Virtual Whiskers — Highly Responsive Robot Collision Avoidance

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Abstract— **All mammals but humans use whiskers in order to rapidly acquire information about objects in the vicinity of the head. Collisions of the head and objects can be avoided as the contact point is moved from the body surface to the whiskers. Such a behavior is also highly desirable during many robot tasks such as for human-robot interaction. Using novel capacitive proximity sensors, robots sense when they approach a human (or an object) and react before they actually collide with it. We propose a sensor and control concept that mimics the behavior of whiskers by means of capacitive sensors. Major advantages are the absence of physical whiskers, the absence of blind spots and a very short response time. The sensors are flexible and thin so that they feature skin-like properties and can be attached to various robotic link and joint shapes. In comparison to capacitive proximity sensors, the proposed virtual whiskers offer better sensitivity towards small conductive as well as non conductive objects. Equipped with the new proximity sensors, a seven-joint robot for human-robot interaction tasks shows the efficiency and responsiveness of our concept.**

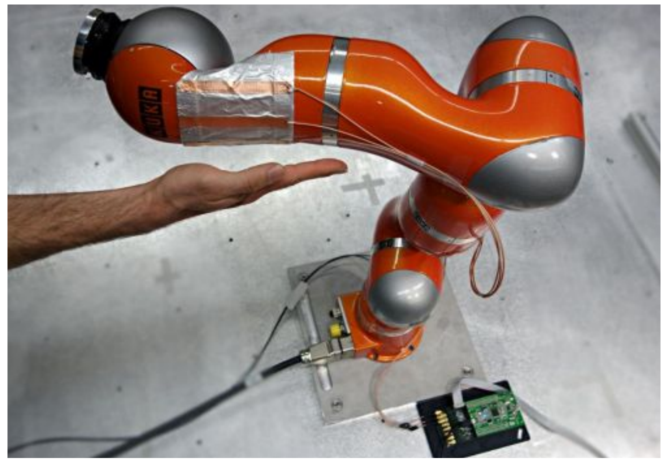

Fig. 1. The presented capacitive sensor detects approaching objects at sufficient distance and measurement rate and allows the robot to avoid collisions in real-time.

I. Introduction

When robots and humans share the same environment special precautions are required to avoid injuries. More general, anytime robots operate in changing environments, their perception and control systems have to be aware of the environment and acquire information by numerous sensors. This is actually similar to the way humans and animals interact with their environment. While vision plays a major role, several other sensing principles are used complementary.

A very successful concept for proximity detection in nature are whiskers. All mammals but humans use whiskers to sense objects in the vicinity of the head [1]. Although whiskers require some mechanical contact they may also be considered as pretouch sensors, as the contact does not involve the actual body surface. Recently, whiskers have been proposed for active sensing in robotics applications [2]. As shown, whiskers are not just simple proximity sensors, they can provide additional information about the surface properties of the object, which may be used for a coarse classification.

We propose a sensor concept that behaves in a similar way to physical whiskers but uses a capacitive sensing technology. Physical whiskers, such as the facial whiskers of rodents have a tapered rod-like structure. These structures get deformed by objects during contact. The force caused by the deformation is then detected by sensors on the surface. In contrast, our virtual whiskers are formed by an electric field that gets deformed by an object without any physical contact. The "deformation" of the electric field is measured by means of electrodes on the surface of the robot. Consequently, we achieve true pretouch sensing without any mechanical interaction. Furthermore, the sensor adds very little bulk to the robot arm, consisting of a surface patch of approximately 350 μm thickness.

Furthermore, we achieve short response times and a wide range of detectable objects. While physical whiskers can provide additional information about the surface properties (e.g. stickiness), our virtual whiskers provide additional information about the volume properties (e.g. conductivity) of objects in the vicinity of the sensor.

II. Related Work

A huge variety of sensor technologies might be applied for pretouch sensing, but only a few can cope with the requirements in robotic applications. For example, there are limitations with respect to spatial dimensions, weight and adjustability in positioning.

In [3] an optical proximity sensor is presented which is used to improve grasping tasks. The detection range is about 30 mm. Although it works for a lot of materials, the sensor signal depends on the color and surface of the objects. Thus, as shown in [3], the sensor will fail for transparent or reflective objects, for instance, a container made of glass or aluminium, respectively. Furthermore, it is difficult to use

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optical pretouch systems for short distances without having blind spots, due to the limited observation angle of each sensor.

Magnetic sensors, such as giant magnetoresistance (GMR) sensors, can be used to detect ferromagnetic objects and conductive objects by means of eddy currents. Since GMR sensors can be made very small, it is easy to implement them on a robotic hand or arm. In [4] and [5] GMR sensors were used to detect ferromagnetic and conductive objects within a detection range of about 30 mm.

A completely different sensor approach is presented in [6]. The so-called Seashell effect uses the resonant frequency of a cavity, where this resonant frequency changes with an approaching object. A microphone measures the resonant frequency and thus the distance to an approaching object can be measured (up to approximately 6 mm). The authors were able to mount the cavity and the microphone into the fingertips of a robotic hand to improve grasping tasks.

Capacitive sensing, sometimes also called electric field sensing, has a long history for proximity sensing in various applications. In [7] and [8] capacitive sensors for collision avoidance for predefined and grounded objects are presented. The measurement range is about 80 mm for a 60 mm diameter steel pipe. In [9] a capacitive human detection system is presented. More recently in [10] and [11] capacitive sensing was used for pretouch functionality for grasping applications of different objects. All these capacitive sensors use amplitude information out of a pairwise electric field sensing system (i.e. differential mode, one transmitting electrode and one or more receiving electrodes or vice versa, compare Sec. III-A) at one frequency with a rather low measurement speed (e.g. 30 Hz in [10], [11]). Thus, these sensors have limitations for certain objects. For instance, the sensors can show inconsistent readings depending on the impedance to ground of the object being sensed (compare [4] and Sec. IV). The presented system in this work e.g. is able to work in both measurement modes, has a variable measurement frequency and a higher measurement speed (compare Table I).

As far as the authors know, the presented sensor system is the first which achieves the presented measurement speed and measurement information (not only amplitude but also phase information) to be used in such a highly reactive robot application (compare Table I). Especially the speed and the use of two different capacitive sensing modes makes it suitable to use for collision avoidance in robot applications (compare Sec. III-A). Furthermore, the sensor is not only sensitive to humans, with the utilization of phase and amplitude information providing additional capabilities for detecting conductive and dielectric objects (due to different properties of the objects parasitic connection to ground, compare Fig. 4) An illustration of the sensor system in comparison with physical whiskers is shown in Fig. 2. Instead of rod-like structures the virtual whiskers are represented by an electric field around the body. The "deformation" of the electric field by an approaching object is illustrated in Fig. 3 (obtained from a Finite Element Simulation).

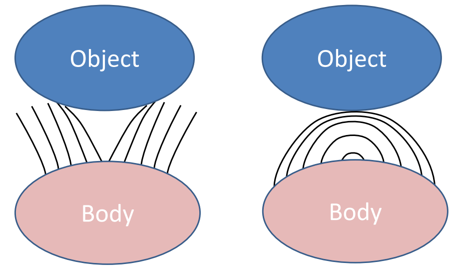


Fig. 2. Illustration of whiskers. Left: Physical whiskers, deformed by an object. Right: Virtual Whiskers, represented by an electric field, deformed by an object.

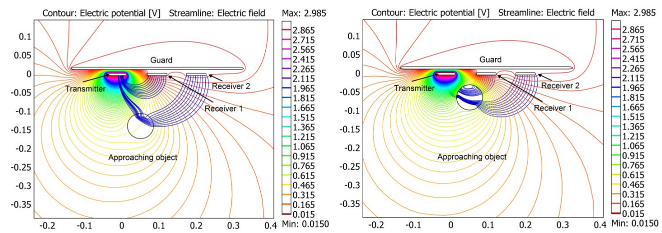


Fig. 3. A descriptive example on how an approaching object deforms the electric field.

III. SYSTEM DESCRIPTION

A. Sensing Hardware

Capacitive sensors usually operate in one of two possible modes: The first mode, usually denoted as differential mode, utilizes measurements of the capacitance between two conductive areas (called electrodes) by applying a voltage on one electrode (transmitter) and measuring the displacement current on the other electrode (receiver) (compare Fig. 4). The second mode, usually denoted as single-ended mode, utilizes measurements of the displacement current originating from one electrode. As shown in Fig. 4, the displacement current corresponds to the capacitance between the electrode (transmitter) and the distant ground, which is essentially the environment. The two measurement modes have different properties (compare Fig. 5). For example, the differential mode can provide MN independent measurements, where N is the number of transmitters and M is the number of receivers. As an electrode may be both a transmitter and a receiver, the number of independent measurements is given by $\frac{N(N-1)}{2}$. In contrast, the single-ended mode can only provide N independent measurements. An advantage of the single-ended mode is that it usually features a better signal-to-noise ratio for well-grounded objects.

It has been demonstrated previously that the differential mode using more than two electrodes can not only detect the proximity to an object but also its orientation (compare [12]). A related technology is Electrical Capacitance Tomography (ECT), which is used in industrial processes to obtain 2D cross sectional image of the material distribution within pipes. ECT is essentially an array of capacitive sensors with heavy signal processing to calculate an image of the region of interest [13]. Recently in [4] we showed that the ECT approach can be transferred to robot sensing. With a

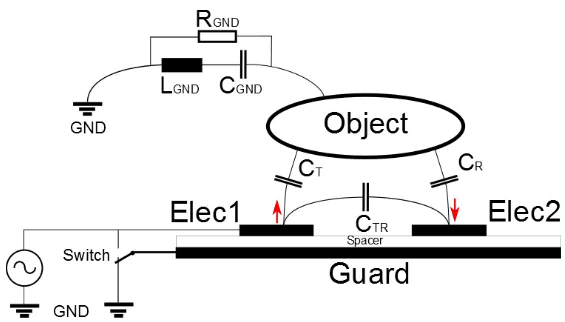
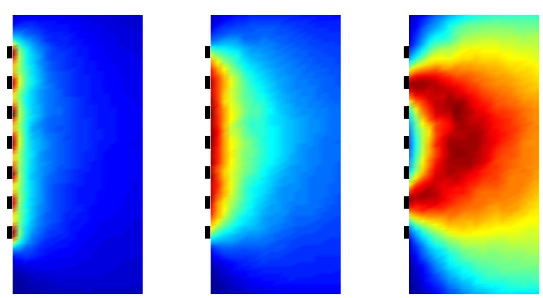


Fig. 4. Sketch of the capacitive measurement principle for one pair of electrodes (Elec1 used as transmitter, Elec2 used as receiver). The red arrows indicate the displacement currents that are measured in the single-ended mode (exiting Elec1) and in the differential mode (entering Elec2), respectively. In single-ended mode, the guard is connected to the excitation signal (i.e., active guarding). R_{GND}, L_{GND} and C_{GND} indicate an equivalent circuit for the object's parasitic connection to ground.

differential mode capacitive measurement we demonstrated the basic functionality, but we also found limitations. For example, it may not be possible to detect small conductive objects. This is due to two competing effects referred to as coupling and shielding mode [14]. At transitions between these modes, signal cancelation may occur. As the shielding mode is strongly related to the single-ended mode, this can be used to identify the presence of both modes (compare Fig. 5). Thus, we propose to combine single-ended and differential mode to avoid the blind spots.



(a) Single-ended mode (b) Differential mode, neighboring electrodes (c) Differential mode, electrode 2 to electrode 6

Fig. 5. Sensitivity maps with respect to grounded conductive objects for different sensing modes as obtained from Finite Element Simulation. The colors correspond to the relative sensitivity (red: high, blue: low) at certain locations within the region of interest. The seven sensor electrodes are located on the left side (black lines). (a) In the single-ended mode (transmitter measurement) the sensitivity increases excessively for objects that are very close to the electrodes. (b) and (c) In the differential mode the sensitivity map varies depending on the pair of electrodes. While the configuration for Receiver 1 has similar behavior as for a transmitter measurement, the configuration for Receiver 2 suppresses the excessive sensitivity for close objects. Consequently, the single-ended mode mainly responds on the shortest distance between a conductive object and an electrode while the differential mode offers better detection capability for non conductive objects.

The sensor proposed in this work is able to work in both modes (single-ended and differential mode) and combines benefits of both measurement modes. Furthermore, it provides a high measurement rate (sample period T_s below 1 ms). A brief summary of the sensor properties is given in Table I.

TABLE I
PROPERTIES OF THE PRESENTED MEASUREMENT SYSTEM

Sensor thickness	$\approx 350\,\mu$m
Excitation signal	Sinusoidal signal
Frequency	Tunable from 10 kHz to 1 MHz
Measurement rate	1.25 kHz (max. 6.25 kHz @ 1 MHz) compared to e.g. [11]: 30 Hz or to [15]: max. 200 Hz
Measurement method	Single-ended and differential mode others (e.g. [11] or [15]): only one mode
Shielding	Active guarding in single-ended mode Grounded shielding for differential mode
Number of electrodes	$N = 7$
Number of independent measurements	28 $\left(=\frac{N(N-1)}{2}+N\right)$ for each frequency

Fig. 6 gives an overview of the sensor hardware. The measurement frequency of the sinusoidal signal can be changed between 10 kHz and 1 MHz. Although not used in this work, a varying measurement frequency will especially be useful for object classification purposes, due to frequency dependency of the parasitic effects as shown in Fig. 4. The generated signal can be applied to one or more electrodes and it is also used as an active guard for the single-ended sensing mode. In the differential sensing mode the backside of the sensor interface (shown in Fig. 11(a)) is connected to ground. Each sensing electrode can be either connected to a receiver amplifier (for differential sensing mode) or to one transmitter amplifier (for single-ended sensing).

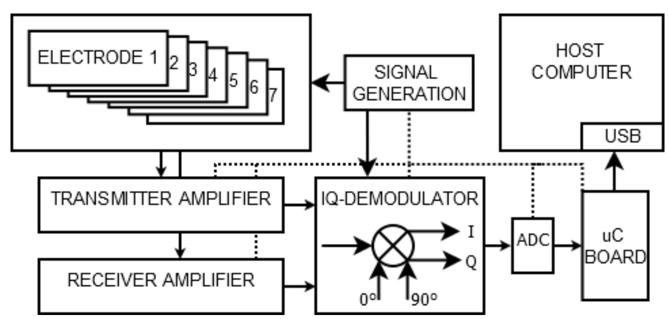


Fig. 6. Overview of the developed capacitive measurement system comprising signal generation, transmitter and receiver amplifiers, IQ-demodulator, ADC, microcontroller, and a USB connection to a host computer. Dashed lines indicate digital control buses such as SPI or I2C and unbroken lines indicate analog signals (e.g., sinusoidal signal from signal generator to electrodes).

The IQ-Demodulator (where I and Q represent the in-phase and the quadrature component, respectively) is used to get amplitude and phase information of the received and amplified signals (compared to the excitation signal). The outputs of the IQ-Demodulator are digitized and collected in a microcontroller which processes the measurement data and has a serial connection to a host computer to post process the measurement data.

Due to the high sensitivity and fast acquisition, the sensor

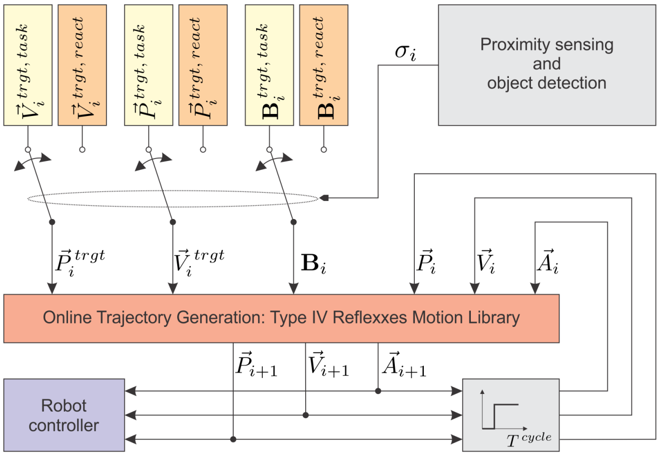


Fig. 7. Overview of one of the simplest possible robot motion generation architectures. The two sets of motion parameters *task* and *react* can be changed from one control cycle to another using the switching signal σ_i. The online trajectory generation algorithms [16] of the Reflexxes Motion Library [17] let robots react to the input signals from the proximity sensor within the same control cycle they occur.

is suitable to be used as a highly reactive proximity sensor in robot applications (as shown in Sec. IV.)

B. *Highly Reactive Robot Motion Generation and Control*

The virtual whiskers can be integrated in many ways in robot motion control schemes. This subsection describes one out of many possibilities. We intend to keep the control scheme very simple. The discrete control scheme shown in Fig. 7 works a sampling period of T^{cycle}. A state of motion at an instant T_i is represented by the robots position $\vec{P}_i$, its velocity $\vec{V}_i$, and its acceleration $\vec{A}_i$. Taking into account kinematic motion constraints $\mathbf{B}_i$ that contain maximum values for the velocity, acceleration, and jerk vectors, the online trajectory generation algorithms [16] of the Reflexxes Motion Libraries [17] compute a time-optimal, jerk-limited, and synchronized trajectory that transfers the robot system from its current state $\left(\vec{P}_i, \vec{V}_i, \vec{A}_i\right)$ a desired target position $\vec{P}_i^{trgt}$ and velocity $\vec{V}_i^{trgt}$. These algorithms are executed at every control cycle, so that the system can always react instantaneously in a deterministic way. The output of the algorithms $\left(\vec{P}_{i+1}, \vec{V}_{i+1}, \vec{A}_{i+1}\right)$ is forwarded to the underlying robot motion controller.

The underlying controller can be a position controller, a trajectory following controller, an impedance controller, or any other controller that is capable of following a trajectory. As long as no object is detected in the proximity of the virtual whiskers, the task-dependent input values $\vec{P}_i^{trgt,task}$, $\vec{V}_i^{trgt,task}$, and $\mathbf{B}_i^{trgt,task}$ are used. At the moment an object is detected, the value of the switching variable σ_i changes, and a different set of input values $\vec{P}_i^{trgt,react}$, $\vec{V}_i^{trgt,react}$, and $\mathbf{B}_i^{trgt,react}$ are used so that the robot can react immediately and try to avoid the potential collision.

IV. Experiments And Results

This work focuses on using the proposed capacitive measurement system in a robotic application for highly reactive proximity sensing and collision avoidance for robot/human interaction. The first subsection presents the results of using the capacitive sensor to avoid collisions with a human. It also presents the benefits for collision avoidance with other objects, when using both measurement modes (single-ended and differential mode). Although the presented capacitive measurement system is particularly suitable for sensing human hands, it can also detect other objects, such as conductive or dielectric ones. The second subsection presents results of measuring different kinds of objects.

A. *Highly Reactive Collision Avoidance Experiments*

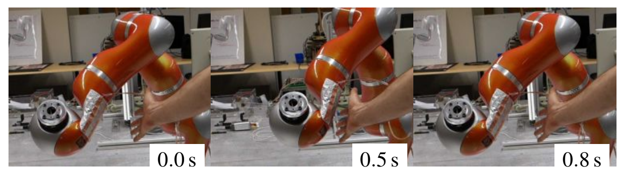


Fig. 8. A robot arm reacts instantaneously to the measurement data of the presented capacitive sensor. Capacitive sensing allows the robot to avoid collision with a human hand, maintaining a minimum distance of ≈ 50 mm.

Fig. 9. If the capacitive sensing system measures in single-ended mode, the empty plastic case cannot be detected early enough to avoid a collision. Thus the arm touches the object before it moves back.

Fig. 10. When using the capacitive sensor in differential mode, even an empty plastic case can be detected early enough to avoid a collision.

A series of experiments with the capacitive sensor mounted on a KUKA Lightweight Robot IV [18] were accomplished in order to show the capabilities of the capacitive measurement system. The KUKA Lightweight Robot IV was interfaced through the *Fast Research Interface* (FRI) [19]. The online trajectory generator provides new pose set points for the joint impedance control interface of the FRI at a rate of 1 kHz. The electronics circuits of the capacitive sensors are connected through a serial communication channel; new sensor signals are sampled at a rate of 1.25 kHz. Once an object is detected by the virtual whiskers, the robot recoils instantaneously to a safe pose that was either pre-defined or computed based on the measured sensor signals. For description about the responsiveness of the control architecture please refer to [20]. As can be seen in Fig. 11(a), 3 electrodes (i.e. 6 independent measurements) are used for the collision avoidance approach.

In the first experiment (shown in Fig. 8), the robot is moving along a certain trajectory. As soon as it senses (i.e., the capacitive measurement signals, I or Q channel, reach a certain threshold) the human hand, it instantaneously moves into the other direction. After the object has left the sensitive area, the robot goes on with its original trajectory.

The second experiment shows the limitations of a single-ended measurement systems. An empty plastic case is in the way of the robot's trajectory. Since the measurement signal of the single-ended mode is too weak, a collision can not be avoided. After the sensor surface touches the plastic case, the threshold is detected and the robot moves in the other direction.

As shown in Fig. 5(c) the differential mode is especially useful for sensing dielectric objects. Compared to the second experiment the plastic case can be detected in experiment 3 (shown in Fig. 10) using the differential sensing mode.

In this work the mentioned threshold was chosen manually to work with all tested objects. Thus, the robot arm reacts at different distances for different objects. In future work the authors want to use object classification to adapt the threshold value to particular object classes. The object classification will be possible due to the additional measurement information (e.g. amplitude and phase, varying sensing frequency, etc.) from the sensing hardware.

B. Sensing Different Objects

Fig. 11(a) shows the sensing electrodes and the objects, which were used to test with the presented capacitive measurement system. In every experiment the used object approaches the sensor surface to a distance of about 5 mm and departs again. The same sensing electrodes as for the experiments in Sec. IV-A are used. Since the presented system measures the change in amplitude and phase (i.e. I and Q channel), two measurements for the single-ended mode and four measurements for the differential mode (two receiving electrodes) are recorded.

The measurement signals for an approaching human hand can be seen in Fig. 12. Both sensing modes are able to detect the approach. In the differential mode at a certain distance to the sensor surface (in Fig. 12 around time 1.5 s) the transition between coupling and shielding occurs (refer to Sec. III-A and [14]). The hand is still getting closer, but due to the increasing coupling effect the measured capacitance (i.e., received displacement current) initially decreases; it increases again for very short distances.

Fig. 13 shows the approach of a metallic rod with a diameter of 7 mm (shown in Fig. 11(b)) in two different configurations. In the first configuration the rod is left floating (not connected to ground). In the second configuration a cable is used to connect the metallic rod to ground (bypass the parasitics C_{GND} and L_{GND} shown in Fig. 4). As can

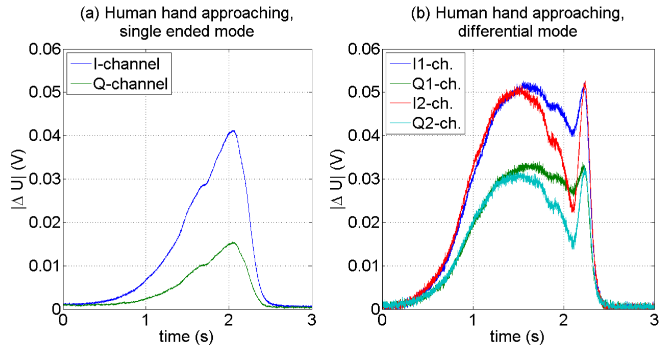


Fig. 12. Sensor signals for a human hand approaching and leaving the sensor surface in both modes, that is, in single-ended mode (a) and in differential mode (b). The sensors maximum signal occurs at a distance of ≈ 5 mm.

be seen in Fig. 13, the measurements in the differential mode for the rod connected to ground result in a different measurement compared to the one without a connection to ground. The measurements for the single-ended mode do not change with a different connection to ground. Thus, in combining both measurement modes, additional information about the approaching object and the environment can be made and conductive objects can be measured more reliably.

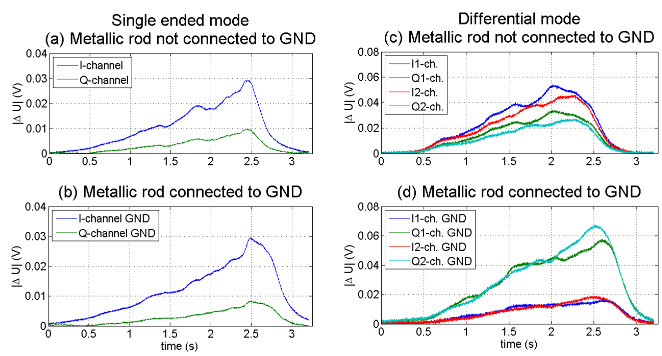


Fig. 13. Sensor signals for an approaching metallic rod. For each mode (single-ended mode in (a) and (b) and differential mode in (c) and (d)) the metallic rod was approached to the sensor surface (minimum distance: ≈ 5 mm) in two configurations. In the first configuration (in the upper figures) it was not connected to ground while in the second configuration the rod was connected to ground.

The developed measurement system is also able to detect dielectric objects. The plastic case in Fig. 11(c) can be detected by the measurement system as shown in Fig. 16. With the single-ended measurement mode, it is very difficult to measure certain dielectric objects, e.g. objects with a very small susceptibility χ and small conductivity σ (compare Fig. 16(a)). With the additional differential mode, the plastic case can be detected and a collision with the robot arm can be avoided as shown in Fig. 10.

Other dielectric objects, such as a wood stick shown in Fig. 11(d)), can also be detected by the presented measurement system (shown in Fig. 14). Similar to the measurement results with the plastic case in Fig. 16, the differential mode is more appropriate to measure these kinds of objects, due to the higher measurement signal.

(a) Sensing electrodes (b) Metal (thin iron rod) (c) Plastic (PVC) case (d) Wood (e) Foam material (PUR)

Fig. 11. Sensing electrodes mounted on the robot arm in (a) and sample objects to test the capacitive measurement system in (b)-(e). (b) An iron rod is used to show the properties for conductive objects (connected and not connected to ground). (c) Dielectric objects such as this polyvinylchloride (PVC) case can be detected even if they are small in volume and have a low susceptibility ($\chi \approx 2$). (d) Also a stick made of wood ($\chi \approx 2$) changes the electric field and can thus be detected. (e) The foam material consisting of polyurethane (PUR), which has a very small electric susceptibility $\chi \approx 1$ and conductivity $\sigma \approx 0$ shows the limitations of the sensor as it cannot be used in collision avoidance.

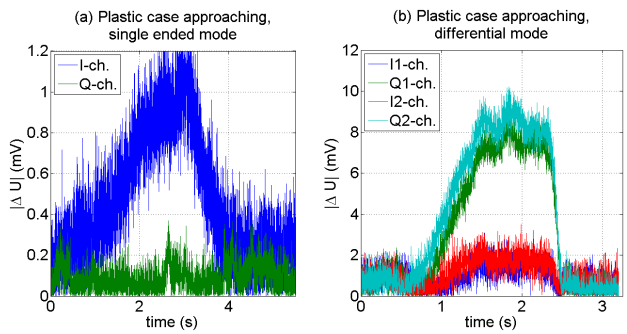


Fig. 16. Sensor signals for a plastic case approaching to about 5 mm and leaving the sensor surface. With only the single-ended mode in (a) it would be very difficult to detect the approaching object (scales differ by factor of 10).

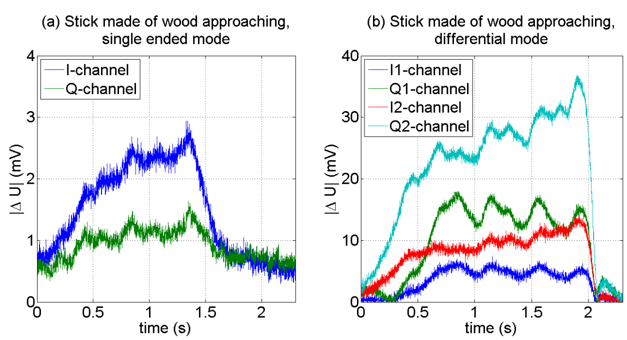


Fig. 14. Sensor signals for a stick made of wood approaching to about 5 mm and leaving the sensor surface.

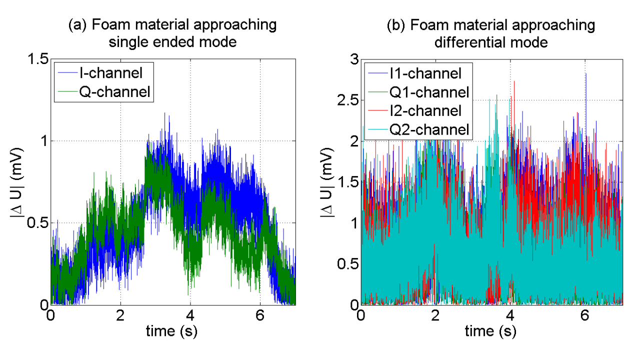


Fig. 15. Sensor signals for a foam material approaching to about 5 mm and leaving the sensor surface. Since the foam's electric susceptibility χ is very low and it is of small volume/density it has only little influence on the electric field. Thus, it cannot reliably be detected by the measurement system.

Capacitive sensing for dielectric objects depends, besides other things, on the electric susceptibility (χ) and the volume of the objects of interest. Thus, it is very difficult to measure objects with a very low susceptibility χ (i.e., close to the one of air, $\chi_{,air} \approx 0$). As can be seen in Fig. 15, an approaching foam cannot be detected in the differential measurement mode.

Even in the high sensitivity single-ended mode, the foam can only be detected at very close distances (< 5 mm) from the sensor. Thus, this mode cannot avoid a collision at a reasonable speed.

V. Conclusion

In this paper, we presented a pretouch sensing method based on capacitive measurements for highly responsive collision avoidance in human-robot interaction. The sensor acts like virtual whiskers by measuring the deformation of an electric field caused by the approaching objects. Due to the high measurement rate and use of two sensing modes (differential mode and single-ended mode), the measurement system outperforms state of the art capacitive proximity sensors. Thus, it is not only possible to sense conductive objects but also non conductive (dielectric) objects, which can be small in volume. Furthermore, this can be done at high measurement rates that are high enough to avoid robot collisions. A series of experiments on a KUKA Lightweight Robot IV in combination with the online trajectory generation algorithms for the Reflexxes Motion Libraries proved the proposed highly responsive collision avoidance behaviors during human-robot interaction tasks.

Appendix

The video attachment shows a series of experiments using the KUKA Lightweight Robot IV. The experiments include several human-robot collision avoidance scenarios (including using human heads) and the use of several materials while the two different sensing modes are applied. An HQ version of the video attachment can be found at: `http://youtu.be/v7C_SHweCxM`.

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