Human-Robot Collaboration: Safety by Design

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Abstract— **High payload industrial robots, unlike collaborative robots are not designed to work together with humans. Collaboration can only happen in situations, where the human and robot is separated with a distance, which allows safety sensors to stop the robot system in any point if the human is in too close proximity of the robot. Safety sensors cannot decide over risks, consequences, neither any counter measures to prevent undesired outcome (e.g. collision between human and robot). Safety sensors are only reacting on proximity and can only give severity signal to the robotic system (e.g. no human, slow speed, full stop). This paper presents a new way to address safety sensors: voxel based, dynamic, collision state-space monitoring for human-robot collaboration with high payload robots. The general architecture and some initial test are presented, along with introduction of the problem statement.**

I. Introduction

Most widespread programming of industrial robots can be done by two ways: offline programming or teaching. Both programming methodologies suffer from drawbacks in applications, where human should assist in the robot programming [1].

In case of offline programming, the industrial robot is instructed by a program, which is uploaded to the robot after it has been compiled to machine code from an external source. The robot program is written in a clear text based editor and this text is compiled to machine code. The machine code can be run on the robot, where the instructions are processed and executed step by step. In case of advanced applications, the coordinates and instructions are based on the CAD model of the workpiece. The CAD model does not contain any information about the manufactured workpiece, only the surface and dimensions are known, thus this cannot be used for this type of application [2]. The method of offline programming is the most common type of robot programming. Also, newer types of offline programming tools were developed to simulate the exact work cell of the robot [3].

A constraint in offline programming is the low accuracy of the robot. Accuracy of an industrial robot highly depends on its built up and load-capacity. The average load capacity of an industrial robot is 400kg, meanwhile the accuracy is 1 mm, but both values can be improved. Ken Young and Craig G. Pickin [4] showed that this can be enhanced by proper calibration process of the industrial robot.

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In case of Teaching, the robot is controlled by the teach pendant, the operator moves the robot along a path in the work cell. The path is built up from points. These points are stored and velocity, orientations are assigned to them. This method is very time consuming and now rarely used in real industrial applications. With Predictive Robot Programming (PRP) [6] improvements have been made to achieve faster Teaching, but the results are used only in manipulator type robots.

Many pioneering activities were started to make robot programming more efficient and flexible [6] [7] [8]. All of these activities used Offline programming methodology. In the beginning, the repeatability was emphasized. An industrial robot was used to do the same task over thousand or million times. As the production number dropped, the robot programming time rose as a constraint in fast production type switching. Not only mass production enterprises wanted to use industrial robots, but the SMEs appeared as new market.

SMEs were expected to use industrial robots in their production chains several years before. In the mass production of the large enterprises, the higher automation degree and higher production number was achieved by using industrial robots. In 1999, industrial robot programming was made easier for SMEs with the introduction of PIN (PC-based interactive programming system for industry robots). Wenrui Dai and Markus Kamper [9] [10] created a robot simulation environment for Offline programming of industrial robots. Their expectations of the spreading of the new methodology in welding processes were high, but did not come through. The industrial robots were still too expensive for SMEs.

These days industrial robots are getting cheaper and robot programming is becoming easier. Specialized solutions and projects exist to deal with small batch sizes [11, 12].

The remainder part of the paper is organized as follows: Section 2 introduces the problem of current safety systems. While Section 3 describes the design of the new safety architecture. Section 4 shows some initial tests, followed by concluding remarks in Section 5.

II. Problem Statement

According to [13, 14], a collaborative operation is a state in which a purposely designed robot system and an operator work within a collaborative workspace. This workspace is further described as a space within the operating space where the robot system (including the workpiece) and a human can perform tasks concurrently during production operation.

In case of uncertainty and vulnerability, trust can be partly rational, but sometimes trust is largely irrational, especially when it comes to non-dangerous situations. Even though the robots are designed in a way to be safe to work with, they can be perceived dangerous. Thus, the transition from working

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without collaborative robots to the work with them may be difficult, and feedback from workers is needed to design a trustable system.

Yet, to ease the transition, a good communication between robots and humans is needed. Since communication is used to being implicit between two humans, it would be relevant that robots can understand human body language. The robot could therefore adapt his comportment, and indicate good intentions such as sounds, lights or decreasing speed to indicate that it is safe to work with.

Therefore, in contrary to a factory with workers only, or robot only, collaboration create the need of psychological requirements which should not be underestimated.

In the following the main challenges of today's safety systems is described.

A. High payload industrial robots are not collaborative

With exception of a few applications in the automotive industry, high-payload robots are not used as collaborative robots today.

B. State-space monitoring based on voxel approach

Unstructured environment, only actions based upon current situation [15].

C. Environment interpretation and connection toward voxels

Robot systems are seen as black-box, without any transparency about the intended behavior. This causes high negative stress impact on human, which is neglectable with traditional, low-payload collaborative robots.

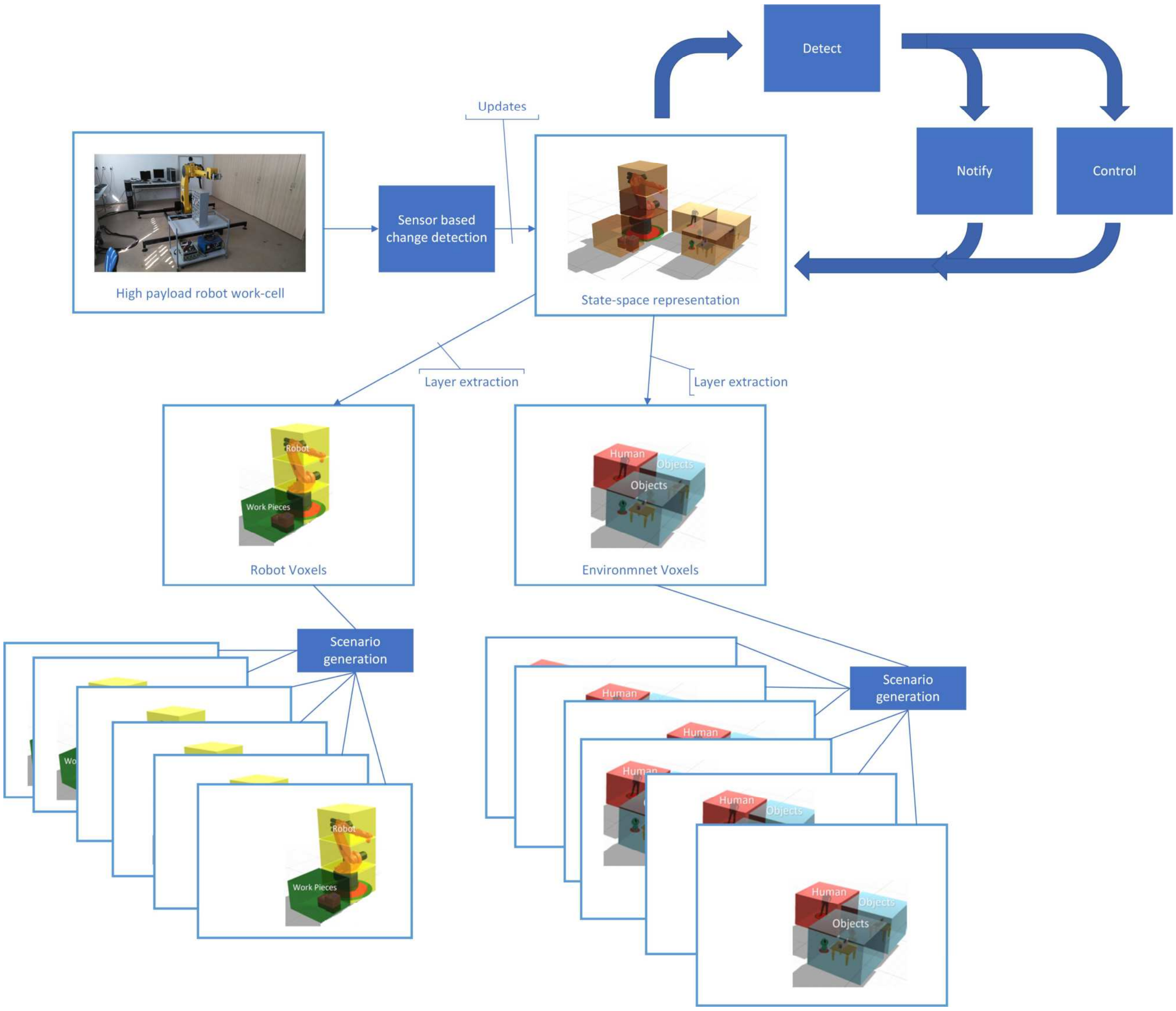

Figure 1. Proposed architecture overview

III. Proposed Architecture Design

The overall structure can be seen in Figure 1. The core of the architecture is the voxel-based state-space representation [16]. This representation is the digitalized description if the industrial robot and the surrounding around it. The environment is continuously mapped by sensors and updated in real-time. A voxel in the state-pace has the following internal state machine:

- Detection: a voxel updates its current state based on the sensory input. If a change is detected, it can either result in notification or control request.
- Notification
- Control

IV. Initial Tests

As the proposed architecture is not yet complying with the safety standards, the initial tests were carried out in a virtual environment. The graphical engine OGRE (Open Source 3D Graphics Engine) is used to create the graphical interface that will be displayed on Augmented Reality glasses.

A. *Virtual industrial robot*

The virtual workspace contains an industrial robot that is connected to its own simulator. Moving the robot in the simulator or in real life also moves it in the virtual workspace. Thus, the position of the robot is known at all time and can be used to ensure safety. For practical reasons, the position of the tool of the robot can also be displayed in the screen (as shown in Figure 2).

B. *Virtual Human Collaborator*

The virtual workspace also contains a virtual 170cm tall human collaborator. The person can be controlled directly by the keyboard. The body parts of the collaborator can be moved independently. Some shortcuts have been created to make the move of the human collaborator easier. For example, R and L move respectively the Right and the Left hand; S handle the Spine; and pressing C would move the whole collaborator, without any movement of the bones.

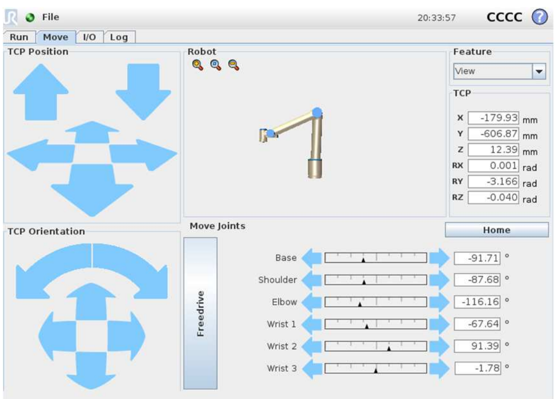

Figure 3. Virtual industrial robot

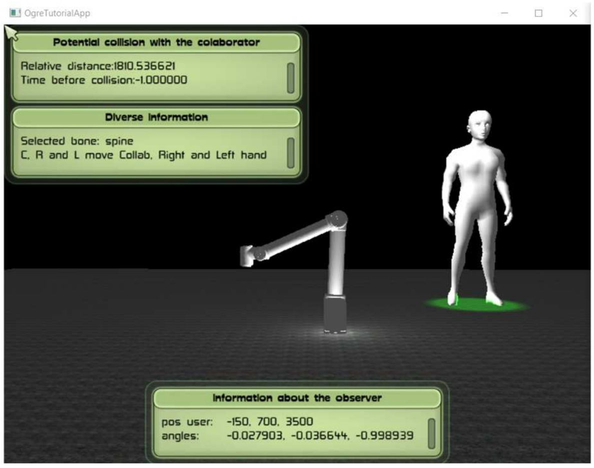

Figure 2. Human Collaborator and an Insutrial Robot in the same space

The most important sensing requirement for the virtual collaborator is the following:

- Accuracy of measurement below 10cm. The robot will never be close to humans in high-speed mode. Yet, the better is the accuracy, the closer can the robot safely move nest to humans.
- 100% coverage: collaborators must be detected wherever and whenever on the work-space. In this application, collaborators skeleton position must be known at all time. If this information is lost, the robots will have to stop.
- The higher is the sampling frequency, the closest can the robots be to the collaborators. The maximum decrease of the distance between a collaborator and their closest robot plus the distance that take to robot to stop at that speed should be lower than the distance between them:

  $$\frac{v_{max_R}+v_{max_H}}{f_{sample}} + d_{stop_R} < d_{H-R} - d_{accuracy},$$

  where v_{max_R} is the robot maximum speed, v_{max_H} is the human's maximum speed, d_{stop_R} robot's distance to stop, d_{H-R} distance between human and robot' s Tool Center Point.
- The system must be very reliable. Complete failure is not an option and must be detected. Then the robots can stop safely until the issue gets fixed. Redundancy is possible to achieve this goal.

C. *Displaying Information*

The virtual environment is to be used together with Augmented Reality that would help the humans to collaborate with robots. Human Collaborators need to know what the robot is about to do, where is it safe to go etc. As of now, there is a light circle around the human collaborator which colour varies with the distance the collaborator is from the robot. if the robot is moving straight toward the collaborator, the time before impact is also calculated (as shown on Figure 3). This calculation assumes that the collaborator will not move and the robot will keep the same speed and the same direction until it crashes. Of course, collaborative work-spaces aim to avoid crashes and the robot would stop long before the crash. But this calculation relate about how safe would the collaborator feel. The latter would feel very unsafe and under a constant stressed if the robot keeps being close to crash into them during their work (as shown on Figure 4).

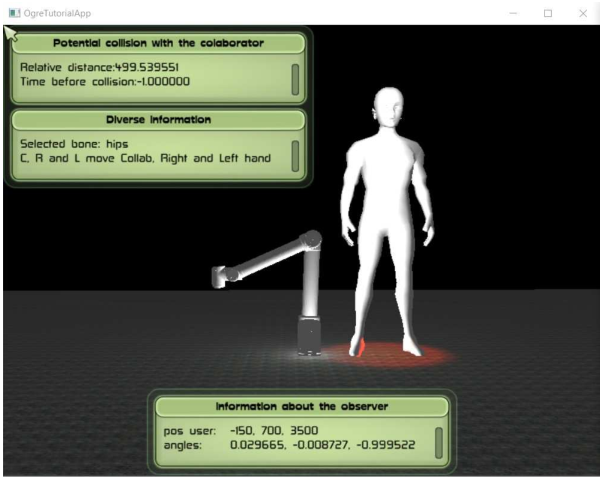

Figure 4. Human Collaborator in danger zone

V. CONCLUSION

In this article the motivation and a proposal for safety by design was presented for human-robot collaboration. With today's setup and safety regulations, the initial tests were carried out by the means of virtual environment. There is a clear benefit over classic approach to safety, where only the distance between the robot and human is taken into consideration.

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