Gesture-based Contactless Control of Mobile Manipulators using Capacitive Sensing

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***Abstract*— Contactless control of serial and mobile manipulators is of interest in highly sensitive environments such as clean rooms and operational rooms to circumvent contamination of surrounding materials and in collaborative robotics to ensure safe and intuitive operation on shared workspaces. We present a contactless control scheme based on capacitive sensing which enables an intuitive control of robot manipulators. Contrary to optical and vision-based systems the capacitive sensor is robust against mechanical impact, dirt and does not suffer from occlusions or bad light conditions. The sensor can be realized on a flexible substrate, which offers a variety of placement options for the sensors, e.g. directly on a robot arm or integrated in the surface of a table or workplace. A comparatively simple model based approach is used to detect gestures thus avoiding the need for large training sets and allowing for easy adaptability to various geometric constraints. The capabilities of the proposed system are demonstrated by controlling the end-effector velocity of a mobile manipulator in 3D task space combined with a visualization of the system as feedback for the operator.**

I. INTRODUCTION

A. Motivation

Today's applications in different fields of industry rely on automation using serial and mobile manipulators. In such production lines, robots are often isolated from humans and fulfill their tasks in a repetitive manner. Usually, when the production line has a malfunction, the process chain must be stopped completely and reset by a human operator. This reduces throughput of the production which can be optimized by incorporating collaborative robots in the production process. These robots can perform tasks in the near vicinity of humans at moderate speeds thanks to novel sensing technologies for robot perception and control. In the past decades, major research efforts have been made in developing sensing devices based on vision and optical systems for robot perception and gesture recognition. Such systems have been successfully employed to solve complex tasks such as decision making, path planning and mapping and localization. In an industrial environment, however, sensor placement can be challenging and sensor readings may suffer from occlusions and degraded performance in harsh environmental conditions due to contamination, e.g. with dirt or due to mechanical impacts. Contrary to vision based systems, capacitive proximity sensors do not rely on a direct line of sight. Awkward preparations of the operator, as necessary with wearables, can also be avoided. Remarkable about the proposed devices is their robustness which makes them ideally suited for an industrial use. Due to the low number of necessary fabrication steps, they can be designed as conformable system and can consequently be attached to surfaces of various shapes and surface textures, e.g. directly on a robot [1] or within the surface of a table to provide direct and intuitive interfacing [2]. Proximity sensors based on capacitance sensors have been successfully implemented and demonstrated in the robotic community in the past years, e.g. for collision avoidance [3], object grasping [4], [5], object contour following [6], material recognition and classification [7], [8], Human-Robot Interaction (HRI) [9]–[11] and as tomographic sensors for collaborative robot control [1].

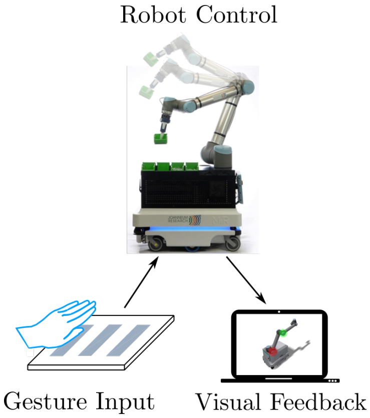

Fig. 1: Schematic overview of the proposed gesture-based interaction with a UR10 6-DoF mounted on the mobile platform MiR100 for mobile manipulation. The system consists of a sensor interface for gesture control, a mobile manipulator and implemented visualization in RViz for visual feedback during control.

B. Background

A great variety of gesture recognition systems relies on optical and vision-based sensing hardware [12]–[20]. A special camera type is the Time-of-Flight (ToF) sensor, which has been employed for gesture recognition in [17]. However, such systems depend on a line-of-sight and usually require complex image processing algorithms at high computational costs. Another common approach is to use wearable sensing devices for gesture recognition. Wu et al. [21] presented a system to control a car robot based on acceleration sensors. Zhang et al. [22] used the readings of accelerometers and

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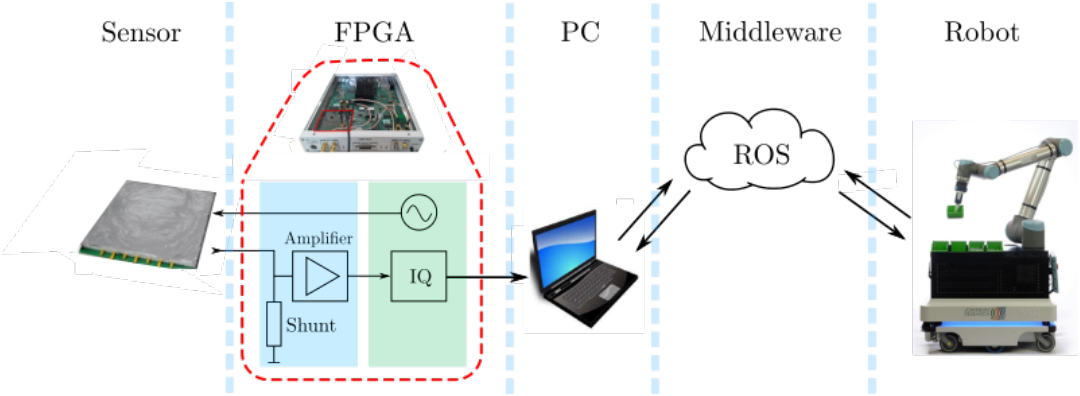


Fig. 2: Overview of the system used for gesture recognition. The demonstration setup uses a versatile Software Defined Radio (SDR) sensing platform which is composed of two major building blocks: the analog hardware (light black) and hardware programmable digital signal processing (light green) implemented in a Field Programmable Gate Array (FPGA).

electromyograms (EMG) for gesture detection. Similarly, Zhu et al. [23] suggested to use Inertial Measurement Units (IMUs) for gesture recognition in robot-assisted living and in [24], the JPL BioSleeve, as based on IMUs and EMG, was introduced for robot control through gestures. Also Coronoado et al. [25] proposed intuitive interfaces for gesture-based robot control using a wearable IMU-system. The authors of [26] proposed ultrasound transmitted as transdermal wave for gesture sensing and also in [27] wearable devices are employed. Asokan et al. [28] present a system which uses a sensor-equipped glove for gesture sensing. In [29] a novel sensor principle, triboelectric quantization, is exploited in a sensor mounted on a human finger is shown for gesture control. However, often wearable devices may not be employed or desirable. This is especially the case in the before-mentioned cleanroom environment. A gesture-sensing device based on radar pulses was presented in [30]. While this system can be operated contact-less, its operation range is rather small compared to the size of a human hand.

C. Contribution

In this paper, we present a contactless and gesture-based control scheme for mobile manipulators based on a capacitive sensor principle. Our control scheme enables intuitive control of the mobile manipulator which extends the capabilities of future collaborative tasks. Our control system comprises the following key facts:

- occlusion-free principle
- robustness against environmental conditions and impact
- easy integration on various surfaces
- large sensing area
- fast and flexible fabrication

Due to the relatively easy and cheap structure of capacitance-based sensors, they allow flexibility in the fabrication process, i.e. the sensor front-end can be manufactured on flexible substrates using novel printing techniques [31], [32]. The proposed signal processing algorithms are of rather low complexity and enables real-time processing without the need for high performance CPUs. A schematic overview of the proposed system is shown in Fig. 2.

The remainder of this paper is structured as follows: An overview of the proposed system is given in Section II followed by a description of the used software framework to control a robot in Section III. The control structure utilizing the capacitive sensor is explained in detail in Section IV, results of conducted laboratory experiments are shown in Section V and a conclusion is given in Section VI.

II. SYSTEM DESCRIPTION

A. Sensing Principle

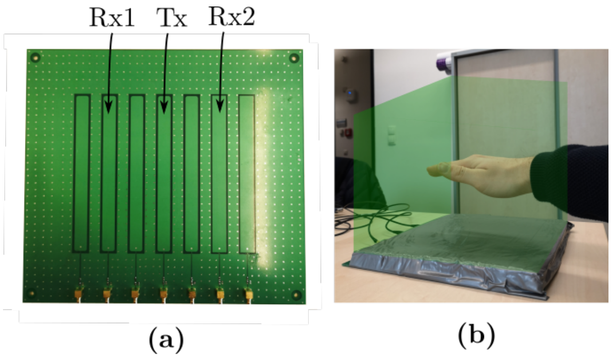
For the gesture-based interaction we operate the sensor in differential mode using two receiver electrodes (R1, R2) and one transmitting electrode (T). Hence, when human tissue, e.g. a hand, approaches the sensor unit, a change of capacitance can be calculated from the sensor readings, which is further processed for control tasks.

B. Sensor Front-End

The capacitive sensor is fabricated on FR4 material by a standard Printed Circuit Board (PCB) fabrication process. The electrode size was chosen with $d_e = 15\,\mathrm{cm} \times 1.2\,\mathrm{cm}$. The PCB comprises seven electrodes in total where three electrodes are used for the contact-less control. The fabricated sensor and its sensing range is shown in Fig. 3. Due to geometrical size, the obtained sensing range was around $15\,\mathrm{cm}$. The center electrode is chosen as the transmitter electrode whereas the receivers are chosen symmetrical around the transmitter.

C. Signal Processing

Signal processing and acquisition is realized using an FPGA-based SDR platform consisting of transmitter and receiver daughterboards with custom made amplifier stages [33]. To extract useful information from the sensor raw data, an IQ demodulation scheme was implemented in the hardware. The complex multiplication is realized on the FPGA and operates at a sampling rate of $f_{sm} = 20$ MHz.



(a) (b)

Fig. 3: (a) Fabricated sensor comprising seven electrodes for capacitive sensing. (b) Illustrated sensing space which can be achieved with the developed sensor.

The proximity behavior modulates the amplitude of the receiver signals which allows signal extraction at DC after demodulation. For further processing on the host the signals are down-converted with a hardware-based digital down-converter to a frequency of $f_h = 400$ kHz. The signals are low-pass filtered to extract the DC content using an Hamming windowed FIR filter with cut-off frequency of $f_c = 100$ Hz. Depending on the impedance of the receiver, the displacement current may be observed in the I or the Q channel. If the impedance is not known accurately and conductive coupling between transmitter and receiver are low, also the signal magnitude can be utilized, which is easily obtained from the I and Q components using

$$V_{A,R1} = \sqrt{V_{I,R1}^2 + V_{Q,R1}^2} \tag{1}$$

D. Mobile Platform

The mobile manipulator CHIMERA is composed of the mobile base MiR100 and the serial manipulator UR10. Furthermore, it includes additional batteries and computing devices and several external sensors like a RGB-D camera on the body and a force-torque-sensor. A whole-body compliance control that handles both, the kinematic redundancies and the avoidance of singular arm configuration has been implemented on the mobile manipulator [34]. In this paper we extend the capabilities of the mobile platform CHIMERA by adding a gesture based control of all components, i.e. base, joint of manipulator and end-effector.

E. Software Design

In Fig. 4 the software architecture of the gesture control is shown. The entire architecture is based on ROS. The key components are the gesture detection, velocity controller and the simulation environment.

III. GESTURE-BASED ROBOT CONTROL

A. Gesture Recognition

For directional movement, a proximity threshold was defined to distinguish between different direction of motion for the mobile platform. Additionally, swiping gestures have been implemented for robot control. These gestures depend on the hand motion of the operator and gesture detection is based on the velocity of the moving hand. Before computing the gestures, the signals are offset compensated by subtracting the mean value of the signals which is stored in a predefined buffer with a length of 200 samples. To recognize the gesture, the cross-correlation of both IQ demodulated receiver signals

$$r_c[k] = \sum_{n=0}^{N-1} V_{A,R1}[n] V_{A,R2}[n-k] \tag{2}$$

where k is the lag number and N is the number of samples is computed. The lag at the peak in the cross-correlation corresponds to the travel time and thus inversely to the velocity. For the gesture recognition, the frame length for correlation was set to $t_c = 400\,\text{ms}$. Setting the correlation window shorter would require unnatural and very fast hand movements, which should be avoided for intuitive control. A threshold for the peak is used to tune the sensitivity of the gesture recognition. A state variable p_j is set depending on the hand motion. As an initial state value, p_j is set to zero so that the user controls the mobile platform. The state variable changes due to the different executed swiping gestures and allows selection between base, different joints and end-effector position.

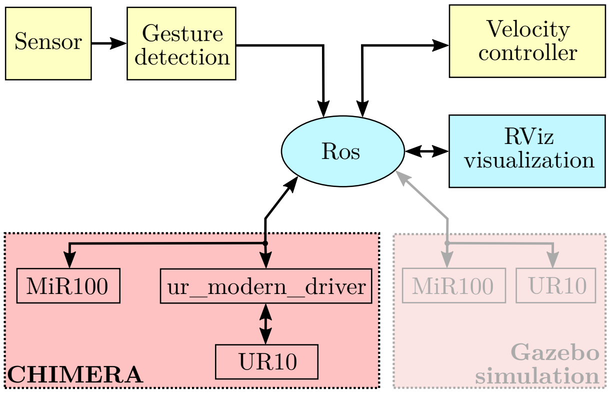


Fig. 4: Software architecture of the implemented gesture-based control of the mobile manipulator. The proposed structure allows to either use the sensor and the controller with the real hardware (left red block) or a simulation environment (right red block).

B. MiR Control

For transportation tasks, the mobile platform can be controlled using our control strategy by three different modes. By placing the hand on one of the receiver electrodes, the platform will rotate in the according direction. Placing the hand over both electrodes, results in a forward movement of the mobile platform. For all three modes, velocity control is enabled by varying the hand distance to the sensor electrodes. Using only a threshold for velocity control would lead to undesired behavior of the platform if objects are placed on the sensor. This is due to the coupling of objects with the sensor and depends on the objects permittivity. This can be

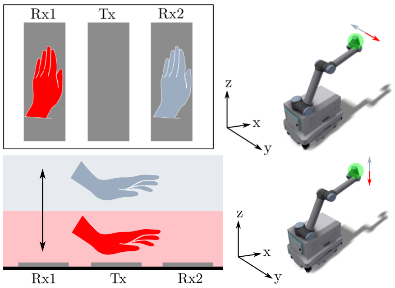


Fig. 5: Illustration of the end-effector control in y-direction. Depending on the hand position, the end-effector is moving in positive y-direction (red) or negative y-direction (gray).

prevent by using a gradient-based control strategy where the velocity controller is only triggered when a smooth gradient of the signal is detected, i.e. when the operator smoothly approaches the sensor. The control scheme is then more robust against sudden signal changes such as objects falling on the sensor.

C. *Robot Joint Control*

To enable joint control in all rotational directions, every joint comprises two states for clockwise and counter-clockwise movement. This results in 12 different states, which can be set by the human operator via swiping gestures. After the joint selection, the movement is realized by using the proximity property of the sensor front-end. The velocity control for the joints is realized by incorporating the hand distance to the sensor element. To avoid self-collision and singularities of the manipulator, artificial joint limits have been set accordingly.

D. *End-Effector Control*

For tasks such as picking and placing various objects, it is of major importance to realize an easy and intuitive control of the manipulator. To achieve this feature, we combined the gesture and proximity modalities of the capacitive sensor to control the end-effector of the mobile manipulator. By moving the hand up and down on the sensor, the end-effectors z-position is controlled. To differentiate between positive and negative z-direction movement, a threshold was implemented as shown in Fig. 5. Also, by moving to the right (R2 electrode) or left (R1 electrode) position, the end-effector is controlled in y-direction. To ensure that the end-effector stops without presence of an operator, a second threshold was set which detects non-presence of the human hand.

IV. EXPERIMENTAL SETUP AND RESULTS

All experiments were conducted in a lab environment using the mobile manipulator platform CHIMERA. The sensor was mounted on a table and connected to the FPGA for signal processing. For all experiments, the transmitter electrode was excited by a sinusoidal signal generated from the FPGA with carrier frequency of $f_c = 1\,\mathrm{MHz}$ and amplitude of $V_p = 1$ V. The receiver electrodes have been set $55\,\mathrm{mm}$ apart from the center of the transmitting electrode. At the receiver side, an amplifier gain of 50 dB was used for both channels and a shunt measurement resistor of $R_s = 47\ \Omega$ was used. The ROS update rate of the system was set to $f_u = 100$ Hz for all experiments. Before the experimental trials, an offset calibration was done by buffering the first 100 samples of the measurements. Experimental trials with different occlusion scenarios have been conducted to quantify the robustness of the sensor. Furthermore, velocity control experiments have been conducted and the control scheme was tested with the mobile manipulator in the lab.

A. *Robustness Evaluation*

Since the swiping gestures are computed using cross-correlation of the offset compensated signals, objects on the sensor surface don't affect the gesture recognition compatibility as much as using other principles. Camera only systems would fail since disturbing objects will lead to occluded situations which yields reduced performance or even failure. Our proposed control scheme is more robust to such effects. To validate the robustness against gestures, we perform experiments with several different objects placed on the sensor and compare gesture recognition rates for both scenarios. Each experiment consists of $N_t = 100$ trials and the success rate defined as the ratio

$$P_s = \frac{N_t}{N_s} \tag{3}$$

is computed for all experiments where N_s is the number of successful trials. The test runs cover the following scenarios which are shown in Fig. 6.

- Test Run 1: Empty Sensor
- Test Run 2: Sensor partially covered with single object
- Test Run 3: Sensor fully covered
- Test Run 4: Sensor covered with multiple objects
- Test Run 5: Sensor covered with tap water

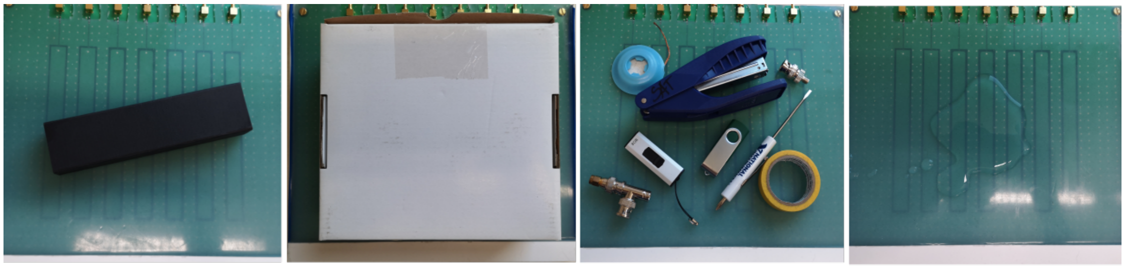
Robustness Evaluation					
	Test Run 1	Test Run 2	Test Run 3	Test Run 4	Test Run 5
P_s	1	0.97	0.87	0.96	0.81

TABLE I: Obtained success rates for different test scenarios.

Table I summarizes the obtained success rates for the different tests. It is notable, that in all scenarios, a success rate greater than 0.8 can be achieved, even when the sensor is fully occluded or covered with fluid.

B. *Velocity Control*

Depending on the hand position, the velocity of the platform can be controlled in an intuitive way. Fig. 7 shows the velocity profile of the platform and the corresponding sensor data during two accelerations within a time interval of $t_i = 15\,\mathrm{s}$. It is notable that the control scheme allows smooth speed variation such that the platform can also be controlled at low speeds. Fig. 8 shows the relation between hand distance to the sensor and velocity of the mobile platform. The velocity starts slowly do increase around 15 cm



(a) (b) (c) (d)

Fig. 6: Test scenarios used for experimental evaluation of the robustness. (a) sensor covered with single objects, (b) sensor fully occluded, (c) sensor covered with multiple objects, (d) sensor covered with tap water.

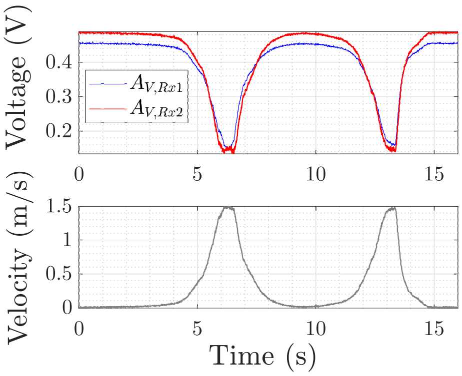


Fig. 7: Acceleration scenario with the mobile platform. Top shows the obtained sensor signals of both channels and bottom shows the velocity of the mobile platform.

which corresponds to the maximum sensing range. Then the velocity increases until 1 cm proximity to the maximum allowed velocity of the mobile platform which is defined by 1.5 m/s.

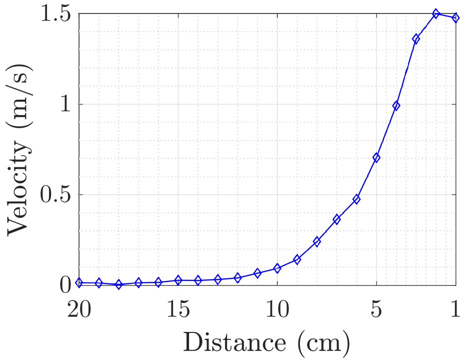


Fig. 8: Velocity output for increasing proximity.

C. Gesture Recognition

Fig. 9 shows the typical signal during a swiping gesture. Due to the defined time interval gestures which are executed too fast (first two peaks in Fig. 9) are not recognized by the system. Thus, the proposed system is also robust against rapid and slow movements which is beneficial in suppressing accidental signal changes.

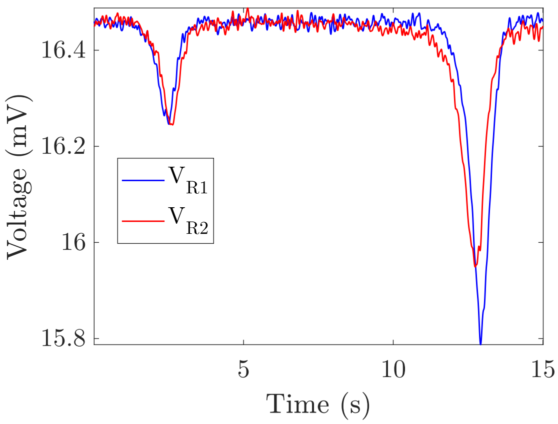


Fig. 9: Typical signal for executing two gestures during a time interval of 15 s.

V. CONCLUSION

In this paper we have presented a contactless gesture-based control system for a mobile manipulator comprised of a 6DoF serial manipulator and a mobile platform. The conducted experiments show the feasibility of the approach leading to capacitive-based robot control in a collaborative manner which enables safe and intuitive HRI. The system successfully shows different modalities of the system, such as end-effector control and isolated control of all components of the robotic system. Also, due to the underlying physical principle of the system, the gesture detection is robust against interferences and disturbances due to objects in the sensing area, which would be prohibitive for other approaches like optical, vision or radar based systems.

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