Development of an intelligent object for grasp and manipulation research

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Abstract— **In this paper we introduce a novel device, called iObject, which is equipped with tactile and motion tracking sensors that allow for the evaluation of human and robot grasping and manipulation actions. Contact location and contact force, object acceleration in space (6D) and orientation relative to the earth (3D magnetometer) are measured and transmitted wirelessly over a Bluetooth connection. By allowing human-human, human-robot and robot-robot comparisons to be made, iObject is a versatile tool for studying manual interaction.**

To demonstrate the efficiency and flexibility of iObject for the study of bimanual interactions, we report on a physiological experiment and evaluate the main parameters of the considered dual-handed manipulation task.

I. INTRODUCTION

Touch is one of the main senses that humans and other higher animals use for coordinated interaction with the world. Unlike industrial robots that perform known repetitive tasks with job-specific grippers, we argue that mastering touch is a prerequisite for having advanced robots that can interact safely with humans and objects in unconstrained situations. Nature has shaped our hands over millions of years, allowing us to carry out a wide variety of tasks, including high precision (surgery), accurate timing and force (piano), high sensitivity (braille reading), heavy-duty lifting and carrying. Therefore, the ability to analyze human hands performing tasks involving touch seems like a good step towards endowing artificial hands with humanlike capabilities.

Researchers in the field of service robotics are working hard to allow robots take some burden away from us humans, not only to take care of our ever aging population, but also to take over tedious or undesired jobs. The dexterity of the human hand is especially fascinating for the robotics community and as yet is still not close to being replicated in current robotic hands that are clumsy when operating in natural environments with objects originally developed for humans. Even if the robot is able to move to its workplace, with the help of wheels or legs, and the objects to be handled can be localized and recognized using computer vision, the daunting task of grasping and manipulating them is still mostly unsolved for arbitrary objects by current state of the art robot hands, which is also due to missing or inadequate tactile feedback.

The dexterity of human hands derives from the interplay of complex hand kinematics (already seen in some robot hands [1][2]) and complex cognitive control processes that are guided by visual and tactile feedback, not yet fully understood. Especially the role of spatiotemporal tactile feedback within the control process was often neglected in studies, because the acquisition of real-time haptic feedback is a difficult problem. However, to illustrate the importance of tactile feedback, consider binding a knot with numb fingers - a condition easily achieved by cold weather without gloves. An experiment, performed by anesthetizing the skin of the hands of volunteers, revealed difficulties in maintaining a stable object grasp [3].

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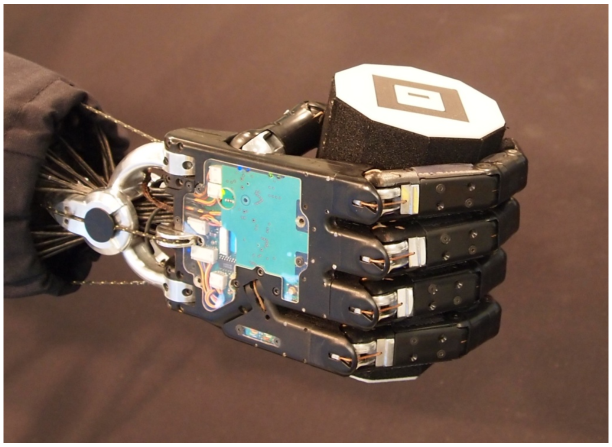

Fig. 1. Intelligent Object (iObject) grasped by the anthropomorphic Shadow Robot Hand.

We argue that a simultaneous analysis of multiple hand modalities, like finger position, contact location, applied pressure patterns and executed motion, during human grasp and manipulation, will allow better control strategies for robotic hands to be developed. Numerous devices have been developed for measuring the human hand parameters during operation, many of which are commercially available. Capturing such data usually involves the wearing of a dataglove equipped with various sensors (e.g., CyberGlove II [4], see also [5] for a comparison of numerous data-gloves), having reflective or active markers fixed on the hand for tracking (e.g., Vicon MX [6], Lukotronic AS series [7]) or require the holding of an object equipped with multimodal sensors (e.g., Nara-IST cylinder [8], UBI Audio-Haptic Ball [9][10]). We believe that manipulation data can only be qualitatively collected by including contact location and pressure information and not only relying on the finger joint positions. Optimally, the measurement device should be wireless, without the presence of intrusive cables to minimize possible behavioral errors and disturbances to the natural manipulation action.

In this paper we propose a novel wireless grasp and manipulation measurement device, called iObject [Fig. 1], equipped with tactile and motion tracking sensors for evaluating the actions of a human or an anthropomorphic robotic hand (roughly the size of an adult hand). Finger and hand contact location and force, object acceleration (linear 3D + rotational 3D) and orientation relative to the earth (3D magnetometer) are measured and transmitted wirelessly over a Bluetooth connection. If the user wears a data glove (such as the popular CyberGlove II) hand posture, contact location, contact intensity and motion data (linear and rotational) can be simultaneously captured [11].

The developed tactile sensing device is not only useful for acquisition of human motor data, but also facilitates the complex task of joint value and tactile sensor calibration of modern robotic hands equipped with tactile sensors, e.g., Gifu Hand II [12], SKKU Hand II [13], iCub Hands [14] [15], Shadow Robot Hand [16].

The remainder of the paper is organized as follows: in Sec. II the hardware elements of iObject are introduced and details of the sensing principle of tactile cells, sensor characteristics, overall iObject mechanical construction, power management, wireless connectivity and elementary on-board data processing are explained. This section also introduces iObject's flexible mounting interface facilitating its use in various research disciplines. In Sec. III the communication and data protocol is described. Sec. IV evaluates the tactile sensor signal curve and the overall system latency. Sec. V demonstrates a simple application in a non-robotic field and finally Sec. VI concludes with a discussion.

II. HARDWARE DESCRIPTION

iObject was designed to fit nicely in the average human hand, to measure contact and motion data, to be cable-free to maintain maximum comfort, and to measure data in a robust way while being used. A standard 330ml beverage can, an ideal object allowing both a firm grasp as well as numerous single or dual handed manipulations to be carried out, was chosen as the model for shape and size. Thus the dimensions of iObject are approximately 80mm (diameter) $\times$120mm (height), providing ample interior space for the numerous required electronic components. In the next sections the components and working principle of iObject are introduced. Fig. 2 gives an overview of the internal component blocks and their connections.

A. Tactile sensors

To measure the contact pressure location and amplitude of a human or robotic hand, a custom built tactile sensor array is implemented throughout the whole cylindrical surface of iObject with a spatial sensor cell separation of 10mm [Fig. 3]. The tactile sensors are based on a resistive working principle, where the interface resistivity between two surfaces changes according to the applied load. iObject uses a chemically golded Printed-Circuit-Board surface as

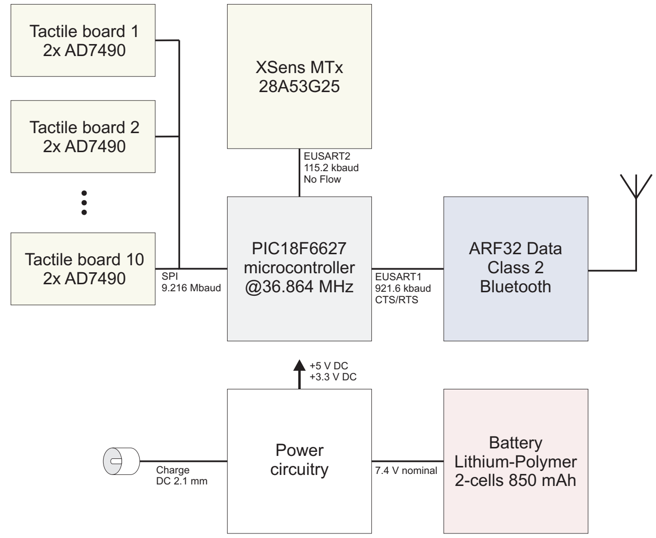

Fig. 2. Internal iObject components and their connection.

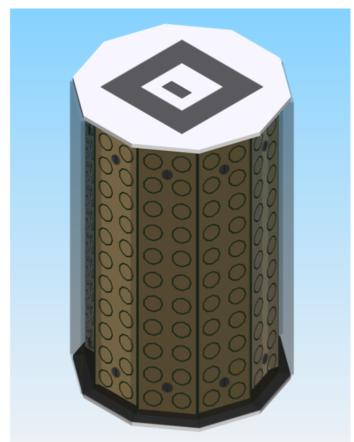

Fig. 3. Tactile sensors as seen through rendered translucent sensor material (optional ARToolKit marker module attached on top).

electrodes and a conductive elastomer foam as the sensor material, a technique first introduced in [17]. As seen in Fig. 4, the tactile sensor cell resistance R_t is the sum of 3 parts – variable surface interface resistance $R_{s1}+R_{s2}$ and a constant sensor material volume resistance R_v.

The resistive sensor approach was chosen as in comparison to capacitive sensors it is robust to electromagnetic interference, and in comparison to load cells it is relatively easy to implement. Resistive sensors also have a very desirable hyperbolic style characteristic between the applied load and the resistance. This is especially interesting for tactile sensors, as it allows detection of first contact and a wide measurement range, although the resolution is sacrificed at higher loads. Due to simple construction of resistive tactile sensors, they are also very insensitive to abuse, like vibration and overload.

Ten identical sensor array boards, measuring 20×115mm and containing 2×11 tactile sensitive elements each, form the decagon surface of the iObject. The 4-layered PCB having 22 electrodes and a common ground-plane on the outer

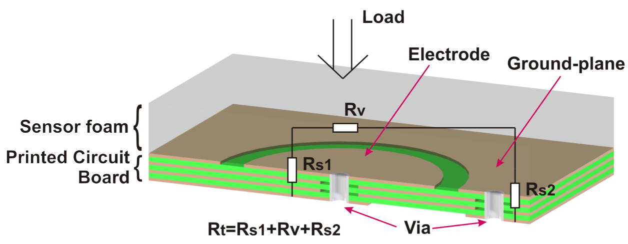

Fig. 4. Resistance of a single resistive tactile sensor cell.

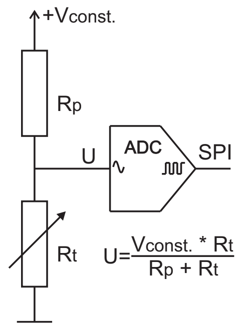

Fig. 5. Sensor cell R_t resistance digitalization with a constant pull-up R_p and analogue-to-digital-converter (ADC) with serial-peripheral-interface (SPI) bus output.

side and signal conditioning circuitry on the backside forms the basis of the tactile sensor. Numerous candidates for the needed conductive sensor material were evaluated, and a high viscosity elastomer foam from Weiss-Robotics was selected. It features favorable low creep and strength to cope with shear forces without rupture. 5mm thick sheets of the foam were processed with a CNC milling machine into a trapezoid form and glued with flexible glue to form an exact fit over the electrode decagon ring of sensors.

The resistance measured between the electrode and a common ground-plane, electrically connected with the conductive elastomer foam, is converted to voltage with a simple constant pull-up resistor attached to a constant power supply [Fig. 5]. The voltage of 22 tactile cells in one sensor board is measured with two 16-Channel 12-Bit analog-to-digital AD7490 converters (ADCs), which provide the data for further processing onto the internal Serial Peripheral Interface (SPI) Bus. Altering the value of a pull-up resistor allows us to shift the measurement range. Higher resistance allows lower pressures to be measured, at the cost of inducing higher signal noise and narrowing the sensor bandwidth. The typical contact forces required for normal handling of the object were measured to be in the range of 5 to 15 kPa, resulting in an optimal pull-up resistor value of 100 kOhms. The tactile sensor sensitivity evaluation can be found in Sec. IV.

If we were to unroll the $10 \times 2 \times 11$ tactile sensors of the decagon surface, it can be imagined to be a 20×11 pixel tactile monochrome camera with 220 tactile pixels (tactels), thus offering the possibility of processing the contact pressure data with numerous existing algorithms from the computer vision domain.

B. Motion and orientation sensor

To measure the motion and orientation of iObject, commercially available MTx-28A53G25 motion tracker internals from XSens were embedded. The MTx incorporates and provides measurement for:

- 3D linear acceleration sensors (full scale 50 m/s^2 $\approx$ 5G, bandwidth 30 Hz)
- 3D rotational acceleration (rate-of-turn) sensors (full scale 1200 deg/s, $\approx$ 3.3 full rotations/s, bandwidth 40 Hz)
- 3D magnetometer sensors ($\pm$750 mGauss, bandwidth 10 Hz)
- ambient temperature sensor

The MTx outputs the measured and digitalized data on a standard serial RS-232 interface at 115.2 kbaud with maximum update rate of 120 frames per second using onboard processing.

C. Power supply

iObjects full range of internal components is powered by a 2-cell Lithium-Polymer (LiPo) 850mAh battery providing nominally 7.4V. LiPo chemistry was used due to its outstanding power to weight ratio and good availability in numerous sizes and forms. With an average power consumption of $\approx$ 120mA, the selected battery can provide around 7h of continuous usage on a single charge. iObject takes extra care to avoid deep discharge of the battery, by powering down the complete device if the voltage drops below 3.0V/cell.

D. Wireless connectivity

To extract realistic grasping and manipulation data, a wireless design without disturbing cabling was decided upon. Instead of collecting the measured data on-board for later off-board processing, the authors chose to wirelessly stream the live data to keep its usage more generic. Adeunis ARF32 Data Class 2 Bluetooth Module was chosen due to its relatively high 723 kbps theoretical maximum data rate. Using wireless communication has the added benefit of actively being able to control key data sampling parameters in an online fashion from the control system. A class 2 Bluetooth module was chosen over the considerably higher range Class 1 module due to power consumption concerns (see Table I for further information about Bluetooth classes). Nevertheless, we note that the best wireless range is achieved with a Class 1 communication partner, as these modules usually embed higher grade components and thus have in addition to considerably higher transmitting rates, more sensitive receivers.

The actual over-the-air data rate is very dependent on the environment, thus hardware flow control with Clear-to-Send/Request-to-Send (CTS/RTS) is actively used to avoid overflowing the buffers and invalidating data packets. The sensors (tactile and motion) are polled at the maximum rate possible for transmission.

TABLE I

BLUETOOTH POWER CLASSES

Class [18]	Maximum Power [18]	≈ Operating Range [19]
Class 1	100mW (20dBm)	100 meters
Class 2	2.5mW (4dBm)	10 meters
Class 3	1mW (0dBm)	1 m

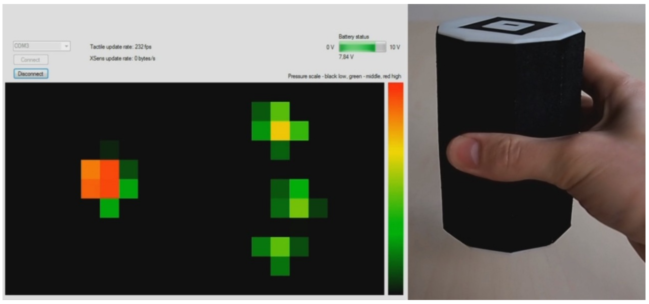

Fig. 6. Typical grasp scenario: only a small number of tactile cells have contact, allowing for a good data compression ratio.

E. Data processing

The sensor data from all sensors is internally collected, encoded and sent to the Bluetooth module for transmission by a custom built main processing unit PCB. At the heart of the main processing unit is the Microchip PIC18F6627, an 8-Bit FLASH-based reprogrammable microcontroller running at 36.864 MHz and providing computational capabilities up to a theoretical limit of 9.216 million instructions per second (MIPS). The microcontroller collects the data from the pressure sensor boards over a SPI Bus; from accelerometer and orientation sensor over an enhanced-universal-synchronous-receiver-transmitter (EUSART) and communicates with the client via the Bluetooth module connected to a second EUSART port of the microcontroller.

To optimize the usage of its limited wireless bandwidth, the microcontroller transmits only the tactels data with non-zero pressure information. In a typical grasping situation only a low percentage of cells are in contact, thus the selective transmission compression algorithm allows considerably higher frame rates to be achieved [Fig. 6].

The microcontroller runs interrupt-driven code, programmed 100% in assembly language (Microchip MPASM) to provide maximum processing efficiency and lowest possible latency.

F. Mechanical construction

The body of iObject was constructed to serve the dual duty of giving an integral strength required during firm grasps and at the same time supplying an optimal mount for all the internal components. The mechanical parts were all designed with CAD software. The plastic parts were manufactured from acrylonitrile butadiene styrene (ABS) thermoplastic using a rapid prototyping 3D-Printer and the metal parts were milled with a 5-axis CNC manufacturing center out of aluminum (EN AW-7075) using CAM software for the mill path programming. An explosion view of iObject's internal construction is shown in Fig. 7.

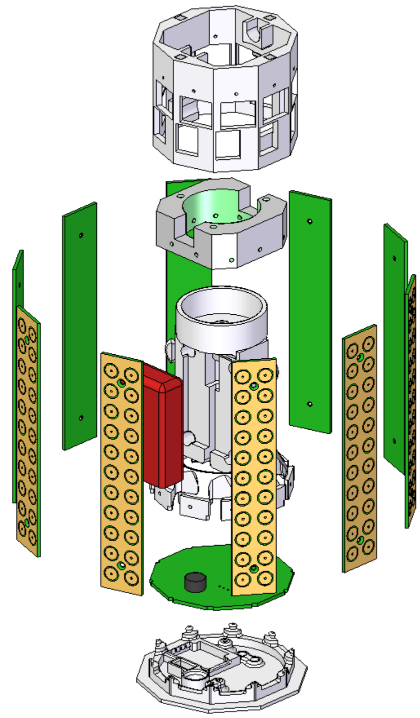

Fig. 7. Explosion view of iObject internals.

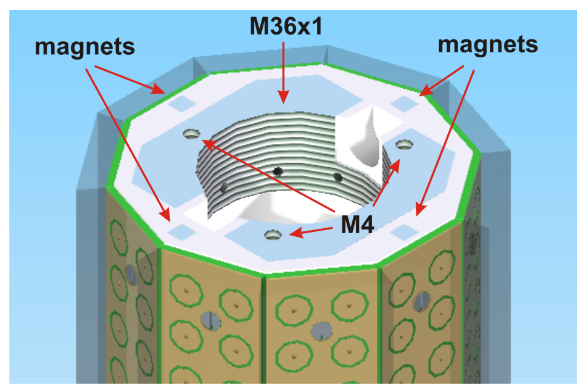

Fig. 8. Multiple mounting options for exchangeable modules.

The bottom surface incorporates a power on/off switch, charging jack, status LEDs and a debugging/programming port for the microcontroller. On top there is a custom mount for exchangeable modules [Fig. 8] that provides instant mounting with Neodymium (Nd) magnets for light modules with limited mechanical loading and M4 screw (x3) and M36x1 mounts for modules that need firm attachment. The base of the mount provides a 4-pole jack for power and digital I/O to be used by active modules.

G. Exchangeable modules

To adhere to the fundamental idea of a generic grasp and manipulation measurement tool, iObject allows mounting of numerous exchangeable modules. Some examples are shown in Fig. 9. The modules can be used for absolute position localization as with ARToolKit marker module [20],

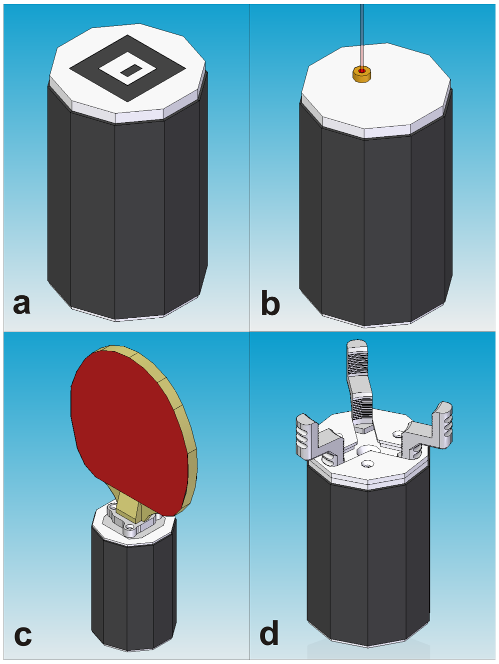

Fig. 9. Some exchangeable modules: a) ARToolKit marker, b) Laser diode, c) Table tennis bat, d) Passive big gripper.

Header	Timestamp	Packet type	Data payload	Checksum
2 bytes	2 bytes	1 byte	1-61 bytes	1 byte

Data count	Include flags	Tactile data
1 byte	3 bytes	0-44 bytes

Fig. 10. Data protocol used by iObject. Generic data packet shown in top half, bottom half displays the data payload fields for a tactile data packet.

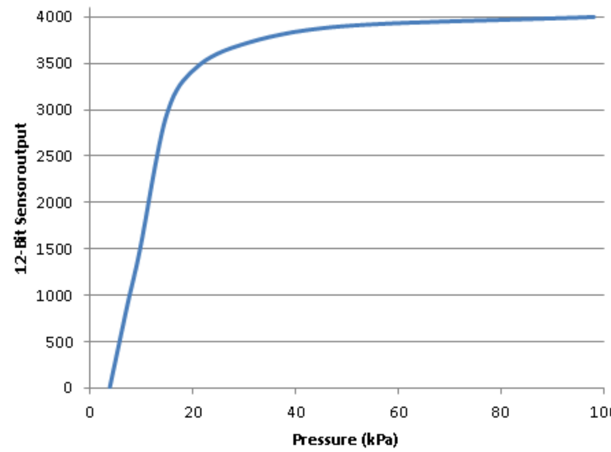

Fig. 11. Characteristic hyperbolic output of resistive tactile sensor cell in iObject.

pointing purposes as with a laser diode module, mounting a specific tool (table tennis bat mount or mounting arbitrary tools or objects with passive grippers). In case none of the existing modules suit the task, an appropriate module can be constructed and built swiftly without the need for modifications to iObject.

III. Communication and Data Protocol

The Bluetooth communication module provides communication over a Bluetooth Serial-Port-Profile (SPP) that is easiest to interact with using virtual serial port at host. The data transmitted from the main processing unit uses a custom data protocol shown in the top half of Fig. 10.

iObject implements 4 packet types for outgoing messages:

- Tactile data packet
- Acceleration and orientation data packet
- Battery status packet
- Internal status packet

A tactile data packet includes compressed data from a single sensor array board and codes it in the data payload field shown in the bottom half of Fig. 10. The low nibble of Packet Type field is used to identify the tactile sensor board while the high nibble is set to 0 to indicate a tactile data packet. Flag bytes indicate by a bit pattern which of the 22 tactels have non-zero values and will be included in the trailing tactile data field. Each tactel data is sent as 16 bits (2 bytes), where the highest 4 bits indicate the channel of one of two 16-channel ADCs.

The acceleration and orientation data packet encapsulates the original XSens MTx packets and relays them to the host.

Data communication in the other direction, from host to iObject, is implemented much more simply: a predefined single byte encodes an enable/disable command for the transmission of individual information from iObject. For easy on-the-fly reconfiguration of the MTx motion tracker, a command is defined that sets the iObject into MTx throughput mode, where all the data sent towards iObject is directly relayed to the MTx.

With favorable wireless link conditions, up to 250 tactile data frames per second can be achieved for a typical grasp scenario (see Fig. 6) while simultaneously transmitting motion tracking data at up to 120 frames per second (a value limited by the motion tracking sensor).

We have implemented data capture and live visualization software for Linux and Windows hosts.

IV. Evaluation

We evaluated the sensitivity of the tactile sensors and their signal curve and report on the latency of the system - an important parameter for time critical tasks such as the real-time control of robots.

A. Tactile sensitivity

The tactile sensor signal curve was verified by ramping up the force on the tactile cells using a push-style scale with a 1.0 cm^2 tip and simultaneously reading out the ADC output. The averaged resulting characteristic curve can be seen in Fig. 11. The usable tactile sensor pressure is in the range of 4 to 100 kPa, with almost linear output between 4 and 17 kPa.

B. Latency

To evaluate the suitability of iObject for controlling robotic devices (e.g., arms, hands, head) in real-time, we measured the latency of iObject using a custom built test rig also based on a PIC18 microcontroller, achieving measurement resolution of 250ns. The effect on latency was examined for variables such as wireless range to communication partner, applied pressure magnitude, concurrent transmission of motion data and concurrent transmission of tactile data with different amounts of tactels active (measuring contact). One tactel was designated for the latency measurement and connected to the test rig electrically with spring probes. Each measurement run started with a field-effect-transistor in series with a resistor closing and thus imitating an instantaneous pressure exertion. 5 different resistor values were used (short-circuit, 1K, 47K, 470K, 4.7M) simulating pressure values from 3 to 100 kPa. To simulate a typical grasp scenario with approximately 20% of iObject tactels in contact, two rubber-rings were wrapped around the sensor surface exerting the appropriate pressure. To test the worst case scenario of maximal tactile sensor transmission, 10 rubber rings were evenly distributed along the cylindrical surface to generate non-zero sensor readings on tactels. For each test case a minimum of 100 measurements were performed in the presence of other active wireless equipment on the used 2.4 GHz band (e.g., wireless LAN, other Bluetooth devices).

As expected, concurrent transmission of other sensor values has a strong impact on latency as illustrated in Fig. 12. In contrast, the applied pressure (or resistance value) has no statistically significant effect on latency (with significance considerably greater than 0.05). The distance between wireless partners increases the latency by approximately 2ms per meter (assuming a linear regression model). In looking at Fig. 12 we notice that for the case of the large area contact, which we note is not very likely to happen in a real world scenario, the average latency was doubled to 82ms compared to 38ms latency observed for a single activated tactel. The transmission of motion data adds an insignificant 2ms to the average latency. As can be seen from the graph, although the standard deviation is relatively narrow, minimum and especially maximum raw values (displayed by the whiskers) vary more heavily, which can be explained by the nature of wireless link which has fixed transmission timeslots and data re-transmission in case of packet loss.

The average latency of iObject has a similar range to that of typical visual sensors used for robotic control (e.g., cameras outputting 25/30 fps). This allows iObject to be used as a real-time input controller for robotic devices, provided that the rare situations of higher peak latency, induced by wireless disturbances, are intelligently handled.

V. APPLICATIONS

As a general grasp and manipulation research tool, iObject is not limited to the field of robotics. We discuss a simple application in which we demonstrate its usage in the field of psychology and sport sciences.

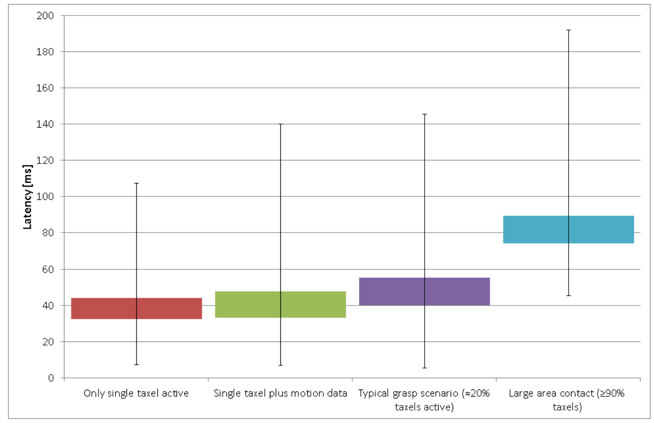

Fig. 12. Latency of the iObject as measured over the Bluetooth link under different conditions. The colored blocks display the standard deviations, while the whiskers show the minimum and maximum values measured.

The goal of this preliminary experiment was to compare the main motion parameters when bimanually rotating iObject around its major axis at maximum comfortable speed, a task similar to the turning motion needed to screw/unscrew caps. The first part involved one participant performing the rotation alone. In the second part two participants were evaluated cooperatively turning the object with one hand each. The direction of rotation and the hand chosen for rotation in the second part of the experiment were not dictated to the participants.

8 subjects participated in the experiment, each one performing a bimanual iObject rotation by themselves once and then performing a cooperative rotation with a partner once (our measurement set therefore consists of 8 solo and 7 twin runs).

We evaluated the duration of contact for each hand (from contact of the first finger to contact loss of the last finger) separately, as well as the accumulated pressure applied to iObject (sum of all tactels during contact) divided by the duration of contact.

The experiment revealed the following (also see Fig. 13):

- Participants performing the rotation alone had an average left/right hand switching time of 0.55 seconds (with standard deviation of 0.15) while exerting an average pressure of 8.97 kPa per hand (with a high standard deviation of 4.65).
- When doing the experiment with a partner, the intersubject hand switching time increased by 93% to 1.05 seconds. The applied average pressure also increased by 116% to 20.24 kPa.

The experiment highlights the higher cognitive load required (slower turnaround time) and higher importance of tactile feedback due to uncertainty (higher pressure exerted) when manipulation is performed cooperatively. In future work, we want to analyze the captured raw data in more detail, including information such as the contact order of the fingers, overlapping finger time durations, rotation speed or angle per hand, and rotational symmetry. This information has the potential to provide new insights into human grasping

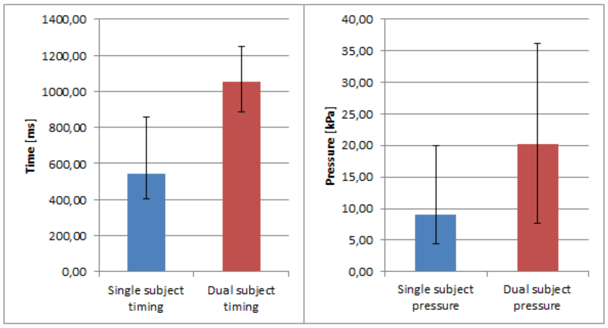

Fig. 13. Bimanual rotation timing and pressure differences between single and dual subject.

and could immediately improve our current robotic setup that can open a jar in an unconstrained setting[21].

VI. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

We presented iObject, a novel wireless device that is equipped with tactile and motion tracking capabilities and whose usage is not limited to robotic research, but extends into fields concerned with the observation of humans performing manual interactions. iObject's internal components, both custom made and third party, were discussed in detail. In particular, the constructed resistive tactile cells and their beneficial output characteristic were described in depth.

We believe that iObject provides a good basis for a broad range of possible future research in numerous fields, including but not limited to robotics, psychology, sport, art and medical sciences. Human, as well as robotic, grasping and manipulation parameters such as contact position, contact magnitude and motion are measured. Furthermore, a distinguishing feature of iObject is that it is cable free, facilitating more natural interactions.

B. Future Works

Imitation learning [22] has seen an explosion of research activity in recent times. iObject could be used in the first stage of imitation learning, observation, to learn the relevant features of human grasps. We expect that this will contribute to endowing robot hands with more dexterous capabilities. For psychological or sport science experiments it would be beneficial to integrate humidity and temperature sensors to sense further modalities of human participants. Another interesting direction for iObject is as a control device in a virtual reality setting. For example, a sculpting application could be developed in which iObject is used as a virtual carving chisel with tactile control for the applied chisel type and magnitude, and position and orientation of the tool are given by the motion tracking sensor.

Increasing the spatial tactile sensor resolution and sampling rate is possible [23] and can be useful for slip detection [24], however this would necessitate increasing the wireless bandwidth of iObject. Two promising solutions are 802.11n WLAN or using visible light [25], although both with the drawback of a considerably increased current draw.

Finally, implementing a component that can provide active feedback to the user, for example in the form of a global vibration or by using more fine grained localized vibration arrays, might open up opportunities for many interesting new research directions.

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