Collision Avoidance for a SCARA Robot on Construction Sites

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***Abstract*—Autonomous robots on construction sites are designed with the objective to take over time-consuming tasks while also relieving human construction workers. However, to operate safely, they must reliably detect obstacles and avoid collisions. The proposed approach targets this problem for a SCARA-like granular-fill insulation distributing robot, using ultrasonic distance sensors. Mounting the sensors on the robot's links allows to observe the workspace at a sufficient rate and accuracy. A microcontroller reads out the sensor data and transfers it to the PLC in charge. Furthermore, an efficient sensor error detection principle for the developed sensor suite is demonstrated. Experiments conducted in a laboratory environment prove the functionality of the system. Collision avoidance with various obstacles commonly found on construction sites is realized reliably over a multitude of test runs. The system dependably detects and reacts to obstacles of varying sizes and materials in a safety margin of 300 mm within at least 160 ms, sufficient for applications in building construction sites.**

***Index Terms*—Collision Avoidance, SCARA, Ultrasonic Sensors, Automation**

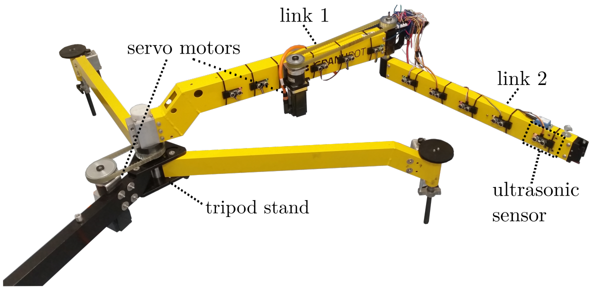

Figure 1. The considered SCARA-like granular-fill insulation distributing robot, equipped with servo motors to enable the actuation of the arm. Additionally, ten ultrasonic sensors are mounted on both links for obstacle detection and collision avoidance.

I. INTRODUCTION

In recent years, the construction industry experiences an increased demand of automation for its applications [1]. Besides economic benefits, such as improved productivity and quality, also enhancements in safety and sustainability are key drivers for the use of robots and automation systems [2]. Especially in the field of building construction, many physically demanding tasks are still carried out by human construction workers. An example is the leveling of granular-fill insulation material, necessary on many sites. This task demands high concentration and is both physically exhausting and time-consuming. The introduction of a motorized and Programmable Logic Controller (PLC)-controlled SCARA-like manipulator lead to an improvement of the usability [3–5], since it allows for automated granular-fill insulation distribution with only minor human intervention.

However, the safety aspect is yet to be addressed. On construction sites, humans or objects are likely to cross the robot's calculated trajectories occasionally. Collisions must be reliably avoided to ensure the safety of humans and to prevent damage to property. To achieve this, the system needs to detect these obstacles, considering site-typical disturbances like dust whirls.

First solutions came up already in the early 1990s, using specifically designed capacitive sensors [6]. Advantages of this sensor type include its independence of obstacle shape, color, or conductivity. Successful experiments with a two link manipulator were conducted. However, the proposed working range is limited to 400 mm. More recently, another capacitive sensor was designed to be applied on a 7-axis robot [7]. This is easily possible due to the sensor's flexibility and thin geometry. Further advantages are the exclusion of blind spots and the fast detection rate. Combined with a highly-reactive online trajectory generator, the robot is able to stop successfully within a short period of time. This kind of capacitive sensor cannot only be applied on an industrial robot surface like a skin, but also inside the robot's links, inherently protecting the sensor [8].

The idea of placing sensors on a robot surface to create an artificial skin can also be achieved with tactile sensors [9–11]. Two drawbacks of this solution are apparent: a collision has to occur to react to it, and the solutions are tailored to specific robot structures and applications, and thus not universally applicable.

Sensors with higher range are distance sensors based on the time-of-flight (ToF) principle. They have been used on different types of robots in various configurations and quantities.

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Partly protected by a cage, as few as one ultrasonic sensor placed near the end-effector or arranged around the links can be sufficient to avoid collisions [12, 13]. Generally speaking, a well-chosen combination of sensors and placement is needed to enable safe human-robot collaboration from both a technical and a legal point of view. Considering that, several sensor principles and mounting possibilities are evaluated in [14]. Matching them to the requirements at hand, the final solution fully covers the links of a six-degrees-of-freedom industrial robot with ultrasonic sensors, with sensors facing perpendicular to the link surface. However, this approach requires a high number of sensors to cover the robot's workspace and thus implies both a high maintenance and financial effort.

In summary, obstacle detection and avoidance are important tasks and thus many successful solutions with different sensors have been proposed. However, most of them focus on 6- or 7-axis robots instead of SCARA-like manipulators, and none specifically target harsh environments, such as construction sites. Thus, the demand for collision avoidance solutions for SCARA-like robots, used in the building construction industry, arises.

The contribution of this paper is the design and implementation of a system for obstacle detection and the subsequent collision avoidance of a SCARA-like granular-fill insulation distributing robot in rough environments, such as construction sites. The proposed solution consists of a set of ultrasonic sensors mounted laterally on the links of a SCARA robot (cf. Fig. 1), in order to grant a perspective towards the workspace. Providing the sensor data to the PLC, which manages the possibly required evasive maneuvers, a successful avoidance can be demonstrated experimentally for a variety of common obstacles. Furthermore, an efficient sensor error detection concept is implemented and analyzed.

System design and implementation are presented in Section II. Experimental results of the implemented obstacle avoidance approach are analyzed in Section III, followed by Section IV with the conclusion.

II. SYSTEM DESIGN

An appropriate solution for the safe operation of the considered SCARA-like granular-fill insulation distributing robot must take into account both the properties of the environment and the robot itself. Expected obstacles on building construction sites can be dynamic or static, humans or items, occluded by dust particles, and exhibit different material properties. Considering the robot properties, the kidney-shaped workspace of a SCARA-like robot can be approximated by a cylinder, parameterized by the length of the full arm and the vertical range of motion. Disregarding the end-effector, collisions can only occur in a flat disk at the height of the links. This characteristic of the SCARA kinematics enormously simplifies the implementation of the sensor system. The regarded manipulator spans a disk of roughly 2 m radius and allows for a maximum planar end-effector velocity of about $1\,\mathrm{m\,s^{-1}}$. For safe operation, the sensor suite should observe as much as possible of this disk. Considering the maximum manipulator velocity, margins of safety, and furthermore also the mechanical play of the belt drives, this shall happen with a minimum scanning resolution of 50 mm and an update rate of 10 Hz. These requirements provide a sound base for collision-free operation of the SCARA-like granular-fill insulation distributing robot.

Before choosing a sensor principle, mounting possibilities are revisited. Although external sensors might cover a larger area at once, occlusions from obstacles or the robot itself will most certainly occur [14]. Consequently, no reliable detection can be guaranteed. Furthermore, the sensors would need multiple relocations per construction site, which results in an increased floor installation time. Hence, for the application of collision avoidance, it is beneficial to place the sensors on the robot manipulator.

Despite offering various benefits, the range of capacitive sensors and robot skins is insufficient for this application. Cameras could provide a remedy, since they offer adequate detection range. However, for full coverage several cameras might be needed, demanding a high computational effort. Furthermore, given the practical workspace reduction possible for the SCARA-like granular-fill distributing robot, meaning movements in solely one plane, cameras are not deemed optimal in this case. The last considerable type are distance sensors. A market review including 25 products of this sensor type indicates that both light-based and ultrasonic sensors reach the desired levels of accuracy and update rate. They allow covering large parts of the workspace when mounted perpendicularly to the robot's links [14]. However, due to their low beam divergence, light-based ToF sensors only discretely observe the surroundings. By contrast, ultrasonic sensors exhibit larger sensor cones, which overlap at a certain distance. This results in larger coverage with a lower sensor number and thus reduced cost, setup effort, and maintenance. In addition, unlike with light waves, prevalent dust particles do not interfere with ultrasonic waves. Hence, the considered collision avoidance system is realized by using ultrasonic sensors, which is presented in the following section.

A. System Implementation

To build the required sensor suite for collision avoidance strategies, multiple instances of the type HC-SR04 with a sensor cone of 30° are mounted on the robot links. Fig. 2 shows such a sensor within a specifically designed, 3D-printed mounting bracket. The aforementioned overlap of sensor cones occurs at a certain distance only, as depicted in Fig. 3. The maximally tolerated blind zone determines the number of sensors needed. The latter can be calculated for each link in two steps with

$$d_s = 2 \cdot d_{blind} \cdot \tan\left(\frac{\alpha}{2}\right) \tag{1}$$

$$n = \left\lceil \frac{l}{d_s} \right\rceil, \tag{2}$$

where d_s is the distance between two sensors, d_{blind} is the tolerated blind zone, α is the sensor cone angle, n is the number of sensors per link, and l is the length of the link.

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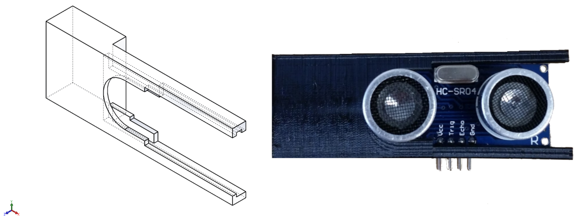

Figure 2. The left part shows the sketch of the mounting bracket, whereas the right part shows the 3D printed part equipped with an ultrasonic sensor of type HC-SR04

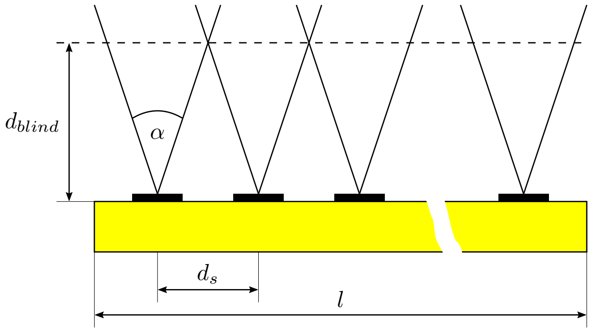

Figure 3. With this bird's eye perspective the amount of sensors needed can be derived. The robot link of length l is drawn in yellow, the sensors and their cones with the cone angle α in solid black, and the tolerated blind zone d_{blind} in dashed black. d_s is the distance to be calculated between two sensors.

The used ultrasonic sensor requires trigger pulses in the range of 10 µs, which is not achievable with standard PLC components. Microcontrollers are more suitable for such tasks. For this application, the Arduino MEGA microcontroller is chosen, as its 54 digital pins allow triggering a sufficient number of sensors. To ensure minimal delays, the internal interrupt functionality is used for readout. By using the open-source library `EnableInterrupt` [15], the interrupt feature can be used on 24 pins instead of only six. To send the sensor data to the PLC via the real-time fieldbus system `EtherCAT` [16], an EasyCAT shield is attached to the Arduino controller [17].

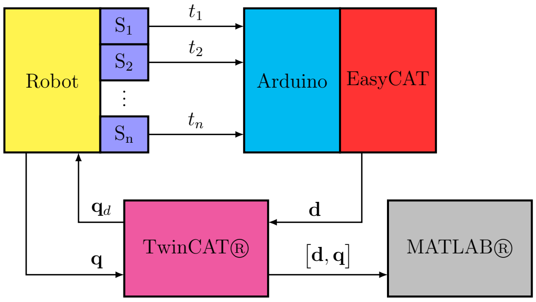

Figure 4. Schematic overview of the overall system. All modules are colored differently for clarity. The robot and its TwinCAT® controller exchange current joint angles $\mathbf{q}$ and desired joint angles $\mathbf{q}_d$. t_1 to t_n are the time durations the sensors' sound waves took to return, and $\mathbf{d}$ is the vector of distances calculated from these times. These distances are sent to the TwinCAT® controller, which uses them to trigger the desired collision avoidance procedure. Both the distances $\mathbf{d}$ and the current joint angles $\mathbf{q}$ are sent to a dedicated MATLAB script for visualization purposes. The SPI connection between the Arduino and the EasyCAT shield is neglected.

The resulting system architecture is depicted in Fig. 4. The TwinCAT® PLC implements the control logic for the granular-fill insulation distributing robot. Thus, the desired trajectories are generated and its associated desired joint angles $\mathbf{q}_d$ are forwarded to the manipulator. In order to enable feedback control, the current joint states $\mathbf{q}$ measured by the motor-intern position encoders are returned to the PLC. The ultrasonic sensors, attached to the links of the robot, are read out via the microcontroller, which subsequently sends the vector of measured distances $\mathbf{d}$ via a fieldbus connection to the PLC. The PLC monitors these distances and triggers the desired collision avoidance procedure in case of a risk.

B. *Sensor Error Detection*

The proposed collision avoidance approach aims to ensure the safety of humans and to prevent damage to property during the operation of the granular-fill distributing robot. To enhance the dependability, an efficient way to detect sensor errors in the proposed sensor suite for obstacle detection and subsequent collision avoidance is designed. This is achieved by utilizing the overlapping sectors of the conical sensor area. The fact that the sensor cones begin to superimpose at a distance of d_{blind}, which is defined by the sensor mounting distance d_s (cf. Fig. 3), results in a redundant sensing zone starting at a distance $d_{err} = 2 \cdot d_{blind}$.

At this distance the two adjacent ultrasonic sensors S_{i-1} and S_{i+1} also cover the sensing area of the ultrasonic sensor S_i, considering a sensor suite of n sensors and $i \in [2, n-1]$. With the distance information of the three sensor entities, a voting procedure is initiated to check the validity of the measurement of sensor S_i. The expected worst-case value $\hat{d}_i$ is calculated via the geometric relationship between the mounted sensors and the measured distances d_{i-1} and d_{i+1} of sensors S_{i-1} and S_{i+1}, respectively:

$$\hat{d}_i = d_j \cdot \cos\left(\frac{\alpha}{2}\right). \tag{3}$$

In Eq. (3), the distance $d_j = \min(d_{i-1}, d_{i+1})$ is denoted as the minimum of the measured values d_{i-1} and d_{i+1}, and α represents the sensor cone angle. If the measured distance value d_i now is greater or equal than the conservative estimation $\hat{d}_i$, the sensor value is considered valid, whereas d_i is considered invalid if it is smaller than $\hat{d}_i$.

As long as a sensor error is present, the robot control discards the associated distance value and substitutes it with the sensor information of the two adjacent sensors. Since the application of distributing granular-fill insulation on construction sites allows the assumption, that distance between obstacles and the manipulator is initially greater than d_{err}, this efficient sensor error detection is implemented.

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III. ANALYSIS AND RESULTS

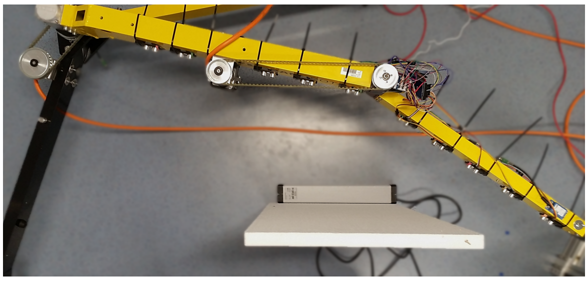
To test the proposed setup, experiments in a laboratory environment are conducted. For safe operations with the given manipulator, we aim at a desired safety margin of 300 mm. To ensure safe detection of obstacles in the workspace, the blind distance has to be equal or smaller than the defined safety margin. In this experiment, we set $d_{blind} = 300\,\mathrm{mm}$ and thus equal to the safety margin. Utilizing Eq. (1) and Eq. (2), and considering the manipulator link lengths ($l_1 = 0.97\,\mathrm{m}$, $l_2 = 0.76\,\mathrm{m}$), this results in a sensor suite of ten ultrasonic sensors mounted on one side of the SCARA-like granular-fill insulation distributing robot. These sensors are read out at a frequency of 10 Hz. This is sufficient for a proof of concept, but the proposed architecture allows for a total of 24 sensors on both sides and overall rates of 15 Hz. The robot is programmed to follow a pre-defined sweeping trajectory, as it is used for the intended task of distributing granular-fill material. If an obstacle comes within the defined safety zone during this motion, the PLC running at a cycle time of 1 ms calls a halt. Due to sensor noise, relying on a single sensor can easily lead to false alarms. Instead, demanding that multiple sensor values drop below the threshold for object detection greatly improves the robustness. In the experiments, a minimum of two sensors signaling a detection is required before triggering the collision avoidance procedure.

For validation of the sensor concept, four obstacles commonly encountered on construction sites are chosen. These vary in both size and material, and are inserted partially dynamically:

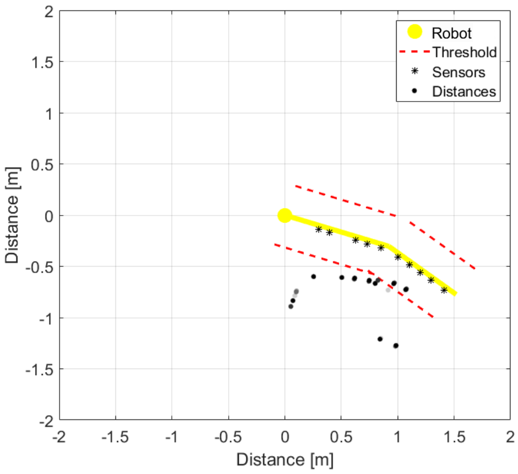
- 600×800×10 mm polystyrene panel
- 600×150×1200 mm plastic case
- 20×60×1000 mm aluminum extrusion
- human leg covered in jeans (diameter 120 mm).

The experimental setup for validating the collision avoidance method can be seen in Fig. 5a. In this scenario, a polystyrene board is positioned within the work space of the robot. As soon as the obstacle is within the defined safety zone of the approaching robot, an emergency stop is initiated. This behavior is also shown in the visualization in Fig. 5b. The black to white points mark the measured distance values by the ultrasonic sensors (represented by black stars). Hereby, black indicates the most current and white the measured value five timestamps ago. As shown in the visualization, sensors of the outer link measure distances violating the programmed thresholds (dashed red) and thus leading to a halt.

Multiple runs with the four chosen obstacles are conducted, where the robot stops successfully in different poses for both static and dynamic obstacles. All obstacles are detected and no material or size caused outstanding issues. For several attempts with each type of material, the average and worst case halt time is measured and listed in Table I. Thereby, the emergency stop is performed fastest in the case of the plastic case with an average halt time of 59 ms and a worst case halt time of 87 ms. Overall, the largest worst case halt time is measured with the polystyrene panel and results to 160 ms. Given a maximum



(a) Test scenario with the SCARA-like granular-fill insulation distributing robot, equipped with ten ultrasonic sensors on one side of both links, and a polystyrene board as a test obstacle. The robot came to a halt after the detection of the obstacle.



(b) The MATLAB-based visualization shows the considered test scenario from above, with the robot depicted in yellow. The ultrasonic sensors on the links are represented by black stars, the dashed red line marks the set threshold, below which an obstacle initiates a collision avoidance procedure; in the present case an emergency halt. The black to white points are the distance values measured, black means most current and white is five timestamps ago. As it can be seen, some sensors measure distances below the programmed thresholds and which caused the halt.

Figure 5. Experimental setup of the robotic system with the proposed sensor suite. The robot follows a pre-defined sweeping trajectory and a test obstacle is placed along its way.

Table I
AVERAGE AND WORST CASE HALT TIMES OF THE SCARA GRANULAR-FILL INSULATION DISTRIBUTING ROBOT DURING A SAFETY VIOLATION, EVALUATED WITH OBSTACLES OF DIFFERENT MATERIALS.

Material	**Average halt time [ms]**	**Worst case halt time [ms]**
Polystyrene panel	150	160
Plastic case	59	87
Aluminum extrusion	110	125
Human wearing jeans	140	150

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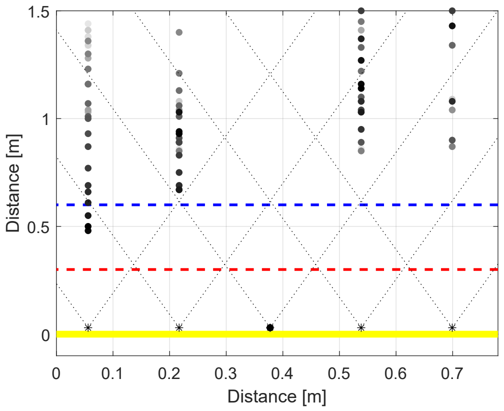
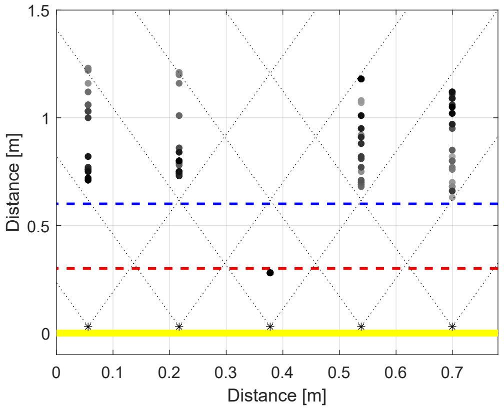
planar end-effector velocity of about $1\,\mathrm{m\,s^{-1}}$ this results in a maximum stopping distance well below the targeted $300\,\mathrm{mm}$, proofing a successful implementation.



(a) This test scenario analyzes the sensor error detection capability of the system. For that reason, the third sensor is simulated to yield an erroneous distance value of $0\,\mathrm{mm}$. During the test, the manipulator is rotating towards a wall. Since the second and the fourth sensor obtain distances above d_{err}, a sensor error of the third sensor is present.



(b) This experiment shows the error detection behavior in the case of a moving human, who walks from right to left. Here, the third sensor is simulated to yield an erroneous distance value of $250\,\mathrm{mm}$. As can be seen, the measurement data yield that the walking human is currently in front of sensor three and four.

Figure 6. Experimental setup for the evaluation of the proposed sensor error detection. For this analysis, only the second link of the granular-fill insulation distributing robot (yellow) is considered. The dashed red lines indicate the collision detection threshold, the dashed blue lines indicate the distance d_{err}, which indicates the minimum distance for sensor error detection. The ultrasonic sensors on the link are represented by black stars, the black to white points are the distance values measured, black means most current and white is 25 timestamps ago. The dotted lines visualize the sensor cone of 30°.

Additional experiments are conducted with the aim of validating the sensor error detection concept, depicted in Fig. 6. For this analysis, only the second link of the granular-fill insulation distributing robot is considered, which in a first test is rotated towards a wall, and subsequently in a second test placed in front of a wall with a distance of $1.5\,\mathrm{m}$. The third sensor is manipulated in a way that it yields erroneous distance values.

In the first test, the manipulator is rotated towards the wall. As can be seen in Fig. 6a, initially the second and the fourth sensor obtain distances above the minimum distance for error detection d_{err}, while the third sensor value is locked at $0\,\mathrm{mm}$. As time passes, all other sensor values decrease and ultimately show a present sensor error at the third ultrasonic sensor.

The second test examines the error detection behavior in case of a moving human, who walks from in front of the manipulator from right to left. Depicted in Fig. 6b, the data yields that the walking human is currently in front of sensor three and sensor four. Slowly disappearing from the right side and appearing on the left side, the human is not perceived by the third sensor, although sensors two and four registered the distance change. Thus, the proposed sensor error detection is capable of recognizing erroneous sensor data.

In summary, collision avoidance on a SCARA-like robot for the installation of granular-fill insulation using ultrasonic sensors is successfully demonstrated. The system responds sufficiently fast and is robust to a variety of obstacles commonly present on construction sites. Moreover, the proposed method for sensor error detection appears feasible for the application in harsh environments, such as construction sites.

IV. CONCLUSION

Autonomous robots can free up workers from demanding and time-consuming tasks. Safely deploying them to construction sites requires reliable collision avoidance. The solution presented in this paper addresses the problem by using ultrasonic sensors mounted on a SCARA granular-fill insulation distributing robot. Placed laterally on the robot's links, the sensors observe the workspace with both sufficient accuracy and speed. A microcontroller allows transferring the data via the real-time fieldbus EtherCAT to the PLC in charge. Experiments conducted in a laboratory environment with obstacles commonly encountered on construction sites approve the functionality of this approach. The system reliably detects and reacts to the test obstacles in a maximum of $160\,\mathrm{ms}$. Furthermore, a sensor error detection is implemented, which is able to recognize wrong sensor data by including the information of adjacent sensors.

To move from the laboratory to real construction sites, a few optimizations must be addressed next. Physical shielding or consistency checks should mitigate the impact of sensor noise. As the controller knows the current joint angles at all times, and additionally, a bounding box model can be used to avoid self-detection. Furthermore, instead of stopping instantaneously when detecting an obstacle, the sensor information can be more tightly connected to the control algorithm. This allows to implement concepts such as obstacle bypassing. The end-effector is currently not protected separately, though further tests can reveal whether additional sensors are actually necessary for it.

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