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Implementation of tactile sensors on a 3-Fingers Robotiq® adaptive gripper and visualization in VR using Arduino controller

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Abstract

Tactile sensors are essential components for the implementation of complex manipulation tasks using robot grippers, allowing to directly control the grasping force according to the object properties. Virtual Reality represents an effective tool capable of visualizing complex systems in full details and with a high level of interactivity. After the implementation of cost-effective tactile arrays on a 3-finger Robotiq® gripper using an ARDUINO controller, it is presented an innovative VR interface capable of visualizing the pressure values at the fingertips in a 3D environment, providing an effective tool aimed at supporting the programming and the visualization of the gripper VR.

Keywords: Virtual reality; Robot; Calibration

1. Introduction

Flexibility has nowadays become crucial in production processes. In order to meet the changing market demand, companies need to be capable of fast modification of their products. On the other hand, traditional manufacturing lines are too rigid and do not allow fast modification of the product features. Consequently, they do not allow to meet the increasing demand for short production cycles and high-quality products.

Industrial robots, and automation technologies in general, are nowadays an essential component of the modern production plants and they will play a significant role in extending the flexibility of the production processes as well. Furthermore, the arising fourth industrial revolution (Industry 4.0), with the introduction of Cyber-Physical Systems (CPS) [1], offers new solutions to the problem of increasing flexibility in manufacturing processes [2]. Nevertheless, new technologies require in general customization in every application. That is particularly the case with industrial robots, whose programming is often still a time-consuming task. Flexible, low-cost, and easy-to-use programming methods are strongly demanded for expanding the potential of robotics in companies. On the other hand, VR is currently an effective technology allowing the user to interact with the virtual environment in real time and with a high level of immersion. The user feels "fully immersed" in the virtual environment, and is able of intuitively performing complex tasks, realistically interacting with the virtual environment by means of input/output (I/O) devices (e.g. flystick), while the feedback are provided to the user typically from head-mounted displays (HMD's) [3], CAVE [4], 3-D sound system [5], or force/touch feedback [6]. The benefits of VR technology have been largely recognized by scientists and engineers, with applications ranging from architectural modeling, manufacturing plant layout, and training. In particular, VR has been proven to be an effective tool in simulating and optimizing both products and production processes in factory plants (Virtual Manufacturing) [7]. An area in which VR has been recognized to be particularly beneficial is in programming of robot manipulator tasks. In [8]

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the coupling of the KUKA LBR iiwa 7 R800 robot with a VR environment was addressed, resulting in a system capable of visualizing the robot motion in VR or move the robot from within the VR environment (teleoperation).

This article addresses a further development of the work described in [8]. In particular, the KUKA LBR iiwa 7 R800 robot has been equipped with a 3-finger Robotiq® adaptive gripper and with inexpensive tactile arrays in order to provide the robot with prehensile capabilities and tactile sensing. A VR interface has been implemented in instantreality [9] with the aim of intuitively visualizing the pressure values at the fingertips of the gripper in VR, in such a way to provide a better user-experience.

2. State of the art

2.1. VR and robotics

Over the years, due to the increasing expectation on robot performances in a wide range of applications, robots capabilities have been extended by means of the introduction of several technologies (e.g. multimodal sensing, neural networks). In recent years, many research efforts have been focused on possible synergy between VR and robotics in several fields [10]. An area in which VR has been recognized to be particularly beneficial is the programming of robot manipulator tasks [11], [12]. Currently, industrial robots are programmed by means of three different methods: using a teach pendants, off-line and at task level. Although a great deal of research has been focused on task-level programming, most industrial robots are still programmed using a teach pendants. This approach has the advantage of simplicity, since it does not require programming skills, but on the other hand it is very time consuming. Furthermore, teach pendants method is not suitable for tasks involving complex manipulator trajectories.

The utilization of VR in robot programming is particularly effective for industrial facilities where the environment is known a priori and well modeled. However, VR can be effective also in remote controlling of the robot by the user in an unstructured environment (teleoperation). Teleoperation is also necessary to conduct operation in adverse environment conditions, e.g. nuclear plant servicing (or decommissioning), undersea operations, space robotics, explosive environments, etc. In such cases, the robot performs the task for the human operator, and protects him/her from any harm.

2.2. Gripper

Many different kind of robotic grippers are available on the market which can be grouped into the following categories:

2.2.1. Two-finger grippers

These are the mostly used grippers in industrial applications. They are basically made up of two fingers that close against each other, remaining parallel, allowing to accomplish only a pinch grasp. For this reason, custom fingertips have to be used almost for each specific application. Adaptive two-finger grippers are more sophisticated than the standard parallel grippers, providing the production with more flexibility. In fact, the underactuated gripper fingers can adapt themselves to the shape of the grasped object (e.g. rectangular, cylinder, etc.) [13]. Since the part is always located at the same place within the gripper, the programming is also very simple.

2.2.2. Three-finger grippers

The three gripper fingers close toward a central axis while grasping the part. These gripper can usually carry a large payload, but similarly to the two-finger grippers, custom fingertips have to be used almost for each specific application. Three-finger adaptive grippers are instead capable of providing a greater flexibility and reliability. In fact, also in this case, the underactuated gripper fingers are capable of adapting themselves to the shape of the grasped geometry [13].

Robotic grippers with more than three fingers are uncommon for industrial applications. They are widely used instead, as prosthetic device for the human body. They have the advantages of flexibility, as they allow grasping a great variety of objects, but often they do not have an accurate repeatability and cannot handle a high payload.

2.3. Tactile sensors

Tactile sensors are an essential component of robot grippers for the implementation of complex manipulation tasks, e.g. contact pressure distribution is considered to be essential for effective manipulation in unstructured environments. Furthermore, assessing the contact pressure also offers the possibility to directly control the grasping force accordingly to the object properties. However, despite the research efforts already spent, and the several commercial tactile array sensors developed, there has been little experimental progress in using tactile information to control grasping and manipulation, especially in industrial environment. The main reason is certainly the cost and complexity of integrating tactile sensing into robot grippers/hands. Many sensing devices have been published in the robotic literature, but their construction often requires custom fabrication using nonstandard techniques [13], [15], [16]. On the other hand, albeit using commercial tactile arrays avoids the need of custom fabrication technologies, they are typically costly, fragile, and cover only a limited area of the hand. However, the integration of both types of sensors into the contact surface of a new robot gripper/hand still requires considerable engineering effort and the development of the multiplexing, cabling, and digitizing to get the sensor signals through the robotic arm and into the control computer is still challenging.

Recently, the use of tactile sensors based on barometric chips has been proposed in literature. Since they are implemented in consumer products, e.g. desktop weather stations and GPS systems, they are relatively inexpensive compared with the other solutions available on the market. However, the construction of the tactile array, generally by means of casting of the barometric sensor in rubber, requires special attention, as defects in casting can tremendously affect the behavior of the sensors [17].

3. Methods

In order to use VR to program and teleoperate a robot, it is firstly necessary to realize a link between the real hardware, i.e. the KUKA LBR iiwa 7 R800 robot, and the VR environment. In [8] a first step toward this direction has been done, linking the KUKA robot controller with VR environment. In this way it is possible to visualize the motion of the real robot in VR and to move the real robot from within the VR environment (teleoperation). This article addresses a further development of the aforementioned work, providing the robot with prehensile capabilities and tactile sensing. To achieve this goal, it has been necessary to evaluate the grippers, as well as the tactile sensors, available on the market, in order to determine the most suitable hardware configuration. Concerning the choice of the robotic gripper, within industrial application scenarios, the best compromise is represented by a three-finger adaptive gripper. As briefly described in the section 2.2, such a gripper is capable of providing a high level of flexibility for a wide range of applications. It can also handle a relatively high payload with a high level of repeatability.

As described in section 2.3, a great deal of research has been done in order to develop tactile sensors suitable for robotic applications. Yet, many of these sensors require custom fabrication technologies using nonstandard techniques. On the other hand, choosing commercial tactile sensors avoid the need of custom fabrication techniques, but they are typically costly, fragile, and cover only a limited area of the robotic hand. However, the integration of both types of sensors into the contact surface of a robotic gripper/hand still requires considerable engineering effort. Several manufacturers provide also fully-embedded tactile arrays, but they are generally cost-expensive, as they use high-resolution tactile arrays, which are not required for most of the industrial applications. For this reason, tactile arrays based on miniature barometric sensor chips have been chosen. These sensors include a Micro-Electro-Mechanical-System (MEMS) pressure and temperature sensors, an analog to digital converter and a bus interface [17]. The first step in order to build the experimental setup has been the calibration of the tactile arrays as well as the evaluation of their performances. Later, in order to visualize the pressure values at the gripper fingertips in VR, an interface must be implemented which allows the VR system to read the output data from the tactile array sensors. Then, different visualization concepts have been developed with the aim of effectively visualize the pressure values in VR in a user-friendly and comprehensible manner.

Furthermore, is it worth emphasizing that the experimental setup has the further advantage of being made of standard and commercially available components, making the maintenance of the system simple and inexpensive.

Fig. 1. 3-Finger Adaptive Robotiq® gripper [18].

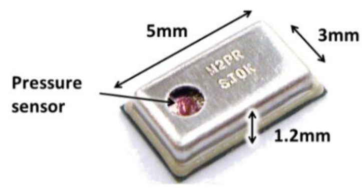


Fig. 2. MPL115A2 sensor from Freescale Semiconductor [17].

4. Experimental setup

4.1. Gripper

To provide the robot with prehensile capabilities a *3-Finger Adaptive Robotiq® gripper* has been chosen, as it provides the best compromise in terms of performances and price (Fig. 1). It is capable of providing a high level of flexibility and reliability for almost any given application, with a repeatability of less than 0.05 mm, and it is also capable of carrying a relatively large payload, i.e. 10 kg [18]. Furthermore, because of its underactuated fingers, the gripper can adapt its configuration to the part geometry (see section 2.2). The gripper can be controlled using either the KUKA smartPAD or the GUI provided by the manufacturer. Furthermore, this kind of gripper has three different preset grasping modes (scissor, wide and regular) which allow a wide range of grasping setups for all kinds of applications.

4.2. Tactile array

TakkTile's array sensors, based on MPL115A2 MEMS barometric chip from Freescale Semiconductor Inc., Austin, TX (USA) have been used to provide the robot with tactile sensing [19]. These chips include also a temperature sensor, an analog to digital converter and a bus interface. Since these sensors are produced for consumer products, e.g. desktop weather stations, they have a small footprint, low power consumption, and are mass produced at low costs. Each sensor has a miniature 5x3x1.2 mm package (Fig. 2), it uses the I2C bus protocol [17] and, it is capable of providing an accurate pressure measurement from 50 kPa to 115 kPa, with a resolution of 0.15 kPa. Within the scope of this article, these barometric sensors represent the best choice between costs and performance. The experimental setup consisted of 33 barometric sensors, 18 of them attached on the three gripper's fingertip (6 sensor on each fingertip) and 15 attached on the gripper's palm. All the sensors are cast in rubber with a thickness of 4 mm (Fig. 3).

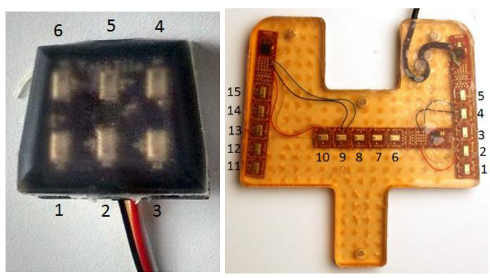


Fig. 3. Fingertip tactile array (left) and palm tactile array (right) based on barometric sensors.

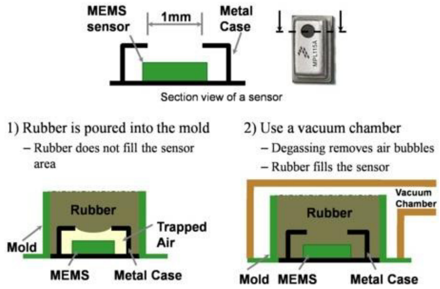


Fig. 4. Rubber casting process [20].

The rubber has the advantage of providing a stable contact surface for grasping and manipulation, and it is capable of transmitting the surface contact pressure to the ventilation hole and thus to the MEMS transducer. It ensures also a solid gripping, a better distribution of the pressure all over the sensor surface and the preservation against impact and high temperatures. However, as highlighted in [17], the casting of the sensors in rubber requires special attention, as defects in casting (e.g. air trapped in the metal case) can tremendously affect the behavior of the sensors (Fig. 4). Since the measured pressure strongly depends on both the rubber thickness and the environment's temperature, several problems were encountered during the calibration of the sensors. Nevertheless, the low cost of the whole tactile arrays make them still appealing for industrial application scenarios.

4.3. Performances evaluation of sensor array

The calibration of each sensor has been conducted applying an increasing load above the ventilation hole, and monitoring the sensor response. The load has been increasingly applied by step of 10 grams in a range between 0 and 250 grams. The load application has been repeated three times for each sensor, and the average of the three results has been considered. The environment's temperature during the execution of the test was between 20 and 24 degrees. Even though the overall behavior of the sensors, determined with the calibration procedure, was coherent with the literature [17], e.g. linear behavior, several discrepancy have been found. Particularly, the sensors' response to the external load was tremendously affected from the environment temperature, even though the temperature correction [17] has been taken into account.

Furthermore, the actual operating range of the sensor appears to be larger than what stated on the sensor datasheet; namely, the maximum measurable pressure value is 0.40 MPa corresponding to the maximal applied load. Since the experimental scenario in our experiments did not require a high precision of the pressure values at the fingertips, a deeper investigation of this behavior has not been conducted.

4.4. Sensor-VR interface / Software interface

Getting temperature and pressure data from the tactile sensors using an Arduino board is straightforward [21]. Once the data have been fetched from the microchip, they can be sent to the host system via a serial communication. The host hooks up into the binary data stream at an arbitrary position. Therefore, it is necessary to find start and end position of a data

...|00|0B 18 2F ... 01|00|...

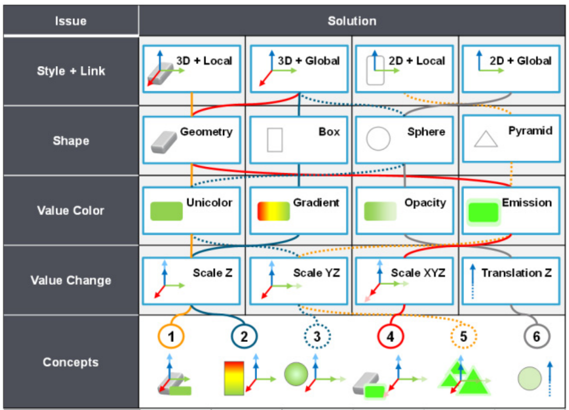
Fig. 5. Data stream structure (green: significant mark).

set to get proper and valid values. The default procedure uses marks in the data stream which can be recognized by the host system. Therefore, a significant/unique pattern for recognition is needed. For that it is possible to exploit the fact that the sensors do not use all of the 16 bits represented in 2 bytes. The unused bits are always zero. By using a bit mask one of the unused bit can be set to 1 (e.g. 0x8000 leads to a 1 in the highest bit of the word datatype). This ensures that the high byte is always nonzero, independently from the actual sensor value. In addition, the masking prevents from having 2 zero-bytes side by side at the same time in the data stream. Therefore, we chose two binary zeros *'00'* as mark. However, because of the necessary data width of 2 bytes a special case can occur. If the lower byte of the value coming right next after the mark is zero (little-endian assumed), then a wrong data segment is present (red mark in Fig. 5).

This special case can be handled by evaluating the length between two marks. Since the sensor values are always 2 bytes long (word), the data-set length must be even. If it is odd, then the aforementioned special case occurs, and the start mark 1 byte must be moved backwards. Afterwards, the system has been coupled with the VR environment as described in [8].

5. Visualization concepts

Once the tactile arrays have been tested and the experimental setup has been built, several concepts for the visualization of the pressure values at the gripper fingertips using VR have been evaluated. Since the contact pressure is a scalar entity, it can be visualized in VR using only one degree of freedom. However, in order to achieve an effective visualization concept, several parameters have been taken into account. Fig. 6 shows the assessment procedure for several possible visualization concepts.



	Weight + Criteria	1	2	3	4	5	6
5	Visibility	4	5	3	3	4	3
4	Information Content	5	4	3	4	3	3
5	Information Resolution	5	3	3	5	3	2
4	Design	4	4	3	4	3	3
3	Adaptability	5	5	4	4	3	2
	Total	4,6	4,1	3,1	4,0	3,2	2,6
	Ranking (1 = top rated)	1	2	5	3	4	6

Fig. 6. Concepts and benchmarking of value visualisation.

Fig. 7. Example of a 2D-colored bar for the visualization of the pressure.

Particularly, the following aspects have been taken into account:

- **Style:** the dimension of the geometry representing the amount of the pressure; namely 3D or 2D, and the reference frame to which the geometry is attached (global or local)
- **Shape:** the shape of the geometry representing the pressure value in VR
- **Value color:** the geometry filling color
- **Value change:** expanding edges of the geometry corresponding to the pressure values

The links between these possibilities are marking six concepts that are benchmarked in the bottom part of the Fig. 6 to find an applicable visualization solution. For the targeted applications the concept scored with “2” has been used, as it represents the best compromise in terms of clarity of representation in a VR environment and the ease of modelling. It consists of 2D bars in the global reference frame whose height and color (in a range from green to red) represents the amount of pressure acting on the related sensors (Fig. 7).

6. Final application

Several tasks have been implemented using the experimental setup in order to test the developed visualization concept. The pressure values have been visualized in instantreality [9] using the VRML file format. Fig. 8 shows the robot grasping a cylinder, while the pressures at the fingertips are displayed on a monitor. Fig. 9 shows the KUKA LBR iiwa 7 R800 robot grasping a wrench. The pressure values are displayed on the monitor. In both applications the robot, as well as the gripper, have been controlled using the KUKA SmartPad.

7. Conclusion and outlook

In this paper, a further step towards the development of a VR environment, that allows programming and teleoperating a robotic arm, is presented. In [8] the KUKA LBR iiwa 7 R800 robot has been successfully linked with a VR environment that allows to visualize the state of the robot in VR and to control the robot motion from VR. In the presented work, the aforementioned robot has been provided with prehensile capabilities by means of a three-finger adaptive gripper from Robotiq, as well as tactile sensing by means of the installation of tactile arrays from Takktile based on barometric sensors. The tactile arrays have been calibrated and, after an evaluation of their performances, they have been installed on the robotic gripper. Despite, the discrepancies of the sensors behavior with what stated in the literature, particularly concerning the temperature dependence of the pressure values, they were still suitable for the targeted applications. Furthermore, the low cost, together with the ease of installation, make these tactile arrays much more interesting in comparison with the other solutions available on the market. Then, the whole system has been linked to VR by means of the Arduino controller.

Fig. 8. KUKA LBR iiwa 7 R800 robot grasping a metal cylinder. The pressure values at the fingertip are visualized on the monitor in the background.

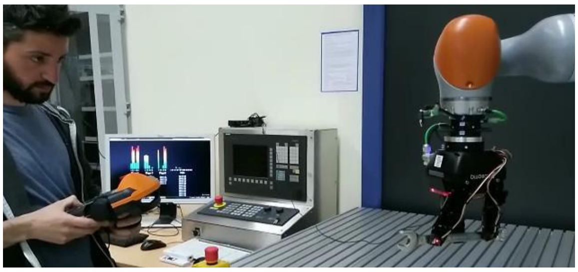


Fig. 9. KUKA LBR iiwa 7 R800 robot grasping a wrench. The pressure values at the fingertip are visualized on the monitor.

Afterwards, several concepts for visualizing the pressure at the fingertips in VR have been evaluated in order to determine the most appropriate solution.

The developed experimental setup was capable of effectively visualizing the pressure at the fingertips of the gripper in VR providing the user an effective feedback about the gripping pressure. Nevertheless, a deeper investigation of the behavior of the tactile sensors should be conducted in order to extend the range of their possible applications.

A further interesting development of the development presented system is certainly the development of a VR interface that allows the user to control and programming the gripper directly from VR.

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