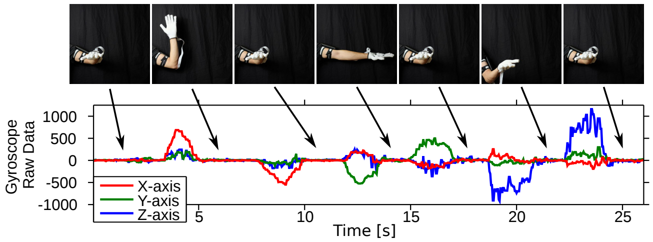

Fig. 8. Example of raw values recorded from the IMU gyroscope for various movements.

the widely used Butterworth filters in human grasping will be investigated in future work. In Figure 7, an example of the filtered data collected from each individual flex sensor for the MCP joints is shown. The flexion of each finger is visible from the data. Flexion of other joints and fingers is observed for some DIP/PIP joint motions due to mechanical couplings in the human hand.

2) IMU: To present the detection of the correct orientation by the IMU, an example of the data collected during various arm motions and poses is visualized in Figure 8. As seen in the motion samples of Figure 8, the aspect of the angular velocity curves behaves as expected for each axis. To validate the precision and drift effects of the gyroscope, accelerometer, and magnetometer, further experiments will be performed in the future.

B. Teleoperation

To investigate human-robot interaction application, direct teleoperation of a robotic hand trough the DAGLOVE is considered. The goal is to demonstrate the benefits of the high number of flex sensors for grasping tasks. Therefore, the humanoid robot iCub shown in Figure 10 which possess 9 DoF for each hand [30] is used as a hardware platform.

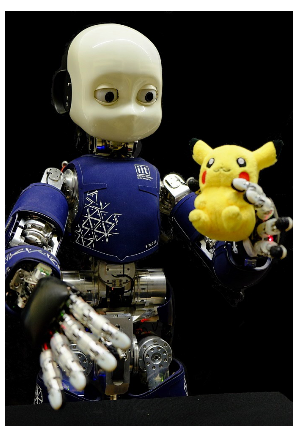

Fig. 10. The humanoid robot iCub used in the experiments.

In the experiments, the flex sensor readings are directly mapped to desired joint angles in the iCub. Let q denote a joint angle with an operational range of $[q_{\min}, q_{\max}]$. A flex sensor reading s is normalized and mapped to a desired joint angle with $q = q_{\min} + (q_{\max} - q_{\min}) * (s - s_{\min})/(s_{\max} - s_{\min})$. The operational ranges of the iCub finger joints and the glove were obtained in a pre-processing phase. Note that the iCub possess three DoF in the thumb (CMC, MCP I and IP flexion) while the DAGLOVE only has two (IP and coupled CMC/MCP I flexion). Thus for the CMC and MCP I joint the same coupled CMC/MCP I flexion signal was used. Moreover, the ring and pinky fingers of the iCub are coupled and jointly controlled by a single DoF while the sensory glove measures four separate DoF. Here we used the average of these four readings for control.

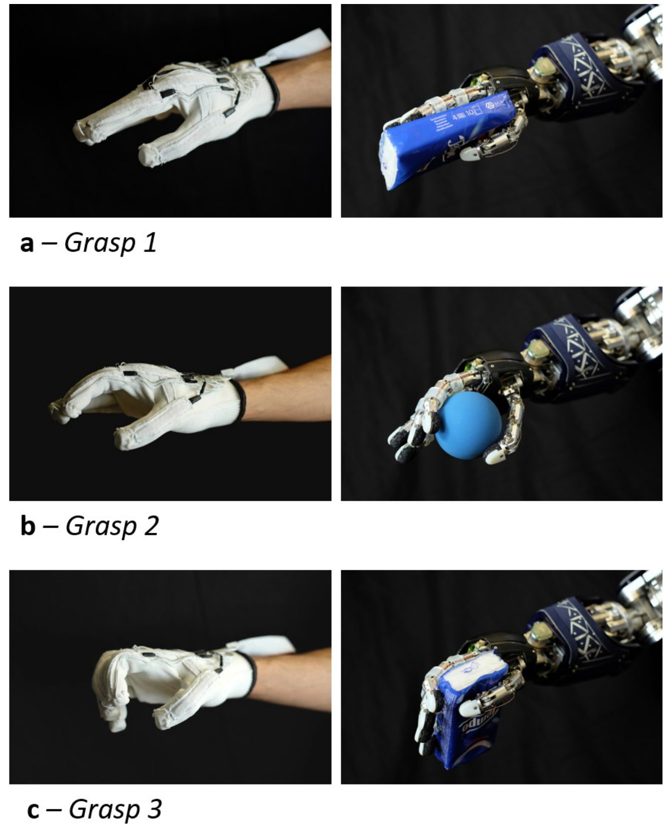

Fig. 9. Various grasping poses with the DAGLOVE *(left)* and the teleoperated iCub hand *(right)*. The different grasp types make use of different correlations between the finger joints, and as such benefit from the use of two separate flex sensors for each finger.

In Figure 9, three grasp poses achieved using the DAGLOVE to teleoperate the hand of the iCub are shown. Performing all these grasp types would not be possible using the same correlation matrix. For example, the grasp in Figure 9b requires both MCP and IP joints to flex, while the grasp in Figure 9c only makes use of the IP joints. Further, the additional thumb sensor enables the control of the opposition of the thumb, which is crucial to stable grasps of different sizes and shapes.

V. CONCLUSION

This paper presents a new sensor glove: the DAGLOVE. The DAGLOVE is designed for human-robot interaction research and therefore combines 2-DoF kinematic sensing for all fingers, vibrotactile feedback and hand position/orientation acquisition. These aspects are integrated in an easy-to-use and low-cost system with wireless connection to the host computer. The key components comprise ten flex sensors, which are separately measuring proximal and distal finger joint motions as well as the flexion of the thumb and the thumb saddle joints. An inertial measurement unit facilitates detecting hand position and orientation. Finally, coin vibration motors are attached to the fingertips, providing vibrotactile feedback. Despite these improvements, the overall material costs of the DAGLOVE is less than 300 €.

As a proof-of-concept, preliminary experiments are performed to qualitatively examine the features of the DAGLOVE and their use. First, the separate acquisition of proximal and distal finger motions as well as the tracking of the hand movements with the integrated IMU are studied. Following, the potential of the extended low-cost glove for human-robot interaction is presented in a teleoperation scenario with the iCub humanoid robot. Although a quantitative assessment of sensor data quality is missing, these first experiments demonstrate that the separate sensing of proximal and distal finger joint motion can enable teleoperating grasps with increased complexity. Moreover, the additional detection of thumb saddle joint motions enables grasping of flat and soft objects without deforming them.

Future works will focus on improving the electronics and software to increase the operating frequency. The quality of flex sensor and IMU data should be quantitatively assessed and filter implementations for these data should be tested. Further potentials are the use of force instead of vibrotactile feedback [31].

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