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FREED FROM FENCES: SAFEGUARDING INDUSTRIAL ROBOTS WITH ULTRASOUND

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ABSTRACT

Industrial robots work behind rigid safety devices in order to lower the risk that persons come in contact with the robot and thus to harm. The IFA, an institute for research and testing of the German Social Accident Insurance in Germany, is working on the state of science in “collaborating robots”, to grant humans safe access to robots.

In the course of the project “EsIMiP”, promoted by the Bavarian Research Foundation, a concept was developed at the IFA, allowing the robot’s arms to be safeguarded by ultrasonic sensors. This enables a flexible collaboration between human and robot.

Keywords: industrial robot, ultrasonic sensors, collaborating robot, EsIMiP, IFA, DGUV

INTRODUCTION

The first industrial robot was invented in 1954 by George C. Devol Jr. and was put into service for the first time in 1961 at General Motors [1]. The first fatal accident occurred in 1979 [2]. End of 2011 already more than 1.1 million robots were in use, thereof approximately 370,000 in Europe and about 157,000 in Germany [3].

Because of requirements, not only within the European market, on the safety of machines, most of these robots carry out their service behind rigid fences. With the approval of laser scanners for safety applications in 1998 [4] and the camera system "SafetyEye" in 2006 [5] some of the rigid fences could be replaced by electro-sensitive protective equipment. But these invisible fences also separate operator and robot along a given rigid border.

A flexible and safe collaboration between operator and robot in the same working area is not possible with today's safety systems. For this purpose, a new system is needed that restricts the workspace of the operator as little as possible. This system should react flexibly on the whereabouts of the operator, optimising safety and the process performance.

In addition to the motivation of the high safety, economic aspects play a major role. A robot, which needs no fence and which can safely be approached promises opportunities for new jobs and the implementation of space-saving concepts in the context of workplace design.

1. COLLABORATIVE ROBOTS

The goal of the research field "Collaborating robots" is, to make the industrial robot safe enough, so that it can work with people in a small area without being rigidly separated.

People can adapt "with rhyme and reason" to changes. An ordinary industrial robot can not perceive its surroundings, however, and has no way to adjust to changes in working conditions. Stoic, it follows its program.

The safety system to be developed by the IFA shall intervene in the robot control and prevent collisions. This is to be achieved by reducing the speed of the robot at approach, up to a halt of the robot.

The tasks arising from this and the objective of this study is to equip a robot with appropriate sensors and at the same time include algorithms in its control, which allow it to adapt its work to the collected values. This is to be done in such a way that requirements from European law and standards can be met by the system.

A suitable sensor must

- supply data quickly and cyclically and
- collect relevant data.

The algorithm must

- process data quickly and cyclically, as well as
- make do with the data supplied.

Both research fields must be coordinated. If the sensor returns unnecessary data, these have to be painstakingly filtered in the algorithms. If the sensors deliver too few data, the algorithms can find no optimal solution. On the other hand, the algorithms may expect any data that can not be measured by the sensors. Algorithms that are tested only on complete records from virtual computer models fail in practice because of the buggy, incomplete data, delivered by real sensors.

2. TASKS OF INDUSTRIAL ROBOT

An important factor for the design of a collaborative robot is its task. The choice of sensors and algorithms is dependent on the following factors:

- the type of industrial robot
  - its power
  - its range
  - its degrees of freedom (number of axes),
- the desired operating speed of the robot
- the task of the robot, such as transport of small, large, complex parts, or other tasks such as welding and painting.

The robot’s task is set in the project EsIMiP. In this project, promoted by the Bavarian Research Foundation (AZ-852-08), the Technical University of Munich, the University of Kassel, the IFA and the industrial partners of Reis Robotics and Baumüller approach the goal, to combine experimental approaches from research with verifiable safety technology.

The robot RV20-16 and RV30-16 from the company Reis were elected as work equipment. The range of these robots is approximately 2m. "Transport and presentation of small parts" was chosen as the task of the robot.

3. SAFEGUARDING OF THE ROBOT (WITH SENSORS)

Suitable sensors are required for the collision detection of robots and humans. The choice of these sensors depends on various factors. The sensors need to

- ensure a complete monitoring of the robotic environment
- work regardless of the equipment of the operator

- provide a safe signal
- provide a fast signal
- be safe from interference.

3.1 Placing of the sensors

For the complete monitoring of the robot's environment in order to achieve safe collision avoidance, three different approaches are possible:

- monitoring by means of sensors which penetrate objects
- monitoring the working area with not penetrating sensors "from the outside"
- monitoring of the environment of the robot with sensors mounted on the robot itself "from the inside".

3.1.1 Monitoring by means of penetrating sensors

Continuous monitoring can be achieved if sensors are used, which respond only to specific tags and penetrate remaining materials. An example is the use of RFID tags, which are worn by the human operator on his body. This technique has already been tested in the IFA for various application areas [6]. However, only those places on the human operator can be found, which are fitted with RFID tags. This leads to the requirement that either the operators are equipped with few tags and need to keep a sufficiently safe distance to the robot, or all parts of the body of the operator, which are at risk, are fully equipped with RFID tags.

This approach has the disadvantage that only those people are protected, who wear the protective equipment. It must therefore be assured by organisational measures that only persons wearing protective equipment are present in the vicinity of the robot. All other persons are not protected.

In safety technology, at first technical measures must be exhausted before organisational measures are appropriate. Organisational measures are subordinated to technical measures.

3.1.2 Monitoring the working area with not penetrating sensors "from outside"

A complete monitoring of the workspace from the outside by sensors installed in the vicinity is difficult to realize. Sensors, whose coverage is blocked by the detected obstacle, have "blind zones" in the space beyond the object's surface for which no data is available. As shown in Figure 1, these zones can be reduced in their size by using many sensors from different directions. Also, fixed obstacles can be taken into account while placing the sensors. Flexible obstacles, such as the human operator, or the dynamically evading robot itself are however difficult to take into account in the planning process. However, in the interaction of man and machine, blind zones are disturbing to the path planning of a dynamic robot.

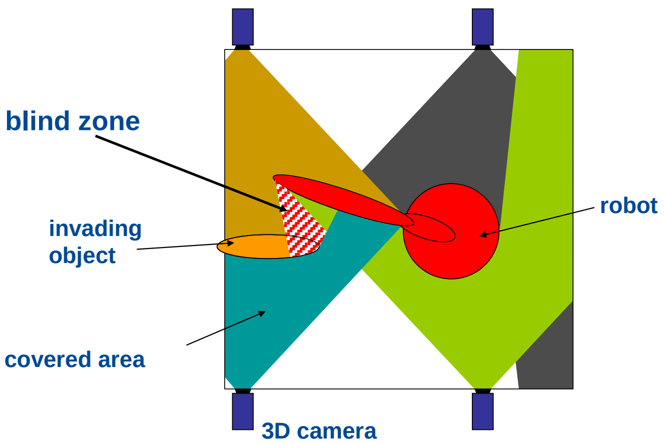

Figure 1: Workspace, monitored from without by cameras

3.1.3 *Monitoring of the environment of the robot with sensors "from the inside"*

Another approach is the installation of the sensors on the robot itself, to monitor the working space "from the inside". As Figure 2 shows, blind zones within the covered area occur when the sensor detects obstacles.

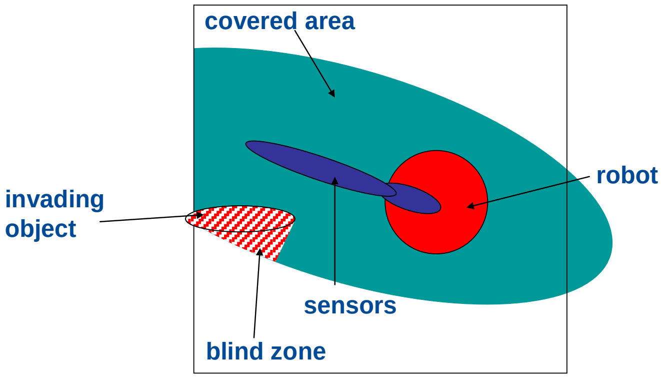

Figure 2: Workspace monitored from within

Safety in the workspace of the robot is not affected by these blind zones, as only the free area around the robot is vital to this task. The information on the entire free space that is required for the optimal planning of a robot's path can thus not be covered. Therefore, monitoring of the space around the robot is suitable only for that part of the control, which is monitoring the safe approach of robot and operator. The sensors must be placed in such a way that parts and equipment held by the robot are completely enclosed by its sensor field. This can be problematic while handling large workpieces.

3.1.4 *Conclusion for the placing of the sensors*

The shown disadvantages of penetrating sensors and sensors that monitor the environment from the inside outweigh those of sensors monitoring from the inside.

Monitoring an environment from the inside will give a better coverage of safety critical zones when robot and human work in close contact. Nevertheless, monitoring an environment from the outside most often leads to a better general overview and is suitable for non-safe path planning.

Monitoring by means of penetrating sensors, using tags on the human clothing, is only suitable in special cases, when areas are too cluttered for any other sensor.

Thus it was decided to research monitoring systems that can be placed on the robot to view the collaborating space from the inside.

3.2 Choice of sensors

Based on the described boundary conditions, the selection of sensors for safe obstacle recognition in the project EsIMiP has been limited to those, which make do without additional marks on the object to be detected and are suitable for use "from the inside". Analyses of already implemented sensor concepts from literature, show that

- Force sensors that trigger only on contact, detect a collision, but can not prevent it [7]
- Capacitive sensors are not yet suitable for safe recognition and have only a limited coverage. Safe capacitive sensors are still being tested for approval by the IFA [8]
- Cameras (2D and 3D) require high computational effort to be fit for safety applications (example: PILZ SafetyEye [5])
- Laser scanner for 3D images [9] provide a low number of images per second
- PMD Cameras are not yet fit for safety applications [10].

After further studies on sensors available on the market, the use of Ultrasonic sensors was concluded. The advantage of these sensors is that they respond to everything entering their detection range, and as a result return the distance to the closest detected object. Also, safe ultrasonic sensors have already been built [4]. The computational effort per sensor is small, so that a greater number of sensors can be used to ensure good coverage.

In the project, a concept was developed to equip the robot with outward-looking ultrasonic sensors. The concept is similar to the parking aid of motor vehicles, in which ultrasonic sensors are integrated into the bumper. However, the number of sensors used on the robot is much larger. The IFA is supported technologically by the company microsonic, which has approved their first ultrasonic sensor for safety applications in 1996.

Figure 3 shows the Reis robot RV30-16 with attached ultrasonic sensors by microsonic. The sensors are placed 10cm apart from each other.

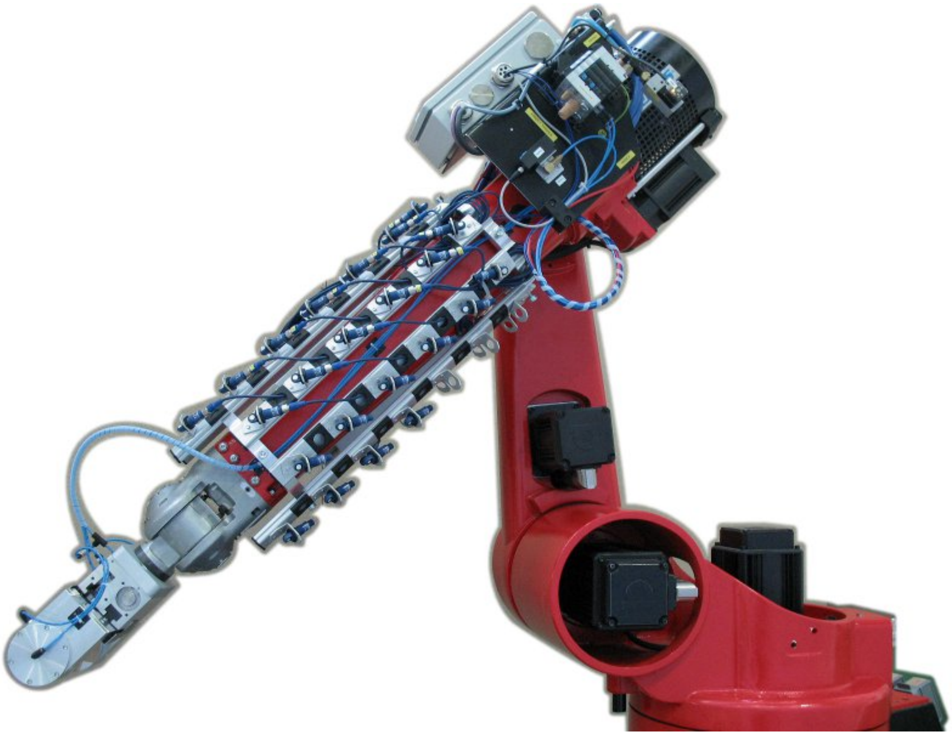

Figure 3: Reis robot with microsonic sensors

The sensor values are transmitted via a Beckhoff EtherCAT interface to the computer running the developed program. After the processing of those values, parameters are passed to the robot’s controller that set the robot’s speed. Currently, it is assumed that the tool will also allow surveillance with ultrasonic sensors.

3.3 Measuring principle of ultrasonic arrays

Ultrasonic sensors emit a short sound burst in the ultrasonic range, inaudible to humans, and measure the time until the signal is reflected by objects and returned to the sensor. The distance to the object is calculated from that time, in conjunction with the current air temperature. Since the sound’s speed in 20 °C air is very low, at approximately 343 m/s, a microcontroller can measure the runtime with the necessary low tolerance to calculate a sufficiently exact distance to the object. Ultrasound required approximately 3 ms for a distance of 50 cm.

In the setup of the sensors it must be ensured that the sound lobes overlap, to achieve verifiable results within the desired safety distance. If an object penetrates the monitored area, as shown in Figure 4, the sensor react to the reflected echo and from this their distance to the object can be concluded.

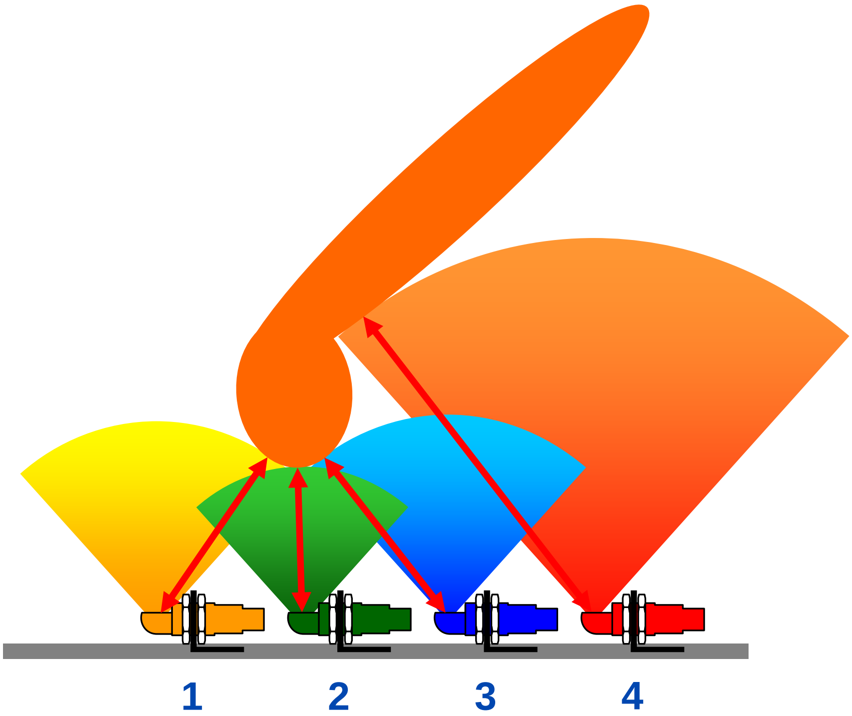

Figure 4: Penetration object throws back echoes; sensor 2 is measuring the minimum distance

The area covered by the different cones of the sensors may be accepted as "free of objects".

In order to get the displayed image, the sensors have to distinguish their individual sound cones. With simultaneous measurements, this is theoretically possible through an encoding of the spectrum. In praxis multiple reflections occur in the area, which prevent an accurate mapping of the received signal. The use of different ultrasonic frequencies is also difficult to realize in praxis. A sound encoding of each sensor is therefore not usable.

Another method would be sequential measurements. The sequence time of each measurement, waiting for the sound level in the environment to normalise after each burst, allows for one measurement every 17 to 20 ms if distances of 60 cm are to be covered. Sequential measurements thus result in a very large sequence time when a large number of sensors are to be used.

As a solution to this problem, the ultrasonic measurements are started at the same time using the same frequency. This results in another problem, as Figure 5 represents. The path from sensor 3 to the object and back to sensor 4 is shorter than that of sensor 4 itself to the object and back. Using parallel measurements leads to sensor 4 measuring the return signal of sensor 3 and thus a shorter distance to the object. The room perceived as "free of objects" becomes shortened at this sensor.

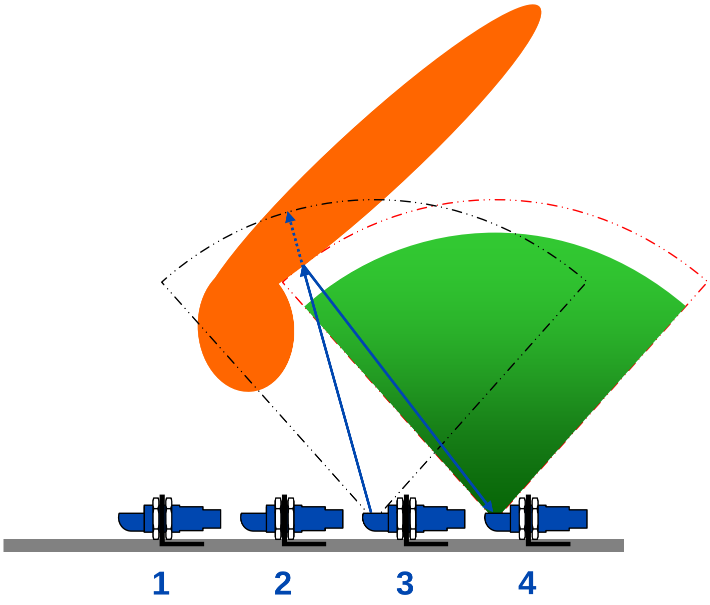

Figure 5: Ultrasonic run-time shortened for sensor 4

The measurement of the minimum distance in the sensor array however remains unaffected by this distortion. In the given example the difference between a possible measurement (grey) and the real measurement (red) are shown in Figure 6.

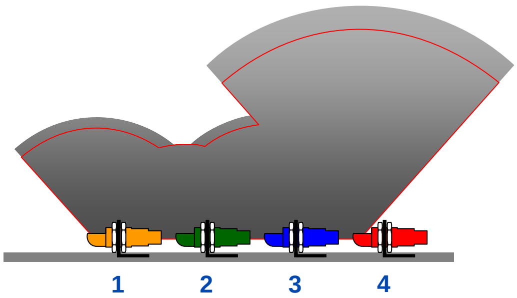

Figure 6: Difference in the space "free of objects"; with and without measurement errors

Since the speed of the robot has to be adjusted to the smallest measured distance to the target, a small distortion of the remaining readings is of no importance to the implementation of the safety function.

4. ALGORITHMS FOR DATA ANALYSIS

As described in Chapter 2, it is the goal of the IFA, to achieve an adjustment of the speed of the robot based on the environmental conditions.

To calculate the currently permissible speed,

- the determined distance values of the sensors must be evaluated and combined to a virtual map of the area, and
- it must be calculated at what given speed the robot would collide with the external borders of the space that is "free of objects".

These steps have been divided more finely for the determination of the desired velocity setting. This chapter describes:

- the relationship between measurement cycle, distance and speed
- the data flow through each algorithm in the developed "fail safe control"
- the determination of the space "free of objects", indicated in figure 6
- the capture of the map of the static environment

  and the final goal:
- the determination of the currently allowable speed through collision testing.

4.1 Connection of cycle - distance - speed

The standard EN ISO 13855 "Safety of machinery — Positioning of safeguards with respect to the approach speeds of parts of the human body" includes calculation bases and formulas, which can be used for the presented sensor concept.

4.1.1 Minimum distance

The DIN EN ISO 13855 presents the formula S=(K*T)+C for the determination of minimum distance "S".

- K: Factor for a person’s approach speed
- T: Delay time of the system
- C: Penetration depth into the danger zone prior to detection

The factor K is 2 m/s at less than 500 mm distance. Otherwise it is 1.6 m/s. Additionally the speed of the robot itself has to be included. According to the above mentioned standard, the delay time is the time between triggering the sensor system and the standstill of the machine. In the project T is considered to be 100 ms. Since the sensors can detect fingers, C can be set to 0 mm. A stationary robot results in a minimum distance of

S=(2m/s*100ms)+0mm=200mm

4.1.2 Speed

The permitted speed of the robot is linear on two sections. A graphical representation of the permitted speed, from contact to the maximal measurable distance of the used sensors is shown in figure 7.

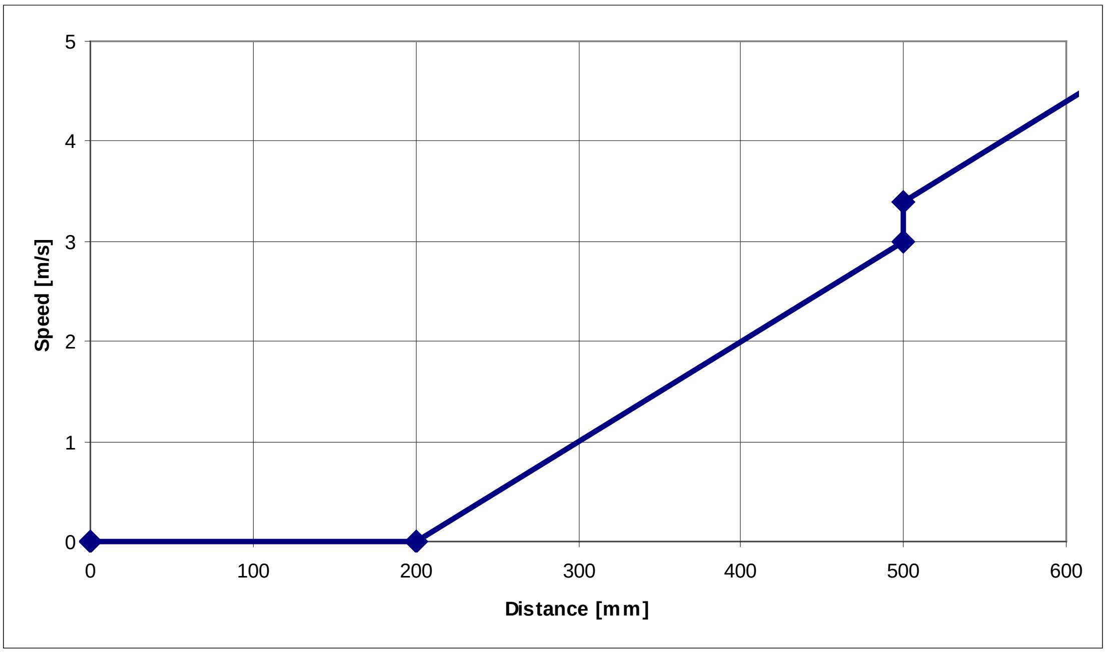

Figure 7: Graph "current distance - maximum permitted speed" for a response time of 100 ms

According to Figure 7, the robot is allowed to move at 4.4 m/s at a measured space “free of objects” of 60 cm.

4.2 Fail safe control (FSC)

To control the safe braking of the robot before collision, the “fail safe control” shown in Figure 8 is developed in the IFA. The sensor values are put together to a map and this map is compared with the robot’s trajectory. These calculations are safety-critical and therefore must be performed in real time.

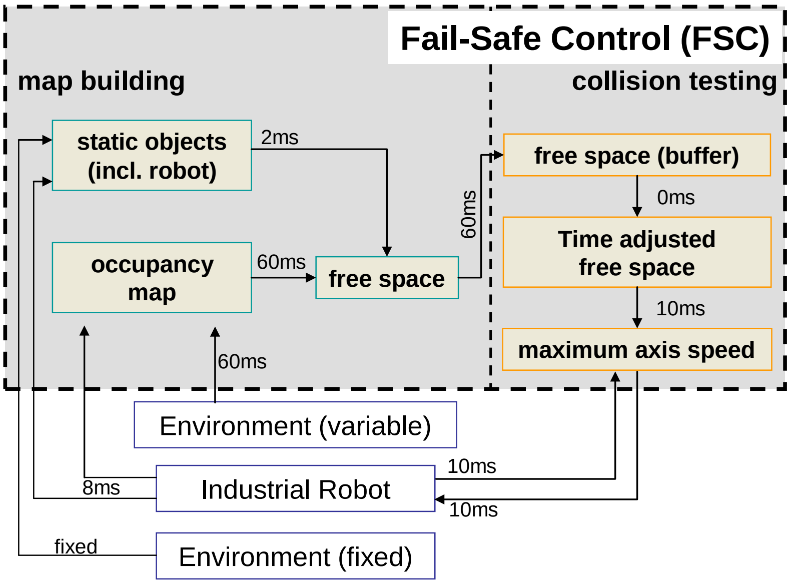

Figure 8: Sequence of calculations

The inputs into the FSC are from

- the ultrasonic sensors, delivering their distance values each 60 ms,
- the robot itself, whose control provides
    - o its own position provides each 8 ms,
    - o the next position to be approached each 10 ms,
- a subpart of the program, which provides the static objects in the environment measured at one time.

The values for the maximum speed of the axes can be issued every 10 ms.

4.3 Determination of free space

The space "free of objects" (see Figure 6) is created from the sensors cones. Basically, the distance of the robot to the external borders of the free space determines the permissible speed of the robot. However it is important to distinguish whether these limits arise by static obstacles, or whether dynamic obstacles restrict the free space.

The speed of the robot shall be reduced only when approaching dynamic obstacles, such as the robot’s user, so that the maximum speed is limited only when it is necessary for safety. Static obstacles, such as desks, are already protected by other features of the robot’s control, for example by software cams. Also, no safety distance needs to be maintained towards a static object.

When measuring with ultrasound, individual objects are indistinguishable from each other. Also, the resolution of the planned sensor array is too low to detect the shape of objects and recognise them. Due to the above requirements, a function is required, which allows the program to differentiate between static and dynamic obstacles. One possible solution is the background suppression. Herein, the static environment of the robot must be known and then subtracted from the evaluation of the sensor values.

4.3.1 Map of the static area

Using a robot that makes no independent change to its programmed trajectory, a preset database can be accumulated, which holds the expected sensory values. Using a robot that dynamically adapts its trajectory to foreign objects in its environment, a map of all static objects in the environment has to be included in the algorithms. This can be set up as:

- a model of all static objects in the room,

or

- a model of the complete space “free of objects”.

Using the ultrasonic sensors, a map of the space “free of objects” is the easier solution. At the beginning of the measurement the whole space, liberated from dynamic objects, is set to “occupied”. With each consecutive measurement the area individual sensors see as “free of objects” is subtracted from the “occupied” space. This way, the working area is gradually taught to the program. For this purpose, the robot is controlled either by a program or by the operator himself. If the space is taught by an operator, a graphical representation of the working area, the robot and the sensor measurements is necessary.

The robot itself is a dynamic adaptation to the static environment. Sensors that are installed on the first arm detect the second arm, or the tool of the robot from a certain angle of the joints. These values must also be excluded from the calculation.

4.4 Collision test

The collision test, as well as the sensor measurement, is cyclic. The duration of a single collision test is however lower than the duration of the sensor measurement. Therefore, it is possible to perform multiple collision checks per sensor cycle. From this it follows that the assumptions about the free space, measured prior to the first collision tests, are out of date for the second collision test in a cycle. In order to work at any given time with safe values for the space “free f objects”, the sensor values must be adjusted to the time that has passed since the last measurement. This can be achieved by taking into account that dynamic objects may have approached the robotic arm. The collision test is then carried out with the time adjusted space.

For collision tests, numerous algorithms were developed, based largely on the background of path planning. In this project a performant solution was developed, which focuses solely on the collision detection.

4.4.1 Adjustment free space and movement prediction - calculation of the speed

The collision detection of a robot and obstacles in its environment is a major challenge in dynamic 6-axis industrial robot motion planning. All six axes can move independently of each other and the position of individual members is dependent on all preceding axes. Also, certain positions of the tool can be achieved through different combinations of axes.

While the process-oriented path planning developed in the project EsIMiP is able to focus on the verification of the robot tool alone, in order to keep the overhead of the calculations low, the safety-oriented collision check must always monitor the complete robot. It is assumed in the project that predicting and checking of all achievable states at any given time is not possible in real time, because the amount of data to be processed is too large.

This problem was solved elegantly in this part of the project by a "movement prediction". The FSC does not intervene in the path planning of the robot. It only sets the maximum speed within the path specified by the path planning. From a safety point of view, it is sufficiently only to monitor the space around this planned path while disallowing all others. To do this, Reis Robotics equipped the robot with a special position delay, giving advance notice to outside components, before the robot executes any movement. Beckhoff allows all axes to be monitored separately, setting safe boundaries for the robots movement in return. Thus, only the predicted and checked movement of the robot can be executed, while all others are safely prohibited. Through this cooperation, the mathematical effort of collision detection is reduced to a minimum, and the safe control of the robot is achievable in real time.

Figure 9 shows the flow of the algorithm. It first checks whether a collision with the environment occurs within the next monitoring cycle, if the robot would move at maximum speed in the planned direction. If this is not the case, the maximum required speed of axes is allowed.

If a collision is detected, the speed of all axes is reduced to 50% of the scheduled speed, and a new calculation takes place. Following this calculation, an iterative algorithm reduces or increases the speed by 50% of the previous adjustment on which the collision is calculated, based on whether a collision was detected or not.

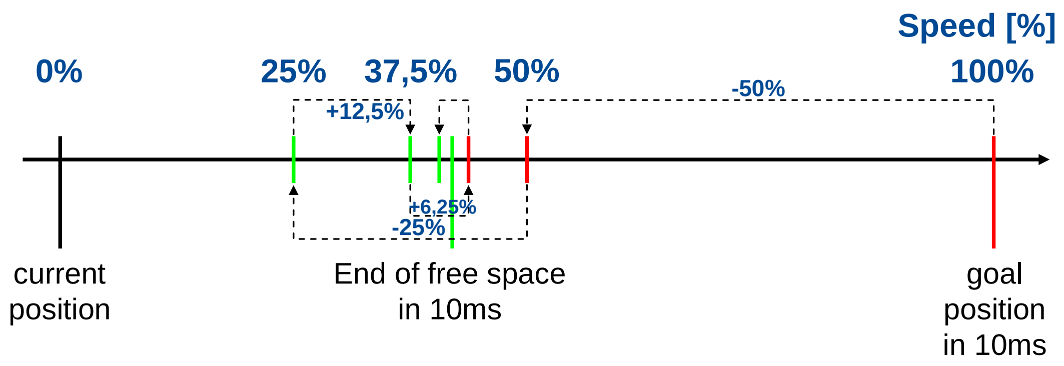

Figure 9: Trajectory based calculation of the current maximum speed

With only 10 collision checks, this algorithm leads to an accuracy of 0.1% for determining the maximum permitted speed. Currently the Beckhoff safety control allows 7 levels of speed, but further development will enhance this to a variable setting.

Using this method it is important that the safe control not only allows for a safe limitation of the speed (method SLS from the standard EN 61800-5-2) but for a safe speed range (SRS, EN 61800-5-2), since a lower speed in any axis results in the robot diverging from the checked trajectory.

5. SUMMARY

The presented system describes a safety concept for collaborative robots. Ultrasonic sensors are used as sensors, which span a safety box around the robot. It is shown how these sensors can measure in parallel, without distorting the results towards the unsafe side. The presented algorithms can be easily integrated in existing robot workplaces, in most cases without changes to the programmed process. A predictive collision check is presented, which reduced the computational effort for maximum speed calculations to a minimum.

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