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Robot collision avoidance using an environment model for capacitive sensors

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***Abstract*— In recent years, the topic of safe human robot cooperation has become important, and with it the requirement to reliably detect humans in the work space. Capacitive sensors mounted to the robot structure can be used to measure the presence of conductive objects. This allows to detect humans, however static obstacles in the workspace also influence sensor measurements. Thus we propose to record an environment model containing the expected sensor values for relevant robot poses. Using this model, distance estimation and real-time reaction can be performed even in the presence of large metallic objects in the robot workspace. A demonstration of our approach has been shown at the Hannover Messe 2015.**

I. INTRODUCTION

Recently, the interest in safe human robot cooperation has increased. Arguments for this are the attempt to automate jobs that cannot yet completely be executed by robots, but also the prospect of demographic change, where robots are expected to help aging workers and relieve them from inconvenient work postures. To facilitate safe human robot cooperation, collisions have to be avoided or at least reduced to a level not causing injuries. To detect humans or collisions, various methods have been proposed or used.

Especially for light-weight robots, methods measuring motor currents or torques (cf. [1], [2]) have been used (e.g. KUKA LBR iiwa, Universal Robots UR5 and the ABB YuMi), as well as tactile sensors (cf. [3], [4]), which however share the disadvantage that collisions can only be detected after they occurred, but not be anticipated and avoided.

To detect collisions before they occur, ultrasonic sensors (cf. [5]) mounted at the robot structure can be used, however the detection field as well as the possible update rate are limited. Furthermore, cameras (either just RGB, or including depth information) can be used (cf. [6]), however with the drawback of areas shadowed by the environment or robot structure have to be handled by using a sufficient number of cameras in appropriate places.

Capacitive sensors have been used to secure robots since the 1990s [7], with various improvements over time. A variant combining tactile sensors for safety stops with capacitive sensors for anticipation [8] is already available as a product, however with some drawbacks concerning influences of the environment. Additionally, current work [9] emphasizes the need for fast measurement and reaction in order to safely stop the robot.

Fig. 1. Demonstration cell with a KR 6 AGILUS at the Hannover Messe. There are three capacitive sensors mounted at the arm and one at the tool.

A drawback of using capacitive sensors however is, that not only humans influence the sensor signals, but in general any conductive material. Without any knowledge of the environment, it is impossible to distinguish between static obstacles (where no collisions are to be expected if the robot is programmed properly) and dynamic, human obstacles (where a collision must be avoided). Therefore, in this paper an approach is presented which uses an environment model which contains information about static obstacles and thus allows to distinguish reliably between the static environment and additional, dynamic obstacles.

This paper is structured as follows: First, the idea of proximity detection using capacitive sensors is explained. Afterwards, our solution to mitigate influences of the environment through using a pre-recorded environment model is introduced, followed by a description of our solution for collision avoidance using capacitive sensors. The approach is demonstrated in an application (cf. Fig. 1) that has been shown at the Hannover Messe 2015.

II. PROXIMITY DETECTION

To detect persons in the workspace of the robot and to avoid collisions, capacitive sensors are mounted at the robot structure (cf. Fig. 2). These sensors consist of copper foil as excitation and measurement electrodes in conjunction with an analog amplification and measurement circuit, and are used to measure the capacitance between the measurement

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Fig. 2. Capacitive sensors are mounted at the structure of a KR 6 AGILUS. The possible detection range is about 35 cm.

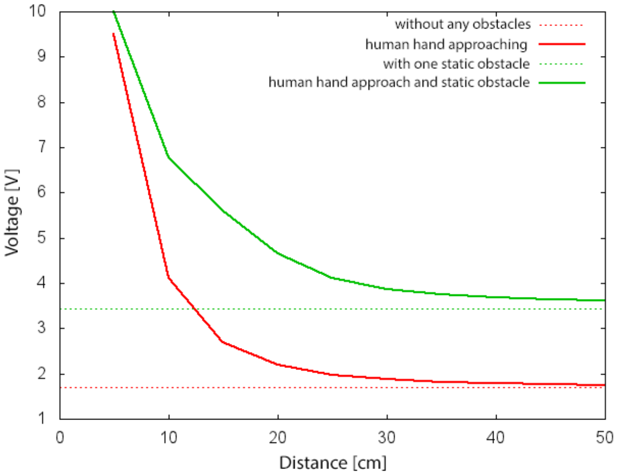

Fig. 3. Measured sensor signals for different scenarios approaching the capacitive sensor with a human hand. Static obstacles add a constant offset to the sensor signal.

electrode and the ground potential. The measured capacitance is expressed as a voltage between 0 V and 10 V.

When comparing the measured voltage to the distance of a human hand (cf. Fig. 3), two aspects become obvious: Keeping the environment constant (i. e. nothing except the hand moves, in particular the sensor keeps the same position), there is a non-linear relation between the measured voltage and the distance between the hand and the sensor. Adding a static obstacle (while keeping the rest of the environment constant) only increases the measured value by a constant voltage that does not depend on the distance of the human hand.

Thus, it is possible to define a distance function $d : \mathbb{R} \mapsto \mathbb{R}$ that maps the measured sensor value s (relative to the basis value for static obstacles, shown as a dotted line in Fig. 3) to a hand distance D.

$$d : s \rightarrow D$$

For a given sensor geometry, this distance function can be determined using measurements as the ones shown in Fig. 3.

Knowing the basis value for a given environment, this function can be used to estimate the distance of a non-static obstacle and thus to react to approaching obstacles. In the given setup (cf. Fig. 1), it is possible to reliably detect an obstacle in a distance up to about 35 cm.

III. ENVIRONMENT MODEL

As described in Sect. II, it is possible to compensate for static influences created by the setup of the robot cell, i. e. the peripherals, work-pieces and further obstacles inside the robot's workspace. As the robot – and with it the capacitive sensors – is moving, these influences are varying for every robot configuration. Hence, an environment model containing the basis values for the capacitive sensors with respect to the robot configurations can be created initially and used during run-time to improve the proximity estimation. This environment model must capture the relevant part of the robot's workspace, i. e. at least all trajectories carried out by the robot program must be contained.

The environment model is a function e which retrieves a sensor value $s \in \mathbb{R}$ for a given vector $\vec{q} \in \mathbb{R}^n$ of n joint angles. The configuration of the robot is specified using joint angles rather than a position in Cartesian space, since the grounded robot structure itself also influences the sensor measurements depending on the joint angles. The function is defined for one capacitive sensor as follows:

$$e : \vec{q} \rightarrow s$$

It can be implemented by sampling the workspace and applying a nearest-neighbor search. Therefore, the robot initially explores its static environment (i. e. without any persons present), records the sensor values for its capacitive sensors and creates the set M of points in a n-dimensional space $\mathbb{R}^n$ where every point represent a vector of n joint angles (where $n = 6$ for a standard industrial robot). For every point $\vec{p} \in M$, an expected sensor value $s \in \mathbb{R}$ is stored which corresponds to the value measured during sampling. To store and organize the data of the environment model, space-partitioning methods (e. g. a k-d tree [10]) can be used in order to increase performance. To evaluate the environment model, a nearest-neighbor search is performed to find the point in M closest to $\vec{q}$, and the corresponding sensor value is returned. For measuring the distance between two points, a metric on $\mathbb{R}^n$ must be defined (e. g. the Euclidean distance). To further increase performance, approximate nearest-neighbor search algorithms can be used, by not searching for the closest point exhaustively.

IV. COLLISION AVOIDANCE

For a reliable detection of a person in the robot's workspace, we compare the expected sensor values in real-time with the current sensor signals. This approach is illustrated in Fig. 4. In each control cycle, an approximate nearest-neighbor search is performed using the current joint angles $\vec{q}$. As a result, we receive the expected sensor value for the current robot configuration (i. e. $e(\vec{q})$), which can be used in the distance estimation. The estimated distance D is calculated as follows:

$$D = d(|s - e(\vec{q})|)$$

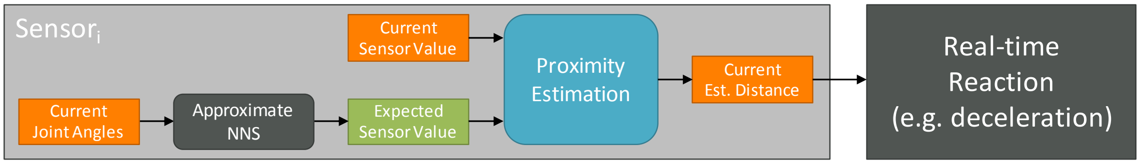

Fig. 4. In each cycle the nominal sensor value is retrieved using an approximate nearest neighbor search (NNS) and compared to the current sensor signal. Based on this comparison the current distance to an assumed person in the robot's workspace is estimated. Subsequently, an appropriate reaction of the robot is calculated (e.g. decelerating).

This way, acceptable distance estimations are possible even in environments with a large amount of influences and disturbances.

We implemented the environment model and the distance estimation using the *SoftRobot* architecture [11]. This architecture consists of the Robot Control Core (RCC) [12], which can execute robot commands with hard real-time guarantees, as well as the Robotics API [13], an application programming interface (API) in Java for programming industrial robots. For the approximate nearest-neighbor search the *Fast Library for Approximate Nearest Neighbors* (FLANN, cf. [14], [15]) was used and integrated into the RCC. The approximate nearest-neighbor search is performed once every cycle (up to 500 Hz) and the expected values for every capacitive sensor are retrieved. Subsequently, for every sensor the distance to an unknown obstacle (usually a human hand or arm) is estimated. These estimated distances are used in every cycle to calculate an appropriate reaction of the robot, e. g. to decelerate depending on the distance to avoid a collision. Further reactions are an emergency stop, or acoustic and optical warnings.

The presented approach was successfully evaluated using a UR 5 from Universal Robot as well as a KR 6 AGILUS from KUKA. For the latter robot, a demonstration cell was realized to exhibit at the Hannover Messe 2015 (cf. Fig. 1). The task is to inspect car engines with a camera mounted at the robot's flange. The static obstacles influencing the capacitive sensors are the four car engines, the flat panel displays and the robot structure itself. In total, there are four capacitive sensors mounted at the robot. Three sensors are mounted at the arm sensing to the right, to the left and to the bottom. The fourth capacitive sensor is mounted around the camera at the flange. The video attachment[1] shows a series of experiments using this setting.

V. CONCLUSION

This papers presents a novel approach to overcome the drawbacks of capacitive sensors for reliably detecting unknown obstacles in a structured (industrial) environment. By using a previously recorded environment model, the current sensor signal is compared to the expected value and the distance to an unknown obstacle (e. g. a human hand or arm) is estimated. The environment model is realized using an approximate nearest neighbor search on data set with a priori sampled sensor signals inside the robot's workspace. A next step is to increase the number of capacitive sensors to improve the performance and the resolution of the obstacle detection. Moreover, a more efficient way to sample the environment model is also part of our future work.

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REFERENCES

[1] A. Albu-Schäffer, C. Ott, and G. Hirzinger, "A unified passivity-based control framework for position, torque and impedance control of flexible joint robots," *Int. j. Rob. Research*, vol. 26, no. 1, pp. 23–39, 2007.

[2] A. De Luca, A. Albu-Schaffer, S. Haddadin, and G. Hirzinger, "Collision detection and safe reaction with the DLR-III lightweight manipulator arm," in *Proc. 2006 IEEE/RSJ Intl. Conf. on Intell. Robots and Systems, Beijing, China*. IEEE, 2006, pp. 1623–1630.

[3] P. Mittendorfer and G. Cheng, "Humanoid multimodal tactile-sensing modules," *IEEE Trans. on Robotics*, vol. 27, no. 3, pp. 401–410, 2011.

[4] E. Cheung and V. Lumelsky, "A sensitive skin system for motion control of robot arm manipulators," *Robotics and Autonomous Systems*, vol. 10, no. 1, pp. 9–32, 1992.

[5] B. Ostermann, M. Huelke, and A. Kahl, "Freed from fences: safeguarding industrial robots with ultrasound," *Safety Science Monitor*, vol. 17, no. 1, 2013.

[6] T. Gecks and D. Henrich, "Human-robot cooperation: Safe pick-and-place operations," *14th IEEE Intl. Works. on Robot and Human Interactive Comm., Nashville, USA*, 2005.

[7] J. Novak and J. Feddema, "A capacitance-based proximity sensor for whole arm obstacle avoidance," in *Proc. 1992 IEEE Intl. Conf. on Robot. & Autom., Nice, France*. IEEE, May 1992, pp. 1307–1314.

[8] P. Heiligensetzer, "Sichere Mensch-Roboter-Kooperation durch Fusion haptischer und kapazitiver Sensorik," Diss., Univ. Karlsruhe, 2003.

[9] T. Schlegl, T. Kröger, A. Gaschler, O. Khatib, and H. Zangl, "Virtual whiskers – highly responsive robot collision avoidance." in *Proc. 2013 IEEE/RSJ Intl. Conf. on Intell. Robots and Systems, Tokyo, Japan*. IEEE, 2013, pp. 5373–5379.

[10] J. L. Bentley, "Multidimensional binary search trees used for associative searching," *Commun. ACM*, vol. 18, no. 9, pp. 509–517, 1975.

[11] A. Hoffmann, A. Angerer, F. Ortmeier, M. Vistein, and W. Reif, "Hiding real-time: A new approach for the software development of industrial robots," in *Proc. 2009 IEEE/RSJ Intl. Conf. on Intell. Robots and Systems, St. Louis, MO, USA*. IEEE, 2009.

[12] M. Vistein, A. Angerer, A. Hoffmann, A. Schierl, and W. Reif, "Flexible and continuous execution of real-time critical robotic tasks," *Intl. J. Mechatronics & Autom.*, vol. 4, no. 1, 2014.

[13] A. Angerer, A. Hoffmann, A. Schierl, M. Vistein, and W. Reif, "Robotics API: Object-oriented software development for industrial robots," *J. of Softw. Eng. for Robotics*, vol. 4, no. 1, pp. 1–22, 2013.

[14] M. Muja and D. G. Lowe, "Fast approximate nearest neighbors with automatic algorithm configuration," in *Intl. Conf. Computer Vision Theory and Application*. INSTICC Press, 2009, pp. 331–340.

[15] ——. FLANN: Fast library for approximate nearest neighbors. [Online]. Available: http://www.cs.ubc.ca/research/flann

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[1] The video attachment is available in high definition at: `http://video.isse.de/safeassistance/hmi2015`