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Dynamic Agile Production Robots That Learn and Optimise Knowledge and Operations

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DELIVERABLE 8.4
Intermediate demonstration

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Contents

1 Introduction

This document reports on the results of the public DARKO milestone demonstration on June 21, 2024. The demo coincided with the second stakeholder meeting with invited industry and academia representatives at the KI.Fabrik lab, located at the Deutsches Museum in Munich.

Building on the system architecture from the second milestone and demonstration (MS2, D8.3), this demonstration presented the improvements realized on the mobile platform used for the previous milestones, and introduced a second mobile platform equipped with the elastic arm developed in the scope of T1.3. The first platform was used to showcase a complete scenario, including risk-aware navigation and the safe motion unit, navigation, perception, manipulation (including throwing with and without a pneumatic tool), and showed separate demonstrations for further components (e. g., human and object detection, motion prediction, and human-aware planning). The second platform presented the possibility to throw an object using an elastic arm, after performing a desired displacement of the mobile base.

2 Integration events

Before the demonstration and stakeholder meeting, the consortium conducted an extended integration phase at the ARENA2036 and KI.Fabrik facilities in Stuttgart and Munich respectively. The integration spanned over several weeks in April, May and June. This phase focused on deploying, integrating, and testing all features developed during the current project period. Unlike the previous integration sessions held at ARENA2036 in 2023, this phase also included assembling and testing a second mobile platform equipped with the elastic arm developed under Task T1.3.

The two three-week integration events in Stuttgart and Munich involved a mix of on-site and online collaboration, marked by an intense and productive work environment. Team members put in extended hours, often working late into the night and starting early in the morning. Figure 1 provides a glimpse into key moments from these integration sessions.

3 Stakeholder meeting

The milestone demonstration on June 21 2024 was performed as part of a stakeholder meeting with invited industry representatives. A video retracing this event is available via this link: https://www.youtube.com/watch?v=Q-M9PuG0DnE. Figure 2 shows some impressions from the meeting and demonstrations and Figure 3 shows the advertised agenda.

The on-site audience included people from the Technical University of Munich (TUM), Munich Institute of Robotics and Machine Intelligence (MIRMI), University of Toronto, Olive Robotics, KUKA, KION and Bosch Rexroth.

As for the previous milestone demonstration, the meeting was divided in two slots, each with presentations and on-screen demonstrations of pre-recorded activities plus live demonstrations.

After registration of the participants, the meeting started in a seminar room with a set of presentations: first, a project overview from the coordinator Achim Lilienthal, followed by a set of technical presentations from the work packages, including perception of objects and humans, mapping and localisation, human–robot spatial interaction, and motion

Figure 1: Snapshots captured during the integration sessions at ARENA2036 and KI.Fabrik, April–June 2024.

planning. This first set of presentation was concluded by a presentation of the KI.Fabrik by Achim Lilienthal.

We then proceeded to the demo area on the KI.Fabrik facilities in the Deutsches Museum for the first demonstration, which consists of showing all the integrated features of the DARKO platform in one dedicated scenario. More details about this demo is presented in Section 4.1.

The second presentation slot focused more on the manipulation related tasks: the development of the elastic manipulator and general-purpose gripper, planning and control for manipulation and throwing, perception for manipulation, and finally the risk representation and operations scheduling of WP7.

For the final demo slot, back in the main demo area, we have separately presented the special features developed during DARKO, such as throwing objects with both the elastic arm and the pneumatic tool, the anthropomorphic and linguistic human-robot interaction (HRI) using the NAO robot on the DARKO platform, human and object perception, the causal discovery of dynamic models in HRI and risk- and context- aware model predictive control. The contents of the demos are further described in Section 4.

After this demonstration, we concluded the stakeholder meeting with a joint standing lunch, socializing and discussing between the invited stakeholders and the consortium members.

4 Milestone demonstration

During a series of live demonstrations, we presented the current implementation of core components for perception, planning and control for picking and throwing, human perception and scene understanding, human-aware mapping and human–robot spatial

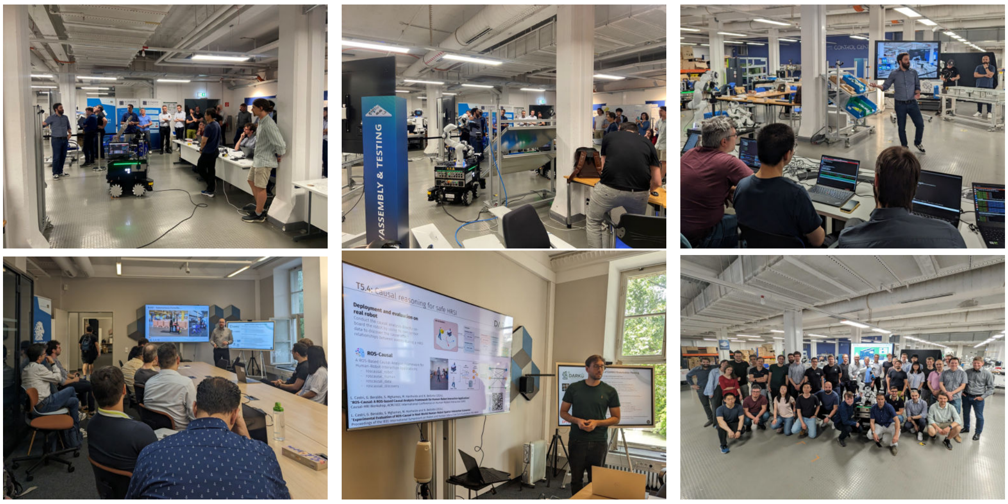


Figure 2: Demonstrations and presentations for the invited audience during the Milestone 3 stakeholder meeting.

interaction, motion planning, task scheduling, as well as the mobile dynamic manipulation platform itself. The throwing capabilities of an elastic arm have also been presented on a second mobile platform.

The demonstrations took place in a designated area on the main floor of the KI.Fabrik lab. This space featured a custom-built setup with shelves containing boxed objects and a conveyor table with larger trays—mirroring the shelves used in DARKO's primary use case at BSH's warehouse. Similar to the BSH warehouse layout, and as in the milestone 2 demo (D8.3), the shelf and conveyor table were positioned close enough for efficient task execution but far enough apart that the robot could not reach both the picking (boxes) and placing (trays) points without either driving or throwing.

Similarly to the demonstrations presented in milestone 2, the audience stood near the demo area, enclosed by barrier tape, where they could observe the robot's actions directly while also viewing RViz visualizations on a large screen.

4.1 Full Scenario

As the first event of the milestone 3 demonstration, we showed a complete scenario, orchestrated by the WP7 task scheduler, including localisation, navigation, perception, picking and throwing. See Figure 4.

In this demo scenario, the robot first had to navigate to the shelf and position itself accurately in order to look inside the boxes on the shelf and reach the objects inside. We then regress grasp poses from the point cloud of the top-mounted RGB-D camera (T2.2) and grasp it with the Softhand 2 gripper (T4.1).

After picking, the hand is held up for the camera to do in-hand perception, verifying that we have a good grasp for throwing. Finally, the robot drives a short distance to be within throwing distance of the conveyor with the target tray, and computes a throwing motion to throw the object into the target tray.

4.2 Object Manipulation

The features related to the manipulation of objects refers to the ability of the DARKO robot to pick up an object from a shelf, and throw it to a desired location. Different approaches,

Agenda of DARKO Stakeholder Meeting @ KI.Fabrik (21 June 2024)

09:30 – 09:40: Welcome (Large meeting room, first floor)

- DARKO in a nutshell (Prof. Dr. Achim Lilienthal, TU München, Germany)

09:40 – 10:30: Presentations, Part I (Large meeting room, first floor)

- Perception I (Dr. Narunas Vaskevicius, Robert Bosch GmbH, Germany)
- Mapping & Localization (Dr. Unal Artan, Örebro University, Sweden)
- Human-Robot Spatial Interaction I (Tim Schreiter, TU München, Germany)
- Motion Planning (Dr. Andrey Rudenko, Robert Bosch GmbH, Germany)
- KI.Fabrik in a nutshell (Prof. Dr. Achim Lilienthal, TU München, Germany)

10:30 – 11:00 Demo, Part I (KI.Fabrik, basement)

- Integrated DARKO demo (navigation, human-robot interaction, picking, throwing, ...)

11:00 – 11:10 Coffee Break (Meeting rooms, first floor)

11:10 – 12:00 Presentations, Part II (Large meeting room, first floor)

- DARKO Platform (Dr. Valentin Le Mesle, TU München, Germany)
- Dynamic Manipulation (Prof. Dr. Paolo Salaris, University of Pisa, Italy)
- Perception II (Prof. Dr. Martin Magnusson, Örebro University, Sweden)
- Human-Robot Spatial Interaction II (Luca Castri, University of Lincoln, UK)
- Handling of Risks & Scheduling (Dr. Nicoló Mazzi, ACTOR, Italy)

12:00 – 12:30 Demo, Part II (KI.Fabrik, basement)

- Special functionality demos (Elastic arm, throwing with a pneumatic tool, anthropomorphic and linguistic human-robot interaction (HRI), causal discovery of dynamic models in HRI, ...)

12:30 - 14:00 Lunch (Meeting rooms, first floor)

Figure 3: Agenda of the stakeholder meeting on 21 June 2024.

described hereafter, have been investigated and implemented on two separate platforms and were showcased in separated demos. The first approach consists in grasping and throwing an object using a dedicated tool (robotic hand or pneumatic tool) connected to a commercially available robotic arm, and the second has required the development of a specific elastic arm.

4.2.1 Picking objects from the shelf

In this section we describe the part of the demo related to the picking and throwing performed during MS3. The demo consisted in the performance of a single cycle of the use-case scenario: the mobile base moves toward the shelf stopping in front of it, then the system uses the perception stack to get information on the location of the desired object and picks it using the manipulator, and, in the end, the mobile base moves in the new position and the arm throws the grasped object towards the target box. To perform this demonstration, several components developed during the project were integrated together. From the previous milestone, the rigid 3-finger gripper has been replaced with the SoftHand 2, a soft anthropomorphic gripper (see deliverable D1.4 for further details on this new gripper). For the generation of the arm's movements, we implemented an impedance control law, to guarantee safe physical interaction with the environment, and a human-like motion planning algorithm, to make the manipulator more predictable by humans. More details on the whole motion generation framework of the manipulator can be found in the deliverable D4.1. The grasp pose for the arm was provided by the vision framework described in deliverable D2.2, which consists of a learning-based algorithm capable to estimates feasible grasp poses for 2-finger grippers using as input directly the point cloud recorded by an RGB-D camera. To adapt the grasp pose for our anthropomorphic gripper

Figure 4: Impressions from the full scenario demonstration. DARKO robot approaching the shelf (left), a successful grasp of an item from a bin (middle), delivery and throw of the item into the target tray (right)

we added an orientation offset to exploit the opposition between thumb and the other fingers. For the throwing motion we used the trajectory generation framework described in deliverable D4.5. Beside the main demonstration, during MS3 we made also the preliminary integration of the elastic wrist to perform object picking (technical details about the elastic wrist can be found in deliverable D1.4). The integration in the overall demonstration of the elastic wrist will be presented during the next milestone.

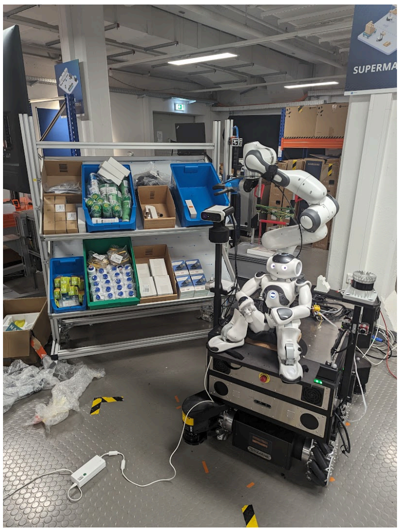


Figure 5: Object manipulation

4.2.2 Throwing with the pneumatic tool

In the MS2 demo, the pneumatic hand-tool was demonstrated in a basic setup, where it was mounted on a known position on the shelf, and used just to show the feasibility of the concept. However, this earlier version lacked integration with perception and the main planning systems. In the MS3 demo, we presented a complete picking and throwing sequence using an updated version of the pneumatic-tool w.r.t. MS2. In this demo, the robot was programmed to perform the entire sequence: it uses our human-like arm movement as described in deliverable D4.1, to approach and pick up the pneumatic tool. Once the tool is acquired, the robot uses it to pick an object from a box on the shelf, and, in the final step, the object is thrown into a target tray by inverting the pneumatic flow. Additionally, we developed a model for the pneumatic throwing mechanism, though it currently depends on the specific compressor used. This limitation suggests that in

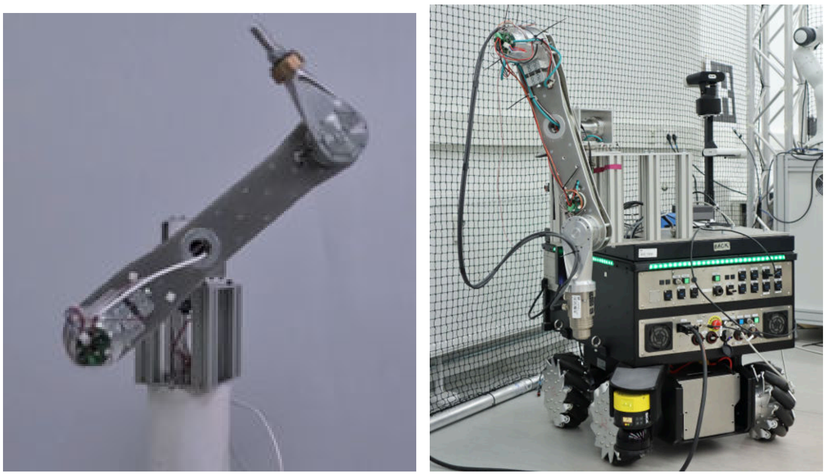


Figure 6: Snapshot of the developed 3-DoFs elastic arm (left) and its integration on the second mobile platform (right).

the next MS4 we will be used a generalized model to ensure broader applicability across different setups and compressor types.

4.2.3 Throwing with the elastic arm

The integration sessions realized for this milestone showed the integration of the 3-DoF elastic arm developed in the scope of T1.3 on the second mobile platform, displayed in Figure 6. The throwing capabilities of the elastic arm are based on the development of the Bi-Stiffness Actuator (BSA), which contains a spring-clutch mechanism, allowing for an efficient energy release. This feature, combined with an optimal control strategy, enables one to perform highly dynamic motions and improve the possible throwing distances. The design and integration of the BSA and the control strategy used are detailed in D1.3. For this demo, the elastic arm is equipped with a magnetic gripper which, even though the variety of objects that can be grasped is limited, was a good option to facilitate the integration process. The arm has been placed on one corner of the platform, and the arm's motion is limited to a vertical plane to avoid any potential collision with other components. More details about the implementation of the arm on the platform is available in D1.5.

As for the platform equipped with the Franka arm and the NAO robot, all the consortium has been involved in setting up the second mobile manipulator. The features that have been integrated include localization and mapping, motion planning, and perception. As these features are already showcased on the first platform, the demonstration performed with the second one focused on throwing with the elastic arm.

In this demo, the mobile platform moves to a location and performs a throw, as illustrated in Figure 7. While the robot is capable of performing high-velocity overarm throws, for the MS3 demo we applied a velocity-based control strategy developed by EPFL, where all the joints of the elastic arm are considered as rigid actuators. Following the event, TUM is working on improving the throwing performances of the elastic arm by evaluating the repeatability of throws and developing a torque-based optimal control strategy.

4.3 Human and Object Perception

The DARKO perception stack consisting of modules developed in WP2 (T2.1, T2.5) was demonstrated jointly with the "Causal Discovery" demo described in Section 4.4. A

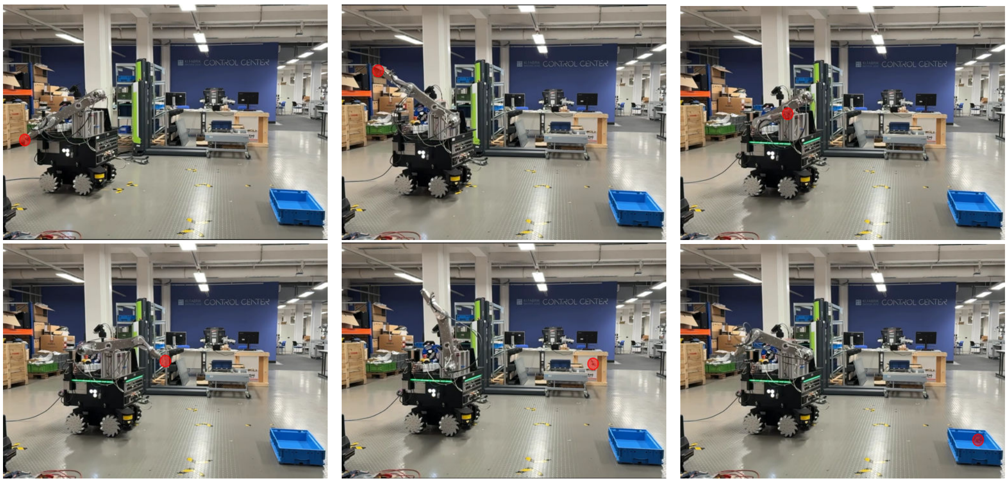


Figure 7: Example of throw performed by the TUM mobile manipulator equipped with the elastic arm. The location of the object at each time instant is highlighted by a red circle.

snaphsot of the demo as well as illustration of different outputs of the perception modules can be seen in Figure 8.

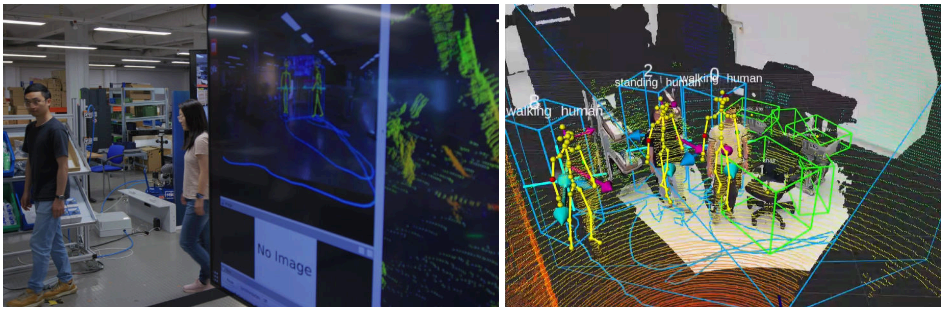


Figure 8: Human and object perception. The left subfigure shows impressions from the demo at KI.Fabrik during the stakeholder meeting. The right subfigure depicts example output of the DARKO 3D perception stack with tracked humans and their articulated poses (skeletons), detected objects and recognized activities.

The demo showcased different perception capabilities from onboard RGB-D sensors including 3D human detection and tracking, articulated human pose estimation in 3D space, activity recognition and 3D object detection. The technical details of the demonstrated methods can be found in the deliverable D2.2. These technologies are necessary for various downstream applications and were utilized in other demos such as “Causal Discovery”, “Risk- and Context-aware MPC”, human-robot interaction, etc.

Beyond the stakeholder meeting, Bosch showcased intuitive task specification for a mobile robot within its robotics lab, utilizing DARKO’s perception components. The demonstration leveraged the DARKO 3D object detector and a hand-held sensor suite (see D2.2 for more details) to semantically reconstruct the environment. This object-level semantic map was then used to specify navigation targets for a mobile ACTIVE Shuttle robot via pointing gestures (see Figure 9). DARKO’s human perception stack played a key role in this interaction by detecting humans and their 3D articulated poses, which then were used to compute pointing direction and the target object.

The next milestone will focus on wide field of view perception based on fisheye and

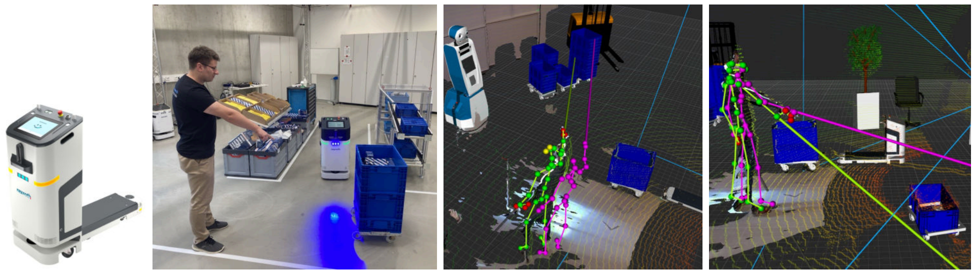


Figure 9: Intuitive robot control via pointing gestures demonstrated in Bosch robotics lab. From left to right: the ACTIVE Shuttle – an autonomous robot used to transport items e.g. in shopfloors of manufacturing plants; an example of pointing gesture; visualization of 3D pose estimation results by several methods from DARKO human perception stack, and the resulting semantic map with inferred pointing directions.

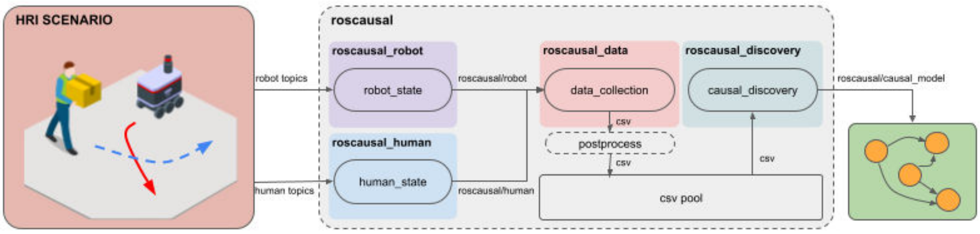


Figure 10: ROS-Causal pipeline: (i) data extraction from HRI scenarios; (ii) collection and post-processing of data to derive a high-level representation of the scenario; (iii) causal discovery conducted on the data, with the resulting causal model published on a dedicated ROS topic.

lidar sensors.

4.4 Causal Discovery

The "Causal Discovery" demo aimed to showcase the DARKO robot's ability to reconstruct a causal model of interactions between two people in a warehouse-like environment in real-time, directly onboard using data from its own sensors. Data acquisition, postprocessing, and causal discovery analysis were performed using the ROS-Causal framework (Figure 10), developed by WP5 as part of the DARKO project.

In the demo, the robot was positioned in a corner of the demonstration area, where it observed interactions between two people and their environment. Specifically, through ROS-Causal, the robot recorded data of human-human and human-target position interactions. It then postprocessed this data to derive the following three variables: v (human velocity); d_g (distance between the person and his/her target position) r(risk of collision with the other person). The robot then performed causal discovery analysis on these variables to reconstruct the causal model representing the relationships between them. (See Figure 11.)

4.5 Risk- and Context-aware Model Predictive Control

In the field of robotics, the ability to navigate autonomously in human-populated environments is a critical capability with numerous real-world applications, ranging from service robots in public spaces to collaborative robots in industrial settings. However, achieving safe and efficient navigation in such environments presents unique challenges, particularly

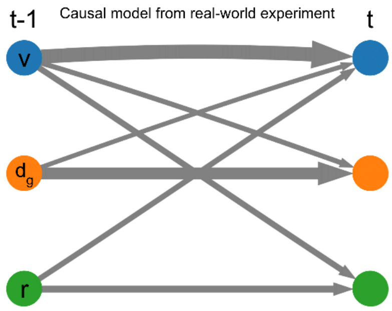


Figure 11: Causal model reconstructed by ROS-Causal using robot sensor data collected during the demonstration.

in anticipating and adapting to human movements. As a result, there is a growing need for robot navigation systems to consider human motion and its predictions as integral components in their decision-making processes.

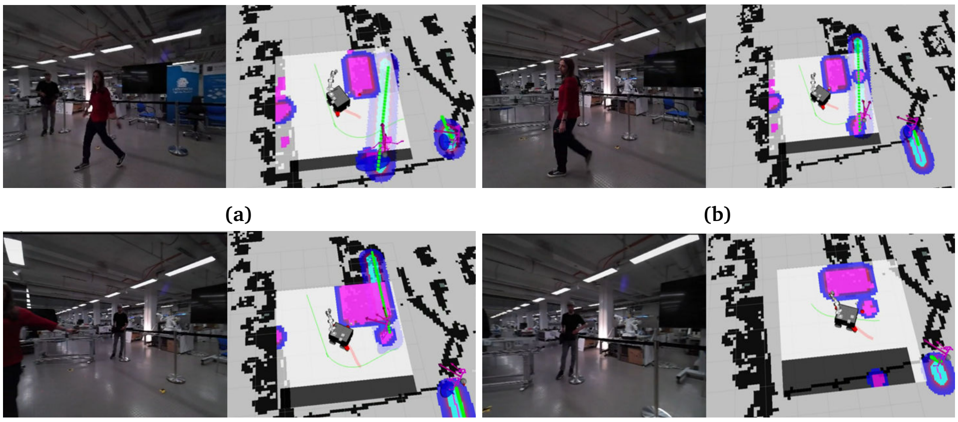
Our team has made significant progress in developing a novel and efficient context-aware model predictive technique for generating robot trajectories. This technique takes into account various cues of humans, such as their short-term 2D predictions, body pose, and detected activity (e.g. standing, walking, sitting). By incorporating these cues into the trajectory generation process, our model predictive technique can better anticipate and adapt to human movements in real-time, leading to more efficient and safer robot navigation in human-populated environments.

Furthermore, we have also integrated the notion of risk into our model predictive control. This includes considering the risk of collisions with both static and dynamic obstacles in the environment. By incorporating risk assessment into the trajectory generation process, our technique can proactively avoid potential collisions and navigate the robot through complex and dynamic environments with greater safety and reliability.

The culmination of our achievements was demonstrated in the milestone demo, where we showcased the successful integration of both the context-aware model predictive technique and the risk assessment component into the overall DARKO project navigation architecture. The demo highlighted the capabilities of our approach in enabling robots to navigate autonomously in human-populated environments while effectively considering and adapting to human movements and potential collision risks (see Figures 12 and 13).

4.6 Bidirectional communication of intent

The milestone demonstration also included an implementation of bidirectional communication of intent from T5.2. This module uses anthropomorphic intent communication by means of a Nao robot seated on top of the mobile DARKO platform (seen in Figure 4). The Nao robot acts as a “driver” and signals its intentions with human-like gestures like pointing to an object of interest or moving its head to make eye contact with a detected person, as well as spoken language. The human-to-robot intent communication in this demo was implemented using a speech recognition interface, where a user could talk about objects in the view of the robot’s camera and the Nao robot would point to the object in question and talk back about it.



(a) (b) (c) (d)

Figure 12: Rviz visualization and onboard camera image, while the robot moves in the KI Fabrik. The risk map is centered on the robot and includes detected objects, and static known risky areas (near the retractable belt stanchions).

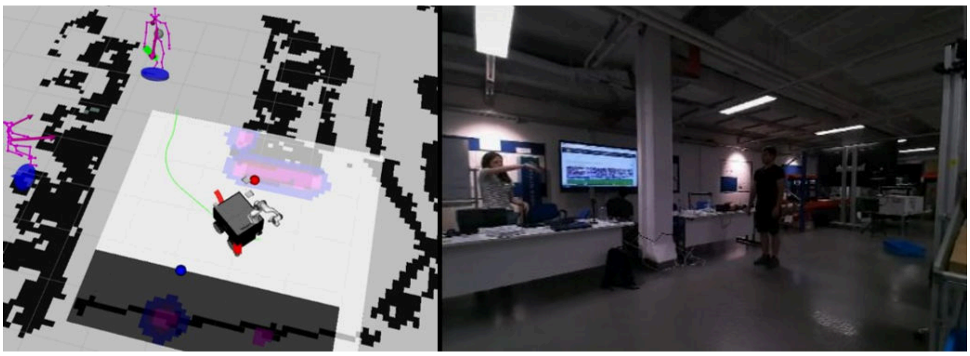


Figure 13: Focus on human skeletons detection and the constraints (blue and red markers) derived from the risk map.

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