Ultrasound Based Object Detection for Human-Robot Collaboration

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Abstract. For safe human-robot collaboration within a defined working area, a technologically diverse and redundant sensor system is developed, which comprises ultrasound sensors and two monocular cameras. The ultrasound sensor system, as well as the developed algorithms for the sensor system are proposed, which allow a distinction between objects. Detected objects within the working area are classified in static and dynamic objects. The sensor system is able to distinguish between these object types. Due to the safe detection of dynamic objects the robot system is enabled to react with an adaption of its trajectories to avoid undesired collisions. To ensure, that the manipulator only reacts on dynamic objects, distances caused by static objects are eliminated.

Keywords: Ultrasound sensor, human-robot collaboration, object detection.

1 Introduction

1.1 Project Framework

The research project "ManuCyte" [1] focuses on the realization of an industrial scale cultivation platform for human cells and tissues. To achieve this, a Hybrid Workplace (HW) is developed, which enables a human operator to work in collaboration with the CARo5X (**C**leanromm **A**pplication **Ro**bot **5** **Ax**es). The developed facility is pictured in Fig. 1. The parts of the facility are described in detail in [1,2].

This paper lays focus on the object recognition due to ultrasound sensors which are mounted on the moving manipulator and are operated in a working area, which is defined by the dimensions of the HW. Also, algorithms are proposed which are able to distinguish, if a detected object is either static or dynamic. Based on this decision, the currently executed trajectory is interrupted to avoid physical contact with the dynamic object. If the detected object is static, the distances caused by these objects have to be suppressed, so that the manipulator is enabled to continue its path within the HW.

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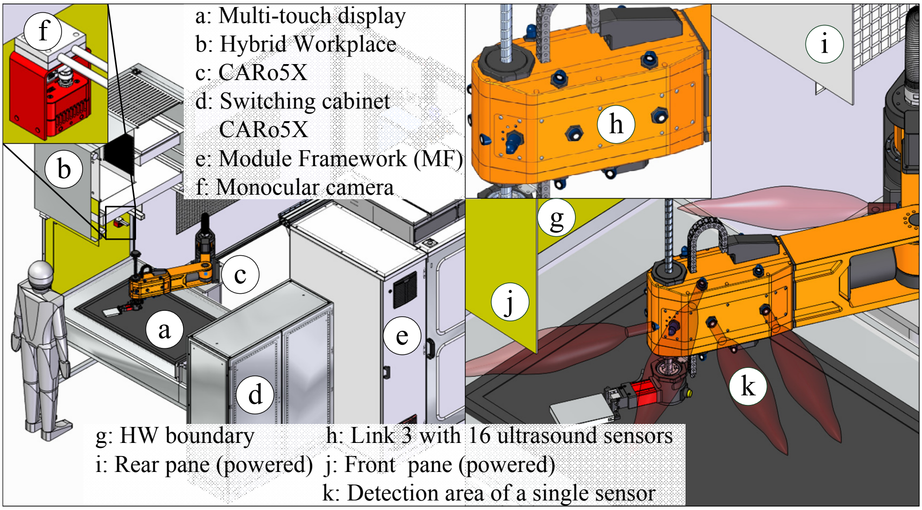

Fig. 1. Projekt "ManuCyte" - cell cultivation plant and sensor setup

1.2 Related Work

The realization of a safe man-machine collaboration using ultrasound sensors is uncommon. For example, the KR 3 SI and KR 5 SI robot, developed by KUKA [3], are operating with capacitive distance measuring sensors. Concerning the field of mobile robots, ultrasound sensors are often used for map generation of unknown environments [4]. Here the focus lies on optimizing the map generation process by eliminating measuring faults, such as specular reflections of ultrasonic waves on obstacles [5,6,7]. However, the frame conditions of the described system, concerning the Hybrid Workplace in conjunction with a collaborative manipulator and a human operator, require a different approach to deal with customary measuring faults like specular reflections or crosstalk-effects. The presented novel approach, concerning the establishment of a safe man-machine collaboration, is to enhance the detection of a human operator, due to the elimination of static objects from the ultrasound sensor signals, by including a-priori information about the manipulators environment in the obstacle detection algorithm.

1.3 Paper Organization

Section 2 outlines the general complex of problems. Section 3 discusses the hardware components and introduces the developed object recognition algorithms, which are discussed in detail in 4. Experimental results are shown and analyzed in Sect. 5. Finally, Sect. 6 concludes the article and gives an outlook on future work.

2 Complex of Problems

The problem to be solved is the safe detection of a human operator by the ultrasound sensor system. The frame conditions are the environmental influences of the HW and a moving manipulator inside the working area (see Fig. 2). Object

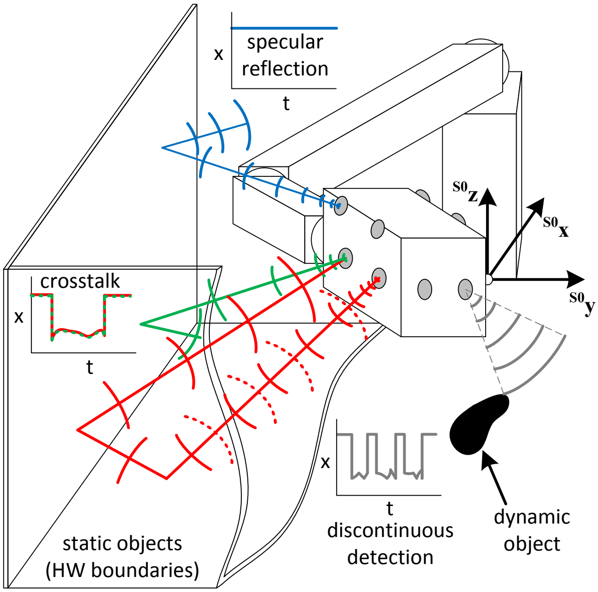

Fig. 2. Object detection and possible measurement errors within confined working area

recognition or rather distance determination via ultrasound sensors is difficult when the sensors are operating in a working area which is confined by reflective boundaries. These boundaries can cause the following measurement errors:

- Specular reflections: Here, ultrasonic waves are reflected from objects in a way that the sensors receive no echo (blue signal in Fig. 2).
- Crosstalk-effects: Due to specular reflections, sensors receive the ultrasonic waves from adjacent sensors as an echo (red and green signals in Fig. 2).
- Limited detection area: The continuous detection of a human operator is limited by the detection area of each sensor (grey signal in Fig. 2).

The aim is to generate an algorithm, which eliminates measurement errors and is also able to distinguish between the HW boundaries (static objects) and a human operator (dynamic object).

3 System Design

3.1 Hardware

Figure 1 shows the manipulator with the ultrasound sensor setup consisting of 18 ultrasound sensors. One can see that most sensors are located on the third axis, the so called robot hand. The robot hand is the part of the manipulator, which most likely has the smallest distance to a human worker. Therefore, the area surrounding this axis, has to be particularly observed by the ultrasound sensor system. By having the ultrasound sensors mounted directly on the manipulator and not stationary in the HW, the robot becomes independent of the remaining facility and is able to react on nearby objects at any time.

The cuboid shaped hybrid working area is limited by flat plates consisting of stainless steel or glas. The form and orientation as well as the surface properties of these boundaries, affect the performance of the ultrasound sensor system, because ultrasonic waves are reflected directional. As pictured in Fig. 2, the reflection of ultrasonic waves is the main reason for two of the three mentioned measurement errors.

For the recognition of objects, ultrasound sensors of type *pico+35/U* and *pico+35/WK/U* from the company *Microsonic* are used. The time between two distance measurements is 16 ms. The sensors indicate the presence of an object with a distance of 65 mm or below (blind zone) by outputting a 0 V signal value. A signal of 10 V indicates that there is no detectable object present in the detection range of 350 mm. All sensors are working in *Synchronous Mode*, which means that ultrasonic waves of all sensors are emitted simultaneously. Except for the temperature compensation, all integrated filters are deactivated.

3.2 Software

The developed data processing algorithm (see Fig. 3) is running on the Control PC in real-time. It was developed using MATLAB/SIMULINK in combination with the toolboxes Simulink Coder and xPC.

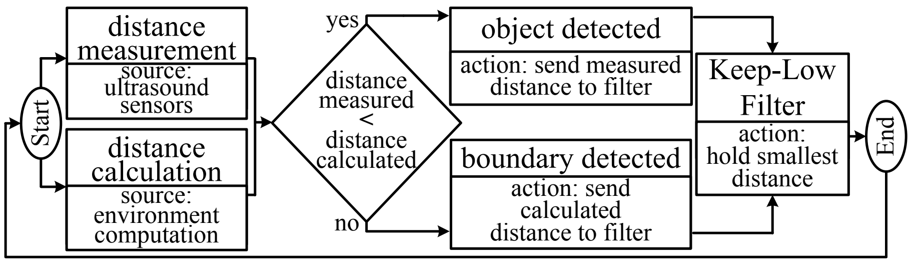

Fig. 3. Flow chart of distance processing algorithm

The pictured algorithm actually consists of two separate algorithms. At first, a distinction between static and dynamic objects takes place. Besides this, measurement errors due to specular reflections and crosstalk-effects are eliminated. The second algorithm is a directional selective filter which receives the processed signals from object elimination (OE) algorithm as an input. The output signal of the filter then is used for the adaption of the manipulators trajectory if a collision with a human operator is imminent.

4 Object Recognition Algorithms

4.1 Distance Calculation

Compared with mobile robots, the cultivation plant setup has the advantage that the manipulator as well as the HW is immobile. By knowing the kinematics of the manipulator in combination with the information from the optical encoders of each joint, the distances of each ultrasound sensor to the boundaries of the HW can be calculated. Figure 4 pictures the relevant coordinate systems (S) for the

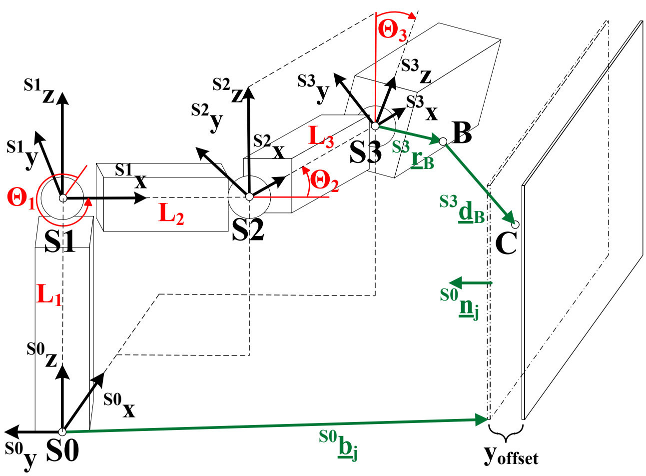

Fig. 4. Coordinate systems involved the distance calculation

distance calculation. With $i = [1, ..., 18]$, the positions ${}^{S3}\boldsymbol{r}_i$ and the orientations ${}^{S3}\boldsymbol{d}_i$ of each sensor i, are gathered from the CAD model of the robot. ${}^{S3}\boldsymbol{r}_{\mathrm{i}}$ and ${}^{S3}\boldsymbol{d}_i$ are constant if referenced on the S3 System. With the rotationmatrix

$$ {}^{\mathrm{S0}}\mathbf{R}_{\mathrm{S3}} = {}^{\mathrm{S0}}\mathbf{R}_{\mathrm{S3}}\left(\Theta_1, \Theta_2, \Theta_3\right) \tag{1} $$

and the translational transformation

$$ {}^{\mathrm{S0}}\mathbf{T}_{\mathrm{S3}} = {}^{\mathrm{S0}}\mathbf{T}_{\mathrm{S3}}\left(L_1, L_2, L_3, \Theta_1, \Theta_2\right) \tag{2} $$

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$$ {}^{\mathrm{S0}}\mathbf{A}_{\mathrm{S3}} = \left[\begin{array}{ccc|c} \multicolumn{3}{c|}{{}^{\mathrm{S0}}\mathbf{R}_{\mathrm{S3}}} & {}^{\mathrm{S0}}\mathbf{T}_{\mathrm{S3}} \\ \hline 0 & 0 & 0 & 1 \end{array}\right] \tag{3} $$

describes the sensor positions ${}^{S3}\boldsymbol{r}_i$ in the S0-System by

$$ {}^{\mathrm{S0}}\boldsymbol{r}_i = {}^{\mathrm{S0}}\mathbf{A}_{\mathrm{S3}} \cdot {}^{\mathrm{S3}}\boldsymbol{r}_i \ . \tag{4} $$

The sensor orientations ${}^{\mathrm{S3}}\boldsymbol{d}_i$ are described in the S0-System by

$$ {}^{\mathrm{S0}}\boldsymbol{d}_i = {}^{\mathrm{S0}}\mathbf{R}_{\mathrm{S3}} \cdot {}^{\mathrm{S3}}\boldsymbol{d}_i \ . \tag{5} $$

Now, with the positions

$$ {}^{\mathrm{S0}}\boldsymbol{b}_j = (x_j \ y_j \ z_j)^T \tag{6} $$

and orientations, defined by the normal vector ${}^{\mathrm{S0}}\boldsymbol{n}_j$ of each boundary j, the vector ${}^{\mathrm{S0}}\boldsymbol{r}_{\mathrm{BC}}$ from every sensor i, to any boundary j, can be calculated with

$$ {}^{\mathrm{S0}}\boldsymbol{r}_{\mathrm{C}} = {}^{\mathrm{S0}}\boldsymbol{r}_{\mathrm{B}} + \frac{{}^{\mathrm{S0}}\boldsymbol{n}_j \bullet \left({}^{\mathrm{S0}}\boldsymbol{b}_j - {}^{\mathrm{S0}}\boldsymbol{r}_{\mathrm{B}}\right)}{{}^{\mathrm{S0}}\boldsymbol{n}_j \bullet {}^{\mathrm{S0}}\boldsymbol{d}_i} \cdot {}^{\mathrm{S0}}\boldsymbol{d}_i \tag{7} $$

and

$$ {}^{\mathrm{S0}}\boldsymbol{r}_{\mathrm{BC}} = {}^{\mathrm{S0}}\boldsymbol{r}_{\mathrm{C}} - {}^{\mathrm{S0}}\boldsymbol{r}_{\mathrm{B}} \ . \tag{8} $$

Finally, the desired calculated distance x_{calc} results with

$$ x_{\mathrm{calc}} = |{}^{\mathrm{S0}}\boldsymbol{r}_{\mathrm{BC}}| = \sqrt{{}^{\mathrm{S0}}x_{\mathrm{BC}}^2 + {}^{\mathrm{S0}}y_{\mathrm{BC}}^2 + {}^{\mathrm{S0}}z_{\mathrm{BC}}^2} \ . \tag{9} $$

The calculation of these distances allows the elimination of the HW boundaries from the distance measuring process, by replacing the distances in which the calculated distance is smaller than the actual measured distance, with a value of 350 mm (maximum detection range). With this approach, no avoiding action of the manipulator takes place, because the measured distance, caused by the HW boundary, is suppressed. In addition, specular reflections on the HW boundaries need no further consideration.

However, crosstalk-effects between adjacent sensors are still an issue which have to be considered. In order to eliminate crosstalk-effects, the algorithm is modified as following. By postponing the computed boundary, pictured in Fig. 4, away from the real boundary (${}^{\mathrm{S0}}y_{\mathrm{offset}} = 60\,\mathrm{mm}$) and closer to the robot base (S0-System), also the influence of crosstalk-effects can be eliminated. The reason for this is, that whenever a sensor A receives the reflected ultrasonic waves from a adjacent sensor B, a distance, which is close to the real distance from a working area boundary, is indicated by sensor A. Depending on the orientation of the manipulator, this false distance can be bigger or smaller than the calculated distance to the computed boundary. Hence, by postponing the computed or rather simulated boundary from the real boundary, even the incorrect measured distances caused by crosstalk-effects are eliminated, because they are still bigger than the calculated ones.

4.2 Distance Filtering

The developed filter aims to improve the measured distance data concerning the signal quality, in order to use the processed data for plausibilization with the camera system and obstacle avoiding actions of the manipulator. The detection area of a single sensor is limited. So it is possible, that objects, which are located at the edge of a detection area, are detected by the sensor in one time step and no more detected in the following time step. Another possibility is, that an object is within the detection area of a sensor, but, depending on its geometry, orientation and surface properties, not continuously detected by the sensor. The result of both cases is that the robot control receives a discontinuous signal from the sensor. Hence, a filter is designed to improve the signal quality. The behaviour of the filter is dependent on the following condition. Approaching obstacles must be detected as fast as possible, in order to enable the manipulator, to react quickly with an trajectory adaption action. Therefore, e. g. a PT1 filtering behaviour is disadvantageous, because, depending on the time constant, the obstacle avoiding algorithm of the manipulator would receive non actual distances.

To sum up, sensor signals with a decreasing obstacle to robot distance must not be filtered or modified by the filter. Signals, indicating a increasing distance to the robot must be filtered. Especially if the detected obstacle speed is physically implausible.

The algorithm of the resulting *Keep-Low-Filter* is pictured in Fig. 5. To fulfill the mentioned requirement, the filter has been designed directional selective. If an object is approaching on a sensor, the measured distances are not modified ($x_{i\_\mathrm{out}} = x_i$). On the other hand, if an object decreases its distance to a sensor, the smallest distance value ($x_{i\_\mathrm{out}} = x_{i-1}$) is hold for a certain amount of time steps (t_{hold}), if the change of the measured distance $|(x_i - x_{i-1})|$ between two time steps is bigger than the maximum velocity ($v_{\max} = 0.002\,\frac{\mathrm{m}}{\mathrm{ms}}$) of a human limb [8].

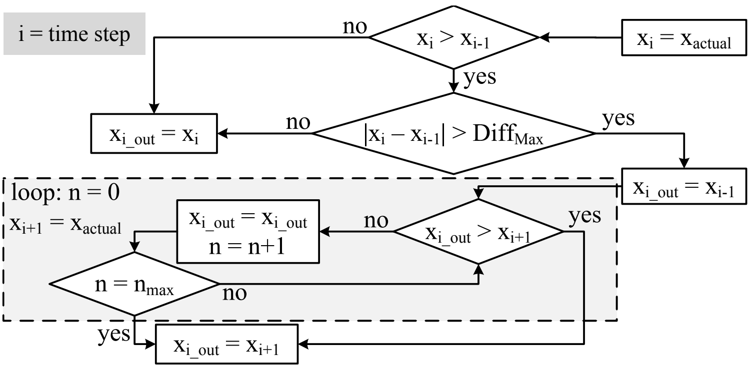

Fig. 5. Keep-Low-Filter algorithm

5 Experimental Results

In the following, the effective detection of a human operator in a confined space, by eliminating the measured distances from static objects, as well as the filtering of desired distances from dynamic objects, is validated by three experiments.

5.1 Object Elimination - Algorithm Validation

To validate the OE algorithm, the manipulator performed an approaching sequence to a single boundary. No objects except for the HW boundary were involved in the test. Hence, at the beginning of the movement, the two relevant sensors (Sensor A & B) in Fig. 6 indicate a distance of $x = 0.35\,\mathrm{m}$, which corresponds the maximum detection range. During the approach towards the boundary, the measured distances (solid lines), the calculated distances (dotted lines) as well as the resulting distances after the object elimination (dashed curves), have been recorded. In Fig. 6 one can see, that the OE algorithm eliminates distances which are caused by the presence of the HW boundary. Otherwise, the signals processed by the OE algorithm would indicate distances below the maximum detection range.

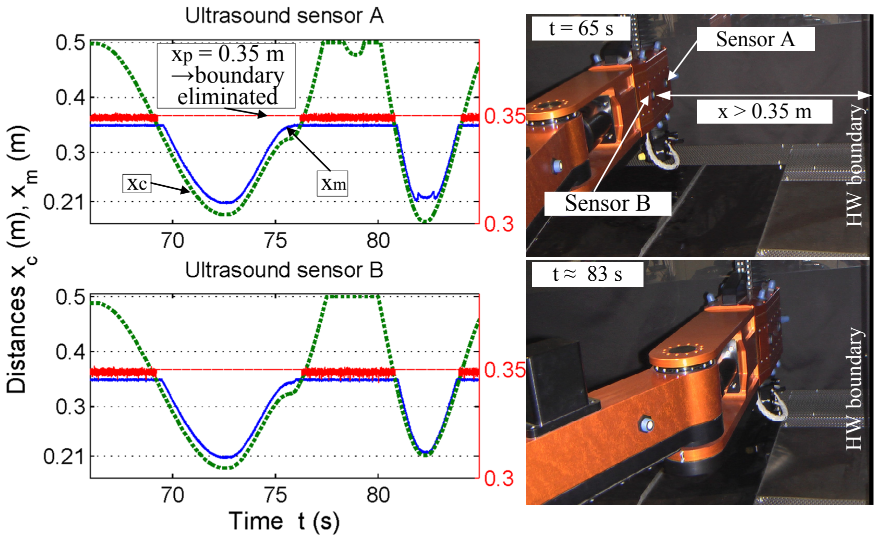

Fig. 6. Experimental validation of the OE algorithm

Also measurement errors are eliminated by the OE algorithm. In the top graph of Fig. 6, crosstalk-effects between both sensors can be seen in the time range between 80 s and 85 s. Due to specular reflections, ultrasound sensor A is not receiving an echo from its ultrasonic waves, but rather receives the ultrasonic waves from Sensor B, which were reflected from the boundary. The result is, that the signal value of sensor A is equal with the signal value from sensor B, as long as the ultrasonic waves from A do not return to sensor A.

5.2 Object Detection and Signal Filtering Validation

The next step, is to improve the detection of dynamic objects. The aim is to reduce a jumping of the distance signal. To validate the filtering algorithm, a cylindrical shaped glass pipette, which is pictured in Fig. 8 C, was moved into the detection area of a ultrasound sensor. Both signals, filtered and not filtered, have been logged and compared. Concerning the geometry as well as the directly reflecting surface, the described evaluation is a worst case scenario for the ultrasound sensor system. Hence, it is concluded, that if the quality of the sensor signal can be sufficiently improved during the detection of the pipette, also the signals caused by every other object with bigger dimensions and better surface properties (e. g. a human hand) can be sufficiently improved. In Fig. 7 one can see, that the not filtered signal (thin curve) is unsteady and alternates between small and big distances. Due to specular reflections of the ultrasonic waves on the surface of the glas pipette the sensor receives no echo. Therefore, the signal jumps back to a distance of $x = 0.3\,\mathrm{m}$, which in this experiment is the maximum detection range of the ultrasound sensor.

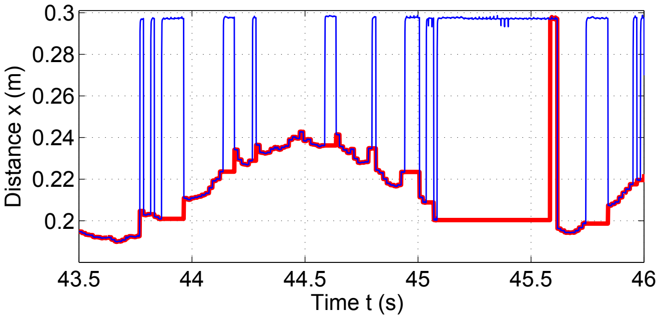

Fig. 7. Signal improvement due to the Keep-Low-Filter algorithm

The broad curve represents the resultant signal after the measured signal was processed by the filter. Whenever the sensor receives an ultrasonic echo from an obstacle in one sample, and no echo in the following sample, the filter holds the last distance value, until a distance, which is smaller than the actually hold value, is detected by the sensor, or the parameterised time ($t_{\mathrm{hold}} = 500\,\mathrm{ms}$), elapses. In this case, the originally held distance value is discarded and the filter outputs the actual measured distance.

This behaviour can be seen in Fig. 7 from $t_1 \approx 45.1\,\mathrm{s}$ to $t_2 \approx 45.6\,\mathrm{s}$. This approach is necessary to allow the robot to continue the movement, when a detected object is removed from the detection areas of the ultrasound sensors.

5.3 Object Elimination - Application Validation

To proof the functionality of the developed algorithms, a third experiment inside the final working area was conducted, in which the manipulator decreased the distance to the HW boundaries and also approached a human operator during a single moving sequence. Figure 8 shows trajectory of the end-effector in the S0-System. In this experiment, a interruption of the manipulators trajectory is

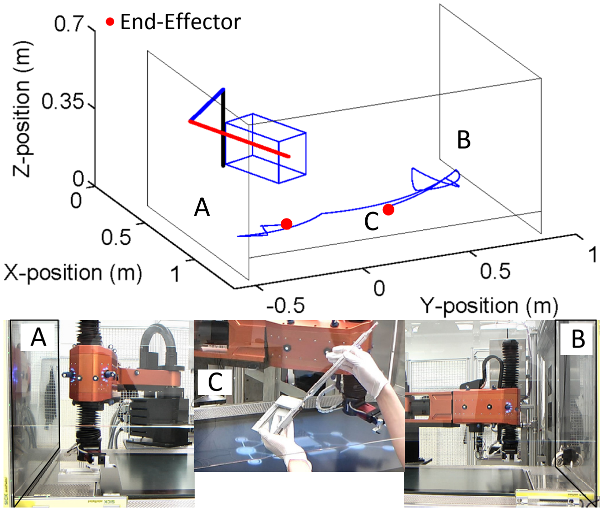

Fig. 8. Experimental validation of the OE algorithm within the facility

triggered (*TriggerStopSequence* in Fig. 10), if any ultrasound sensor is indicating a distance smaller than 0.30 m. The criteria for a successful validation of the algorithms are, that

- the manipulator is able to continue the movement, without any interruptions of the sequence caused by the presence of static objects (front pane and boundaries A & B in Fig. 8).
- a interruption of the trajectory is initiated as soon as the human operator is detected (see picture C in Fig. 8).

Figure 9 shows the calculated distances x_{c} (dotted lines), the measured distances x_{m} (solid lines) as well as the distances processed by the OE algorithm and the Filter x_{p}, during the approach of boundary A (time range 85 s to 120 s) and boundary B (time range 130 s to 150 s).

Both boundaries are successfully eliminated by the algorithm, because the calculated distances are smaller than the acutal measured distances at any time. Therefore, the processed distance, on which a trajectory adaption would be triggered, never falls below the maximum detection range of the ultrasound sensors. To analyse the detection of dynamic objects and the adaption of the sequence based on ultrasound sensor data, a human operator entered the HW during the experiment. The left plot in Fig. 10 pictures the end-effector position in the robot base coordinate system (S0) during the sequence. One can see, that the trajectory is interrupted at second 154 s, because the processed distance x_{p} of one ultrasound sensor (see the right plot in Fig. 10) decreased below the distance of 0.30 m (due to the presence of the human operator) and therefore triggered the interruption of the sequence.

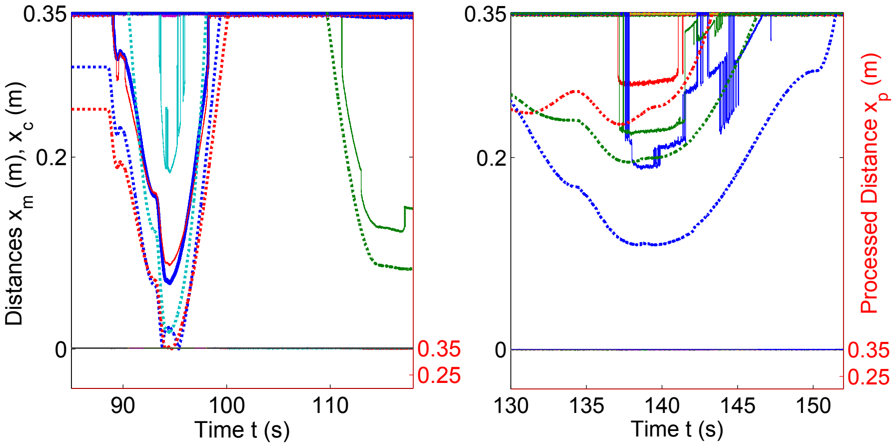

Fig. 9. Distance signals during the approach of boundary A (left plot) and boundary B (right plot)

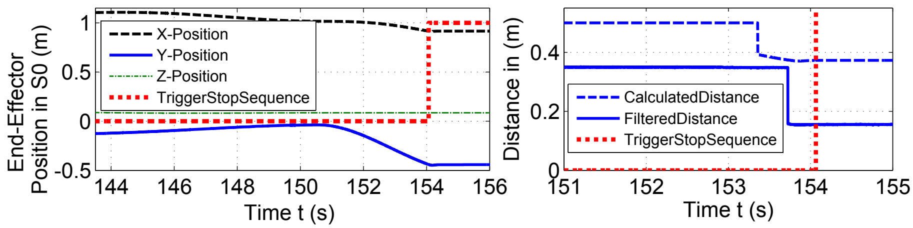

Fig. 10. Trajectory adaption due to detection of human operator

6 Conclusions and Outlook

Algorithms to support the detection of human extremities by an ultrasound sensor system have been developed. One algorithm suppresses measured distances of the ultrasound sensor system, if a static object is detected. Thus, the manipulator is enabled to react with an adaption of its trajectories, based on distances, caused by a human operator. A second algorithm improves the signal quality of the ultrasound sensor system, in order to avoid an undesired alternation between a interruption and a resumption of the manipulators trajectory. The concept of the elimination of undesired measured distances due to static objects was proved under experimental conditions and also under the frame conditions of the finalized facility. Until now, the OE algorithm is only able to distinguish the boundaries of the working area from other detected objects. A possible improvement of the OE algorithm is, that the cameras evaluate the positions and dimensions of the used tools inside the Hybrid Workplace and the gathered information is used to create computed areas, in which measured distances, caused by the tools inside the HW, are suppressed. The resulting adaptable OE algorithm could suppress the detection of any non-human object inside the HW. A further enhancement of the algorithm is the fusion of the ultrasound sensor data with the camera data, in order to establish a plausibilization between the sensor systems and therefore increase the safety during the collaboration.

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References

1. ManuCyte: Modular Manufacturing Platform for Flexible, Patient-Specific Cell Cultivation. Fraunhofer Institute for Manufacturing Engineering and Automation (IPA). Nobelstr. 12, D-70569 Stuttgart, http://www.manucyte-project.eu/
2. Höcherl, J.: Recognition of Human Extremities in Monocular Camera Images for Human-Robot Collaboration. In: Applied Research Conference, pp. 236–244 (2012)
3. Heiligensetzer, P.: Aktuelle Entwicklungen bei Industrierobotern im Bereich der Mensch-Roboter Kooperation. Tag der Arbeitssicherheit in Fellbach (2009)
4. Leonard, J.J., Durrrant-Whyte, H.F.: Directed Sonar Sensing for Mobile Robot Navigation. Springer, Germany (1992)
5. Moravec, H.P., Elfes, A.: High Resolution Maps from Wide Angle Sonar. In: Proceedings of IEEE Conference on Robotics and Automation, pp. 116–121 (1985)
6. Yi, Z., Khing, H.Y., Seng, C.C., Wei, Z.X.: Multi-ultrasonic sensor fusion for mobile robots. In: Proceedings of the IEEE Intelligent Vehicles Symposium, pp. 387–391 (2000)
7. Xianzhang, Z., Junfang, Z., Yibo, G., Rui, G., Yiping, Y.: Multi-ultrasonic sensor fusion based on dezert-smarandache theory. In: International Technology and Innovation Conference, pp. 1858–1862 (2007)
8. Thiemermann, S.: Direkte Mensch-Roboter-Kooperation in der Kleinteilmontage mit einem SCARA-Roboter. Ph.D. dissertation, Faculty Mechanical Engineering. University Stuttgart (2005)