Safe Human-Robot Cooperation with high payload robots in industrial applications SAPARO

Deliverable 4.2 – Working prototype

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1 Introduction

This document aims in presenting the current state of the working prototype. As this deliverable is defined as prototype the efforts and works are mainly presented as screenshots and pictures commented by short textual descriptions.

2 Implementation of safety space generation algorithms

The implementation of different safety space generation approaches based on the distance formula described in ISO TS 15066 was a main objective of task 5. Other than defining manually a static safety space that will cover the entire space of a planned robot trajectory, the said distance formula will allow a dynamic generation of safety spaces based on the current state of the robot and the human's behavior.

$$S_{current}(t) \geq \int_{\tau=t}^{\tau=t+T_R+T_B} K_H(\tau)\, d\tau + \int_{\tau=t}^{\tau=t+T_R} K_R(\tau)\, d\tau + \int_{\tau=t+T_R}^{\tau=t+T_R+T_B} K_R(\tau)\, d\tau + C + Z\_S + Z\_R$$

Distance formula defined in ISO TS 15066

2.1 Simulation environment

For implementing this distance formula we firstly developed a simulation environment (see figure 1) that can be used to load various robots and related robot environments. This tool allows defining angles and velocities of every robot's joint and visualizes the robot accordingly. Further on, the user can define the parameters of the distance formula like brake distance, reaction time, human's speed and constants. It is also possible to define a human's position, movement direction and speed. The robot as well as the human is approximated by particular collision primitives to reduce the overall computing complexity. So, the safety distances are not related to the surface of the real robot but to the surface of the collision primitives. As these collision primitives enclose the real robot's geometry the resulting safety distances are slight longer.

In figure 1 the simulation tool is depicted. The main window visualizes the current state of the KUKA KR60 L45 and its corresponding collision primitives like cylinders, cubes and spheres. Furthermore, the main window visualizes the safety distances as blue distance vectors. In the left part of the GUI all relevant parameters can be defined. That is the adjustment of the robot's angles and velocities, robot's pose, human's pose and further parameters of the distance formula. A change of these parameters affects directly the visualization in the main window.

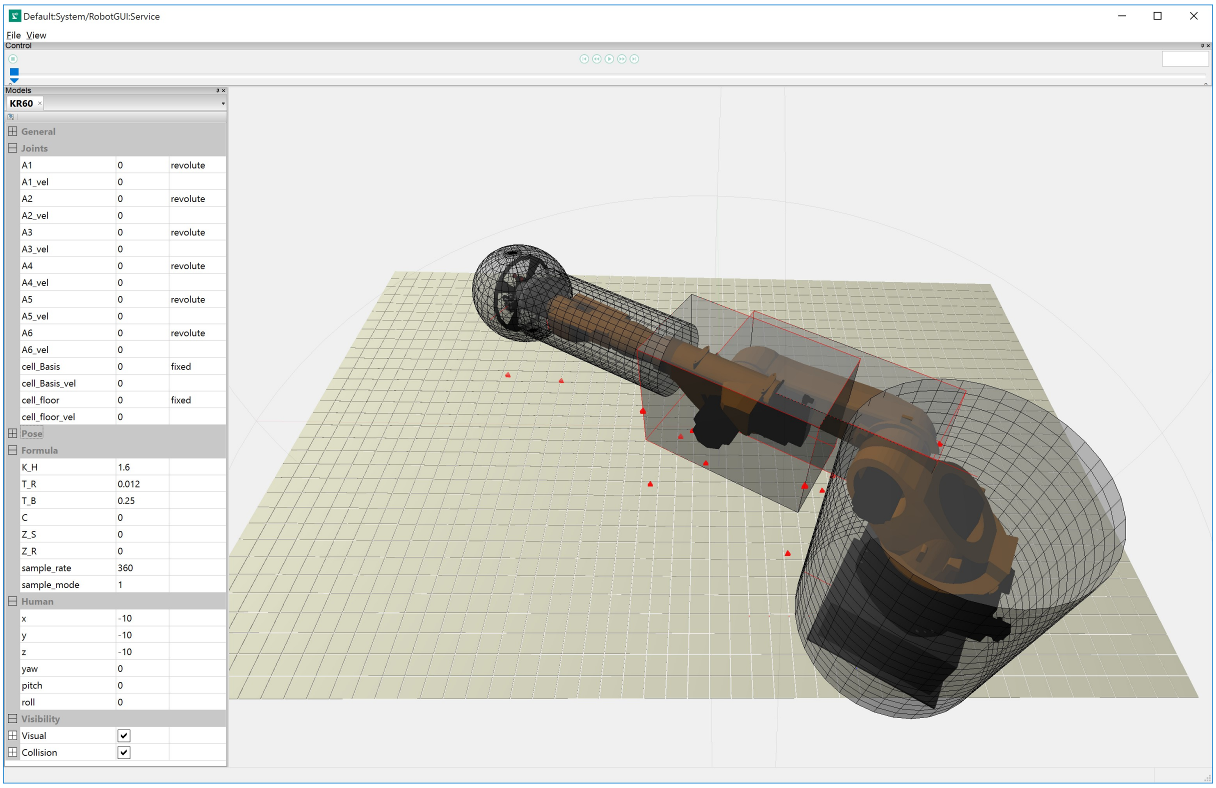


Figure 1: Simulation environment used to develop and implement the single safety approaches that are based on the distance formula described in ISO TS 15066.

2.2 Safety approaches

2.2.1 Dynamic on basis of current robot state:

In this safety mode the size and shape of the safety space depends entirely on the current robot's joint positions and velocities. The position, movement direction and speed of the human are unknown. Therefore, it is assumed that the human can move to the robot with a worst case speed of 1.6 m/s from any position in the environment. As the resulting safety distances are maximal this safety approach leads to a worst case safety zone. In the following pictures the robot is moving by an axis speed of 0.8 rad/s for joint A1. The safety distances of the collision primitives are visualized as blue distance vectors. As seen, the distance vectors increase in robot's movement direction.

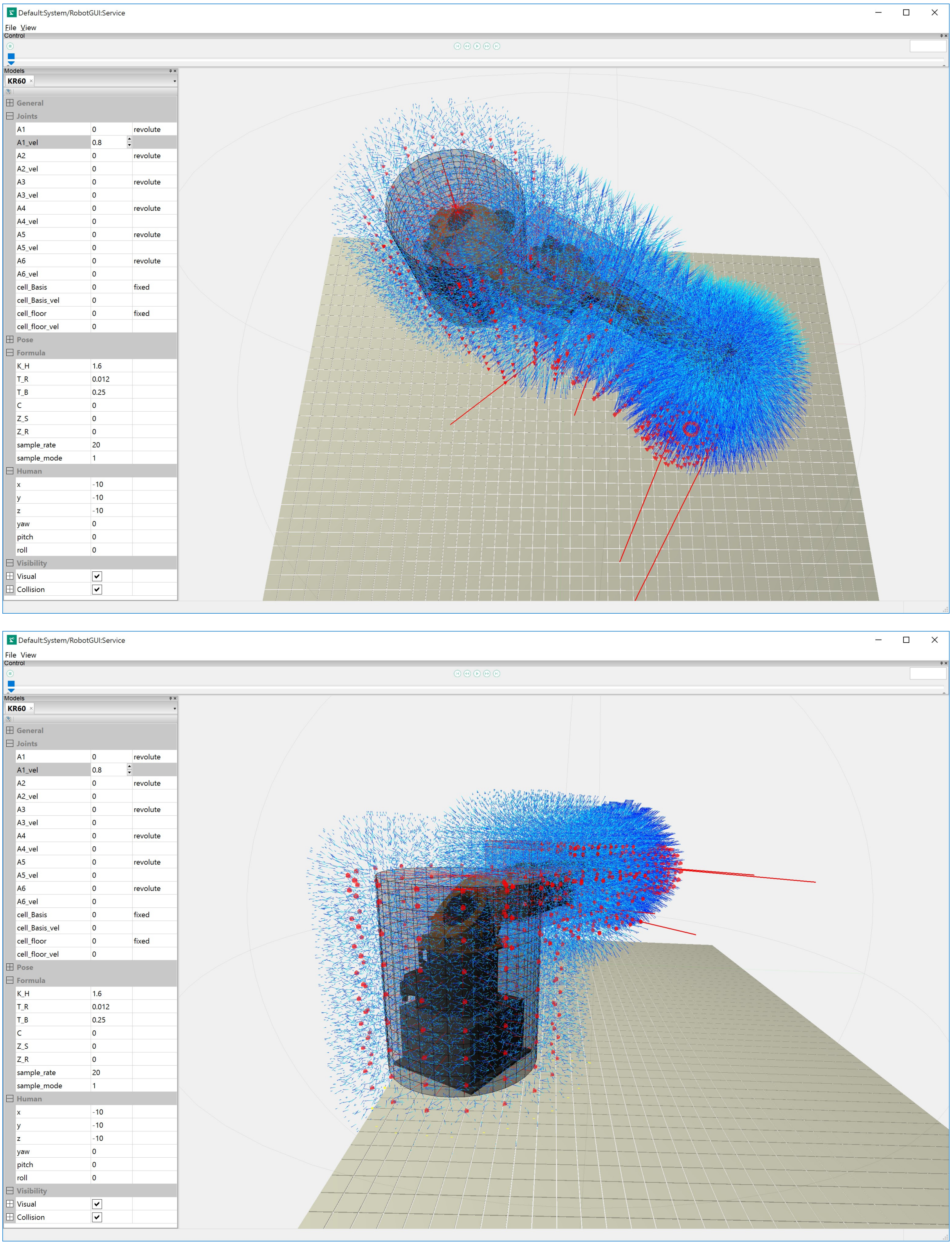
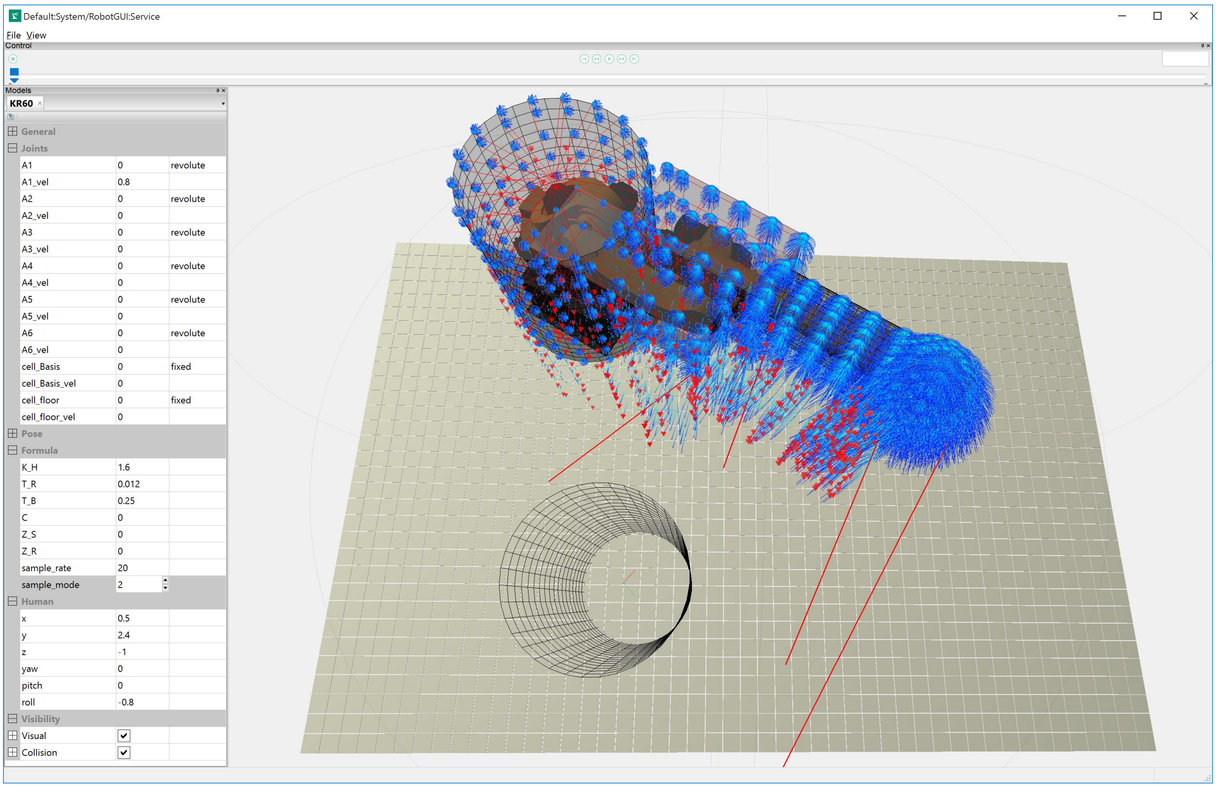


Figure 2: Resulting safety distances (blue) at robot movement by a joint (A1) velocity of 0.8 rad/s.

2.2.2 Dynamic on basis of current robot state and human position

This safety mode enhances the first approach by incorporating the human's position to the safety distance calculation. As there is no information regarding the movement direction and speed of the human it is assumed that the human can move with a maximal speed of 1.6 m/s in any direction from its position. In figure 3 the resulting safety distances are visualized. The human is approximated by a cylindrical geometry with a diameter of 1.0m.



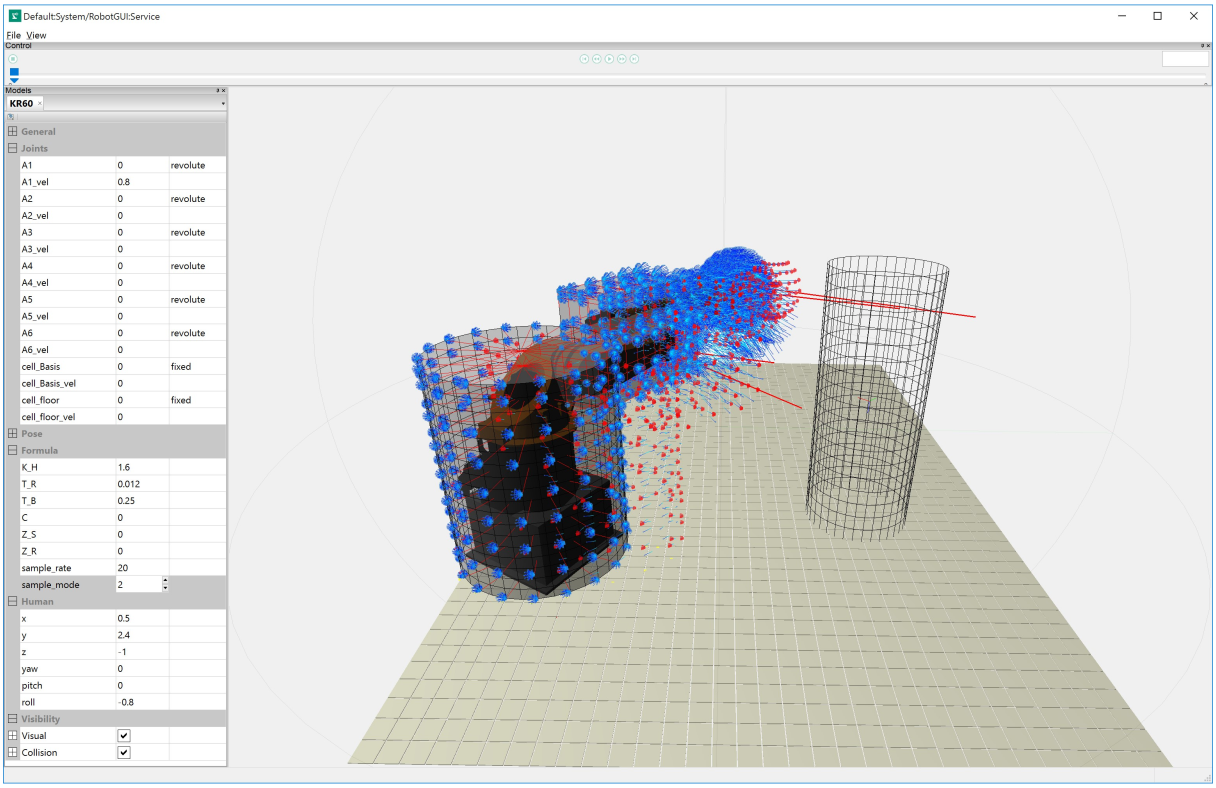


Figure 3: Safety distances with known human's position and a robot movement with a joint (A1) velocity of 0.8 rad/s.

2.2.3 Dynamic on basis of current robot state, human position and movement direction

The knowledge of the human's position, movement direction and movement speed allows very specific and minimalistic safety spaces. As the direction of human's movement is known only safety distances relevant for this movement need to be determined. Figure 4 depicts the safety distance if the human moves with a speed of 1.6 m/s towards the tool center point (TCP). The movement direction is the positive y-axis (green axis line) of the human's coordinate frame inside the cylinder. Here, the lengths of the safety vectors are similar to the ones of the second approach because of the same human speed. Reducing the human's speed to 0.8 m/s leads to safety distances as can be seen in figure 5.

The difference between approach 2 and 3 is even more concrete if the human is moving away from the robot. As visualized in figure 6 the safety distances are very small in contrast to the ones in figure 4 or figure 5.

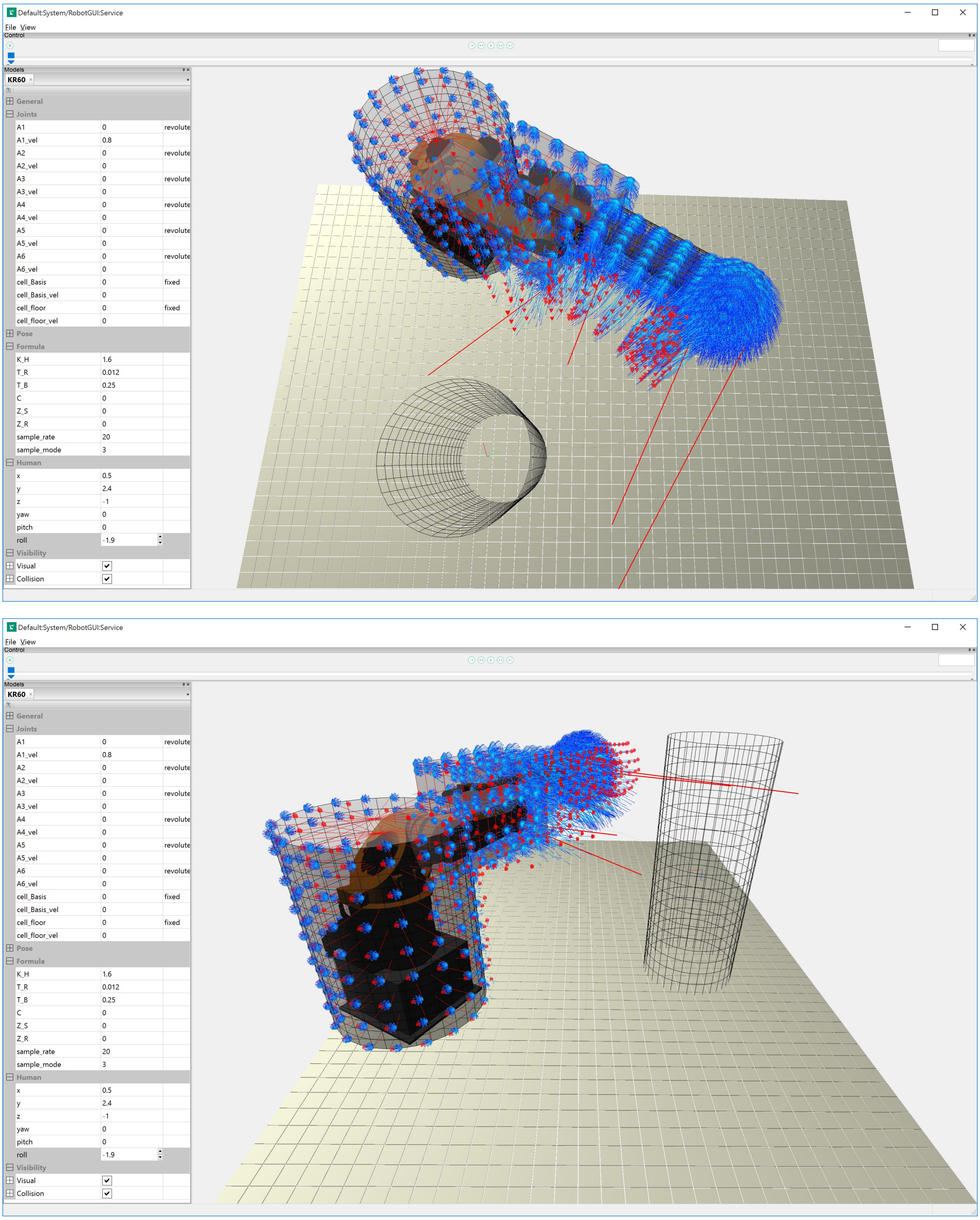
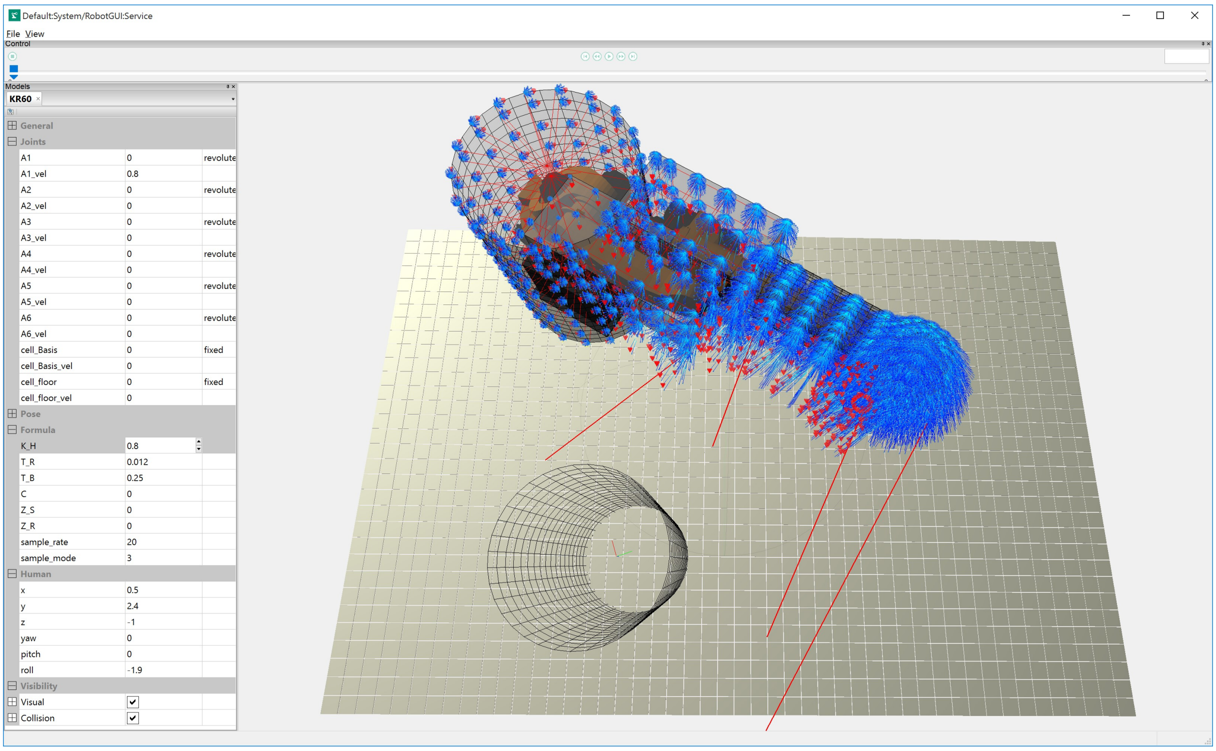


Figure 4: Human moves towards robot's tool center point with a speed of 01.6 m/s.



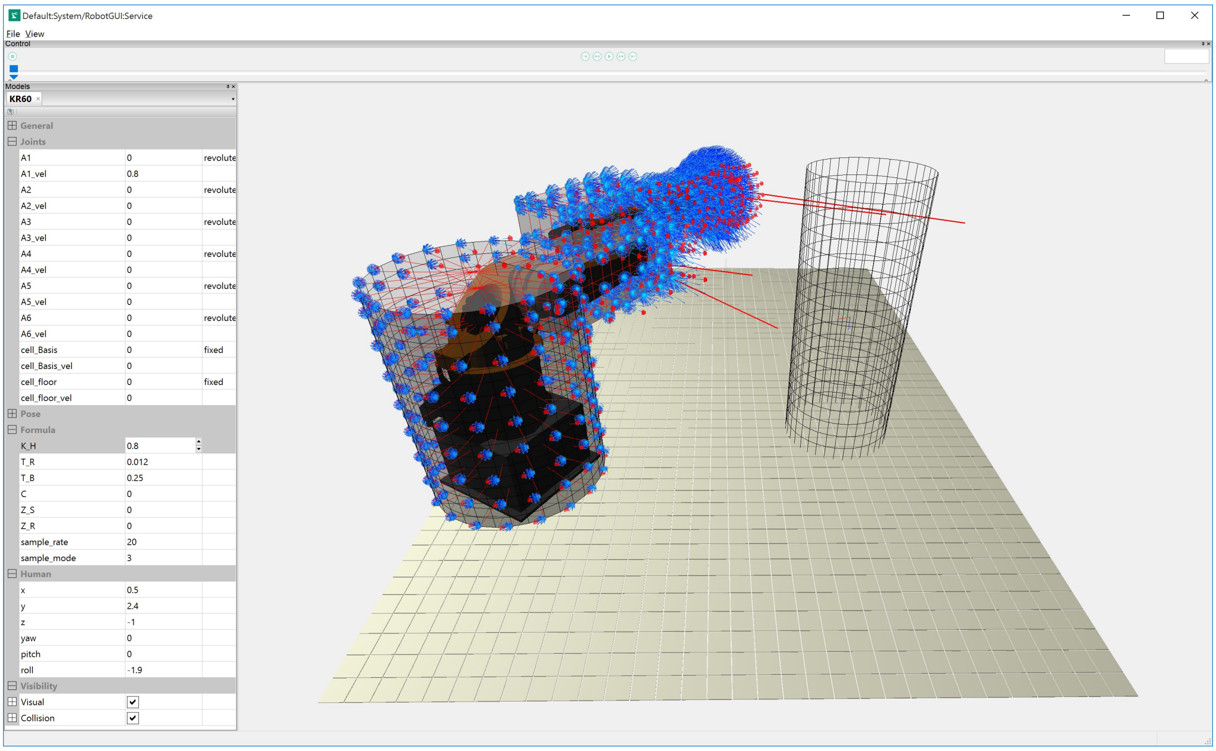


Figure 5: Human moves towards robot’s tool center point with a speed of 0.8 m/s.

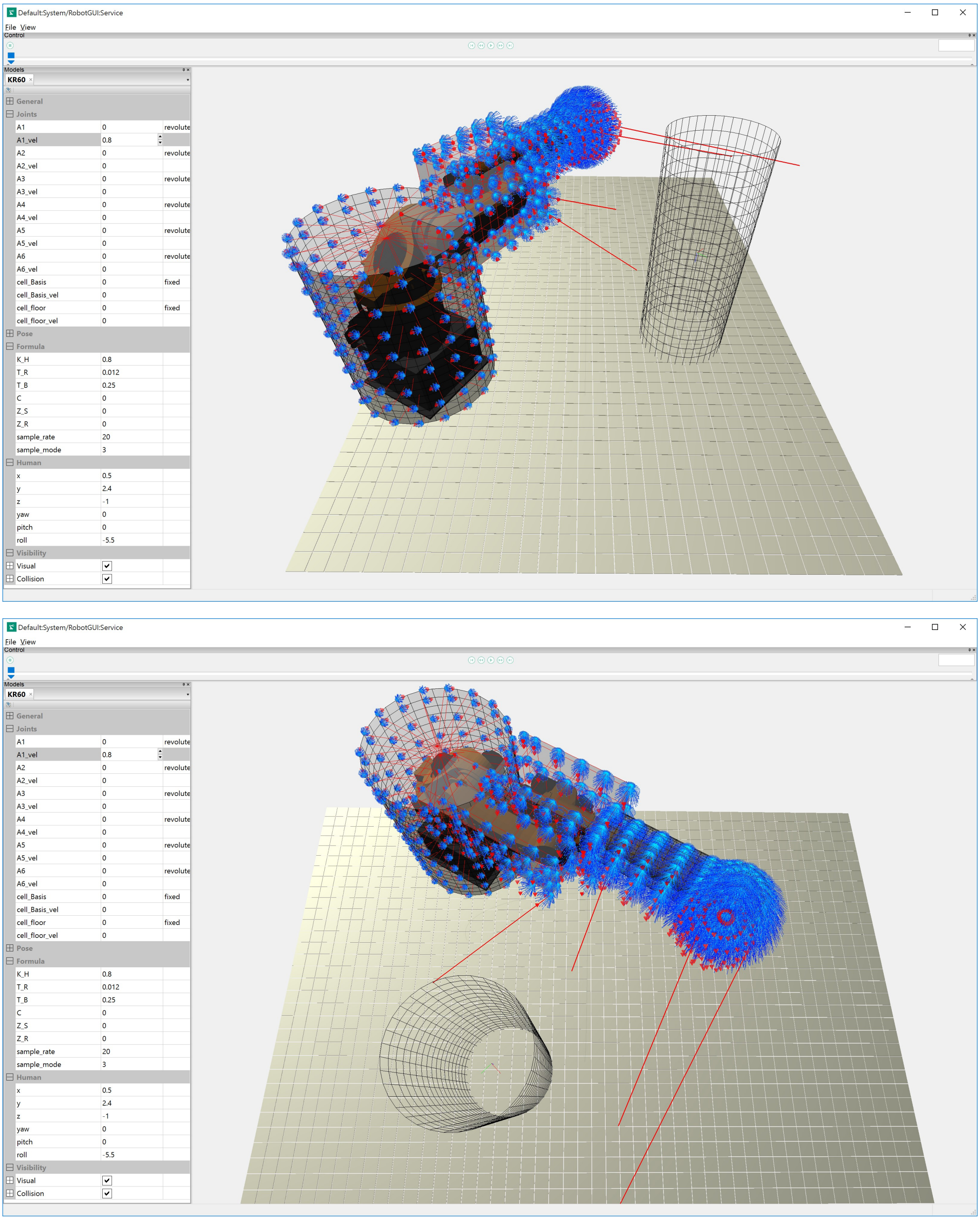


Figure 6: Human is moving away from robot's position with a speed of 0.8 m/s.

3 Integration of safety approaches

Next steps include the integration of the algorithms to the real-time system to allow a computation of the safety spaces in operation. Because of the high amount of safety vectors a reduction of the data was necessary. Here, we implemented a voxel-based structure (octree) to reduce and manage the data in a convenient way.

The objective of further processing is the determination of the set of sensor cells of the tactile floor that belong to the critical safety space. At first, on basis of the octree we determine the boundaries of the safety space. The corresponding distance vectors are transformed to the floor plane by orthogonal projection. Further on, these 2-dimensional points are used to determine a convex hull that approximates the entire shape of the safety space. Finally the corresponding sensor cells are computed by transforming the area of the convex hull to the coordinate frame of the tactile floor.

As the resulting sensor cells represent the critical zone that will lead to an immediate stop of the robot's motion at entering, we expanded this area to compute a warn zone around them. Entering the warn zone will reduce the robot's motion speed according to the distance of the human to the critical zone. So, if the human enters the warn zone near the free zone, the robot will only slightly reduce its speed. On the other side, the robot will nearly stop its motion if the human will enter the warn zone near the critical zone. This floating reduction of robot's speed allows a smooth transition between different robot's speeds, especially when the human is standing and the robot moves to the human's position.

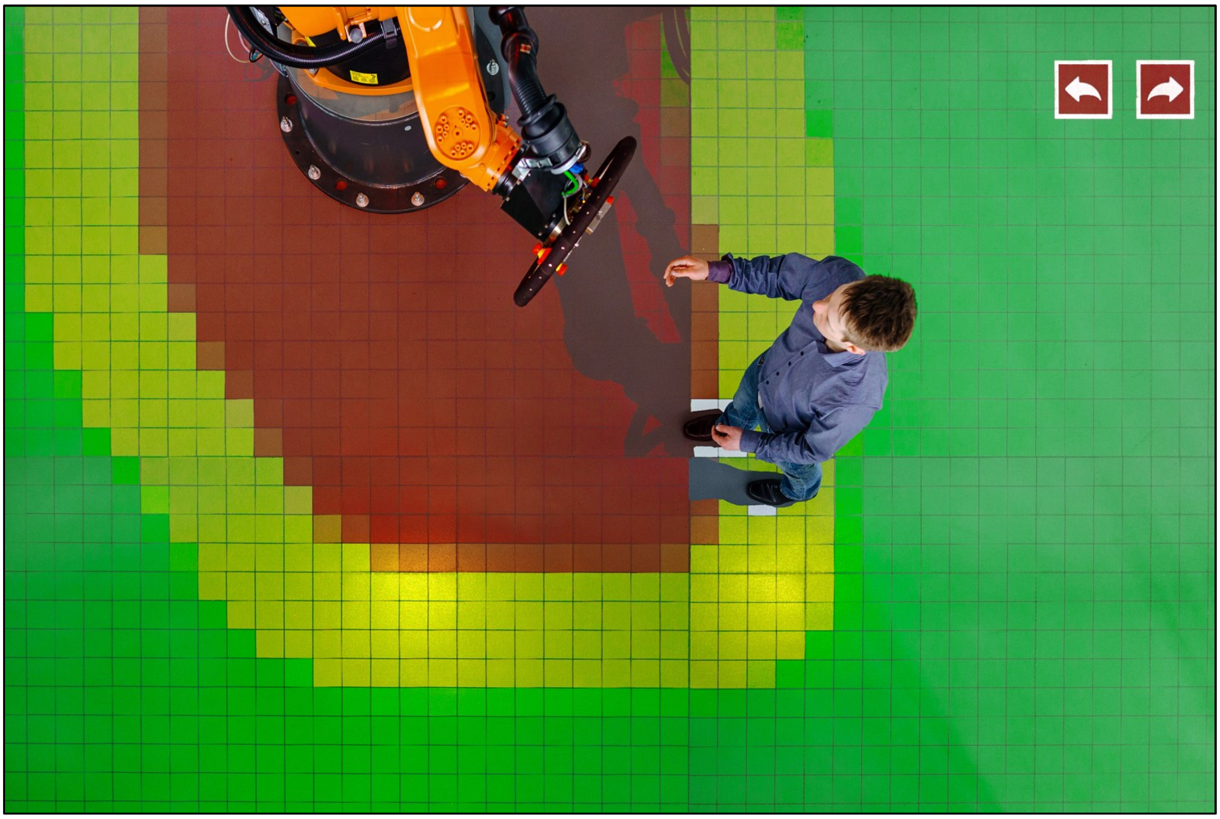


Figure 7: Dynamic generated safety zones consisting of a critical zone (red area), warn zone (yellow area) and free zone (green area).

4 Implementation of industry-oriented process

As specified in deliverable D1.1 the scenario comprises the assembly of a turbo-charger and motor block. So, the robot supports this process by carrying the heavy turbo-charger while the human tightens the turbo-charger to the motor block.

This process consists of the following single steps (see also figure 8):

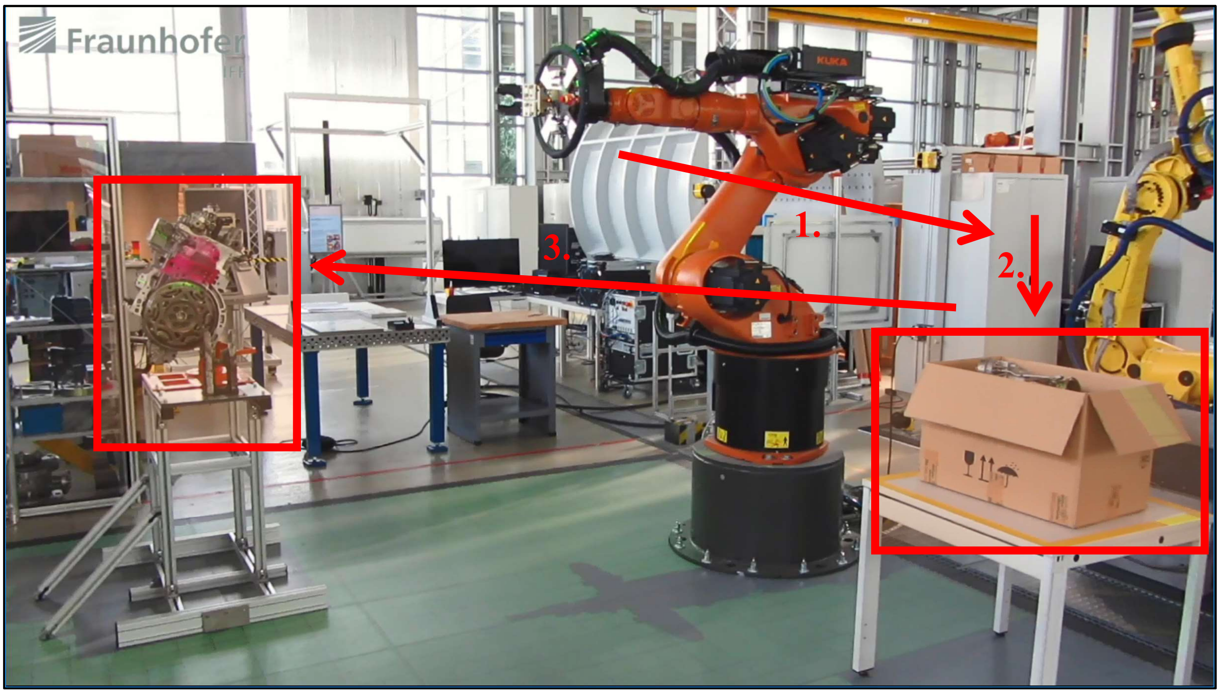


Figure 8: Single steps of the assembly process: mounting turbo-charger to motor-block.

- **1. Preparation of grasping the turbo-charger**
  Robot moves to a predefined position above the box with the turbo-charger. As the position of the turbo-charger is undefined inside the box, the user will guide the robot by hand. So, after arriving the destination position above the box, the gripper opens, the safety spaces are deactivated and the hand-guidance is activated automatically.

- **2. Hand-guidance and grasping the turbo-charger**
  The user can guide the robot by hand and can position the gripper at the turbo-charger optimally. After that the user activates (see figure 9) the robot to grasp and to move the turbo-charger to the motor block. While the robot moves autonomously the safety spaces are activated and monitored.

Figure 9: Left: Hand-guidance for positioning the gripper. Right: Interactive buttons for activating next process step.

- **3. Mounting the turbo-charger**
  The robot transports the turbo-charger to the predefined position at the motor block. After arriving the safety spaces are deactivated and the user can start mounting the turbo-charger to the motor-block. When the mounting of the turbo-charger is finished, the user confirms this by an interactive button and the robot moves to its initial position.

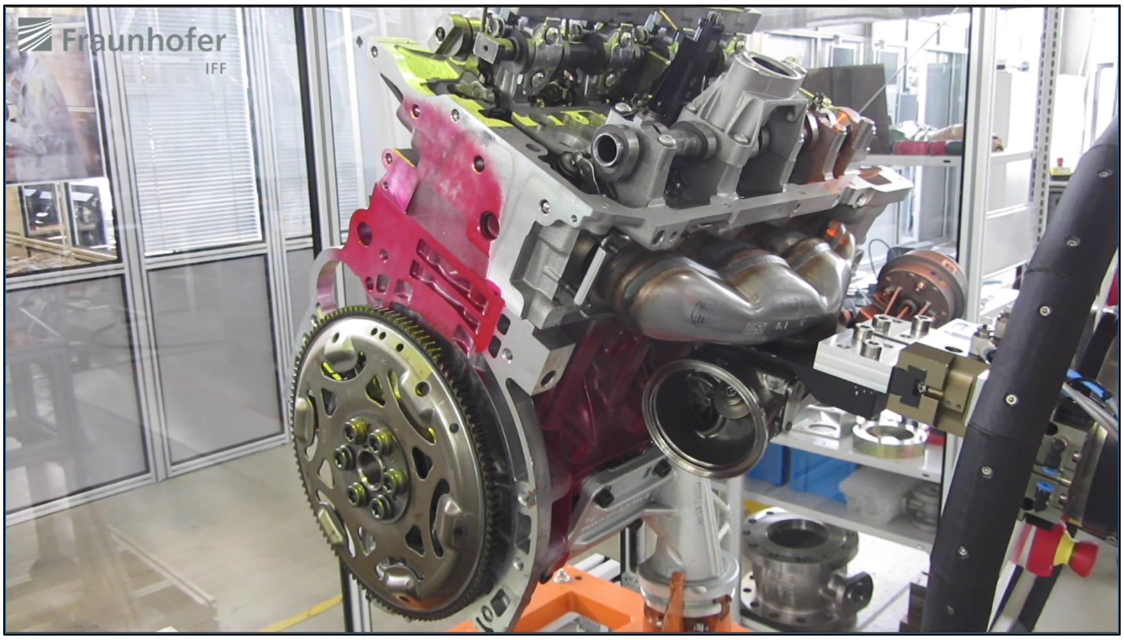


Figure 10: Autnomous positioning of the turbo-charger. User can start mounting them.

In general, every time the robot is moving autonomously the safeguarding is activated.

5 Estimating human's behavior

As described in section 2.2 the human's behavior is required for some safety approaches. So, we used the sensor information of the tactile floor to estimate the position, as well as movement direction and speed of the human. The method is based on a detection and localization of "blobs" that consist of single triggered sensor cells activated by the human's foots. These blobs are further correlated over time and form the basis for estimating human's steps. These steps are used to approximate the human's movement direction and speed.

The human's behaviour is visualized by a white circle representing the estimated position and a red line that points in movement direction. The length of the line demonstrates the speed of the movement.

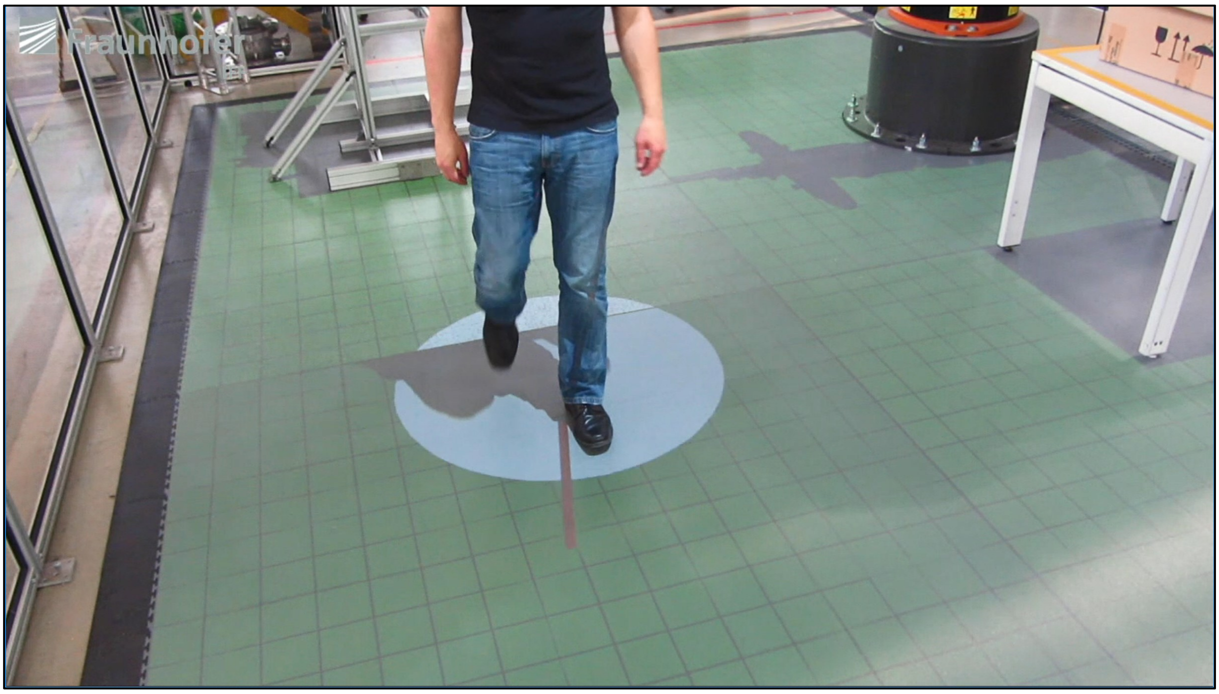


Figure 11: Estimating human's behaviour by sensor information of the tactile floor. Visualizing human's behaviour by a white circle (position) and red line (movement direction and speed).