H2020 ICT-46-2020a: Research and Innovation Actions (RIA): Robotics Core Technology

DARKO

Dynamic Agile Production Robots That Learn and Optimize Knowledge and Operations

Participant No.	Participant organization name	Participant short name	Country
1 (Coord.)	Örebro Universitet	ORU	Sweden
2	Technische Universität München	TUM	Germany
3	Robert Bosch GmbH	Bosch	Germany
4	Università di Pisa	UNIPI	Italy
5	École Polytechnique Fédérale de Lausanne	EPFL	Switzerland
6	University of Lincoln	UoL	United Kingdom
7	ACT Operations Research	ACT	Italy

Work program topics addressed
H2020 ICT-46-2020: Robotics in Application Areas and Coordination & Support

Project duration: 4 years

Name of contact person: Prof. Dr. Achim J. Lilienthal
Email of contact person: achim.lilienthal@oru.se
Fax no of contact person: +46 19 30 3463
Phone no of contact person: +46 19 30 3602

Abstract Agile Production crucially depends on the effectivity of intralogistics processes. Robots as components of these processes have the potential to be a game changer provided they are highly flexible, capable, cost- and energy-efficient, safe and able to operate in work environments shared with humans. However, the current state of the art falls short of providing these capabilities given the requirements for future production systems. Thus, DARKO sets out to realize a new generation of agile production robots that have energy-efficient elastic actuators to execute highly dynamic motions; are able to operate safely within unknown, changing environments; are easy (cost-efficient) to deploy; have predictive planning capabilities to decide for most efficient actions while limiting associated risks; and are aware of humans and their intentions to smoothly and intuitively interact with them. To maximise its impact, DARKO is aligned with use cases at the largest manufacturer of home appliances in Europe. It will demonstrate, in relevant scenarios, autonomous capabilities significantly beyond the current state of the art in dynamic manipulation (e.g., throwing of goods, picking and placing objects while in motion), perception, mapping, risk management, motion planning and human-robot interaction. Beyond its impact through improved capabilities in these areas, DARKO will provide answers to the questions where and how dynamic manipulation should be integrated as the most efficient solution in intralogistics. Since arm manipulators can, in principle, display super-human performance in terms of accuracy and repeatability, the value of integrating dynamic manipulation, e.g. throwing, into transport processes may well exceed current expectations. The DARKO consortium is uniquely placed to tackle this ambitious and challenging project. It brings together leading academic and corporate researchers, technology providers and end-users, with the required long-standing expertise.

Contents

1 Excellence

Today's robotics research shifts its focus from automated repetitive motions to more interactive robots dealing with an unknown environment, dynamic manipulation and interactions with humans. Correspondingly, a new generation of **agile production** robots is at the horizon that are highly efficient, compliant and flexible in all system layers. Such systems should be equipped by new actuation technologies that are not solely position controlled and are able to respond to contact forces with desired impedance and compliance in order to execute highly dynamic yet efficient motions using the elastic joints and inertial coupling as temporary energy tanks. In order to fulfil their potential as a game changer in the logistics domain, professional service robots are needed that operate flexibly, safely and highly efficiently in work environments shared with humans. This new generation of professional service robots for the logistics sector needs to be efficient in its operations, economical in energy use, and aware of humans and their intentions at all times to be able to smoothly and intuitively interact with them. They need predictive planning capabilities that allow to decide for the most efficient actions while keeping all associated risks at an acceptable level (higher risks are usually acceptable regarding the integrity of goods than the safety of humans) and easy (thus cost-efficient) to deploy.

DARKO sets out to research and innovate within **cognitive mechatronics**, with the aim to investigate where and how dynamic manipulation should be integrated as the most efficient solution in automated intralogistics processes. Correspondingly, it addresses relevant areas in *perception, mapping, human-robot interaction, risk management and motion planning* where the current state-of-the-art does not sufficiently support the introduction of autonomous service robots featuring the ability for *dynamic manipulation*. In manipulation, DARKO is inspired by the elasticity of biological muscles to develop an inherently elastic manipulator with flexible end-effector mounted on top of a commercial mobile platform to enable **Dynamic Agile Production Robots That Learn and Optimise Knowledge and Operations**. In particular, the project aims to exploit Elastic Actuators as the actuation technology to develop an elastic arm that surpasses the commercial manipulators in the market in terms of dynamic motion capabilities. Technically, intrinsically elastic joints enable robots to implement major characteristics of the human musculoskeletal system and demonstrate human-like performance, and in DARKO we exploit the inherent capabilities of our intrinsically elastic manipulator to culminate robot performance.

Industrial end-users at all scales, from international corporations to SMEs, are in need of innovative solutions for autonomous robot manipulation of their current warehouse facilities to increase productivity and substantially decrease the cycle time. Existing manipulators that can be mounted on a mobile base are in their vast majority limited to lightweight robots with classical motor-gear-joints and not inherent elastic joints with inherent compliance. The latest generation is equipped with sensors to measure contact forces, essential to manipulation. On-board controllers remain simple and do not exploit yet the spectrum of capabilities offered by inherent elastic joints. DARKO pushes forward the use of dynamic actuators by developing algorithms to exploit the effective compliance at run time in a reactive and feed-forward manner to enable dynamic manipulation. It seeks to generate control systems that are energy-efficient following human-like dynamics.

Today, certain types of dynamic manipulation (e.g., throwing of goods, picking and placing objects while in motion) already plays an important role in logistics processes. Many of these manipulation tasks are still carried out by humans, as automated solutions still do not match the agility, flexibility, and speed of humans. DARKO addresses the key difficulties that have so far prevented transferring this skill to autonomous robots – primarily that current robot arms are not designed for dynamic manipulation and that *dynamic manipulation comes with high demands on accuracy in perception* and *an increased importance of risk management*. On the other hand, dynamic manipulation of goods can be faster and more energy-efficient than transporting them with a heavy mobile robot.

DARKO is primarily aligned with use cases at BSH (Bosch Siemens Home Appliances) where throwing of a large number of goods (by humans) is already part of the logistics process. BSH Home Appliances as a part of Bosch is the largest manufacturer of home appliances in Europe. Currently, the parts thrown are rather small (in the order of max 10 cm), distances covered rather short (up to 50 cm) and target boxes stationary. Inspired and guided by these use cases DARKO widens the issue to the questions of how to control accurately for fast and dynamic manipulation such as throwing into moving boxes (e.g. placed on conveyor belts or on wheeled mobile robots) from a moving base – it seeks methods that can scale by demonstrating throwing of small and heavy objects, over short and long distances. Importantly, it will investigate whether and how throwing can be the most efficient way to handle a large class of goods. Arm manipulators can, in principle, display "super-human" performance in terms of accuracy and repeatability. The value of including robot throwing into logistics processes may, hence, well exceed our current expectations. Slow and imprecise perception has limited the exploitation of robots' super-human mechanical performance. DARKO seeks to endow manipulators with learned models of objects' motion dynamics to compensate for imperfect perception.

The ultimate goal of DARKO is to surpass the current boundaries in robot navigation and control which limit the efficient application of robots in warehouse intralogistics for end users at all scales. To this end, the DARKO consortium brings together academic and corporate researchers, technology providers and end-users, with long-standing expertise and strong interest in safe human-aware dynamic manipulation. In order to maximise the impact of our research and technology on the European logistics industry, DARKO demonstrates intralogistics use cases in relevant scenarios, involving a mobile platform performing dynamic manipulation in environments shared with human workers.

1.1 Objectives

DARKO has as its main overarching objective to research and innovate for *efficient and safe* intralogistics robots in agile production. These two aspects are reflected in the numbered objectives listed below. The scientific objectives are aimed at realising the fundamental enabling technology that will make intralogistics in agile production flexible, robust and easily deployable. (Measures of success for achieving all objectives are listed in the WP descriptions in Sec. 3.1.) Although the scientific objectives are ambitious, as can be seen in comparison with the state of the art described in Sec. 1.4, the consortium is uniquely placed to tackle these challenging goals, as described in Secs. 3.3 and 4.1.

O1: Efficiency in manipulation Static and quasi-static pick-and-place of objects, which is traditional in the industry, requires a reduction in velocity that reduces efficiency. Pick and place while in motion, is more efficient time-wise but comes with a wealth of challenges. It requires accurate control of the base and manipulator (with human-like performance) simultaneously to swipe the object in and out, while avoiding inadvertent collisions when humans are in the vicinity. Throwing objects, e.g. onto a conveyor belt, is also advantageous as it enables the robot to place objects outside the arm's maximum kinematic range. This can also increase time efficiency compared to driving the robot to the desired location. DARKO aims to ease such *dynamic manipulation tasks* by exploiting *inherently elastic manipulators, inertial coupling effects, flexible end-effectors* and endow robots with the required *high-speed perception*. It further develops algorithms to increase *efficiency* and *safety*. To meet this objective, a) we plan to a design an inherently elastic mechatronic arm and a compliant gripper, novel controllers with the capability of fully exploiting store/release energy mechanism b) develop real-time pick and place and obstacle avoidance mechanisms for the base and manipulator, c) dynamic model of object's dynamics for throwing. These objective are addressed by WP1, WP4, and WP2.

O2: Efficiency in human–robot co-production We will increase efficiency and safety in environments shared between robots and humans in particular by means of *learning and exploiting activity patterns*, *prediction and mutual communication of intents*, as well as a novel framework for *risk-aware planning and coordination*. This will support predictive planning of activities to ensure zero-risk of collision.

We postulate that in order for intralogistics robots to be efficient, they must co-exist with human staff. Rather than building new fully automated warehouses, end users of all scales (from SMEs to international corporations) require smart automation that can effortlessly integrate with current warehouse facilities and, for the foreseeable future, efficiently interact with human workers.

By learning the typical motion and activity patterns, and using them in motion planning and scheduling, robots will be able to plan, and also execute their planned tasks and trajectories, more efficiently (WP3, WP6). We will substantially extend our previous work on human detection, tracking, and motion prediction, as well as spatial augmented reality for communicating robot intent (WP2, WP5). Underlying this work will be extended context-aware representations for human–robot spatial interaction (HRSI), and using them in causal reasoning for inherently safe and efficient HRSI.

O3: Efficient deployment One of the main barriers to market of intralogistics robots today is deployment effort. Ease of deployment (low effort & high flexibility) is consistently listed as a top priority of industry stakeholders.

We will address the objective of efficient deployment in particular from the point of view of failure-aware and failure-resilient mapping and localisation, as well as "auto-completion" of robot maps and information transfer using map priors from heterogeneous sources (WP3). Semantic 3D scene understanding typically requires large amounts of labelled training data, and use-case specific data sets are difficult to acquire. This makes data-efficient methods particularly important, and we will develop semi-supervised and self-supervised perception methods to reduce semantic annotation effort (WP2); which will in turn contribute to better-informed localisation algorithms.

O4: Risk-aware operation for safety and efficiency Efficiency and safety in intralogistics robotics can be achieved only by including risk assessment as a driving principle for the decisions taken by one or more intelligent agents acting at shop floor level, and must be done not only locally (through decentralised risk-aware intelligence) but also globally, guaranteeing that the overall orchestrated behaviour of robots, humans and machines takes explicitly into account the probability associated to different types of risk; e.g., strain on the robot hardware, failing to meet mission criteria, as well as human safety.

Aiming at this comprehensive risk awareness and minimisation, DARKO proposes to implement a functionally horizontal risk management layer, capable of gathering risk-related data from multiple sources (WP2, WP3), exploiting it to train corresponding predictive models (WP7), and using them to track and adjust robot trajectories within a so-called *risk space*. Endowing the cognitive mechatronic system with this capability to assess and anticipate the probability of an undesired event to happen facilitates much more robust behavioural management; both off-line, when scheduling the operational tasks,and on-line, by continuous planning and control of the robot actions (WP4, WP6).

In addition to the achievement of its scientific objectives, DARKO also aims to *demonstrate the feasibility* of its efficient and safe intralogistics system for agile production in a realistic setting. This will not only serve as a milestone for measuring project outcomes, but also as a first step in exploitation of project results.

O5: Demonstrate feasibility in an integrated system The scientific objectives can only be fully effective and reach the desired impact if they are also combined and demonstrated in an integrated system in a realistic setting.

To this end, we will construct a permanent demonstrator at the ARENA2036 research campus,[1] which will be a replica of a use case combined from real-world requirements of end-users associated with the consortium through stakeholder workshops. Having access to this facility is an excellent opportunity to validate and demonstrate the system in a setting that is tailored not only to a specific end user but can be adjusted given input from a range of stakeholders in agile production.

Specifically, we aim to reach TRL 6 for the integrated system by the end of the project. Catering to this objective is the main purpose of WP8, and also WP10 and WP1 contribute significantly.

1.2 Relation to the Work Programme

1.2.1 Work Programme

DARKO targets **ICT-46-2020: "Robotics in Application Areas and Coordination & Support"**, and is designed to directly meet the specific challenge posted in this call:[2] that <u>robots are often faced with new technical and non-technical challenges</u> when <u>spreading to more and more application areas</u>, outside of large-scale mass manufacturing; and in doing so <u>reduce the barriers that prevent a more widespread adoption of robots</u>. In particular, the targeted Priority Area is **Agile Production**, and more specifically, the key application of *intralogistics*, both in factories and warehouses, that is at the heart of agile production. No production can function without a reliable and agile on-site flow of products. While building on the core technologies further detailed in the technical work packages in Sec. 3, central to our concept and methodology (Sec. 1.3) is to develop and demonstrate a cognitive mechatronic system that is <u>proved and tested through pilot demonstrators that embed within real or near real environments</u>. Specifically, we will construct a permanent demonstrator at the ARENA2036 research campus, which will be a replica of a use case combined from real-world requirements of end-users associated with the consortium through stakeholder workshops. This will be a <u>near real environment</u> where we are not limited to a single end-user site (which could lead to a kind of "overfitting" the solution to one specific user in a real environment). We will maintain an active presence, to continuously test and validate the results of the project during its lifetime, including public milestone demonstrations on a yearly basis.

The project partners (in particular ORU, EPFL, TUM and UNIPI) have been active in raising <u>awareness</u> of <u>safety, ethical, gender, legal, societal and economic aspects</u>, as well as <u>privacy</u> and <u>data integrity</u>, and intend to continue highlighting these issues also as part of DARKO. For example, via the AGAINST workshops[3] at ICRA 2019 and 2020 co-organised by ORU, where we delved into the issues listed above, as well as possible *technical methods* for addressing them, together with a multidisciplinary cast of speakers (including those disciplines closer to real-world use of robotics, such as economics, gender studies, and philosophy).

DARKO falls into **Scope a) Research and Innovation Actions (RIA) – Robotics Core Technology**. Although we include several of the Core Technologies put forth in the work programme, the gravity lies in **"Cognitive Mechatronics"**. We target the difficult challenge to make robots both highly efficient by generating inherently dangerous and fast manipulation, while remaining safe to work with by humans. We endow robots with a cognitive awareness of these two challenges, and with the ability to balance them at run time. Part of this cognitive awareness will be embedded in hardware through elastic actuators whose compliance can be modified live to mitigate risks at contact or, conversely, improving energy efficiency, when safe to do so. Crucially, we also dedicate several project tasks to *risk-aware* operation, including a multidimensional risk space framework with input from reliability-aware perception modules, which orchestrates planning and navigation tasks at all levels.

We will deliver <u>improved control</u> and <u>motion</u> in several aspects, both in terms of manipulation with novel manipulator and end-effector hardware tailored for efficiency, and associated control & planning algorithms, and in terms of motion of the mobile robot platform. Via the *novel elastic manipulator* (including mechanically compliant clutch

[1] https://www.arena2036.de/en/, see Fig. 5
[2] In this section, underlined text is exact wording from the Horizon 2020 Work Programme.
[3] http://against.aass.oru.se, https://against-20.github.io

elastic actuators) and *flexible end effector* (dexterous enough to pick a wide variety of objects and reorient them in the hand for accurate throwing) developed in WP1, we will deliver a system capable of much more energy efficient and fast manipulation and throwing, compared to the state of the art. This manipulator will be integrated on a mobile base to comprise a system that will interact with goods and products relevant for the application, as well as with existing staff. We will deliver improved motion of the mobile base by means of integrating several planning layers, including predictive planning using *long-term human motion prediction*, novel representations of *flow-aware maps of dynamics*, and *safety maps*.

This mechatronic system will have sensing and actuation closely coupled with cognitive systems, in part by means of novel perception modules that are designed for learning and adaptation by *self-supervised* training to learn site- and application-specific skills. This includes closely coupled perception for manipulation that *regress feasible grasps directly from sensor data*, including *in-hand grasp perception and re-manipulation* (WP2).

Sensing, acting, and cognitive systems are also combined for improved interaction in several ways. In WP5, we will focus on *human-robot spatial interaction* (HRSI) for more efficient co-production. In particular, we will create *new context-aware representations* of describing the relative motion of humans and robots, and use them in *causal reasoning* for human-robot interaction, to facilitate safer and more efficient HRSI during local, direct encounters. The maps of dynamics mentioned above will contribute to safer and more efficient HRSI on a global, map-level scale, enabling the robot to plan with the activities of its fellow humans in mind even before encountering them. As a further modality of improved interaction we will include an improved system for *communicating robot intents* via *spatial augmented reality*.

Critically, DARKO will also result in safer systems. Guided by Objective **O4**, the DARKO system will integrate risk-awareness (risks for the robot itself, its tasks, and the people around it) in its planning and scheduling. WP7 involves designing a *multi-dimensional risk space definition* to be used when planning, as well as learning *risk trajectories* for forecasting imminent risks. The mapping and localisation framework (WP3) will also be *failure-aware* which is crucial for safe operation. A *vehicle safe motion unit* will ensure that both manipulator and platform are adhering to motion constraints that are guaranteed to be biomechanically safe near humans, but still efficient and not too conservatively throttled.

The contributions listed above also contribute to the Core Technology of “Socially Cooperative Human-Robot Interaction”, especially efficient and safe navigation in complex work environments: via causal reasoning in HRSI, flow-aware and predictive local and global motion planning, the vehicle safe motion unit, human detection/tracking.

In addition, WP3 in particular will contribute to the Core Technology “Model-Based Design and Configuration Tools”. DARKO’s mapping system has as its main ambition to provide easy-to-use configuration tools for the mapping part of the deployment phase. In fact, one of our main driving forces (**O3**) is to make deployment easier, thus allowing also smaller players to capture value through a *transition to automation*. The system will include *automatic consistency checks* and *map cleaning tools*, as well as an improved system for *auto-completion* of the robot map using prior information, which will make it possible to do point-and-click navigation even before the robot has seen the whole site. Finally, partner ORU contributes to standardisation via its leading involvement in the IEEE working group for standard map representations for robot navigation in 2D and 3D [7].

1.2.2 Digital Innovation Hubs

As called for in scope **a)**, DARKO also dedicates resources specifically for connecting with the DIH actions arising from DT-ICT-02-2018, as explained in this section.

Of the five DIH actions arising from DT-ICT-02-2018 (DIH-HERO, DIH^2, TRINITY, RIMA and agROBOfood), the ones that are relevant for DARKO are DIH^2 and TRINITY. In the work plan (Sec. 3.1), our connection with these two DIH networks are reflected primarily in WP8 and WP10 (T8.1, T10.3, T10.4), and we have a dedicated task T10.1 for engaging with them.

The DARKO consortium is heavily dedicated to strong and reoccuring mutual interaction with stakeholders and end-users throughout the project: in eliciting the initial requirements evaluation criteria (T8.1), dissemination of results as well as eliciting constructive feedback of the goals and achievements through regular stakeholder meetings at three yearly milestone demonstrations, as well as interaction with our Advisory Board with a scientific network as well as one foot in robotics for logistics and transport.

The main objective for our collaboration with DIH^2 and TRINITY is to provide an even more solid foundation and wider interface to a broader range of interested end users and other stake holders, that might otherwise not be accessible to the consortium. We will seek out the Hubs with an aim to (i) increase awareness inside the consortium of the industrial requirements that have to be considered, (ii) assessing the technical as well as societal impact of the project together with the audience offered by the Hubs, (iii) maximise exploitation and dissemination of project results by providing the technologies developed in DARKO as modules within the architecture of the Hubs.

Task T10.1 lists in further detail how we will engage with the Hubs in the project.

Figure 1: The DARKO lead use-case: spare parts commissioning at BSH Home Appliances group from a spectrum of 140.000 parts (left). Parts of varying shapes, weights and packaging are currently being picked and thrown by hand (e.g., from cardboard boxes at the right side of the centre picture) into the target trays on conveyor belts (left side of centre picture). The parts (right) are a selection whose shape, weight and packaging is representative for around 70% of the 25.000 parts that are handled on a daily basis; 85% of the avg. throughput is achieved with only 6% of the parts.

1.3 Concept and Methodology

1.3.1 Concept

The DARKO concept draws from several use-cases in the agile production, using experience from our close and well-established collaborations with many end-users and other stakeholders from ongoing and past projects. These include, among others, end users in the food industry (e.g., Orkla Foods in Sweden, Bakkavor food production in the UK, Conad and Coop in Italy, and Condis in Spain), clothing and retail (e.g., H&M in Sweden, Asda in the UK, OVS and Benetton in Italy), as well as system providers (e.g., Kollmorgen Automation and Toyota Material Handling or Bosch Rexroth in Germany). Common to all these partners, is the need for higher levels of flexibility and automation in their operations, thus motivating the research proposed in DARKO.

The *lead* use-case of DARKO will be order picking/commissioning of home appliance spare parts at Bosch Siemens Hausgeräte (BSH Home Appliances group or BSH). BSH is a Bosch business unit, the largest manufacturer of home appliances in Europe and one of the worldwide leading companies in this sector with multiple global and local brands with revenues of over 13 bn € (2019). The spare part commissioning department at BSH manages around 140.000 different parts of which on average 25.000 are shipped in 6.500 orders per day. Due to this large variety, several order picking approaches, all according to *person-to-goods* principles are in place, from classical list commissioning, pick-by-light to pick-by-voice and others. A key aspect of this use-case is that already today, for efficiency reasons, many parts are being manually thrown into the target boxes over a distance of several decimeters. Boxes as well as the parts are suitable for this: the boxes are large (75×47 cm opening) and many parts are robust and light-weight to allow for throwing. Examples include gaskets, screws, hinges, caps, handles, or cables, see also Fig. 1. The weight of most parts is 250–500 g. End-user pain points include and are not limited to labour cost and availability, increasing average age of workers due to demographic effects and degrade of occupational health due to ergonomic issues.

This use-case highlights the concrete need within agile production for efficient on-the-fly mobile manipulation with robotic throwing and navigation in shared human-robot spaces. It is both an excellent motivation and benchmark for the five overarching research objectives detailed above, as well as an exploitation opportunity for an end-user that has concrete pain points in a significant use-case with a very large potential positive economic impact. To further maximise the project's exploitation potential, we will build up and deploy a near-real replica of the BSH use-case at ARENA2036, a German nationally funded interdisciplinary research platform for the factory of the future.

We firmly believe that the technologies to be developed are of great public and societal benefit, as we strive to develop cognitive mechatronic systems that are safe and efficient both from the point of view of the workers that will interact and work together with them, as well as for the economy at large. Nevertheless, we also acknowledge that are inherent societal risks with increased automation and that measures should be taken for public and societal engagement on issues related to the project. In the consortium's previous work; e.g., in the ILIAD project; we have actively engaged in communication with union representatives when it comes to the project goals as well as on-site data-gathering activities and experiments (e.g., when designing informed consent forms, and conducting focus group interviews about experimental results). ORU have also included perspectives on labour market effects, privacy and gender in the a workshop series at the ICRA conference (see Sec. 1.2). We intend to continue highlighting these issues also as part of DARKO.

Relation to other projects

Linked activities The following ongoing national and international activities are closely connected to DARKO. Output from these projects will serve as starting points for work in DARKO, and we will seek to exploit synergies wherever possible, as also indicated below.

ILIAD (H2020, Jan 2017 – Dec 2020) developed a heterogeneous fleet of mobile robots for intralogistics applications, focusing on long-term operation, mobile manipulation and safety in human environments. Although it shares some of the objectives with DARKO in terms of safe and easily deployable intralogistics robotics, DARKO's goals are much more ambitious in terms of mobile dynamic manipulation, including throwing and catching moving objects, and efficient human-robot co-production, based on predictive planning and context-aware human-robot spatial interactions. DARKO will build on and substantially extend the outputs from ILIAD in terms of flow-aware and reliability-aware navigation, efficient end-effectors and perception for manipulation, human-robot spatial interaction and intent communication, tracking and prediction of human motions.

I.AM (H2020, Jan 2020 – Dec 2023) develops control algorithms for robots to handle large impact. DARKO will leverage on the algorithms developed by EPFL/TUM in I.AM to enable robots to precisely throw objects into moving boxes. I.AM uses only fixed-based commercially available manipulators; however, DARKO will develop an elastic arm mounted on top of a mobile base to achieve highly dynamic motion and manipulation. Moreover, while I.AM. made it clear that it would not consider humans in the vicinity of the robot, DARKO complements this work by assuming the presence of humans and develops safety control to avoid any injury.

CogIMon (H2020, Feb 2015 – May 2019) proposed a new approach for human-robot physical interaction that involves whole-body impedance actuation and advanced skills for compliant soft catching and throwing. Their research, which goes under the name of "cognitive compliant interaction in motion", differs from the intrinsically and energy efficient compliant manipulation with elastic joints proposed in DARKO, which can bring us closer to human-like performance. DARKO will further expand the research performed during the CogIMon project. The focus will be given on the development of cognitive interaction methods, with an application on intralogistics scenarios. Furthermore, DARKO will extend the impedance control mechanisms of passively compliant robots in order to perform dynamic manipulation tasks under increased safety requirements.

Other projects In addition to the projects listed above, whose outputs will feed into DARKO, here we describe how DARKO's concept and ambition relates to that of other related projects.

REFILLS (H2020, Jan 2017 – Jun 2020) targets the use case of monitoring and sorting products in supermarkets with multiple robots, including a passive-mobility platform with a robotic arm to handle goods. Besides the different use case scenario, DARKO's objectives include more advanced solutions for autonomous navigation, as well as new research in hardware and software technologies for dynamic manipulation of moving objects.

PAN-Robots (FP7, Nov 2012 – Oct 2015), while also focusing on cost and energy efficient robotic solutions for intralogistics applications, proposed relatively limited technical innovations compared to DARKO. In particular, range-based navigation and local planning in static environments in the former are replaced by multimodal SLAM and global planning in the latter, with the addition of advanced capabilities for dynamic manipulation and safe operation in human environments.

SafeLog (H2020, Jan 2016 - Jun 2020) focused on the development of large-scale flexible warehouse systems where humans and robots collaborate. Although one of their objectives has been to provide certifiable safety in shared human-robot spaces, this is addressed by using safety vests and ad-hoc environment sensors, instead of the robust robot perception for human detection and tracking proposed by DARKO. Their project also does not address the challenges of mobile manipulation.

ColRobot (H2020, Feb 2016 – Jan 2019) is a recent project on mobile manipulation for human-robot collaboration, in which the robot assists the operator by delivering tools and parts for assembly tasks. Their solutions have been validated in real world scenarios of the automobile and aerospace industry, using ad-hoc environmental and wearable sensors to guarantee human safety during robot navigation. DARKO proposes a more flexible perception system using only onboard sensors for safe robot navigation and manipulation, and further advancing the state-of-the-art of dynamic manipulation by handling objects in motion.

FourByThree (H2020, Dec 2014 – Nov 2017) developed new modular robotic solutions for human-robot collaboration, including spring-based safe actuators, which have been tested in four pilot scenarios for industrial manipulation tasks. DARKO instead proposes an alternative technology for dynamic manipulation, using robotic arms with elastic joints that are mounted on autonomous mobile platforms, and which operate in different application scenarios (i.e., intralogistics).

THOMAS (H2020, Oct 2016 – Sep 2020) considered industrial scenarios similar to CogIMon, but in this case adopting a dual-arm mobile manipulator to assist workers in a typical shop floor. DARKO differs from this project in robot manipulation of dynamic objects, as well as in the advanced and newly proposed perception skills for predictive planning and human-robot spatial interaction for warehouse environments.

VERSATILE (H2020, Jan 2017 – Dec 2019) is another project focusing on dual arm robots for advanced and reconfigurable manipulation tasks. Although both static and mobile manipulators are considered, robot manipulation is mostly confined to semi-structured environments to replace the human operator. Besides these differences, DARKO's dynamic manipulation will also handle moving objects in highly dynamic, populated environments.

1.3.2 Methodology

The project will work towards a final integrated demonstrator (**O5**), showcasing how the different components can work together in a system that is close to commercialisation. The demonstrator will be guided by the BSH use case described above, but adjusted to better highlight novel scientific contributions that are not directly applicable in the BSH scenario, and contributions that apply to other use cases of intralogistics in agile production. ARENA2036 will be used throughout the project for development and testing. A repeatable demonstrator addressing all aspects addressed in DARKO will be developed. This demonstrator will also be used as a dissemination tool for increasing the exposure of DARKO's results towards the public and other stakeholders.

The activities can be roughly divided into three phases. In Phase A (month 1–24) the final platform is not yet available. While development of the final platform is ongoing, remaining work packages focus on developing the general software architecture, a system demonstration in simulation (with mock-up modules where necessary), and a simple proof-of-concept demonstrator, using the initial hardware platform developed in Task T1.1. In Phase B (Year 25–42) the final platform, including the novel elastic manipulator and end-effector hardware will be made available to the consortium. This phase incrementally increases the integration between individual components from Phase I. The milestone demonstrations (MS2 and MS3) will show individual components demonstrated at TRL 5 and 6,[4] although the system as a whole may still have a lower TRL. In Phase C (Month 42–48), efforts will shift more towards full system integration on the final hardware platform (see Task T1.4). This implies verification and validation of all interfaces, adjustments of the models and algorithms using the experimental data collected at Phase II of the project. At this phase the focus is placed on extensive experimentation and integration. As is also apparent in the Gantt chart (Fig. 7), the last months of the project are dedicated to integration, validation and dissemination, as most scientific work packages should be finalised at month 42.

The final demonstration (MS4) will showcase a system with TRL 6: an integrated system prototype will be demonstrated (over an extended period of time) in an industrially relevant environment.

1.4 Ambition

This section describes how DARKO will extend the state of the art in several key technologies.

Elastic-joint manipulation Energy efficiency has always been one of the main objectives of robotics [171, 206]. This is even more relevant in case of mobile robots [170, 228, 154]. Guaranteeing the efficiency of the intralogistics is particularly important to warrant the use of automation in place of human labour. In DARKO, by efficiency we mean to correctly manage the energy passing by each robot joint in order to maximise the performance in manipulation tasks. DARKO seeks to achieve this objective by improving the efficiency through the *design* and *energy-aware, possibly optimal control* of an intrinsically elastic robot. Its links and inherent joint elasticities as temporary energy tanks enable efficiently storing, releasing and transforming to kinetic energy in the joints, which facilitates dynamic manipulation tasks and demonstrating human-like performance [98]. By intelligently controlling at run-time the robot's elastic actuators it is possible e.g. to minimise the cycle time of the picking and placing tasks in case of both moving or fixed objects/boxes, maximise speed, energy efficiency, distance of throwing and the success rate of picking moving objects as well as of placing and throwing them in moving or fixed boxes.

Related to this ambition, in previous studies, TUM has significantly contributed to research in the field of compliant actuator and compliantly controlled system and was substantially involved in the development of numerous projects such as the DLR lightweight robot LWR III [157, 27], the hand-arm DLR system [85] and the humanoid robot DLR Justin [31]. Parts of the concepts and technologies were successfully transferred to the lightweight robot KUKA LBR[5] and after further development, commercialised with the FRANKA EMIKA® lightweight robot.[6] Most recent developments include a test-bed for a pneumatic joint with an antagonistic actuation concept and real-time compliance control [249]. These concepts also laid the foundation for the development of the compliant and impedance controlled 2-dof prosthesis "μLimb" based on torque controlled joint modules. For the design of the elastic manipulator we will use our experience from the previous work performed at different projects.

For what concerns the generation of optimal control strategies for increasing performances in cycle motions, UNIPI presented a methodology to optimally adjust stiffness profile in variable stiffness actuators for reducing the

[4] Using the definitions in General Annex G of the work programme.

[5] https://www.kuka.com/de-de/produkte-leistungen/robotersysteme/industrieroboter/lbr-iiwa

[6] https://www.franka.de/technology

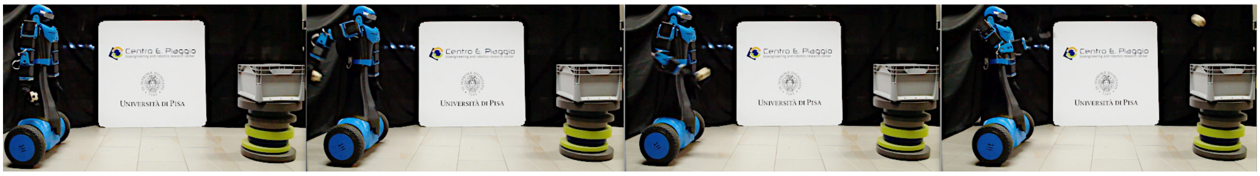

Figure 2: EGO robot at UNIPI while throwing a ball into a box.

energy cost for mechanical systems that perform desired tasks [257, 256]. Similarly, an optimal methodology for determining an efficient walking cycle for a planar biped with elastic joint was instead presented in [81]. For what concerns the generation of optimal control policies for increasing performance in very dynamic tasks, UNIPI presented the problem of choosing the inputs that maximise the velocity of a link at a given final position but free final time [79], e.g., for maximising the effect of a hammer impact, and at a given final position and fixed terminal time [78], e.g., for maximising performance of a first-time kick. Finally, during the writing of DARKO, UNIPI has experimented a proof-of-concept of throwing a ball in a box positioned one meter away from our EGO robot which is a robust and versatile mobile system with a functional anthropomorphic upper-body powered by variable stiffness actuators that exhibit a stiffness behaviour similar to that of human muscles (see Fig. 2). The upper body is mounted on a two-wheels self-balancing mobile base to minimise the robot footprint and increase agility.[7].

End-effector design DARKO includes in its core efficient picking, placing and throwing of single items, which differ in size, weight and consistency – i.e., both rigid and soft.

A wide overview of the most recent development in gripping devices can be found in [65]. Currently, the most employed devices used to accomplish such tasks are mechanical and vacuum grippers. Vacuum grippers are widely employed for grasping and usually they approach the upper side of the items [223, 8]. Mechanical end-effectors for prehensile tasks are certainly the most widespread and some of them fall into two categories which can be considered to be polar opposites: simple grippers and complex anthropomorphic hands. Simple grippers have few degrees of freedom (DoF), generally one or two. They feature a reduced complexity in terms of hardware components, a simple kinematic structure and a basic sensing system. With such complexity reduction comes simplicity in motion planning, actuation and control. However, the downsides lie in low flexibility and specialisation to limited types of tasks. Conversely, complex hands are the subject of a large body of research. They incorporate many DoFs into multi-fingered hand designs aimed to imitate some of the human hand characteristics [200]. Several four- and five-fingered hands are able to perform grasping tasks using the palm and the inner surfaces of the fingers. They feature extraordinary adaptability; e.g., the ability of a prehensile device to follow the external shape of an object resulting, to some degree, in a robust enveloping grasp.

Notwithstanding the research effort and devices presented in the literature [200], still there are no end-effectors that fulfil the needs of an efficient logistics robot that match the use case of DARKO: that is grasp a large variety of objects and at the same time quickly move their fingers to accomplish picking and placing fast enough to grasp objects in motion, as well as throwing them. DARKO will *improve existing end-effectors* in terms of the following characteristics: (i) *low-reduction-ratio-high-power-density synergistic actuation* to enable quick pick and place movements, (ii) *in-hand manipulation skills* to re-orient the object for placing in motion and throwing, (iii) *sensing elements to estimate the object pose*. To achieve this objective, the consortium will leverage existing technologies. Concerning soft grippers, UNIPI designed the WRAPP-up system: a novel human-inspired dual-arm robot for intralogistics. Its development relies upon the observation of the techniques used by human pickers in warehouses. Based on these observations we designed a dual-arm robot composed of two 7-DoF manipulators and two different end-effectors: an adaptive end-effector able both to grasp a large variety of objects and to stably interact with different shapes and a tray with an actuated belt. Furthermore, we encoded the human observed picking strategies into parametric motion primitives adopted in the trajectory planning of the robot. Relevant to DARKO is also our recent work on a grasping robot for food industry: the SoftHandler [11]. This is composed by a parallel manipulator powered by Variable Stiffness Actuators [40] and a soft gripper able to autonomously perform bin picking of fruit and vegetables[8].

3D scene understanding A key enabling technology in order to achieve the goals of DARKO is to obtain a robust understanding of the environment that the mobile robot is operating in. A broad understanding of semantics, 3D geometry and scene dynamics provides the necessary context to motion planning, mapping/localization and human-robot spatial interaction, and increases safety and efficiency by enabling robots to take more informed decisions.

Tremendous progress has been made in 2D computer vision, particularly object recognition [281, 153, 115, 248, 28], through deep learning-based methods and benchmarks based upon large-scale datasets which are often crowd-

[7]https://www.dropbox.com/sh/yp6i45o5f7e3r4w/AACE_cdAcZvvfT8FkzcF2_TQa?dl=0
[8]https://www.dropbox.com/s/kzd5eki30qwx3w2/Angelini_RAM19.mp4?dl=0

sourced from the internet [148, 141]. However, the challenge for robotic applications is to transfer these results into 3D space [89, 149, 280]. Existing systems often rely on multiple cameras, RGB-D sensors or 360-degree lidar, and combinations thereof [203, 150] in order to increase the limited field of view of vision-based sensors while retaining the geometric accuracy of lidar-based systems. Omnidirectional cameras with a wider field of view are recently becoming more popular, but so far only few mobile robotics use-cases like [168] explore related deep learning-based approaches in detail. From an application perspective, most research on 3D scene understanding is focused on domestic applications [234, 203, 164, 63] and autonomous driving scenarios [82, 203, 66], but recent experiences gained in the ILIAD project show that methods for instance from the autonomous driving domain [266, 142] do not easily transfer to other domains such as intralogistics. Besides domain-specific peculiarities in the data, such as low ceilings in indoor environments, one reason for this is that most approaches for 3D object recognition are strongly supervised and require accurately labelled 3D groundtruth. However, publicly available datasets of sufficient size to train deep neural networks in such industrial contexts are scarce due to necessary protection of privacy, security and intellectual property. One way to approach the lack of data is to develop simulators that generate synthetic data with precise 3D labels [181, 164, 163], which Bosch began to explore in ILIAD for the 3D human detection task [151].

Human detection and tracking has a research community of its own [143, 19], and partners Bosch and UoL have extensive background in the field [150, 149, 269, 19]. While a lot of the underlying concepts are similar to more generic object detection and tracking approaches, unified approaches that handle both tasks using a shared structure to exploit synergies are rare. Instead, research on the adjacent topic of 3D human pose estimation often uses methods specifically targeted at the articulated nature of human bodies with their strong variation in shape and appearance and specific dynamics [280]. Methods based upon volumetric heatmaps, including work that Bosch has contributed to [221, 222], have shown to provide good localization of body joints in 3D space, but these top-down root-centric results still need to be combined with a 3D detector to achieve global localization in the scene. Here, the contextual modeling of interactions and relations with other individuals and objects in the 3D scene, which can help to explain and resolve partial occlusions, is currently underexplored.

In DARKO, we will address several of these open issues. To facilitate efficiency in human-robot co-production (**O2**), we will extend the existing human detection and tracking system developed during the ILIAD project with the ability to estimate metrically accurate, articulated 3D human poses using the robot's onboard sensors. For this, we will close the aforementioned gap and bring together existing RGB(-D) methods for 3D object recognition, human detection [149] and 3D human pose estimation [222] that have so far been developed independently. Inspired by [209], we believe that significant synergies can be exploited by *combining the underlying methods into a single, unified module for 3D scene understanding* and leveraging multi-task learning across relevant datasets, in order to reduce computational overheads and improve cost-efficiency. To improve robustness and bridge temporary occlusions, we will further explore novel strategies – e.g. based upon graph neural networks – to *incorporate spatio-temporal relations and interactions with the environment* into such models.

One of our key ambitions for 3D scene understanding is to strive for more efficiency when deploying mobile robots in industrial scenarios (**O3**), by requiring significantly smaller amounts of labelled 3D training data specific to the use-case. To achieve this, we will study and devise novel *data-efficient perception approaches* based upon semi-supervised and self-supervised learning, and show that these can work in the DARKO context. Using appropriate transfer learning techniques [239, 52] to reuse knowledge from conventional real-world image datasets, and by extending existing 3D simulations [151, 181], we will *incorporate new sensor models* for panoramic cameras [21] in order to cover the necessary field of view that is required by DARKO's higher-level reasoning tasks with a minimum amount of sensors, thereby *improving computational and cost efficiency* over existing, more complex multi-view sensor setups that are e.g. common in autonomous driving scenarios.

Finally, we will stress the *real-time capability* of the developed algorithms, and overall, aim at particular robust and safe holistic perception of humans and the overall 3D environment, as needed for risk-aware operation that takes both safety and efficiency into account (**O4**). Therefore, in summary, our planned research on 3D scene understanding will address important challenges that are tightly related to the DARKO objectives (**O2**), (**O3**) and (**O4**).

Perception for picking and throwing of objects Perception is a fundamental capability required for autonomous object manipulation in *unstructured* environments. Accurate and efficient 3D perception for autonomous item handling is especially sought after in intralogistics industry [3]. The demand is also reflected by a number of commercial products available in the market e.g. Photoneo AnyPick[9], MVTec HALCON[10]. However, existing solutions usually depend on accurate depth measurements from expensive industrial-grade sensors (e.g. Photoneo PhoXi[11], Zivid One Plus[12]) and can usually deal only with *picking* of rigid known objects or limited number of object shapes. Therefore, they fall short of meeting the requirements imposed by the scenarios envisioned in DARKO. Our ambition is to bridge

[9] https://www.photoneo.com/anypick/
[10] https://www.mvtec.com/products/halcon/
[11] https://www.photoneo.com/phoxi-3d-scanner/
[12] http://www.zivid.com/zivid-one-plus

Figure 3: The figure on the left demonstrates typical shelving with storage boxes of spare parts for commissioning at BSH Home Appliances group. It exhibits the main challenges for modern perception systems. Namely, the parts are either neatly stacked or tightly piled within the storage boxes making it difficult to perceive boundaries between the objects. Most of the objects are packed in transparent and deformable plastic bags introducing significant noise in depth measurements even from high-end RGB-D sensors. This is reflected in the example scan (right) of a mock-up scene (center) obtained by an industrial-grade sensor Photoneo PhoXi where majority of measurements are missing.

this gap and solve the unique perception challenges that arise directly from the project's lead use-case: namely, the recognition, pose estimation and tracking of spare parts stored in plastic bags. We aim at developing perception modules that recover the configurations of these objects throughout the manipulation cycle: for grasp acquisition from heaps, piles or trays (Fig. 3); during handling within a gripper; and during placement or flight towards a target bin.

Object detection and pose estimation for the purposes of manipulation have been extensively studied [109]. In reference to bin picking for known objects, robust solutions already exist [128]. The above methods are tailored to rigid objects with known geometry or appearance, and almost inadvertently are used in the context of top-down grasping with a parallel jaw gripper or suction cup [274]. Methods that operate for unknown objects and support complex grasp acquisition have also been proposed [30, 74, 237], but generalisation between different object types and stacking configurations is still an open problem. Detecting objects wrapped in semi-transparent material is even more challenging. Special care needs to be taken to counter perceptual disturbances, caused by transparent materials. Recent approaches [216] learn to estimate the shape of transparent objects from RGB-D images and supervised examples, but only work for known rigid objects. Prior work [275] has also demonstrated that end-to-end learning of grasps from perceptual data results in more robust grasping when a more complex task is included in the loop: that is, picking an object and throwing it requires more stable grasps than just lifting the target object. These results are encouraging, and our ambition within DARKO is to extend prior work to the more challenging scenario of unseen objects wrapped in deformable plastic bags (see Fig. 3). Object pose estimates are needed throughout the manipulation problem: especially so as the manipulation task increases in complexity. Prior work has demonstrated that pose can be recovered, even when objects are nearly completely occluded by the gripper [261], but requires knowledge of the precise object geometry. Even in the case that object models are available, the presence of plastic bags in the DARKO scenario entails that methods based on visual perception alone would still suffer from degraded RGB-D sensing.

In DARKO we will go beyond the state of the art by developing a robust end-to-end perception for manipulation system capable of *selecting appropriate grasp configurations for previously unseen objects*. The envisioned system will be trained to filter out visual interference caused by plastic wrapping and environment variation and to select *task-appropriate grasps*. We will go beyond top-down picking and simple parallel jaw grippers and aim at regressing full grasp configurations for *complex underactuated grippers*. The developed system will in addition aim to push the state of the art in terms of execution speed, where we aim at *instantaneous recognition* at realtime operation at sensor frame rate. In addition, we aim at pushing the state of the art in terms of in-hand object perception by fusing proprioceptive and exteroceptive sensing modalities to reconstruct object inertial properties and infer the suitability of the current grasp with respect to a given task (object placement or throwing into a target bin). The above technologies will be demonstrated in an integrated manner and are critical in enabling picking and throwing objects while moving.

Mapping and localisation Although there have been great advances in methods for simultaneous localisation and mapping (SLAM), the state of the art still does not allow efficient and reliable deployment of robot systems by non-expert users, nor fail-safe long-term operation in uncontrolled environments. This issue has been raised by several industrial participants (e.g., Magazino, Kollmorgen Automation, Bosch Rexroth in the ERF[13] workshops on robotics for logistics and transport) and was also a main driving force in our previous project ILIAD, guided by needs elicited from logistics stakeholders. These limitations stem from *unsolved fundamental questions* relating to failure awareness and adaptivity [36]. Developing mapping methods that are fail-safe and self-tuning in new environments is of great practical significance (as deployment and long-term operation is a significant barrier to market for deploying

[13]European Robotics Forum

robots today, in the intralogistics sector and beyond), and would bring about a step change to the field. Therefore, DARKO's overall ambition w.r.t. mapping is to enable *hands-off, failure-aware and failure-resilient* construction of rich map representations (beyond mere geometry), and exploit them for reliability-aware localisation in shared dynamic environments.

Many solutions for robot mapping have been proposed, many of which can demonstrate good quantitative results on benchmark tests such as the KITTI benchmark [82]. In earlier work, ORU have also developed the 3D-NDT method [160] and variations thereof [236, 10], which perform favourably in benchmark comparisons [161] and have been widely deployed; e.g., in the "Natural Navigation" product for AGV localisation marketed by Kollmorgen Automation and Toyota Material Handling,[14] as well as the AutoWare framework[15] which is qualified for driverless vehicles on public roads in Japan since 2017. The current leader in the KITTI benchmark is the (V-)LOAM method [277, 276]. LOAM [277] separates edge and planar parts of scans for better data association in scan matching. Using a similar idea, other recent developments have shown that including semantic segmentation in the objective function of scan matching [272, 271, 12, 105] can help increase robustness, both in variants of Iterative Closest Point (ICP), NDT, and other frameworks. Notwithstanding the benchmark results, state-of-the-art methods can still fail without warning, e.g., when (rotational) speed is too high, or there is a lack of reliable features, or the environment has changed. The above references relate to lidar-based SLAM approaches, and the same applies for current methods for Visual Odometry [179, 244], where tracking failures can occur spuriously. While catastrophic failures can be detected with ad-hoc measures (point-to-point distances), more subtle drifts and mis-matches are harder to spot algorithmically, as thresholds are heavily environment-dependent. What is needed, then, are methods for automatic map quality assessment. Most existing work has been done in the context of competitions and SLAM benchmarking [226]. Such methods, even though they are very useful in competitions, are not applicable for new deployment, where a reference-free map quality assessment is needed. Existing implementations that maintain an estimate of the confidence in localisation, given a known map, typically employ a Bayesian filter (e.g., particle or Kalman filter) and use the estimated covariance of the posterior. However, that is not a reliable indicator, and is prone to both overconfident and underconfident estimates. Other methods for directly assessing the quality of scan alignment have to a large extent been ad hoc [231, 162], although some recent contributions treat the problem in a more systematic way [2, 6]. While SLAM is typically run in an environment-agnostic way, there is also much to be gained by exploiting prior information that may be available about a site, especially for efficient deployment in a factory or warehouse. Some recent work has explored localisation in existing CAD drawings [29, 258], non-rigid alignment and merging of layout and robot maps [83, 172], and even hand-drawn sketch maps [173, 159]. There is also related active work in learning-based methods for matching range scans with satellite imagery [245]. However, most of these methods assume both map modalities to be mostly consistent and with a constant scale factor. This assumption is not valid when working with prior indoor maps (emergency evacuation maps, or as-planned CAD drawings) which typically have locally varying scale errors, and potentially large discrepancies in terms of clutter or walls that have been added or removed. In recent work [172] we have shown how one can achieve mutual map improvement by incorporating also uncertain prior map information in the SLAM process; while at the same time forgoing exploration and use the prior map to "auto-complete" the robot's map. However, current limitations include being dependent on corners for data association between the map modalities, as well as an inability to perform global localisation in uncertain prior maps. Very robust SLAM back-ends is another important research direction, since data association is inherently difficult for maps of different modalities and with semantic features coming from deep-learned object detectors. Modern approaches use, e.g., an ensemble of robust back-ends [172] or probabilistic data association [56], but joint compatibility approaches for data association, as well as more discriminative descriptors, is likely to improve the state of the art.

In DARKO, we will contribute both to failure-resilient and failure-aware mapping and localisation methods. For *failure-resilience*, we will extend the state of the art in terms of self-supervised learning of semantic classes that aid scan matching for mapping and localisation (T3.1 and T2.1), which will provide benefits of modern scan matching also in environments where pre-labelled training data are not readily available. We will also work on the theoretical foundations of the NDT representation, to investigate alternative statistical models that may help robustness where scan data are sparse. For *failure-awareness*, we will work on reference-free self-assessment of map quality by means of self-supervised learning of valid surface configurations in 3D. We have seen in preliminary work that this may be used for automatic map cleaning and clutter removal. We will also build on recent [6] and ongoing work on measures for detecting slight misalignments of scan data for early detection of imminent failure; in particular by measuring local relative entropy between scan pairs (see T3.4). Finally, we will advance the state of the art in heterogeneous map merging for more efficient deployment (faster exploration) through incorporating semantic segmentation for inter-map data association, and mutual transfer of information (from prior to robot map and vice versa).

In summary, these contributions will substantially reduce the deployment effort (**O3**) by making the manual tasks of map surveying, verification, refinement, and cleaning easier; as well as improving long-term operation in dynamic environments via more robust, and failure-aware, mapping and localisation.

[14] https://youtu.be/QnIlmWOYsdo

[15] https://www.autoware.org

Maps of dynamics As robots enter human-inhabited spaces there is a drive towards efficient co-working with people, as opposed to simply treating people as obstacles. Critically, there is a need to go beyond geometry reconstruction. To that end, robots need to acquire and encode *actionable* higher-level understanding in map representations, and to do so without extensive re-training in new environments. The emerging topic of *maps of dynamics* (MoDs) is concerned with map representations that encode patterns of changes – typically, flows of people and vehicles [136]. These types of maps make it possible to include statistical information about environment dynamics already in the *planning* phase, so that the robot can anticipate which path to take in order to best avoid going against the flow, even before seeing a particular place along the route. This way, the robot can interact with workers on site in a way that is both safer, more efficient, and less intimidating, compared to a robot that is unaware of the site-specific flow patterns.

The state of the art in MoD representations include FreMEn [131] (modelling periodic occurrences of binary state variables), STeF-map [177] (periodic patterns in discretised motion directions), and CLiFF-map [135] (continuous multimodal flow models, without periodicities). A common limitation is that these require long-term data, and lack online update mechanisms. Periodic representations [131, 177] assume that observed frequencies extend infinitely, which limits flexibility and requires manual setting of the expected period length of a reoccuring pattern.

In T3.3, DARKO will push the state of the art in MoDs in all these directions: by studying data imputation methods for alleviating temporally and spatially sparse data, by online consistency verification in order to to add or remove components of the MoD model and properly handle ranged periodicities, and also by clustering consistent patches of flow patterns in order to improve flow-aware motion planning [243].

Safe Manipulation Increase in demand for robotic technologies fosters the use of safety concepts and regulations for safe physical Human-Robot Interaction (pHRI). Basically, accidental collisions that endanger human safety should be avoided by predicting dangerous situations in advance, and the effects of unforeseen collisions should not exceed a certain level of injury. Recent progress in torque-controlled, dexterous and intrinsically compliant robot arms, which enables dynamic manipulation and in particular physical human-robot interaction, has caused new safety concerns. Lack of data, standards, sophisticated safety algorithms and methods are critical drawbacks for embedding this new generation of robots into intralogistics applications.

Collision detection and reaction were widely studied to implement safe reaction strategies after collision [53, 96]; however to make an unforeseen collision safe, biomechanical injury data [91, 92] for formulating the safety limits is necessary. Thus, a new paradigm called Safe Motion Unit (SMU) was proposed to exploit the injury database information and the robot configuration to shape the safe velocity profile in order to ensure human safety [100]. Later the concept was developed to make a global perspective of a robot's collision safety [167]. Potentially, SMU can impose constraints on robot velocity upon human detection around the robot. This may reduce the range of velocity and efficiency, which was addressed in a recent study [166]. Alternatively, we can increase the safety level in design by using the intrinsic joint elasticity to improve collision safety [188].

DARKO pursues the goal of increasing efficiency, without neglecting safety. Dynamic manipulation as envisioned in the project demands a higher range of velocity, beyond safe velocity that comes from SMU once a human is around the robot. Such dynamic manipulation can hence be performed only when there is zero risk of injury. In this regard, DARKO develops the SMU and safety map for intrinsically elastic robots while integrating human state and prediction and the risk map to ensure human safety. Our proposed safety module will be capable of generating fast and safe velocity shaping for inherent elastic manipulators by relying on a predictive low-level motion interpolator.

Planning and control of manipulation and grasping of objects in motion One of the main goals of DARKO is to endow soft robotic end-effectors with advanced autonomous grasping and manipulation capabilities with particular emphasis for objects in motion. Moving close to the human skills still represents an open issue, especially for the case of dynamically manipulating objects for their use. Indeed, while a lot of effort has been devoted to the mechanical design of these adaptable end-effectors, their potential for autonomous grasping is still largely unexplored, due to the lack of suitable planning and control strategies [46, 252] that are limited to stationary objects. Moreover, [252] requires accurate knowledge of physical parameters which are rarely available in real hands and real objects. [112] formulated the combined problem of grasp contact selection, grasp force optimisation, and manipulator arm/hand trajectory planning as a problem in optimal control. This work also did not address the problem of grasping moving objects, although it considers the finger contact forces that are needed for moving an object after it has been grasped. One of the most investigated solutions to the problem of generating meaningful and safe robot motions is to ensure their human-likeness [60]. State-of-the-art techniques are usually model-based and rely on the analysis of kinesiology-related literature to identify possible features that can be used for optimisation problems; e.g., through jerk minimisation for robotic planning algorithms [32]. Other approaches exploit learning methods to compute a set of parameters for non-linear dynamical systems [178, 196]. However, although promising, all these techniques come with some limitations, which are mainly related to the unavoidable approximations of the real phenomenon they introduce – which may affect the variability of the planned motion – or the unbalanced trade-off between the achievable performance and the computational cost. For what concerns the potential of soft end-effectors for autonomous grasping, machine learning tools have recently been employed, e.g., combining learning by demonstration with reinforcement learning [90], or applying autoencoders and generalised regression neural networks [180]. Learning methods have also preliminarily been used for grasp-failure characterisation based on object and manipulator poses and loads of the actuators [232].

To overcome the limitations of the state-of-the art solutions related to the twofold problem of motion generation and soft-end effector control, in particular for moving objects, we propose a hybrid approach. More specifically, on one side, we plan to directly embed human principal motion modes (e.g., characterised through functional Principal Component Analysis – fPCA) in the optimisation algorithm for the generation of anthropomorphic robotic manipulative actions, moving from the search for optimal paths to the identification of a reduced number of scalars weighting the functional components. This can enable to rapidly achieve a solution for the planner, which is intrinsically human-like. On the other side, we intend to develop integrated end-to-end data-driven deep learning architectures, which can suitably translate the human example and purposefully exploit raw sensory data to endow soft grippers with autonomous advanced grasping capabilities. We believe that these solutions have potential to also accomplish the tasks of grasping objects in motion that are envisaged in DARKO.

For generation of human-like trajectories, UNIPI previously presented a motion generation algorithm based on the optimal combination of human data-driven functional modes (fPCA). This method was preliminarily theorised in [15] and extended for its usability with generic redundant anthropomorphic manipulators, whose kinematic architecture differs from the one used to extract human functional modes [14]. In DARKO, we will consider the extension of these techniques with different kinematic chains, either serial or parallel. For what concerns the end-to-end methods for soft end-effector control, UNIPI recently presented an approach to enable soft hands to autonomously grasp objects, starting from the observations of human strategies [220]. Visual information on the object scene was fed through a deep neural network to predict which action a human would perform. In this manner, we defined the evolution of the soft hand mounted on a manipulator as a combination of anticipatory action and touch-based reactive grasps. The latter was based on IMU data [24], which we also very recently exploited [13] to predict grasp failure through deep learning with different types of soft robotic hands. In DARKO we will extend this approach and apply it in situations that go beyond "single-table-top object" scenarios for further generalisation.

Object throwing Throwing is one of the key dynamic manipulation tasks considered in DARKO. For the past decade, robotics has shown interest in the action of throwing objects primarily to extend their operation space and allowing them to perform manipulation tasks within a wider range compared to conventional placing actions [155, 195, 247, 278]. This capability also contributes towards more efficient robotic systems since the time required to perform the action is considerably less compared to navigating towards the placing location; and in many cases the energy cost of throwing and object is also lower than moving the whole platform. Thus, the significant advantage of efficiency makes the ability of robotic systems to throw objects very important for application within intralogistics scenarios where the requirements for placing accuracy are low.

The majority of works on object throwing tasks focuses on the development of motion planners, capable to provide the necessary trajectory profiles alongside with states for releasing the object [195, 278]. Such methods take into account the dynamic and kinematic constraints alongside with the the object release state, resulting in a constraint optimisation problem which is solved using either sampling-based [278] or nonlinear optimisation methods [155]. Furthermore, the derivation of the optimal release state usually derives from analytical physics models which take into account the distance with the target and the dynamic state of the manipulated object at the moment of release. The aforementioned motion planning approaches have disadvantages in terms of time efficiency since they have to re-plan the trajectory in case of external perturbations. Moreover, the models which are used for the derivation of optimal object release states and throwing trajectories can be hard to derive. An alternative approach, in order to achieve compliance to external perturbations, is the use of time-invariant dynamical systems with stability and convergence guarantees as robot control policies [68]. Such approaches have been successfully applied to dynamic manipulation tasks such as catching objects in flight [217]. Such task shares many common characteristics with object throwing since it has requirements for dynamic motion generation and coordination between the gripper and the manipulator. Furthermore, dynamical systems can be learned from human demonstrations [123] which allows the data-driven derivation of optimal policies without the need of computing physical based models. Additionally, the use of coupled dynamical systems [230] can provide the desired coordination between the gripper and the manipulator in order to efficiently release the object.

DARKO will extend the research on robot throwing through dynamical systems in two-ways: first, it will seek to find optimal coupling of arm-gripper dynamics to achieve energy-efficient and error-prone releases, exploiting the concept of coupled dynamical system; second, it will address the need to generate energy-efficient arm and gripper motion. Optimal control will be used in an off-line manner to determine the optimal dynamics for a variety of object. Trajectories so generated will then be embedded through learning in a closed-form expression via dynamical systems encoding. The dynamical system encoding is advantageous over running optimal control live, as it avoids to solve for an optimisation and enforces feasibility. To guarantee safety, we will use obstacle avoidance through

Figure 4: In DARKO we will enhance the efficiency and the accuracy of state-of-the-art long-term human motion predictors. **Left**: Long-term human motion predictions in the ATC shopping mall [33] obtained with our background algorithms [212]. The current position of each person is indicated by a yellow circle, ground truth trajectories are shown in white. **Right**: Semantic-aware long-term human occupancy prediction, on left hand side an urban scene from the Stanford Drone data-set [208], on the right-hand side the predicted occupancy distribution.

dynamical systems [117], and derive stability and convergence guarantees under kinematics and dynamics constraints. Additionally to the manipulator and the gripper, we will explore how the mobile platform can also contribute to the throwing task by coupling its motion with the other robotic agents in order to achieve a wider range of object throwing. As humans can generate highly energy-efficient throwing motions, we will record human throwing motion, using very fast accurate vision system available at partner EPFL. This data will inform models of coupling of dynamical systems to determine the dynamics of release time. Use of electromyography (EMG) sensors will also be considered to determine the magnitude of human efforts along side the throwing motion.

Human-robot spatial interaction Intent communication between robots and humans is key in ensuring smooth and safe human-robot spatial interactions [51]. In the direction robot-to-human, ORU previously developed a Spatial Augmented Reality (SAR) system to enable a robot forklift to communicate its navigation intent on the shared floor space and evaluated it [43, 42, 41] with encouraging results and also discovered the limitations with such a mode of communication. In this direction, we will investigate what more a robot forklift could communicate in addition to the navigation intent, and how the robot's intent communication ability can be improved by using other modalities in addition to SAR. In the direction human-to-robot, a key to the safety control approaches envisioned in DARKO is human detection and tracking (which is covered as part of 3D scene understanding, p. 10). Yet, detection is only solving one part of the problem. In order to enable safe human-robot spatial interactions [18], we need models of human behaviour that take into account sensing uncertainties, imperfect environmental challenges, but also social and psychological aspects characterising the large variety of human movements in real-world scenarios [37].

For example, understanding and anticipating human intents [75] and motion [213] can help to plan safer and human-aware robot motion behaviours [67]. To this end, causal modelling [193] provides a theoretically-sound methodology to reason on past and future effects of interventional variables, for example the impact of a new drug on patients in an observational study. Similar models could be used to represent and understand causal (spatial) relations between humans, robots, and their environment. An inference system based on these models could then answer questions about past human-robot trajectories (e.g., why did a person overtake the robot rather than walking behind it?) and future actions (e.g., should the robot slow down to let people pass or accelerate to keep pace?). However, while causal inference is now a well established field in statistics [194], it is still underdeveloped in machine learning and robotics.

In DARKO, therefore, we propose to *advance human-robot spatial interaction by developing new causal models of human behaviours, which are influenced by robot's "interventions", to enable safer and more efficient motion planning algorithms* for intralogistics applications. Another research aspect that we will look at is how to compute accurate long-term human motion prediction. In the last years a large number of studies [213] have presented methods that could accurately predict human trajectories and full body motion for short time horizons. Those methods achieve good accuracy results if the human motion are not disturbed by external stimuli; e.g., obstacles in the environments, or unexpected behaviours of hostile neighbouring humans. Long-term human motion predictors can be used to overcome those limitations. The latter, in contrast to short-term ones, reason about long-term interactions between the agents and the environment [212], see Fig. 4. In DARKO, *we aim to further enhance prediction algorithms for human motion and intents in terms of accuracy and efficiency, by also considering contextual, semantic and environmental cues*.

The relationship between spatial attention of humans and how they planned their future movements is an extensively studied research area and it has been demonstrated that eye gaze is linked, in time and location, to the momentary task requirements [191, 246, 190, 119], since the human vision system acts proactively in gathering information ahead of time before future movements [104, 191]. Hence, eye gaze can convey navigation intent beyond what can be inferred from the trajectory and skeletal and head pose of a human. Therefore, we propose eye-tracking glasses as a special safety equipment in industrial environments shared by humans and robots to facilitate implicit intention transference. Researchers have investigated inferring human intentions using eye gaze in situations where the human is static and would interact with a robot arm [116, 1, 39], a surgical robot [145] or a mobile robot [144]. Our research goal is to achieve implicit intention transference from human-to-robot in scenarios where both human and robot are mobile. By considering also devices like the Microsoft HoloLens 2, equipped with in-built augmented reality and eye-tracking, we further aim to achieve *bi-directional* intention communication in DARKO-like use-cases.

Safe and predictive planning Predictive models of human motion (see above), combined with models for dynamic self-localisation of robots, can then be used to generate safe plans for the robot to manipulate objects and navigate in crowded and cluttered environments. In many factory of the future visions[16], in particular in intralogistics scenarios, robots co-operate and work among humans. In such scenarios, robot planning and control considering future human motion and environmental contextual cues play a key role for safe robot operation [213, 94].

Current state-of-the-art planning algorithms find complex paths in cluttered environments, considering often only pure geometric and kinodynamic constraints [121, 132, 224]. Such approaches are often limited to planning and controlling by using only a limited amount of information surrounding the robot (purely geometric ones), therefore limiting the set of available actions for the robot operation. For example, the state-of-the-art approach Safe Motion Unit (SMU) [100] employs injury safety database information and the robot configuration to limit and shape the safe velocity profile of manipulators in order to ensure human safety. This module was frequently employed to guarantee human safety in collaboration with fixed-base manipulators and later developed to safety map concept [167]. Moreover from a local planning point of view – i.e., planning in dynamic environments considering short horizons – several state-of-the-art approaches have proposed solutions that span from pure risk- and collision-aware reactive methods [207, 214] to joint optimisation approaches [132, 198, 45]. Reactive methods, also if risk-aware, are myopic and do not consider all potential future human robot-interactions, meanwhile joint-based approaches scale poorly with the number of humans surrounding the obstacles. All these limitations result in a state of the art that is inefficient and unable to provide good solutions in real time – in densely cluttered, crowded and dynamic environments.

In DARKO, we aim to overcome those shortcomings and to build efficient, safe and predictive planning components that will improve robot operation in cluttered, crowded and dynamic environments. In particular, we will provide a safe and efficient decision making system by reasoning on different planning and control layers. We will enhance those by proactively and jointly considering human motion predictions with environmental contextual and semantic cues: a novel and unique feature of the DARKO planning system wrt. state of the art. From a global planner perspective (i.e., planning considering a large portion of the environment), we will exploit more environmental semantic information to reduce the search space and therefore enhancing planning efficiency. Specifically, a recent number of works have suggested that planning considering Maps of Dynamics (see ambition on page 14) improve the overall quality of the resulting paths and the social behaviour of the robot [187, 243], by allowing it to produce paths adhering to the learned human-flow motion patterns. We will further go into this direction and extend the state-of-the-art by also *considering contextual information and by proposing additional heuristics (e.g., deterministic sampling [186]) to improve the overall planning efficiency and to enable an easy robot deployment in intralogistics settings*.

To overcome the limitation of the current local planning techniques, in DARKO we will further investigate solutions for fast and reliable local planning based on safe and robust nonlinear model predictive control (NMPC) [225] combined with learned deep generative models [140, 84]. The combination would allow the DARKO robots *to embed learned contextual and semantic cues of the environment and proactively consider human motion predictions* directly in the inexpensive MPC optimisation step. Moreover, we will enhance robot safety by extending the original SMU scheme to a vehicle Safe Motion Unit (vSMU) and combining it with human motion prediction and risk metrics to increase efficiency and avoid unnecessary limitations on robot motion. The final system will be able to plan in a proactive manner to avoid foreseeable collisions with a larger predictive time horizon than common reactive state-of-the-art methods, and it will avoid an expensive joint optimisation of human and robot motion.

Risk representation and operation When navigating in a dynamic and unstructured environment, the robot is constantly exposed to potentially hazardous events. Moving obstacles, moving humans or other moving robots may lead to potential risks, like undesired interactions, damages to fragile objects or the robot itself, or – conversely – the robot may pose a safety risk to humans. It is therefore imperative that these different risk factors are explicitly taken into account during operation: minimising the risk and consequently maximising the probability to safely accomplish the task even if with certain cautions. Endowing autonomous agents with a keen sensitivity to uncertainty and risk of failure is key in enabling them to reliably complete missions in real-world environments. Moreover, in safety-relevant application domains, optimising performance is not enough, for utility must be traded-off against the risk of jeopardising operation goals. In these domains, autonomous agents should seek to optimise expected reward while remaining safe by deliberately keeping the probability of violating one or more constraints within acceptable levels.

[16]https://www.bosch-presse.de/pressportal/de/en/the-factory-of-the-future-bosch-is-turning-vision-into-reality-185920.html

Temporal scheduling of operations for intelligent robots must therefore be extended to include KPIs and goals that make them trustworthy under environmental uncertainty and different sources of risk [17, 26, 156]. This obviously means also being able to assess and quantify the levels of risk the agent is currently facing or might encounter depending on its choices. *Cautious control* is a term from the adaptive control literature to describe a reduction of the control action magnitude in presence of high uncertainty of a system's parameters [69]. In robotics, similar problems have been addressed; e.g., the problem of robustly controlling a manipulator in presence of uncertainty in the Jacobian matrix is studied in [44]. However, a general approach capable of adapting its behaviour to reduce the likelihood of a risk is currently lacking. In certain conditions, control algorithms based on inverse kinematics require modifications [124]. For instance, when a joint is locked, the corresponding column of the Jacobian should not give contributions in a closed loop inverse kinematics control scheme [55, 227]. In the same way, when a joint is overheated, the corresponding Jacobian column should be weighted to consider a reduced use of such joint. The ability to compute trade-offs between risk and reward has been extensively studied in the game theory literature, in relation to robust control purposes [16], and particular solutions exist in the framework of economics portfolio optimisation [202]. When hierarchical control frameworks are considered, solutions to the planning problem can be found at the task level by controlled motion primitives [229]. With respect to the envisaged risk-aware planning framework, some promising work has been investigated for navigation of autonomous robots in human populated environments: a Risk-RRT algorithm has been proposed in [207], where models of human interactions are used to minimise the risk for an autonomous vehicle to collide with, or disturb, a human crowd.

Various approaches for dealing with the problem of achieving the best performance under the condition that safety is provided throughout task execution have previously been examined at UNIPI [47]. In [25], the problem of safe human-robot interaction has been tackled from a mechanical point of view by designing joint-actuation mechanisms that can allow fast and accurate operation of a robot arm, while guaranteeing a suitably limited level of injury risk. The problem has been also approached by studying an optimal control policy, the "Safe Brachistocrone", whose solutions are joint impedance trajectories coordinated with desired joint velocities [250]. In [100], the risk has been studied from a medical injury analysis point of view in order to formulate the relation between robot mass, velocity, impact geometry and resulting injury qualified in medical terms. In [70], Failure Mode and Effect Analysis [20] has been applied to assess the safety and dependability of variable impedance actuators.

To extend previous techniques to the problem of risk-aware planning and control, UNIPI will define a risk Jacobian to represent the mapping between the robot internal states (which can be at joint, Cartesian or, more generally, robot health state level) and the risk space. In this way, task priority methods can be profitably adopted to impose a hierarchy considering the accomplishment of Cartesian tasks in a risk populated environment. One of the main challenges addressed within DARKO is to find suitable methods to use caution in control actions without resulting in conservative performance, thanks to enhanced information coming from the risk-reasoning framework developed within the project (WP7). DARKO's work on reliability-aware mapping and localisation (WP3) will also contribute to a risk-aware spatial map representation for navigation, including risks stemming from, e.g., expected people motion and estimated localisation performance.

2 Impact

2.1 Expected impacts

2.1.1 Contribution to work programme expected impacts

DARKO develops key technologies that are relevant to various kinds of cognitive mechatronic systems with dynamic manipulation capabilities and where robots and humans operate in the same environment. Efficient and safe operation in shared human–robot environments is a particularly crucial aspect, with an extremely high potential for impact in terms of digitising European industry, especially in agile production, but extending also to professional service robots in other sectors (logistics, retail, etc). Most of DARKO's objectives (**O1**–**O5**) will have a direct impact also in health-care (e.g., intralogistics in hospitals, including navigation along untrained people and flexible and efficient handling of pills and packages) and agri-food (where food-distribution logistics centres have particular requirements on flexibility in their logistics, as manifested in less automation than currently in other sectors).

In the following, we describe how DARKO will contribute to the three expected impacts that are specifically called for in H2020 ICT-46-2020a, Research and Innovation Actions (RIA): Robotics Core Technology.[17] The project focuses on an application and use case that embodies all aspects of the call. The **degree of achievement** of the expected impacts will be measured during the project by the consortium in close interaction with the end user and the stakeholder group. The achievement of improved technical capability in each core technology will be assessed via the technology-specific measures outlined in the technical work packages in Sec. 3.1. Impact on state of the art will be measured via number of publications in conferences and journals related to the core technologies.

[17] In this section, underlined text is exact wording from the Horizon 2020 Work Programme.

1: Improved technical capability in each of the core technologies over the current state of the art AI and cognition permeates the DARKO work plan, from AI-enabled 3D perception and scene understanding starting with raw sensor data in WP2, through the risk-aware planning and scheduling in WP7. As expressed in **O2**, one of the primary objectives of DARKO's cognitive modules is to equip robots with the ability to safely – *and also efficiently* – interact with people. Expected state-of-the-art contributions from DARKO that support this objective include (WP2) unified methods for 3D human and object pose estimation, (WP3) improved and more efficient actionable map representations that explicitly model human activities, (WP5) new causal models of human behaviours that can be linked to motion planning, as well as mutual intention communication via human pose and activity awareness, eye tracking as well as anthropomorphic and visually projected signals, and accurate long-term human motion prediction, (WP6) that will be incorporated directly into novel safe and predictive motion planning and control algorithms, (WP7) and a unified risk framework for supporting planning and scheduling to make decisions with constraints based on safety and task efficiency. In addition, WP3 includes tasks aimed to derive knowledge about site-specific activities during long-term operation. All the above contributions also contribute to the core technology of socially cooperative human-robot interaction, with particular focus on navigation in complex work environments (such as the one in Fig. 1).

Cognitive mechatronics is our main designated Core Technology. We take this to mean deep interconnections between 3D perception and scene understanding, high-level human-aware and risk-aware planning and orchestration, and DARKO's novel mechatronic system for mobile manipulation. All the objectives (**O1** manipulation, **O2** co-production, **O3** efficient deployment, **O4** risk-awareness, and **O5** integration) contribute to this technology.

DARKO's **O3** focuses on easy-to-use configuration, as we strive for easy deployment in application areas where tasks need to be defined by the user, as opposed to tasks that are crafted as part of deployment engineering. All of this is expected to have significant impact in the core technology of model-based design and configuration tools. In addition, WP3 in particular will contribute to the Core Technology "Model-Based Design and Configuration Tools". DARKO's mapping system has as its main ambition to provide easy-to-use configuration tools for the mapping part of the deployment phase. In fact, one of our main driving forces (**O3**) is to make deployment easier, thus allowing also smaller players to capture value through a *transition to automation*. The system will include *automatic consistency checks* and *map cleaning tools*, as well as an improved system for *auto-completion* of the robot map using prior information, which will make it possible to do point-and-click navigation even before the robot has seen the whole site. Finally, partner ORU contributes to standardisation via its leading involvement in the IEEE working group for standard map representations for robot navigation in 2D and 3D [7].

Finally, as manifested in **O5**, DARKO strives for deployable system platforms that meet the requirements of applications and we will contribute to the expected impacts also in this regard, through early and reoccuring workshops with end users and stakeholders, and yearly public demonstrations and stakeholder meetings (T8.1, T8.3); thus further extending the consortium's considerable existing interface with industry and its requirements.

DARKO's contributions to the work programme expected impacts are described in more detail in Sec. 1.2.

2: A greater range of applications in the prioritised application areas that can be demonstrated at TRL 3 and above We expect to be able to demonstrate all innovations developed in DARKO well beyond TRL 3 ("experimental proof of concept"). In fact, we aim to achieve TRL 6 ("technology demonstrated in relevant environment") at a system level during the demonstrator at the end of the project (**O5**).

3: The lowering of technical barriers within the prioritised applications areas DARKO's objectives are specifically targeted at lowering technical barriers that currently hinder widespread adoption of robotics in agile production and intralogistics. Although production and logistics are increasingly robotised (from warehouse handling with robot arms, to moving around pallets, from sorting products for kitting and commissioning to delivery of meals in hospitals) the growth potential is still very large. As a case in point, every year 200–300 thousand forklifts are sold in Europe, of which only 1% are automated – and this is due to technical barriers that DARKO will reduce. Crucial hindrances faced today by the industry in five domains are [9]: *dependability*, *vehicle types*, *efficiency and safety*, *the dynamic nature of the environment*, and *planning*.

We address *dependability* through failure-aware and failure-resilient mapping and localisation (WP3) as well as a multidimensional risk representation that allows for informed trade-offs of task and hardware risks at runtime (WP7). We address *efficiency and safety* via a focus on real-time capable perception of humans and scene understanding (WP2), learning and adapting to people's activity patterns (WP3, WP5, WP6), and – uniquely – inherently efficient and safe hardware for manipulation (WP1,WP4). As for *dynamic environments*, we perceive, track and predict the activities of humans and other moving entities (WP2,WP5). We will also enable self-supervised learning of how objects that are likely to change appear, thus being able to predict dynamic changes before they happen (WP3). Finally, *planning* is handled intelligently by actively including predictions of people and other dynamics, as well as risks (WP6, WP7).

The extent of progress in lowering of technical barriers will be measured against KPIs defined in the work packages, further KPIs elicited during the project with the stakeholder group and feedback from our end user.

In addition to the above three expected impacts from the work programme, DARKO is expected to have an **impact on European competitiveness and innovation capacity**. EC data shows that the manufacturing sector in the EU employs 30 million persons directly and provides twice as many jobs indirectly. This notwithstanding, EU manufacturing has slightly declined in the last few years. Agile production, through[18] ICT-enabled intelligent manufacturing and more sustainable technologies and processes, has been identified as the major driving force for improving competitiveness of the European industry. To guarantee flexibility [61], the European industry needs to adopt new paradigms of production models, focusing on highly advanced robotics, capable of working in presence and collaboration with humans, as one of the key drivers to invest R&D efforts on. DARKO aims at a generational step ahead in how autonomous robots will behave in highly dynamic environment, especially in presence of human operators. This will allow to overcome the challenges that the European manufacturing industry must face in the years to come. Another key aspect that DARKO will impact on for improving European competitiveness, is the potential for jobs creation by bringing back production to Europe (i.e., re-shoring). For the past 25 years manufacturing offshoring to low-cost locations has been dominant. However, with "Industry 4.0" technologies, we are seeing a change in this strategy. Until now, the speed of this shift has been limited because, for the most part, factories and warehouses used expensive industrial robots that for safety reasons had to operate separately from humans. However, the outcomes of DARKO can *accelerate the shift towards inexpensive collaborative robots, which can work alongside human operators increasing their efficiency*. With its disruptive concepts, DARKO answers the challenges of re-shoring with a concrete technological and methodological framework that will drastically facilitate the extension of robotics to currently unexplored areas. This will not only create new jobs position but it will also help freeing the operators of repetitive and low-added-value tasks while maximising the importance of their adaptability and cognitive flexibility.

2.1.2 Barriers and obstacles to expected impact realisation

Obstacles A research project like DARKO encounters typical obstacles that may compromise its scientific and economic impact. We will consider them and give measures to address and overcome them.

We see no obstacles for the scientific impact of DARKO as the consortium consists in renowned partners with an excellent scientific track records in their fields.

Regarding the exploitation impact, several partners have considerable expertise in bringing research results into products in the market, and based on this experience, we can state that technology transfer is a *leaky pipeline*. Along this pipeline, that starts at fundamental research in academia and ends at products that generate business in the market, are obstacles at four typical locations (the "leaks").

- **Obstacle 1, within academia**, consists in low-quality research with little novelty that does not lead to differentiating USPs for industry. Part of this barrier are also technology risks, i.e. when technical approaches turn out to be not viable given the requirements.

- **Obstacle 2, at the interface of academia and industry**, consists in mismatches between technology push and market pull including mindset and cultural gaps as well as mere lack of information between academia and industry. Examples include technological solutions that do not match an economically viable problem in industry or problems that do not find mature solutions from academia.

- **Obstacle 3, within industry**, consists in a lack of resources, priorities or specialised competences to commercialise a new technology after first adoption at obstacle 2. Reasons include opportunity blindness or inaccurate assumptions about the technology by decision makers, insufficient market size, or legacy technologies, competences and business cultures that can create high barriers for innovation acceptance.

- **Obstacle 4, at the interface of industry and market**, consists in products that have no market success due to insufficient attractiveness, novelty, UX, business model innovation, marketing, etc.

Countermeasures. In DARKO, we will confront obstacles 1 and 4 by the scientific excellence of the consortium and the significant innovation potential of the DARKO objectives. This cutting-edge research enables industrial partners that adopt DARKO outcomes to offer USPs with a clear differentiation potential from their competitors. Such USPs include e.g. robotic throwing (**O1**), safe yet efficient, socially and semantically aware collaborative mobile manipulators (**O2** and **O4**) or highly automated self-deployment technologies (**O3**).

Obstacles 2 and 3 are the highest to overcome and deserve particular attention. We will address them by the following measures:

1. To maximise outreach to decision makers of industrial key players, we will setup and integrate the DARKO demonstrator at the ARENA2036 platform, an excellent place for networking with a large number of stakeholders from manufacturing and logistics as well as policy makers (Sec. 2.2.1).

[18] https://ec.europa.eu/commission/presscorner/detail/en/MEMO_14_193

2. The project specifically tackles the methodological challenges of working with SMEs, which usually have lower resources dedicated to R&D (obstacle 2). DARKO's technological solutions will be easily applicable by SMEs, as we will produce a modular architecture T8.2 and crucially aim for easy and low-cost deployment (**O3**). SMEs will also benefit from the fact that we push for standardisation of interfaces [7], addressing obstacles 3 and 4.
3. One common instance of obstacle 2 is the use of restrictive open source licenses (copy-left). We will follow the principles set out by Points 1 and 2 of the Code of Practice annexed to the Commission Recommendation on the management of intellectual property in knowledge transfer activities. Specifically, we will take support from Digital Innovation Hubs (T10.1), as well as innovation offices at ORU and other academic partners, in redacting appropriate licenses for research software, to ensure that intellectual property (IP) is safeguarded and exposed to exploitation under terms that are fair and profitable and encourage industrial uptake.
4. By partnering with the Corporate Research branch of Bosch, we have a low-threshold entry point into a large company and can exploit their internal professional processes for technology transfer into the Bosch business units that operate in the markets.

Regulatory Issues In DARKO we face two potential types of issues related to regulatory aspects. The first one is strictly related to the adoption of AI-based techniques, in particular machine learning. Within the context of the EU Machinery Directive 2006/42/EC, which provides a set of indications concerning machine safety requirements, there is no clear indication of how safety-related aspects should be managed when the real-time behaviour of a system is, at least partially, governed by dynamics that were not specifically developed at the design stage. DARKO will study this topic as part of its exploitation strategy, eventually providing feedback to relevant standardisation activities.

The second potential regulatory issue is linked to some human-robot interaction scenarios that might arise within the use-cases proposed by the project. In fact, we consider operators as potentially involved in the learning mechanisms of some of the project technological modules, especially when training of predictive models is foreseen, interacting and supervising the behaviour of the robotic systems. This is clearly an extension of the concepts of Human-Robot Collaboration (HRC), normally dealt with in collaborative robotics.

The introduction of the ISO 10218 standard, published in July 2011, started providing some regulatory background for machines running in the presence of people. A set of clauses is there reported with the goal to drive the design and development of safe interactions between human and machine operators. In case of practical experiences found in the use-cases where human-machine interaction will be needed, these clauses will be used to create a proper evaluation layer intended to certify the compliance of DARKO solutions. Supportive information will also come from the following, used as guidance: IEC 615058 – Functional safety, ISO 12100 – Risk Assessment, EN ISO 13849-1 or IEC 62061:2005 – Safety of machinery, ISO 11161 – Integrated manufacturing systems. The compliance to these standards will also be used as relevant metrics to be considered for risk assessment in WP7.

DARKO will also adhere to the Ethics Guidelines for Trustworthy Artificial Intelligence by the High-Level Expert Group on AI.

2.2 Measures to Maximise Impact

2.2.1 Dissemination and exploitation of results

Scientific dissemination The academic partners will disseminate the research outcomes of the project through peer-reviewed and high impact factor journals in the field of robotics, control and machine learning. The research results during the project are expected to be published in conferences and journals including the International Journal of Robotics Research, IEEE Transactions on Robotics, International Journal of Machine Learning research. Furthermore DARKO will disseminate its research to flagship conferences of the field, e.g., IEEE ICRA, IROS and CoRL. Dissemination activities will also include the organisation of workshops and demonstrations of the robotic system during events such as the European robotics week and the European Robotics Forum.

Industrial exploitation of results Partners Bosch and ACT, the two industrial partners of DARKO, have a particular and important role in the exploitation strategy towards industry.

ACT's approach follows **three lines of action**. On one hand, ACT is provider of Innovation Services towards many relevant players in agile production, both in Italy and in other European countries (Spain and UK mostly); this will guarantee to ACT a privileged channel of transfer of DARKO technology from the project into selected end-users, that might be willing to test and integrate some of the most mature modules. The second path is sustained by ACT's mother company, SPINDOX spa. As one of Italy's leading IT groups, SPINDOX takes the products developed by ACT and integrates them in its portfolio of solutions, offering them to key Italian industrial leaders, such as Ferrari, Maserati, Vodafone, Lamborghini, Pirelli, etc. Finally, ACT is currently in the process of launching an International Foundation for Decision Science, that will be created between the end of 2020 and the beginning of 2021, with the

Figure 5: Left: The ARENA2036 platform in Stuttgart, Germany, where we will set up and integrate the DARKO demonstrator. ARENA2036 is a nationally funded research platform for mobility and production of the future, an excellent place for stakeholder networking during regular events and demonstration days. In addition to Bosch, members include Daimler, Siemens, DLR, KUKA, Nokia, Pilz, Fraunhofer, BASF, Festo and many more. Center: The total space is around 1000 m^2, the Bosch area is highlighted in green. Right: the planned Bosch Factory of the Future demonstrator into which we will integrate the DARKO demonstrator. With the goal to maximize exploitation and dissemination of the project outcomes to key industrial players, we will, where possible, integrate the DARKO demonstrator into existing installations at ARENA2036 and participate in ARENA2036 events.

mission of aggregating a community of research and industry experts and practitioners of the DS domain. ACT being a founding member, it will be in a perfect position to exploit the Foundation and push the technologies of DARKO within high-level tables of discussions.

Partner Bosch will likewise play an important role in dissemination and commercial exploitation of project results. The Bosch Group is a leading global supplier of technology and services. The company is present in over 150 countries, and with its roughly 400,000 associates generated sales of 77 billion euros in 2019. For DARKO, Bosch is *both* end-user with over 270 own production plants and numerous logistics centers (such as the BSH spare part commissioning department that provides the DARKO use-case), *and* a technology provider with its industrial business units Bosch Rexroth and Bosch Connected Industries (BCI). Through Rexroth and BCI, Bosch provides cutting-edge I4.0 automation and IoT solutions for their customers and pursue a forward-thinking vision of future production and logistics systems. Robotics products include, for example, the new autonomous transport system ActiveShuttle, Locator, a retrofit localisation system, and the production assistant APAS, a family of certifiably safe human-robot collaboration solutions for manufacturing and logistics. In DARKO, **we will build upon past technology transfer successes** such as the motion planning system for *ActiveShuttle* which leveraged results developed in the H2020-project ILIAD and we expect a very high exploitation potential also for DARKO results. The research objectives to facilitate deployment (**O3**) and improving core robotic technologies (**O1**, **O2**, **O4**) are of high interest for Bosch, both in the role of an end-user like BSH, and of a technology provider like Bosch Rexroth. In particular, Bosch Rexroth has recently announced partnership with the **Klinkhammer Group, a German material handling and intralogistics company, in smart item picking and robotic commissioning systems**[19]. Klinkhammer is active in the rapidly growing sectors of e-commerce and order fulfilment and their use-cases are a strong match for DARKO's concept and methodology.

ARENA2036 One particularly **exciting means for exploitation and dissemination** is the setup, integration and deployment of the DARKO demonstrator at ARENA2036 in Stuttgart, Germany,[20] a high-profile demonstration area perfectly suited for dissemination of project results to key industrial stakeholders. This long-term demonstrator will also ensure that we meet Objective **O5**: proven feasibility through an integrated system. ARENA2036 is a research platform for mobility and production of the future, funded by the German Federal Ministry of Education and Research (BMBF) as one of nine research campus of the funding initiative "Research Campus – Public-Private Partnership for Innovations". Bosch is a founding member of ARENA2036 with a designated permanent area. ARENA2036 is a physically shared space where its members from science and industry across various disciplines (automotive, manufacturing, aerospace, textile, materials research etc.) meet and develop, deploy, and evaluate their visions of the factory of the future (Fig. 5). As confirmed in the attached Letter of Intent (Appendix A), the DARKO team will be given **a dedicated demo area** to setup a near-real replica of the BSH use-case in which we will deploy the DARKO demonstrator. We will have regular presence to show both system demonstrations and scientific presentations. Furthermore, in conjunction with milestone demonstrations, **we will arrange specific *stakeholder meetings***, where we will invite key individuals from relevant industries as well as academic partners in order to maximize uptake of project results and strengthen academic–industrial collaboration.

[19] https://www.klinkhammer.com/en/warehouse-systems/order-picking-technology/robotic-piece-picking
[20] https://www.arena2036.de/en/

In addition to the main demonstrator at ARENA2036, individual partners also have demo facilities, and several robot platforms will be available in the consortium both for development and dissemination for increased impact. We have budgeted for two complete platforms, including DARKO's novel hardware for elastic manipulation and dexterous grasping, and two additional platforms with more limited manipulation capabilities, for showcasing parts of the DARKO system at other partner locations. With one platform located at ARENA2036, the other platforms will be distributed in the consortium.

Additional activities In addition to the strategies listed above, we will maintain the plan for exploitation and dissemination of results (PEDR) in T10.4. The purpose of this task is to coordinate the activities and to ensure effective and target-oriented dissemination. Given the significant organisational control and efficiency benefits of this research we expect to see a high degree of industrial dissemination/engagement activity. Following a Responsible Research and Innovation approach, and to identify to which stakeholders dissemination/exploitation activities will be directed, a full stakeholder analysis workshop will be held within the first 6 months of the project – see D8.1.

Results that will be exploited by consortium members or licensees will undergo proper protection (patent) procedures with the help of the patent and innovation offices of the respective partners. (See also Sec. 3.2.3.)

We will *opt out* of the Pilot on Open Research Data in Horizon 2020, as some of the data may be commercially sensitive, including data collected from end-user sites. With that said, we intend to make our research data available to the extent possible. Regarding the dissemination of research data and software, DARKO will store data collected and generated during the project in publicly accessible archives hosted by the partners. ORU can host several terabytes of data on storage services curated and maintained centrally, by the university. Types of data will include sensor logs used for evaluating deployment and long-term learning, navigation and SLAM, sensor fusion, tracking, etc. However, some data may need to be anonymised or restricted for privacy or commercial reasons. Software and data will be made available by the partners throughout the project, as it becomes ready for external use, and a **coordinated release** of all available software and data is planned for MS5 at the end of the project. Map data for navigation will additionally be stored using the IEEE 1893 standard format.[21] Members of the consortium have contributed to the development of this standard, and are contributing to the ongoing work on a 3D standard. Adhering to an IEEE standard format will ensure longevity of the archived data.

2.2.2 Communication activities

The goal of the external communication plan (to be implemented in T10.3) is twofold. We aim to maximise the awareness of DARKO's goals for key audiences, and also engage in two-way exchange to steer the development as well as find new application areas, not only with industry stakeholders as indicated above, but also with the general public. We have identified the following key audience groups: **(1)** technology providers within the logistics industry, **(2)** business leaders from end users with logistics needs in a wide range of scales, **(3)** the academic communities relevant to the technical work packages, and **(4)** the general public, including media as well as policy makers, to raise awareness of progress in the field. Part of the communication plan will be to maintain a proactive media relation on local, national and EU-wide levels, create talking points and key messages about the project, develop a positive relationship with all stakeholders to strengthen support for the project in particular, and EU research and innovation actions in general, design of a unified project identity including logo(s) and templates for presentations and display project material (posters etc).

We will put effort in developing early interest in the project by targeting media outlets with key messages. These messages will specifically include why non-practitioners should be interested in the project and its results. (E.g.: Making robots "greener" by making them more energy efficient. How can service robots be safer around humans? How can robots learn to adapt to their environment and its inhabitants?). To maximise the impact of the different media channels, we will use resources from the partners' public relation offices to work with communication and media professionals that are experienced in the public presentation of research projects. Early communication will provide an opportunity to build up an audience for later dissemination and exploitation work. We will also benefit from existing contacts with industry press that has been following, e.g., the ILIAD project, and are likely to be equally as interested in the results of DARKO.

Intended communications channels include: (i) **Project website and social media.** During the course of the project the website will be updated with latest results and to announce events and achievements of the project. A strong presence of the project on popular social media platforms will increase the outreach to all target audiences, not least (4). A YouTube channel will be used to disseminate information about the robot system in action, including the milestone demonstrations (1, 2, 4), as well as scientific presentations (3). Social media channels are planned to be updated on a weekly basis. (ii) **ARENA2036.** Our regular presence at the ARENA2036 show room will provide a permanent display window of current project results in particular to target groups (2, 4). (iii) **euRobotics topic groups.** We are co-coordinating the euRobotics "Robotics for Logistics and Transport" topic group, which provides a

[21] https://standards.ieee.org/standard/1893-2015.html

forum for European research projects and industry stakeholders concerned with robots for logistics applications. This topic group regularly arranges workshops at the ERF, through which we will communicate with European stakeholders in industry and academia; mainly target audience (1) and (3) above. (iv) **Press.** Print media as well as TV and radio will be targeted actively through press releases of the partner's external relations offices, coordinated by ORU.

International workshops for industry stakeholders and academia will be arranged at least once per year. As also described in Sec. 2.2.1, specific stakeholder meetings with key invited end users and technology providers will be arranged at the milestone demonstrations, and our presence at Arena2036 will give many opportunities for communication outreach also at other points in time.

The success of the communication plan will be constantly monitored (community feedback, website hits, media coverage) and adjusted to the needs of the different audiences.

3 Implementation

3.1 Work Plan

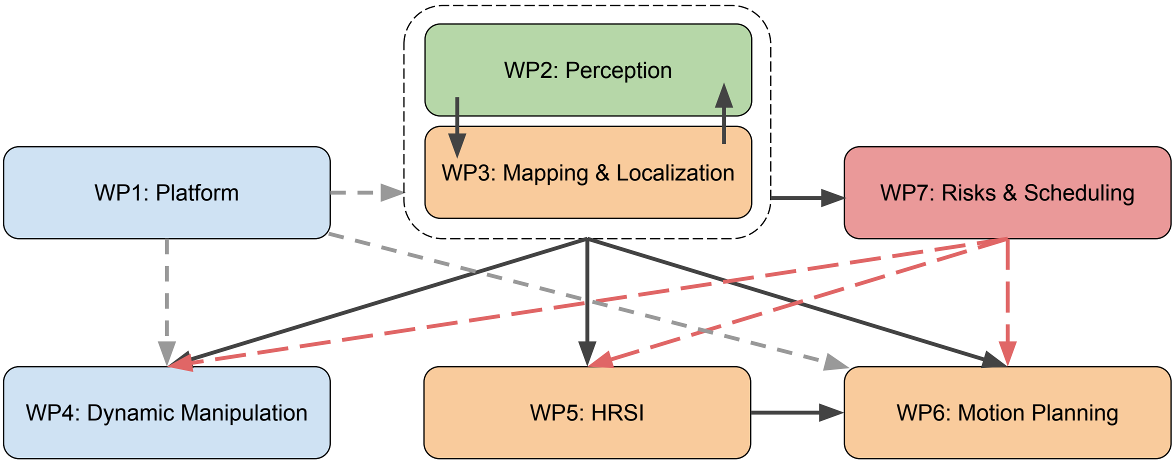

Figure 6: Work package dependencies. Black arrows denote data flow during operation, dashed red arrows indicate constraints and orchestration, and dashed grey arrows indicate hardware dependencies. The blue boxes are primarily related to mobile manipulation and throwing. The yellow boxes are primarily related to navigation and deployment of a mobile robot in shared environments. The green box (Perception) provides input to both blue and yellow. The red box (Risks) ensure overall risk and safety management.

The DARKO workplan is designed to meet the five objectives outlined in Sec. 1.1. We have divided the work into ten Work Packages, seven of which contain core technical development. Fig. 6 illustrates how these technical work packages are related to the objectives, and how the work packages relate to each other. In addition, one work package ensures that the scope, requirements, and methods of evaluation are adequate; one focuses on maximising scientific and industrial uptake; and one on administrative and technical management.

WP1 (Efficient Mobile Dynamic Manipulation Platform) will provide as its main outcome a novel intrinsically safe elastic manipulator and a general-purpose gripper, enabling energy-efficient, safe and precise mobile manipulation and throwing. WP2 (3D Perception and Scene Understanding) extracts information from the sensor data on the DARKO robot platform and provides semantic and geometric understanding of the objects and people working with the robot. WP3 (Multimodal Mapping and Safe Localization) aims to deliver a multi-modal mapping system that can learn both geometry and explicit dynamics characteristics, incorporate heterogeneous map sources, and introspect to reason about its performance. WP4 (Efficient and Safe Dynamic Manipulation) provides the control and planning strategies for safe and efficient dynamic manipulation; including moving objects, and throwing. WP5 (Human-Robot Spatial Interaction) focuses on human-robot co-production by implementing new solutions for long-term human motion prediction, intention communication, and novel representations and causal inference methods for human-robot spatial interaction. WP6 (Predictive and Safe Motion Planning) delivers safe and human-aware motion planning and control for the mobile base. WP7 (Risk Representation and Operations Scheduling) establishes a multidimensional risk representation, taking into account risks in terms of hardware, perception software, task fulfilment, and human safety; and provides objective constraints to minimise risk for the operational components delivered by the above work packages. WP8 (Requirements and Evaluation) is dedicated to eliciting requirements, developing a project-wide system architecture, and evaluating the results. Finally, WP9 (Management) and WP10 (Dissemination and Exploitation) support the realisation of DARKO's ambitious work program. The latter in particular explicitly includes efforts to maximise exploitability of results by packaging selected technologies for use by third research and industrial parties.

The work plan, as structured in work packages and tasks, is summarised in Table 1, while Fig. 7 supplies a Gantt timeline of the activities. Table 2 lists the deliverables of the project.

Table 1: Work package overview.

WP	**Work package title** (Type)	**Lead** (no.)	**PMs**	**Start**	**End**
WP1	**Efficient Mobile Dynamic Manipulation Platform** (RTD)	TUM (2)	140	M01	M36
	T1.1: Initial DARKO mobile dynamic manipulation platform	TUM			
	T1.2: General-purpose gripper	UNIPI			
	T1.3: Elastic manipulator	TUM			
	T1.4: Final DARKO mobile dynamic manipulation platform	TUM			
WP2	**3D Perception and Scene Understanding** (RTD)	Bosch (3)	126	M01	M42
	T2.1: Object-level semantics	Bosch			
	T2.2: Perception for manipulation	ORU			
	T2.3: In-hand grasp perception	ORU			
	T2.4: Detecting successful throws	ORU			
	T2.5: Perception of humans and their poses	Bosch			
WP3	**Multimodal Mapping and Safe Localization** (RTD)	ORU (1)	94	M01	M42
	T3.1: Efficient mapping	ORU			
	T3.2: Heterogeneous map merging and exploration	ORU			
	T3.3: Maps of dynamics	ORU			
	T3.4: Reliability-aware mapping and safe localisation	ORU			
WP4	**Efficient and Safe Dynamic Manipulation** (RTD)	UNIPI (4)	132	M01	M42
	T4.1: Planning and control for efficient manipulation	UNIPI			
	T4.2: Safe, risk-aware planning and control for manipulation	TUM			
	T4.3: Picking and placing in motion	UNIPI			
	T4.4: Throwing	EPFL			
WP5	**Human-Robot Spatial Interaction** (RTD)	UoL (6)	110	M01	M42
	T5.1: Prediction of human motion and intents	ORU			
	T5.2: Communication of robot intent	ORU			
	T5.3: Context-aware representations of HRSI	UoL			
	T5.4: Causal reasoning for safe HRSI	UoL			
WP6	**Predictive and Safe Motion Planning** (RTD)	Bosch (3)	71	M01	M42
	T6.1: Predictive local planning	Bosch			
	T6.2: Risk-aware planning and control for mobile robots	UNIPI			
	T6.3: Efficient and context-aware global planning	Bosch			
	T6.4: Safety for wheeled mobile robots	TUM			
WP7	**Risk Representation and Operations Scheduling** (RTD)	ACT (7)	54	M04	M42
	T7.1: Multi-dimensional risk space definition and metrics	ACT			
	T7.2: Continuous learning and forecasting of risk trajectories	ACT			
	T7.3: Risk-optimal scheduling of operational tasks	ACT			
WP8	**Requirements and Evaluation** (RTD)	ORU (1)	39	M01	M48
	T8.1: Requirements and evaluation metrics	ORU			
	T8.2: System architecture development	ORU			
	T8.3: Evaluation and system demonstrations	Bosch			
WP9	**Management** (MGT)	ORU (1)	29	M01	M48
	T9.1: Administrative and financial management	ORU			
	T9.2: Technical management	ORU			
	T9.3: Project status monitoring	ORU			
WP10	**Dissemination and Exploitation** (MGT)	ORU (1)	27	M01	M48
	T10.1: DIH Networks	ORU			
	T10.2: Scientific dissemination	ORU			
	T10.3: Communication plan	ORU			
	T10.4: Exploitation	ORU			
	Total		822		

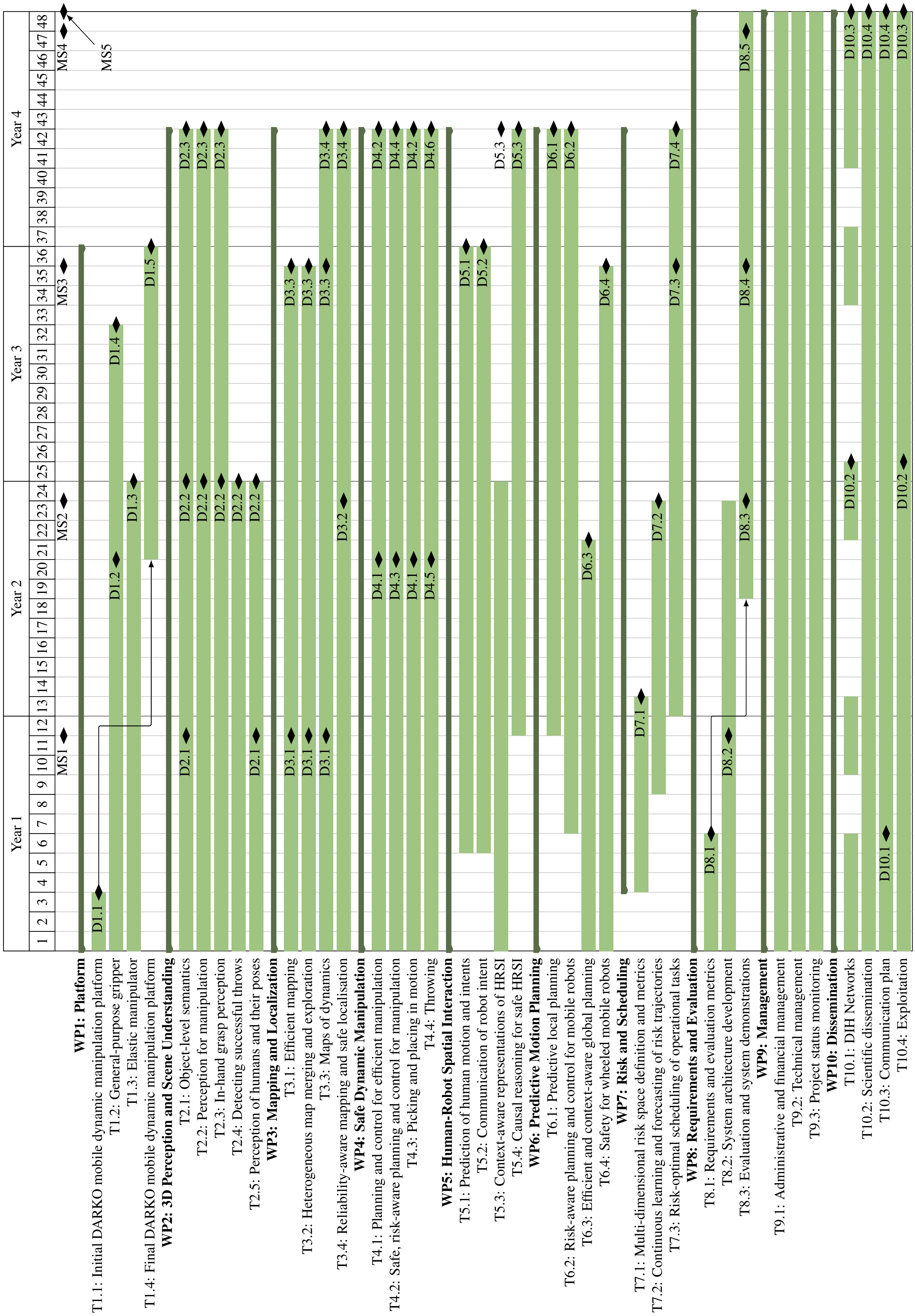

Figure 7: Gantt chart for tasks and deliverables.

Table 2: List of deliverables. The nature for each deliverable is either R (report), DEM (demo, prototype, etc), DEC (web, patents, press, etc), O (other/software module). The dissemination level is either CO (confidential) or PU (public).

Del no	Deliverable name	WP	Type	Diss. level	Due date
D1.1	Initial DARKO mobile dynamic manipulation platform	WP1	DEM	PU	M3
D1.2	Preliminary DARKO end-effector	WP1	DEM	PU	M20
D1.3	Final DARKO elastic manipulator	WP1	R	PU	M24
D1.4	Final DARKO end-effector	WP1	DEM	PU	M32
D1.5	Adaptation and finalised DARKO mobile platform	WP1	R	PU	M36
D2.1	Initial perception system for objects and humans	WP2	O	CO	M11
D2.2	Initial report on perception in DARKO	WP2	R	PU	M24
D2.3	Final report on perception in DARKO	WP2	R	PU	M42
D3.1	Prototype implementation of mapping system	WP3	O	PU	M11
D3.2	Prototype implementation of map quality assessment and localisation assessment tools	WP3	O	PU	M23
D3.3	Implementation of the complete mapping system	WP3	O	PU	M35
D3.4	Final mapping report	WP3	R	PU	M42
D4.1	Preliminary planning and control software developments for efficient manipulation	WP4	O	PU	M20
D4.2	Planning and control algorithms for efficient manipulation	WP4	R	PU	M42
D4.3	Preliminary planning and control algorithms for safe manipulation	WP4	O	PU	M20
D4.4	Planning and control algorithms for safe manipulation	WP4	R	PU	M42
D4.5	Preliminary robot control for dynamic throwing of objects	WP4	O	PU	M20
D4.6	Robot control for dynamic throwing of objects	WP4	R	PU	M42
D5.1	Report on prediction of human motion and intents	WP5	R	PU	M36
D5.2	Report on system for communication of robot intent	WP5	R	PU	M36
D5.3	Representations and reasoning algorithms for HRSI	WP5	R	PU	M42
D6.1	Report on techniques for predictive local planning	WP6	R	PU	M42
D6.2	Report on risk-aware planning and control	WP6	R	PU	M42
D6.3	First prototype of the DARKO motion planning system	WP6	O	CO	M21
D6.4	Report on safe dynamic mobile platform planning	WP6	R	PU	M35
D7.1	Risk-space modelling and assessment metrics.	WP7	R	PU	M13
D7.2	Learning and forecasting tools for risk assessment.	WP7	O	CO	M23
D7.3	Off-line nominal scheduling and decentralised re-scheduling module – v1	WP7	O	CO	M35
D7.4	Off-line nominal scheduling and decentralised re-scheduling module – v2	WP7	O	CO	M42
D8.1	Report on software and functional requirements, evaluation metrics	WP8	R	CO	M6
D8.2	System architecture	WP8	O	PU	M11
D8.3	First demonstration	WP8	DEM	PU	M23
D8.4	Second intermediate demonstration	WP8	DEM	PU	M35
D8.5	Final demonstration	WP8	DEM	PU	M47
D10.1	Communication plan	WP10	O	PU	M06
D10.2	Initial plan for exploitation and dissemination of results	WP10	R	CO	M30
D10.3	Final plan for exploitation and dissemination of results	WP10	R	CO	M48
D10.4	Report on success of dissemination and communication activities	WP10	R	CO	M48

3.1.1 Work Package 1: Efficient Mobile Dynamic Manipulation Platform

WP1		Efficient Mobile Dynamic Manipulation Platform							
Type:	RTD	Part.no.:	1	**2**	3	4	5	6	7
Start:	M01	Part.:	ORU	**TUM**	Bosch	UNIPI	EPFL	UoL	ACT
End:	M36	Effort:	6 PM	**91 PM**	2 PM	39 PM	0 PM	2 PM	0 PM

Task T1.1: Initial DARKO mobile dynamic manipulation platform
Task T1.2: General-purpose gripper
Task T1.3: Elastic manipulator
Task T1.4: Final DARKO mobile dynamic manipulation platform

Objectives

The main objective of this work package is to develop platforms as test-beds to fulfil the project requirements. Within the first three months of the project, an initial mobile base integrated with a Franka Panda Emika [22] will be customised and the partners will use it to pursue the project goals (Phase A) while in parallel an elastic manipulator and a general purpose gripper will be developed and integrated with the mobile base for the second phase (Phase B) of the project to increase the efficiency and achieve human-like performance. The development tasks in this work package will use the input from WP2 and WP3 to integrate the necessary sensors for perception and mapping and WP4, WP6 to take into account safety and efficiency requirements for manipulation, motion planning and whole-body control in the system design. The risk analysis from WP7 will be exploited for developing an intrinsically safe arm. More specifically the objectives of this work package include:

i) Providing a customised initial mobile manipulation platform using off-the-shelf state-of-the-art components for the first phase of the project. ii) Developing a general purpose compliant gripper capable of performing dynamic tasks of the project such as throwing or grasping in motion. iii) Developing an intrinsically elastic manipulator that fulfils the project requirements and surpasses commercial manipulators in the market in terms of dynamic motion and manipulation abilities as well as energy efficiency. iv) Integrating the intrinsically elastic manipulator with the mobile base and developing software and hardware units to enable a whole-body control scheme.

Task 1.1: Initial DARKO mobile dynamic manipulation platform **TUM,** Bosch, UNIPI, ORU, EPFL, UoL

This task aims at providing an initial hardware platform consisting of a mobile base, a torque-controlled manipulator with a gripper and a set of sensors derived from requirements of perception (WP2) and mapping (WP3). We will begin with off-the-shelf components to prepare an initial platform that the consortium can work with during the initial phase of the project, while a new intrinsically elastic manipulator is being developed in T1.3 to achieve project goals in terms of simultaneous energy efficiency, robustness and performance. Currently, there are several commercial mobile robots available on the market, some of which offer the option of installing a lightweight manipulator. In this task we will investigate the applicability of available mobile robots on the market for DARKO and make required customisation to fulfil the project requirements. Specifically, we focus on the following main parts:

Fixed-base manipulator: In the DARKO scenario, we require a torque-controlled manipulator to enable the measurement of contact forces, which is an important capability in performing dynamic tasks such as grasping. Moreover, since energy efficiency is one of the main targets of this project, the arm should be a lightweight robot with enough capability to fulfil the project requirements and avoid toppling incidents. Franka Emika Panda[23] is a lightweight, low power robotic arm equipped with torque sensors in all seven axes. It is inspired by human agility, dexterity, and sense of touch, and is readily available. It has a full support for the ROS middleware including MoveIt!, URDF model and real-time interfaces. Therefore, and due to existing expertise within the consortium, we plan to use it as the initial arm at beginning of the project.

Gripper: The manipulator should be equipped with a gripper providing flexible and scalable automation to implement dynamic manipulation tasks. Indicatively, we will use the RightPick gripper which has a central extendable finger with suction cup and three flexible fingers are located around it. Due to this structure, RightPick has flexible grasping capabilities and is able to handle various types of irregular shaped objects without damaging them.

Mobile platform: Different mobile platforms on the market will be investigated to identify the most suitable option for DARKO. While the final decision will be made after project start, we consider the Boxer platform by

[22] **Declaration regarding possible Conflict of Interest Professor Sami Haddadin and Franka Emika**
Professor Sami Haddadin, director of the Munich School of Robotics and Machine Intelligence (MSRM) at the Technical University Munich (TUM) is one of the founders and a minority shareholder of the company Franka Emika. He does not hold any operational position at the company. Professor Sami Haddadin uses robots sold from the company Franka Emika within his research activities because of the technological specifications and interfaces provided by the robots.
All project partners have taken notice of the declared potential conflict of interest and raise no objections concerning the project.

[23] https://www.franka.de/

Clearpath as a good candidate due to its easy extendibility, including various mounting options for different sensors and manipulators; for instance, a combination of the Boxer mobile base and a Franka Emika Panda manipulator can be readily purchased from Clearpath. The use of such an off-the-shelf platform can significantly reduce the required initial setup time, allowing us to quickly focus on the core research tasks of DARKO.

Sensors: To achieve the scientific goals of DARKO, we need to take into account different sensor requirements. For 3D scene understanding (WP2) and mapping (WP3), we will use the following configuration of sensors. (i) 3D LiDAR with 360° field-of-view for long-range sensing, such as Ouster OS0 or OS1. (ii) Wide-angle RGB camera (fisheye or panoramic) for complementing the 3D LiDAR with semantically rich RGB data. (iii) Two lightweight RGB-D sensors with low power consumption for medium to close range sensing, such as Intel RealSense LiDAR Camera L515 or Azure Kinect DK. One sensor will be mounted on the mobile base, and one close to the end effector on the manipulator.

Odometry for motion planning will be provided by wheel encoders and an IMU in the mobile base. We will leverage additional exteroceptive sensors that come pre-installed with the mobile base, such as a 2D safety laser and ultrasonic sensors, to provide low-level collision avoidance during the development phase. These are not part of the scientific research plan of the project.

Task 1.2: General-purpose gripper **UNIPI,** TUM

The main factors which make the grasping task challenging and push towards the development of a new gripper are: i) to individually pick up small boxes that can fit in a human closed hand, large boxes that cannot fit into a closed hand, transparent objects, and deformable objects; ii) to estimate the position and the mass distribution of a grasped object; iii) to re-orient the object w.r.t. the manipulator wrist in order to facilitate the throwing phase iv) fast opening and closing of the hand to allow the picking and placing of the above-mentioned type of objects, especially if they are in motion, as well as throwing toward a desired moving or fixed box far away from the robot.

To achieve these objectives, in this task we will develop a novel end-effector based on: i) multi-synergystic, soft and self-adaptive hands for both maximising the variety graspable objects in terms of shape, dimension and deformability, including the possibility of in-hand manipulation for reorienting the object or redistributing the weight, ii) high power-density electric motors with low reduction ratios for allowing fast opening and closing movements, iii) a sensing system fusing force and torque measurements at the wrists with position measurements of the finger phalanges via IMU. The gripper we will propose in DARKO, on one side will improve manipulability and dexterity w.r.t. state-of-the-art under-actuated and synergistic hands, on the other side not have the well-known limitation of suction grippers (or end-effector including suction grippers like Right-Pick by RightHand Robotics) able to grasp objects only from mostly flat and non-porous surfaces. T1.2 receives input from T8.1 and provides output to the integration task T1.4.

Task 1.3: Elastic manipulator **TUM,** UNIPI, EPFL

Through the elastic musculoskeletal system, the human can achieve outstanding performance and robustness. Technically, elastic joints and interlinked dynamic coupling enable robots to mimic major characteristics of the human musculoskeletal system and achieve close to human-like performance in terms of speed, energy efficiency and robustness. In the last few years, Series Elastic Actuators (SEAs) and Variable Stiffness Actuators (VSAs) were widely studied [255]. The spring stiffness in a VSA is altered by a second actuator. In contrast, SEA includes a motor in series with a mechanical stiffness (fixed, possibly nonlinear stiffness). Based on our previous studies [99, 95, 97], SEAs have lower reflected inertia during collision and are able to provide remarkable performance benefits, such as allowing the execution of highly dynamic manoeuvres, impact tolerance, more accurate and stable force control and in particular the possibility of energy storage and release. On the other hand, our previous experience in design [62, 86], modelling and control [5, 101] of VSAs shows that although we can achieve high energy efficiency and robustness against disturbances, such mechanisms are still rather bulky, complex and heavier [255]. This may limit the possibility of making a light-weight, close-to-commercial manipulator with dynamic motion capabilities. Thus, we use SEA as the elastic actuation unit to release/store energy.

In order to precisely throw an object, humans intuitively exploit physical effects of multibody systems. The speed of a wrist, and consequently the velocity of the thrown object, can be increased by suppressing or braking the motion of the elbow [111]. This effect can be explained by the conservation of energy which only can be maintained if the last moving element, here the wrist, increases the joint velocity. Such capabilities can be found when looking at clutch mechanisms with the possibility of mechanical coupling and decoupling between motor and link side. In this task, we aim at developing an intrinsically elastic manipulator presumably equipped with SEA and clutch mechanism to outperform commercial manipulators on the market in terms of dynamic motion capabilities such as throwing. The clutch mechanism allows the use of inertial coupling effects and together with the elastic joints we can demonstrate novel and unexplored dynamic manipulation capabilities such as throwing.

As the first step, we will identify the specific requirements in terms of well-established metrics (e.g. energy storage capacity, maximum force/torque, velocity, payload capacity, workspace) based upon project goals. We will then exploit the notion of SEA and clutch mechanism to develop new inherently clutched elastic actuator concepts (e.g. up to three new proposals) that will be used in developing the new elastic manipulator. The goal is to elaborate a systematic design process that generates a joint concept that is applicable to the entire arm, simulation and experimental test. Based on the state-of-art in system identification, complex mechatronics simulation during the design process, a control compliant scheme will be developed so that the performance can be analysed in simulation and experiment. A modular test-bed will be designed in which both the elastic elements and clutch are interchangeable. Based on the consortium's previous projects, a systematic data sheet of the elastic actuators will be generated that can be used to quantitatively compare the performance increase of proposed actuators relative to each other and to previous systems. We expect to pass this milestone within the first nine months of the project, by which the selected elastic mechanism should demonstrate higher dynamic capabilities in terms of energy storage/release, speed, torque transmission and bandwidth, impact undergoing, etc compared to the state-of-the-art. We will investigate both physical and functional aspects to successfully implement the use-case scenario while optimising for efficiency from an energetic perspective.

After selecting the most appropriate elastic actuator(s), we will upscale the concept to a 3-DOF Scara-type system and then to a full serial manipulator. The development will be based on specific kinematic, dynamic, and safety requirements that were formulated in the beginning of this task. Since the mobile platform was selected by the T1.1, the mechanical and electrical interface of the developed arm will be designed to be fully compatible with the commercial mobile base. The gripper from T1.2 and set of sensors derived from requirements of perception (WP2) and mapping (WP3) will be added and integrated with the elastic manipulator. The final step is to test and receive feedback from other work packages to ensure the performance and efficiency of the system. Existing and novel joint- and task-level compliance and energy-aware controllers will be implemented and tested in WP4. With this overall process, we develop a manipulator that will fulfil the project requirements while the continuous objective is to improve performance and system integration. From an energy efficiency perspective, the overall system shall outperform current all commercial manipulators in terms of performance and weight.

Task 1.4: Final DARKO mobile dynamic manipulation platform **TUM,** Bosch, UNIPI, ORU, EPFL, UoL

This task aims at providing the final system consisting of the integrated mobile platform (T1.1) and the new elastic manipulator (developed in T1.3). We intend to dismount the manipulator of the initial platform and attach the elastic manipulator on top of the mobile base, to reduce the effort and cost for the consortium. As described in T1.1, the Boxer platform is designed to be easily extensible with additional sensors and manipulators and thus represents a good candidate to be used in both the initial and the final platform.

Based on the previous tasks, for the combined system of mobile platform and manipulator we will develop a real-time control interface that can be easily accessed by the project partners, and a ROS interface for perception and planning as well as other interfaces if necessary. For model-based control we provide an accurate robot model and a simulator with the project partners for optimal testing within the various work packages. Basic torque control and task planning schemes will be provided to carry out a majority of industrial tasks. The objective is to develop sub-complete and concrete modules that fit the requirements of whole-body control scheme.

Deliverables

D1.1 Initial DARKO mobile dynamic manipulation platform — TUM / M3
The deliverable demonstrates the the initial (phase A) DARKO's platform, which will be operational and available for the partners' use by the end of the third month of the project, and describes the customisation efforts.

D1.2 Preliminary DARKO end-effector — UNIPI / M20
Preliminary version of the gripper to be used in the DARKO platform.

D1.3 Final DARKO elastic manipulator — TUM / M24
This deliverable will describe how the elastic manipulator has been developed including the elastic joints, building the prototype, the final set of sensors and integration with the general-purpose gripper from T1.2. The metrics and the database of elastic joint will be presented to show the superiority of the proposed elastic actuator compared to existing systems.

D1.4 Final DARKO end-effector — UNIPI / M32
Finalised version of the gripper to be used in the DARKO platform.

D1.5 Adaptation and finalised DARKO mobile platform — TUM / M36
This deliverable will report the efforts to integrate the elastic manipulator with the mobile base and adaptation based on the feedback from partners.

Measures for Success and Benchmarking

- For Task T1.1: Initial DARKO mobile dynamic manipulation platform

In this task, we take into account project requirements and necessities and compare available commercial mobile robots to identify the most suitable options for the project. The task will be evaluated based on the fulfilment of the project requirements and the customised platform will be operational after three months of project starting.

- For Task T1.2: General-purpose gripper

  The end effector designed and realized in tasks T1.2 will be evaluated through experiments in realistic scenarios and in the DARKO demonstrators. The quality of the end effector is measured in terms of the weights, shape and dimensions of objects that can be picked thrown.

- For Task T1.3: Elastic manipulator

  In this task an intrinsically elastic arm will be developed, which should be able to surpass commercial manipulators. More specifically, we establish metrics (e.g. energy storage capacity, maximum force/torque, velocity, payload capacity, workspace) and compare the developed arm with the initial manipulator used in the project and show that the developed arm overcomes the initial baseline specially in dynamic manipulation tasks such as throwing.

- For Task T1.4: Final DARKO mobile dynamic manipulation platform

  In this task we will integrate the intrinsically elastic arm with the mobile base. The final integrated platform will be compared with the system used in the initial phase using a well-established metrics and benchmarking.

Risk Assessment and Problem Resolution

- Failure in providing initial platform (Franka Emika Panda + mobile base) *Impact: high, Risk: low*

  To prevent this from becoming a problem in the first phase of the project, we will gather project requirements from the partners within the first month of the project in order to deliver the most suitable platform by the end of the third month. Since we have investigated the applicability of Boxer integrated with Franka Emika Panda we are aware that this commercial product from Clearpath Robotics is able to fulfil the minimum requirements for this project. We intend to provide the most suitable existing product, but in case we still fail to select and integrate the mobile base with the manipulator, the consortium can use the commercially available integrated Franka Emika Panda with the Boxer and only need to integrate few sensors.

- Failure in providing final platform (elastic manipulator + mobile base) *Impact: high, Risk: low*

  In the past, some partners of the consortium, i.e. TUM, UNIPI, have developed elastic actuators in various projects. In DARKO we will exploit our previous experience and build the new elastic arm. Since the mobile base is ready, we don't need a lot of effort for preparing the final platform. Moreover, commercial mobile bases in the market such as Boxer are designed to be plug-and-play compatible with third-party sensors, and we can simply integrate our sensors and manipulator with the mobile base.

- Delay in providing gripper for picking and throwing *Impact: high, Risk: low*

  The available technology, developed in previous projects, is already working and, in the worst case, can be provided to the other partners to speed up testing activities and integration process.

- The clutch mechanism is not reliable and doesn't work well *Impact: medium, Risk: low*

  Clutch mechanism is an add-on to the elastic manipulator and in case of problem, we can limit the design to elastic joints. This may cause a reduction in efficiency, but still the efficiency of our developed manipulator will be higher than the state-of-the-art.

3.1.2 Work Package 2: 3D Perception and Scene Understanding

WP2		3D Perception and Scene Understanding							
Type:	RTD	Part.no.:	1	2	**3**	4	5	6	7
Start:	M01	Part.:	ORU	TUM	**Bosch**	UNIPI	EPFL	UoL	ACT
End:	M42	Effort:	38 PM	3 PM	**44 PM**	10 PM	24 PM	7 PM	0 PM

Task T2.1: Object-level semantics
Task T2.2: Perception for manipulation
Task T2.3: In-hand grasp perception
Task T2.4: Detecting successful throws
Task T2.5: Perception of humans and their poses

Objectives

The main objective of WP2 is to develop theory, methods and experiments that enable robots to perceive the 3D environment that they are operating in and interacting with, in real-time – with a focus on the particular challenges encountered in DARKO such as cluttered and dynamic environments shared with humans, and picking and throwing tasks involving closely spaced complex objects such as piles of workpieces wrapped in transparent plastic bags. Tasks in WP2 provide the necessary semantic and geometric understanding to higher-level work packages such as mapping (WP3), manipulation (WP4), human-robot spatial interaction (WP5) and motion planning (WP6). They include: (i) gaining a broad semantic and geometric understanding of the 3D scene in which the robot is operating; (ii) perception for manipulation by directly regressing feasible grasps; (iii) in-hand perception of grasped objects using proprioceptive and exteroceptive sensors prior to throwing; (iv) detection of successful or failed throws by tracking flying objects using onboard sensors; (v) real-time perception of humans and their 3D poses.

Task 2.1: Object-level semantics — **Bosch,** ORU, UoL

In this task we aim to create an efficient perception module for 3D scene understanding that provides real-time semantic and spatial information using the robot's on-board sensing. We will follow a multi-modal approach where we will leverage rich semantic information present in color data and geometric accuracy of depth and range measurements. We will extend our work on accurate human detection in 3D via RGB-D fusion [149] towards a unified and more generic 3D object detector, by considering a larger variety of object types and regressing also the poses of objects and their extents. Moreover, we will look into other emerging efficient and real-time DNN architectures for object detection, semantic and panoptic segmentation [279, 248, 38, 28, 113, 63, 114], while addressing the multi-modal and 3D aspects relevant to DARKO.

One of the limitations of current RGB-D sensors is their relatively narrow field of view. In DARKO, we aim at acquiring a broad semantic understanding of the environment to enable efficient and safe robot behaviors. Therefore, we will also investigate the potential of fisheye and panoramic RGB cameras to maximise the perceived field of view. Most of the research on wide-angle cameras is focused on object detection and semantic segmentation in 2D, e.g [239, 52], while only a few more recent methods provide 3D detections [87, 259]. We will look into enhancing these methods to provide accurate 3D information by directly estimating depth from RGB measurements, or fusing RGB and 3D lidar data without requiring extensive domain-specific annotated training datasets.

A key challenge in DARKO is the lack of domain-specific datasets required for supervised learning. To reduce manual annotation effort, we will study deep learning techniques to transfer knowledge from existing datasets across domains and sensor modalities (e.g., from regular 2D images to 360-degree spherical images [239]). To obtain accurate 3D groundtruth, we will exploit simulators [181, 151] and extend them, where required, with a larger variety of 3D objects and environments and simulated sensor models, e.g., for panoramic cameras [21]. To complement synthetic合成的 data, we will look into semi-supervised and self-supervised learning methods that show promising results in different robotic applications [54, 88] and complement generic object detection [153, 201], tracking [182] and class-agnostic segmentation [139, 115] techniques. Combining such methods with information on robot motion and supervisory signals from higher-level tasks like SLAM/WP3 (map and localization quality) would enable self-supervised learning of relevant structures and their 3D attributes.

The output of T2.1 – a semantic snapshot of the scene with, e.g., detected doors, pillars, walls, shelves, carts, work benches, and storage boxes – will be integrated over time in a coherent manner by T3.1 to create a global and persistent semantic representation of the environment. While ensuring spatio-temporal consistency in inherently noisy semantics [56], T3.1 will benefit from semantic representations in the data association step. This is also true for T3.2 where semantic data abstraction will aid correspondence search between heterogeneous map representations. Furthermore, we will investigate how 3D semantic information about the environment can facilitate and inform higher-level tasks such as motion planning for the mobile base (T6.1, T6.3) and context-aware human-robot spatial interaction (T5.3).

Task 2.2: Perception for manipulation — **ORU,** UNIPI, Bosch

This task will develop perception methods that inform object picking (T4.3) and aid in acquiring stable and task-relevant grasps for a wide variety of target objects.

Several challenging factors complicate this perception problem in DARKO. In particular, we will develop methods applicable to both bin and shelf picking. Objects will often be stacked together very tightly, which poses challenges to object detection, pose estimation, and manipulation planning. In addition, some objects are wrapped in transparent plastic bags, causing degradation of both appearance and geometric sensor data. Finally, picking objects while moving poses demanding runtime requirements on perception.

To meet the challenging requirements from our use case, we will forgo the traditional object-centric integration of perception and manipulation planning: Instead of reporting candidate object poses, in this task we will directly regress feasible grasps from sensor data. By imposing a tighter integration between perception and manipulation we aim at supervising the perception modules developed with task-relevant information, enabling the perception module to learn features that are important for successful object picking. In this task we will investigate two approaches for integrated perception and manipulation:

Grasp configuration interface. As a first step, we will investigate methods for end-to-end trainable selection of task-relevant grasps directly from sensor data. We will develop methods based on recent work [30, 74] to select feasible grasps directly from point clouds. To overcome challenges posed by a cluttered workspace, we will extend the approach to operate on semantically annotated point clouds and experiment with multi-view information fusion. In addition, we will also devise an end-to-end trainable machine learning module for selecting the best suitable grasp configuration. We will follow up on prior methodology [274, 275] and extend to more complex underactuated grippers with higher state space dimensionality. An open challenge in training this approach is the choice of supervision signal: while learning a detector through trial and error (reinforcement learning) can produce good results, the sample complexity is high and may be impractical. To meet this challenge we plan on investigating single-shot transfer- and meta-learning for quickly adapting the learned regressor to novel objects.

Manipulation primitive interface. While grasp configurations are a feasible interface to manipulation planning in simple scenarios, they are also severely limiting the space of possible arm motions during grasping. Certain object–environment configurations do not afford direct grasp acquisition: e.g., objects aligned with an obstacle [64], thin objects resting on a flat surface [102]. Picking an object in such cases necessitates a more complex joint gripper-manipulator control sequence. To enable such interaction, we will leverage a rich base of *manipulation primitives* developed within T4.3 and regress full trajectories in parametric space. This approach represents a compromise between on one side single-shot grasp selection, and on the other full end-to-end reinforcement learning of feedback policies in the robot configuration space. By composing a combination of parametric manipulation primitives we will in essence lean on prior knowledge of a set of feasible manually chosen control policies.

Task 2.3: In-hand grasp perception **ORU,** EPFL, UNIPI

Successful execution of manipulation tasks is predicated on achieving a stable and task-appropriate grasp. While the methodology followed in T2.2 and T4.3 aims at devising and executing grasp acquisition motions, in this task we are concerned with reconstructing the state of the gripper-object system after grasping.

Even under simplifying conditions (e.g., simple parallel jaw gripper and well known object model) execution errors can result in failed grasps. In DARKO we are additionally targeting underactuated grippers: i.e., the gripper configuration upon grasp acquisition is determined via interaction with the grasped object, and is difficult to predict even given knowledge of the contact surfaces. In addition, some of the objects may be wrapped in deformable plastic or cardboard packaging, further complicating grasp analysis. In order to predict grasp stability and task suitability it is thus necessary to devise methodology for estimating the relation between gripper and object.

In this task we will combine proprioceptive sensing capabilities of the manipulator (force/torque sensing) and gripper (contact, encoder, inertial measurements) with exteroceptive observations of the gripper-object system. We will fuse these measurements to regress the relative pose between the gripper and an object reference frame. In addition, we aim at estimating grasp stability and task suitability scores to further inform the throwing controller developed in T4.4. Three distinct cases of gripper-object relations will be considered: i) *Small object completely covered by gripper:* Here, model identification will be performed to estimate the centre of mass and inertia of the grasped object. ii) *Medium-size partially occluded object:* A combination between proprioceptive sensing and visual estimation of the gripper configuration will be deployed to reconstruct a maximum-likelihood full gripper configuration. iii) *Large objects with minimum gripper occlusion:* An object tracker will be used to estimate the object pose.

In addition to the above dedicated methodology, we will design a machine learning module for self-supervised learning of grasp stability and task suitability metrics based on experience and streaming sensor data.

Task 2.4: Detecting successful throws **ORU,** Bosch, EPFL

This task is related to T4.4, which will devise methods that allow for throwing goods into target containers, thereby extending the reach and throughput of the envisioned mobile manipulator. As accurate throwing from a moving platform is a very challenging task, it is very important that the throwing system can monitor the success of executed throws: i.e., did the object successfully reach the goal or not. This information is important for two reasons: first, it allows for incremental improvement of the throwing accuracy, and second, it can be used to trigger corrective action if an unsuccessful throw occurs during operation. In this task, we will therefore devise on-board perception methods for estimating the quality and success of object throwing.

Visual trajectory estimation of fast-moving objects is a challenging problem in many respects: it requires data acquisition at high frame rates, object recognition and tracking, pose estimation and in some cases trajectory prediction. These problems are additionally more complex if the sensor itself is in motion relative to the static environment.

In this task we will estimate the full flight trajectory of thrown objects by combining recent advances in generative models for trajectory estimation [84] and learning of physics simulation from observations [219, 147]. Modelling object spin and air drag during flight is in general intractable analytically: therefore, we will instead concentrate on data-driven approaches to estimate a trajectory, given sparse observations. The sparsity of observations is induced by our ambition to use the available on-board sensors for this task, forgoing the need to instrument the environment, or invest in expensive high frame rate camera systems. Given sparse sample detections and an egomotion estimate for the platform, we aim to predict the maximum-likelihood object trajectory in a global frame of reference. We will investigate several architectures for solving this task: either purely data-driven by encoding trajectories in a generative model and subsequently sampling given observations; or by imposing stronger inductive bias by incorporating physics-inspired priors. Training data will be collected for a subsample of objects either in simulation, or through instrumentation. By following a trajectory-centric approach, we aim at estimating the landing location of the thrown object, relative to a target bin, which will provide a dense supervision signal for improving throwing. An alternative approach, namely estimating a binary success/failure label by directly observing the target bin using the onboard sensors, will be considered as a fall-back option.

Task 2.5: Perception of humans and their poses **Bosch,** UoL

A key aspect of DARKO, reflected in **O2** on efficiency in human–robot co-production, relates to the deployment of robots in spaces shared with humans. To enable maps of dynamics (T3.3), prediction of human motion and intents (T5.1) and reasoning about human-robot spatial interactions (T5.3), which serve as inputs to safe and risk-aware control (T4.2) and local and global motion planning (T6.1, T6.3), a robust perception of humans and their 3D poses is required. Therefore, this task deals with the real-time detection and tracking of humans and the estimation of their articulated poses in 3D space from the egocentric perspective of a mobile robot and its onboard sensors.

As an initial baseline at beginning of the project, we will be building on our previous work on human detection and tracking using RGB-D and lidar data from the EU projects ILIAD, SPENCER and FLOBOT [23, 149, 150, 268, 269] to quickly set up an initial tracking system for 3D human centroids and be able to provide inputs to higher-level work packages early on in the project. Our subsequent research will then be focused along two lines:

Firstly, and differently from T2.1 which is centred on rigid objects, we aim to achieve a more fine-grained understanding of humans by not just tracking their centroids and bounding boxes, but also their individual body joints. For this, we will integrate the generic 3D object detector from T2.1, based on our previous work on 3D human detection [149], with a top-down articulated human pose estimation method [222] to obtain refined 3D skeleton estimates in real-time. This is especially challenging under partial occlusion and at very close-range (truncations). To reason over temporarily occluded body joints, we will extend our current tracking system [150] with the ability to track articulated objects over time, while incorporating scene context from T2.1 in order to model interactions with other subjects and objects in the environment, for example through geometric pose affordances [146, 260]. We will study different filtering techniques to reduce jittering, e.g., based on long-short term memory units [49], and consider anatomically-inspired and spatio-temporal models of body joint relations and human dynamics [50, 241, 192, 120] for pose regularisation. These techniques can be complemented with suitable data augmentation strategies at training time; as opposed to existing work that performs augmentation in 2D image space during training [221], here we will instead focus on 3D augmentation strategies within our synthetically rendered RGB-D dataset [151].

Second, similar to T2.1, we will aim to identify a minimal set of sensors that allows us to maximise the observable field of view at sufficient accuracy, while at the same time being computationally- and cost-efficient. One key challenge here is the limited amount of available real-world training datasets with accurate per-joint 3D groundtruth, especially if we are e.g. interested in fisheye cameras from a mobile platform. For this reason, we will strongly rely on synthetic training data as well as suitable domain adaptation and transfer learning techniques [110, 239, 149] to enable accurate metric localisation in 3D space.

Deliverables

D2.1 Initial perception system for objects and humans — Bosch / M11
This software deliverable will provide a basic detection, tracking and pose estimation framework for objects (T2.1) and humans (T2.5) to enable functionalities of dependent tasks early on during initial integration (MS1).

D2.2 Initial report on perception in DARKO — Bosch / M24
This deliverable will report on initial research results of this work package, including novel scenario-specific datasets for training and evaluation. We will provide basic functionality for the more general tasks T2.1–T2.3, and report final results for the more specialized tasks T2.4 and T2.5.

D2.3 Final report on perception in DARKO — ORU / M42
This deliverable will report on the final perception system developed in DARKO, covering more challenging scenarios and providing all required functionality for a successful final demonstration. We will further assess whether the success measures described below have been met, and how the research within work package WP2 has contributed to the overall objectives of the project outlined in Sec. 1.1.

Measures for Success and Benchmarking

- For Task T2.1: Object-level semantics

  For detection of 3D object centroids and bounding boxes, we will report average precision (AP) over multiple intersection-over-union (IoU) thresholds following MS COCO protocol [148], and average orientation similarity (AOS) as per KITTI protocol [82]. We will also provide precision/recall curves. We aim to be close to the level of state-of-the-art methods while requiring significantly less manually annotated data and achieving real-time performance (>10 Hz). Moreover, this task will be partially evaluated by the downstream tasks (T3.1, T5.3, T6.1, T6.3) by comparing semantically informed methods with methods utilising only geometric information.

- For Task T2.2: Perception for manipulation

  For grasp pose estimation we aim at achieving translation and orientation errors within the gripper tolerance (expected 0.01 m, 0.1 rad). For end-to-end integration, the success metrics of T4.3 apply. In both cases, we target close to real-time performance at roughly half sensor frame rate (10 Hz).

- For Task T2.3: In-hand grasp perception

  We will measure in-hand object pose estimation accuracy against ground truth observations obtained via fiducial markers. Target values depend on hand-object occlusion, but we will aim at an error below 5 mm for the object centroid relative to the ground truth.

- For Task T2.4: Detecting successful throws

  We will report classification accuracy of throw success/failure, as well as metric error of estimated landing positions. For this, we will use a motion capture system to obtain metric groundtruth. We will aim for a classification accuracy of at least 90% and a metric error of less than 20 cm for medium-sized objects and a throw distance of less than 2 m.

- For Task T2.5: Perception of humans and their poses

  To evaluate human tracking in 3D space, we will use the CLEAR-MOT metrics [22, 143], where our goal is to improve upon the results obtained at the end of ILIAD. For 3D articulated human pose estimation and tracking, we will report mean per joint position error (MPJPE) and percentage of correct keypoints (PCK), see e. g. [222]. We will aim for PCK of 90% or more and an average metric error of less than 5 cm per body joint at close range (< 1 m) and less than 20 cm at medium range (< 5 m). We will target frame rates of at least 10 Hz on GPU.

Risk Assessment and Problem Resolution

- Failure to robustly perceive certain types of objects for manipulation. *Impact: medium, Risk: medium*

  To prevent this risk, we will at the beginning of the project (T1.1) evaluate different sensor options in order to identify one that is most likely able to perceive the relevant object types at sufficient accuracy. If we still fail to recognise certain types of objects (e.g. transparent plastic bags, piles) we will collect further in-domain training data to understand if this is a limitation of the method, or due to lack of data. A second strategy is to explore alternative algorithms and ways of modelling the problem. Only if that fails, certain object types or configurations would be substituted with less challenging counterparts for demonstration purposes, in order to not negatively affect other tasks.

- In-hand object pose estimation is not accurate. *Impact: medium, Risk: very low*

  If the estimated poses are too inaccurate to guarantee robust throwing, we can as a fallback instrument objects with markers. As prior work has demonstrated performance within the minimal required accuracy, this risk is however very low.

- Visual detection/tracking of successful throws fails. *Impact: low, Risk: medium*

  If we are not able to visually track the flying object at sufficient real-time speeds with the available sensors onboard the robot, fallback options would be to install weight sensors inside the target trays, to visually inspect them via active sensing using the robot arm, or to use a marker-based motion capture system that is already available at EPFL for tracking. Therefore, sufficient other options are available to provide feedback to the throwing controller.

- Insufficient metric accuracy in perceiving objects with wide-FOV cameras. *Impact: low, Risk: medium*

  As part of the requirements analysis for integration at project start, we will examine under which exact circumstances which metric accuracy will be required; e.g., there might be larger tolerances when dealing with context-aware qualitative human-robot spatial interactions in T5.3, compared to close-up interactions of a human and the manipulator in T4.2). If we find that RGB information from panoramic cameras alone does not provide sufficient accuracy, we can, as a first step, easily fuse lidar data with the panoramic images to improve spatial localisation. A lidar will be present on the robot anyway for mapping and localisation (WP3). If that fails, we will fall back to fusing information from multiple narrow-field RGB-D sensors and our existing expertise in this field [149, 242] in order to provide reliable detection and tracking results to higher-level tasks.

3.1.3 Work Package 3: Multimodal Mapping and Safe Localization

WP3		Multimodal Mapping and Safe Localization							
Type:	RTD	Part.no.:	**1**	2	3	4	5	6	7
Start:	M01	Part.:	**ORU**	TUM	Bosch	UNIPI	EPFL	UoL	ACT
End:	M42	Effort:	**80 PM**	0 PM	3 PM	5 PM	0 PM	4 PM	2 PM
Task T3.1: Efficient mapping									
Task T3.2: Heterogeneous map merging and exploration									
Task T3.3: Maps of dynamics									
Task T3.4: Reliability-aware mapping and safe localisation									

Objectives

The overall objective of this work package is to work towards *hands-off, failure-aware construction of rich map representations beyond mere geometry*. This goal directly maps to **O3** (efficient deployment) and **O2** (human-robot co-production). The approach for reaching the objective is centred around developing a probabilistic framework for self-supervised environment learning using heterogeneous sources of information.

Concretely, we will address the following research questions. (T3.4) How can a mapping system be endowed with introspective capabilities such that it becomes both failure-aware and failure-resilient? (T3.3) How can we efficiently learn and represent, and exploit, flow and activity patterns in the mapped environment? (T3.2) How can disparate sources of spatial information (e.g., unstructured human input) be combined in order to provide mutual benefits?

This work package also uses input from the semantic perception that is provided by WP2 in order to improve mapping (in T3.1), while feeding back information to WP2 in order to better determine semantic labels depending on *where* percepts are recorded. The rich map representations provided by this work package are crucial input for, in particular, WP5, WP6, and WP7.

Task 3.1: Efficient mapping — **ORU,** Bosch

In this task we will develop the main consolidated map representation that will be used for planning, navigation, etc., in the other technical work packages.

The basis of the work in this task is the probabilistic factor graphs that underpin much of SLAM research today. We will build on the consortium's proven track record in mapping and localisation, which is already deployed in commercially available intralogistics systems.[24]

这里是描述的是对NDT模型进行的修改，也就是说这里面有一个工作是关于mapping的

The starting point of the geometric 3D maps used for navigation and planning will be the NDT-OM representation [238] that has also been used successfully in several other projects and applications, in particular the new `graph_map` implementation (public release pending). Although NDT and NDT-OM have been well used in several applications, a thorough investigation of the underlying model is so far missing in the literature. We will study alternative robust estimation techniques, compared to the standard Gaussian/uniform mixture model used in NDT, which may provide better performance (in particular for sparse data) and provide a theoretically more well-founded model.

Recent addition to the NDT-based mapping framework (from our ongoing work in the ILIAD project) includes semantics-assisted scan registration [272, 271] and loop-closure detection [273]. Initially, we aim to improve on the state of the art by learning the *relevance* of (pre-specified) classes for localisation and mapping, in order to increase robustness. Furthermore, we will interact with T2.1 and investigate how to forego pre-specified class labels and investigate *self-supervised* learning of features that can facilitate scan matching and loop detection. In particular, we will research self-supervised learning of the appearance of *dynamic and semi-dynamic* features that cannot be reliably used for data association when revisiting places. This is particularly valuable for easy deployment in environments where pre-labelled training data is not readily available. 主要是对于场景中动态/半动态物体的特征检测

这两部分都是关于SLAM的

Both of the research directions outlined above address *data efficiency*. For the former, efficiency w.r.t. sparse sensor data (e.g., from cost-efficient 3D lidars or camera-based range points); and for the latter, efficiency w.r.t. training data and labelling labour. As such, this research will contribute to DARKO's **O3**. 这部分的工作其实包含两个部分，一个是地图；一个是语义信息

[24] In particular, ORU's work on NDT mapping and localisation [238, 215] is the basis for the "Natural Navigation" commercialised by Kollmorgen Automation for Toyota Material Handling, and Bosch Rexroth markets the "Locator" system for long-term mapping and localisation.

Task 3.2: Heterogeneous map merging and exploration **ORU,** Bosch

This task focuses on learning robust associations between features of disparate and uncertain sources of spatial information including, e.g., unstructured human input in order to transfer information between maps, and by doing so, attaining mutual improvement of the different map sources.

A particularly relevant use case for this ability is the deployment of a new robot system. Instead of manually driving the robot around its workspace to construct an initial map, or performing autonomous exploration, deployment could be much more efficient (both in terms of time, energy, and labour; as well as improving the quality of the resulting map) if the robot could make use of already available map information from, e.g., CAD layouts or sketched drawings; thereby directly addressing **O3** on efficient deployment.

Our starting point in this work is the Auto-Complete Graph [172] which improves on earlier work [189] by allowing for much larger discrepancies and scale uncertainties between map representations, in part by means of using an ensemble of robust graph-SLAM backends. It uses corners and walls for cross-map data association, which are features that are readily available in prior maps from most built environments. However, additional features should improve matching, not least in industrial environments where large open spaces are common. Therefore, we will explore a bi-directional connection between this task and T2.1: We will study how using map features (e.g., doors) detected from raw perception data in WP2 can be included in data association between heterogeneous maps. Likewise, annotations in the prior map may be transferred, via the non-rigid map matching developed in this task, to supply priors for object detection in T2.1.

Task 3.3: Maps of dynamics **ORU,** UoL

In this task we will develop methods for building adaptable spatio-temporal models of dynamics – *maps of dynamics (MoD)* – that enable the system to quickly adapt to changes in the patterns of dynamics in the environment.

The work in this task aims to further the state of the art of MoDs in four distinct ways: (i) We will enable MoDs to be created from small amounts of data, resulting in faster deployment (**O3**). Furthermore, (ii) we will develop algorithms allowing on-line update of the maps based on the incoming data, as opposed to batch processing which is required in existing implementations. In consequence, the MoDs will faster adapt to changes of patterns followed by the dynamics in the environment what will facilitate more efficient human-robot co-production (**O2**). (iii) We will also enable MoDs to handle *bounded* periodicities, making it possible not only to add new temporal patterns to the map but also to discard obsolete ones; thus enabling more flexibility in global and local motion planning as discussed in T6.1, and T4.3. (iv) Finally, we will also develop methods to detect and label structures in the dynamics, thus contributing to more effecting motion planning (**O2**).

1. data-driven
2. on-line update
3. bounded prodictions
4. label

In DARKO, we will in particular focus on flows of humans, and thus we will use human tracking data from T2.5 as input. We will build upon our previous work on MoD, including CLiFF-map [135] and STeF-Map [177]. The problem of learning from small data sets (i) can be decomposed into spatial and temporal. In order to tackle *spatially* sparse data, we will study imputation methods that, based on the shape of the environment and available data, generate virtual observations in unobserved locations. For tackling *temporally* sparse data, we will develop methods searching for correlations between locations in the map and using them as input to generate virtual observations. To allow on-line updates of the map (ii) we will develop methods for monitoring the consistency between the data and the model. This will make it possible to decide on addition of new components to the model and discarding of the obsolete ones. This will allow not only to make the model more robust and more flexible, but also will allow to properly handle bounded periodicities. (iii) It is important to remember that changes in patterns of dynamics are not only limited to global permanent changes. Thus, in this work package we will also develop methods to enable event-based MoD change. Finally to to improve the memory complexity of the MoDs and further facilitate motion planning and motion prediction we will develop methods for structure detection in MoDs (iv).

Task 3.4: Reliability-aware mapping and safe localisation **ORU,** UoL

In this task we will tackle the problems of (i) reference-free map quality assessment and (ii) on-line localisation quality estimation, contributing to **O4**. Reference-free map quality assessment will not only assure safe operation but will also substantially shorten the deployment time and the associated cost (**O3**). This is a technology that is highly sought-after by the industry. Specialised software providing the score of the map will allow untrained personnel to deploy a safe and efficient robotic system, without the need for tedious manual checking and map cleaning. Furthermore, accurate assessment of localisation will lead to lowering the number of interruptions of operations enabling the system to mitigate potential localisation errors.

To achieve reference-free map quality assessment we will build on our previous work on structure extraction [137]. We will extend the idea of structure extraction to facilitate symmetry detection in the environment. Furthermore, we will implement active map quality assessment, where the robot will not only identify potentially broken parts of the map, but also autonomously verify it through observation of said location in the environment.

To achieve autonomous localisation failure identification we will develop two approaches; one off-line (Localisation Risk Map – LRM) and one on-line (Localisation Quality Assessment – LQA). LRM is a map of the environment with labelled areas where localisation errors are more likely to occur because of the environmental conditions. LQA is built on the concept of point cloud alignment assessment, where misalignments between sensor readings and the map are indicative of localisation failure. (Promising and potentially groundbreaking first results by ORU in this respect are currently under review). We will also include consistency checks between different sources of instantaneous velocity estimations, as indicators of localisation errors.

To mitigate localisation failures, we will build on an idea of dual-timescale localisation where, apart from the global static map for localisation, the robot uses a local map built during the current run of the vehicle. The combination of these two maps allows the robot to safely operate in the environment (it is still localised in the local map) and to recover from a localisation failure through aligning the local with the global map.

Finally, LRM will provide invaluable input for T6.3 where information about areas with potential localisation errors. LRM and LQM will also provide direct input to the risk representation developed in WP7.

Deliverables

D3.1 Prototype implementation of mapping system — ORU / M11
The initial implementation of functionalities for tasks T3.1, T3.2 and T3.3.

D3.2 Prototype implementation of map quality assessment and localisation assessment tools — ORU / M23
The first implementation of functionalities for tasks T3.4.

D3.3 Implementation of the complete mapping system — ORU / M35
The complete implementation of functionalities for tasks T3.1, T3.2 and T3.3.

D3.4 Final mapping report — ORU / M42
Report on the final version of DARKO mapping system. Including advanced functionalities for tasks T3.1, T3.2, T3.3, T3.4.

Measures for Success and Benchmarking

- For Task T3.1: Efficient mapping

  The mapping system will be evaluated in terms of absolute trajectory error (ATE) while constructing the map, compared to using a ground-truth positioning system while mapping. We will also use the novel metrics from T3.4 to assess map quality in DARKO compared to the baseline at the start of the project.

- For Task T3.2: Heterogeneous map merging and exploration

  The main measure of success for heterogeneous map merging will be the time needed until a usable map that covers the workspace of the demo area exists, compared to mapping without priors.

- For Task T3.3: Maps of dynamics

  The on-line MoD methods will be assessed by comparing the divergence between the model estimated with the on-line method and underlying data, to the divergence between the model estimated with the off-line method.

- For Task T3.4: Reliability-aware mapping and safe localisation

  In this task we will compare the assessment results provided by human operators with the assessment result provided by our system.

Risk Assessment and Problem Resolution

- Map quality is not sufficient. *Impact: high, Risk: low*

  The mapping technique we will use at the starting point has shown to produce accurate maps in relatively large environments already. Additional sensing capability to assist loop closure, such as WLAN based fingerprints can be added in the mapping phase if necessary.

- No enough dynamics in the test environment *Impact: low, Risk: low*

  In case there will be not enough of dynamics in the test environment we will use publicly available data sets to evaluate the quality of the models in T3.3.

- Localisation does not provide enough accuracy. *Impact: high, Risk: low*

  In case the system does not generalise well to the scenarios in DARKO, it is possible to equip more high-accuracy sensors, or to exploit existing infrastructure such as WLAN networks.

3.1.4 Work Package 4: Efficient and Safe Dynamic Manipulation

WP4		Efficient and Safe Dynamic Manipulation							
Type:	RTD	Part.no.:	1	2	3	**4**	5	6	7
Start:	M01	Part.:	ORU	TUM	Bosch	**UNIPI**	EPFL	UoL	ACT
End:	M42	Effort:	4 PM	15 PM	0 PM	**59 PM**	54 PM	0 PM	0 PM
Task T4.1: Planning and control for efficient manipulation									
Task T4.2: Safe, risk-aware planning and control for manipulation									
Task T4.3: Picking and placing in motion									
Task T4.4: Throwing									

Objectives

The main objective of WP4 is to provide path planning and control strategies that enable safe and efficient dynamic manipulation, especially for moving objects, while guaranteeing at the same time minimum failure in picking and placing, and high precision in throwing objects into potentially moving targets at increasing distances from the robot (**O1**). Thereby, this work package will contribute to improving the efficiency of the whole plant. WP4 receives inputs from WP2 about robot perception for manipulation. It shares information with WP7 to devise a planning that minimises internal risks and with WP6 in order to manage combined planning of arms and mobile base.

Task 4.1: Planning and control for efficient manipulation — **UNIPI,** EPFL

This task will focus on developing optimal motion planning and control strategies devoted to maximise the efficiency of the manipulation tasks, and by consequence of the whole plant. To evaluate the plant efficiency, some possible indicators, also to be used as cost functions in our optimisation framework, can be: cycle time of picking and placing tasks in case of both moving or fixed objects/boxes, maximum speed and distance of throwing, and success rate of picking moving objects as well as of placing and throwing them into moving or fixed boxes. In order to reach this goal, it is important to manage the available energy furnished by the actuators and the intrinsic ability of storing it in the springs of a manipulator actuated by a Variable Stiffness Actuator (VSA) and then release it when needed, with the aim of increasing the above-mentioned indicators.

UNIPI will start from previous work [80, 257] where an optimisation method aimed at improving the performance of a VSA in very dynamic tasks (hammering a nail or walking) was proposed. The method is based on optimally storing energy in the springs of the actuators and then realising it at the right time. We will extend this method to the problem of controlling the whole elastic arms, to increase performance of all the manipulation tasks considered in DARKO. Given the highly dynamic nature of the tasks, all planning and control strategies will take into account the dynamic model of the robots as well as dynamic-related constraints – speed, acceleration, and jerk. In order to provide optimality and feasibility guarantees the methods will rely on state-of-the-art convex and global deterministic optimisation approaches. In order to cope with the real-time constraint of an online implementation of our methods, we will adopt mixed on-line/off-line strategies based on trajectory-libraries and machine-learning empowered generalisation. For the real-time optimal motion planning and control strategies, this task will capitalise on [184, 183].

Task 4.2: Safe, risk-aware planning and control for manipulation — **TUM,** UNIPI, EPFL

In order for the technologies developed in DARKO to become practically useful and exploitable, it is imperative that the system runs both safely and efficiently. Previously, partner TUM have developed a control scheme referred to as the Safe Motion Unit (SMU), which ensures that a certain level of injury (e.g., a contusion) is not exceeded upon a dynamic, even entirely unforeseen collision between a robot and a human [100]. Depending on the current inertial and surface properties, the controller limits the robot velocity (if necessary) to a biomechanically safe value. The Safety Map concept [166] captures human injury occurrence and robot inherent global or task- dependent safety properties in a unified manner, making it a powerful and convenient tool to quantitatively analyse the safety performance of a certain robot design. In DARKO, TUM will extend the SMU and Safety Map concept to intrinsically elastic manipulators and utilise it with the knowledge of the environment potential risks (WP7) and human states and prediction (WP5) to increase the efficiency.

Our goal is to develop a real-time capable risk- and human-aware decision-making method that finds the best compromise between safety and performance for the intrinsically elastic manipulators (Phase B) instead of reducing velocity whenever a camera detects a human in the vicinity the robot. To achieve this goal, we exploit the risk analysis (T7.1) and risk map (T7.2) to extend our previous SMU concept [100] and integrate human tracking (T2.5) and intention prediction (T5.1) with the SMU. This will provide a flexible implementation of risk- and human-sensitive velocity shaping controller for the SMU framework to generate fast and safe robot motion by relying on a predictive low-level motion interpolator.

Moreover, EPFL will contribute by developing robot controllers which guarantee safety during task execution. This aspect of safety will provide guarantees of stability, convergence and robustness to external perturbations which may occur during operation of the manipulator. Those characteristics will be achieved based on EPFL's previous work [125, 133] where the manipulator's velocities and accelerations derive from time invariant and autonomous dynamical systems with analytical guarantees of stability, and passivity. The robotic system is guaranteed to converge to the desired state regardless of external perturbations and to not exceed bounds in the force generated at contact. The current work will be expanded within the DARKO project in order to cope with constraints. Particularly, will be considered velocity constraints as they derive from the SMU and also kinematic constraints based on the risk factors as they will be expressed through the *risk Jacobian*.

Another objective of this task is to tackle the problem of planning and control in presence of internal risk factors, taking as inputs the robot health state indicators developed in T7.1 and the risk map developed within T7.2. UNIPI will define an extended robot state upon which novel concepts of risk kinematics will be built. This will allow the definition of an augmented Jacobian, that we call *risk Jacobian*. Thanks to this, hierarchical prioritisation methods will be extended to obtain an integrated task-risk prioritisation method. Inverse-kinematics control algorithms will be extended to integrate such developments, to consider the problem of control in presence of locked (i.e., null contribution in the Jacobian) or overheated (i.e., reduced weight in the control action) joints. Another concept that will be explored is recruiting, where certain tasks might require excessive overload on one joint/actuator and one or more actuators might be used to supply the lacking resources in terms of mobility or load capacity.

Task 4.3: Picking and placing in motion **UNIPI,** ORU

This task will focus on generating trajectories or finding control strategies with the aim of grasping a moving object and deploying it on a moving destination. The estimation and prediction of the trajectory of the object to be grasped will be given as output of T2.2. Once the object in relative motion w.r.t. the robot is grasped, the motion of the end-effector will be planned according to the motion of the target tray in which the object has to be placed, provided by the algorithms developed in T2.1. In both the picking and placing actions, motion of the robot will be planned to reach the goals while avoiding obstacles, guaranteeing safety and limiting the risks defined and expected in WP7.

For the motion planning phase, we will also capitalise on the technical framework for human-like motion generation with anthropomorphic manipulators, by leveraging a functional description of human upper limb kinematic data [15, 14], extending these techniques to dual arm manipulators with different kinematic chains, either serial or parallel. At the same time, we will explore the possibility to develop end-to-end deep learning approaches that, by relying on the observation of human demonstrations and the availability of visual scene cues and contact sensor data from the end-effector (e.g. IMUs), determine robot trajectory and end-effector pose for picking and placing tasks. This could be achieved by combining feed-forward action and feedback sensor-triggered components [220]. The usage of contact sensory information collected from the end-effector T2.3 will also be investigated for grasp failure detection, prediction and triggering of corrective actions [13].

For better object manipulation, this task will involve close synergy with WP6 in order to generate cooperative motion planning and control strategies of the mobile base that facilitate manipulation (thereby increasing the success rate of grasping moving objects). EPFL will contribute in this task by providing the necessary controller for achieving coordination between the manipulator and the mobile platform during picking and placing in motion. The work will be based on [175, 218] where multiple robotic agents are coordinated through coupled dynamical systems for grasping moving objects. Within DARKO, this work will be further extended in order to increase safety by further including obstacle avoidance capabilities for both the manipulator and the mobile platform. For this, EPFL will leverage on most recent achievements in EU SECONDHANDS project [35], in which the dynamical systems which control the manipulator are coupled with those of the mobile base, with obstacle avoidance for both base and arm [35].

The primary mode of integration of perception and manipulation explored within this task is through incorporating candidate grasp poses obtained in T2.2 as targets for planning and control. As an alternative, we will also explore an approach for learning a direct mapping between sensor observations and parametrised motion controllers. Thus, we will also devise a minimal set of parametric robot skills, which will define the target space for T2.2. We will lean on prior work within stack-of-tasks controller frameworks [72, 134, 237] to define a set of composable primitives, which will then provide a basis for motion generation.

Task 4.4: Throwing **EPFL,** UNIPI, TUM

The goal of this task is to develop the necessary controller for the elastic manipulator that will enable the system to perform dynamic throwing of objects into stationary or moving boxes and trays that have been detected by T2.1. This task will contribute towards the achievement of Objective **O1**. The work will be based on EPFL's previous research on robot control through dynamical systems which has been applied on the dynamic manipulation task of catching objects in flight [127, 217]. In detail, dynamical systems with analytical guarantees of stability, using Lyapunov or contraction theory, will be developed for this task which will contribute towards the safety of the task execution which is crucial in such cases. The previous work will be further extended in order to deal with the dynamic requirements of the task. Specifically, the throwing task requires the achievement of a desired state before releasing the object. Such requirements will be added at the dynamical system as a waypoint which has to be reached during the motion. Furthermore, analytical stability guarantees of dynamical systems will be provided in order to take into account kinematic and dynamic constraints in order to ensure safe operation. The desired object release state alongside with the joints' torque and trajectory will derive through learning from demonstration [205], using either solutions found through optimal control and using data where a human will perform a set of throwing tasks with various throwing targets, or a combination of the two. We will combine analytical models of the dynamics of the objects with learning to determine the range of control parameters of the robot that maximises chance to be successful taking into account uncertainties when releasing resulting in undesired effect (toppling).

Furthermore, a crucial component of the throwing task is the ability of the robotic system to release the manipulated object when the arm has reached the desired state. In order to achieve that, a mechanism will be developed that guarantees the coordination between the manipulator, the gripper and the mobile base. The required coordination will be achieved by controlling the gripper's state through a dynamical system that will be coupled with the dynamical system of the manipulator and the mobile base. The development of this approach will be based on EPFL's previous work on achieving coordination using coupled dynamical systems [158, 230]. This work will be extended to arm-gripper-mobile base coordination for achieving the throwing task with increased range but also and most importantly to throw at moving targets, such a free location on a conveyor belt. For this, we will further extend the notion of coupling across dynamical systems to anchor the arm motion to the dynamics of the moving target. Uncertainty associated to these changes will be added taken into account to decide what is the best release time.

Deliverables

D4.1 Preliminary planning and control software developments for efficient manipulation — UNIPI / M20
Preliminary software development on efficient planning and control algorithms for picking of objects in relative motion w.r.t. the manipulator and placing objects in moving boxes.

D4.2 Planning and control algorithms for efficient manipulation — UNIPI / M42
Finalised report on the developed efficient planning and control algorithms for picking of objects in relative motion w.r.t. the manipulator and placing objects in moving boxes.

D4.3 Preliminary planning and control algorithms for safe manipulation — TUM / M20
Preliminary software deliverable to provide a controller that guarantees safety and stability of task execution according to the safe velocity from risk- and human-aware SMU and kinematic constraints based on risk factors.

D4.4 Planning and control algorithms for safe manipulation — TUM / M42
Finalised report for describing the developed controller and adaptions made for generating safe and stable motion during Phase B (elastic manipulator on top of the mobile base).

D4.5 Preliminary robot control for dynamic throwing of objects — EPFL / M20
Preliminary report and benchmark on the developed machine learning and robot control algorithms for the throwing task.

D4.6 Robot control for dynamic throwing of objects — EPFL / M42
Final report on the applied robot control and learning algorithm for the throwing task.

Measures for Success and Benchmarking

- For Task T4.1: Planning and control for efficient manipulation

  The planning algorithms developed in T4.1 will be evaluated through productivity-based efficiency criteria such as number of objects moved per minute per square meter as well as average speed of moved objects.

- For Task T4.2: Safe, risk-aware planning and control for manipulation

  The developed risk-aware optimal planning and control algorithms will be evaluated based on risk impact, efficiency and cycle time compared to the previous version of SMU in ILIAD, the success rate of picking and placing moving objects as well as the overloading of actuators.

- For Task T4.3: Picking and placing in motion

  The developed planning and control algorithms will be evaluated based on the precision of the final execution of the picking and placing motion. Safety of the objects is a fundamental requirement and hence the success rate of grasping will be a measure of success of the algorithm.

- For Task T4.4: Throwing

Algorithms for throwing will be assessed in terms of success rate at landing objects on the desired location and with the desired orientation. Efficiency in terms of speed and energy consumption will also be measured as additional metric.

Risk Assessment and Problem Resolution

- Picking and placing planning and control do not work *Impact: high, Risk: low*

  The major challenge is the trade off between the collision avoidance constraint satisfaction and the optimality of the solution. To manage this trade off in critical conditions we will prioritise the collision avoidance constraints with respect to the optimality that is then relaxed.

- Risk-awareness may result in slow manipulator movements *Impact: medium, Risk: medium*

  Optimisation methods taking into account the dynamic of the robot will allow not to over-constrain robot motion differently from purely kinematic planning approaches

---

3.1.5 Work Package 5: Human-Robot Spatial Interaction

WP5		Human-Robot Spatial Interaction							
Type:	RTD	Part.no.:	1	2	3	4	5	**6**	7
Start:	M01	Part.:	ORU	TUM	Bosch	UNIPI	EPFL	**UoL**	ACT
End:	M42	Effort:	38 PM	1 PM	9 PM	0 PM	4 PM	**54 PM**	4 PM
Task T5.1: Prediction of human motion and intents									
Task T5.2: Communication of robot intent									
Task T5.3: Context-aware representations of HRSI									
Task T5.4: Causal reasoning for safe HRSI									

Objectives

The main objective of WP5 is to enable efficient human-robot co-production (Objective **O2**) by implementing new advanced solutions for human motion prediction and intention recognition, complemented by novel context-aware representations and causal inference methods for human-robot spatial interaction (HRSI). These are further enhanced by a system for adaptive robot intent communication that combines spatial augmented reality (SAR) and anthropomorphic gestures. This work package receives input from WP2 and WP3 about robot perception, the semantic environment map and localisation, respectively. It shares information also with WP6 and WP7 to devise efficient and safe robot motion plans.

Task 5.1: Prediction of human motion and intents — **ORU,** Bosch, UoL, EPFL

Prediction of human intents and future motion is important because it enables a robot to take more informed decisions by anticipating behaviours and reacting in a timely and safe manner. Following DARKO's objectives, this is especially important when striving for efficiency in time, where waiting for human actions to be completed could lead to unnecessary delays. In this task, we aim to investigate this topic along three different lines: 1) long-term prediction of 2D human trajectories based on input from human tracking (T2.5), 2) anticipation of human intents through observation of articulated body motion (also T2.5) and 3) intent recognition via eye-tracking glasses, which human co-workers would wear as special safety equipment.

Our previous works for long-term human trajectory prediction reason about maps and social constraints [211, 212]. In these, we solve the prediction problem by adopting using dynamic programming (i.e. value iteration). The latter learns and reasons on the environment and on the social grouping constraints of humans that are walking around. To further improve accuracy, we now aim to extend the method by considering maps of dynamics (T3.3), such that predictions will also be informed on learned site-specific flow behaviours. We will also explore recent learning techniques that make use of spatio-temporal graphs [176], which we aim to extend to longer time horizons and by taking skeletal data from T2.5 and contextual information (T2.1) into account.

Related to the challenge of forecasting human motion trajectories is the problem of estimating the more general *intentions* of people around the robot, for example to predict whether a person is likely to perform some actions as part of an activity (e.g. putting an object down, restocking a shelf, grabbing something from a box). Bosch will approach this sub-task by combining information from skeleton tracking (T2.5) with semantic and contextual cues (T2.1) and derived human-object affordances [129, 146] in a graph neural network [263] to capture spatio-temporal aspects of articulated human body motion and environmental interaction. While such approaches have been studied before for action recognition [265], our aim here is to devise solutions that can anticipate intents with only a few input frames at test time, and at the same time also limited supervision at training time given the scarcity of datasets for this task. Here, we will explore different multi-task, transfer learning and fusion strategies [264, 282], where UoL will contribute their knowledge on social activity recognition from continuous streams of RGB-D data [48].

As a complementary strategy to the use of skeleton tracking data and other visual cues, ORU will extend their work on implicit intention transference through eye-tracking glasses [41] to the DARKO scenario. Gaze points will be identified in world coordinates using head pose and person tracking from T2.5 and the environment model from WP3. This will also allow to reason on a semantic level about patterns of visual attention. Second, we will learn which gaze patterns, either represented as spatial sequences or as semantic scanning signatures, indicate specific motion or action intentions from real-world interaction sequences. Third, the long-term human trajectory predictions will be exploited, to infer likely intentions from gaze sequences that are represented relative to predicted trajectories. Finally, the predicted intentions from skeleton and eye tracking will be fused. The resulting predicted intentions from this task will be further processed by T5.4 for causal reasoning.

Task 5.2: Communication of robot intent **ORU,** UoL

In order to facilitate smooth and safe HRSI, it is important for the robot to communicate its motion and action intentions to nearby people, so that they are aware of its presence and can react accordingly. Intent communication between autonomous vehicles and pedestrians is a very active research area [37]: several methods are being investigated, e.g., to communicate the intentions of an autonomous car at a pedestrian crossing. In our previous work [43, 42, 41], we developed a Spatial Augmented Reality (SAR) system and evaluated its effectiveness for an logistics robot that projected different patterns on the floor to indicate its motion intentions; using human trajectory analysis, eye-tracking information, and interviews to assess the influence of the projected patterns on the people's behaviour. Although encouraging, it was found these projections were not always sufficient to be noted or understood. In this task, we will extend over previous research in four ways. First, we will investigate suitable ways to communicate more than only motion intentions, in particular the intention to manipulate objects in a way that could affect people (e.g., throwing). Second, we aim to improve the communication of robot intents by exploiting *anthropomorphic* social signalling, inspired by recent literature in social signal processing [233] and promising results of ongoing initial work at ORU in which a small humanoid robot, acts as a "driver" and signals its intentions with human-like gestures. Third, while in all previous work intention communication was unidirectional, we will develop, implement and test more *interactive* modes of communication that take into account the current activity of people and their intentions which will be identified from patterns of visual attention. Finally, besides informing the user about the robot's motion intention, depending on navigation plans (T6.1) and human behaviours (T2.5, T5.1), the intention communication system will be further improved by suggesting possible walking speeds and directions, for example to "give precedence to a human", based on the robot's current understanding of the environment and desired HRSI (T5.4).

Task 5.3: Context-aware representations of HRSI **UoL,** Bosch

Human spatial interactions, defined as the mutual influence of motion behaviours between two or more people, depend on both human activities (e.g. speed and destination) and objects or constraints (e.g. nearby door, narrow corridor, etc). Similarly, human-robot spatial interactions (HRSIs) are influenced by the robot's motion (e.g. to approach the user) but also by other factors outside the direct control of the two interacting agents.

In order to better capture the nature of HRSIs in realistic scenarios, and therefore enable safer and more socially-acceptable robot motion behaviours, this task will create new context-aware representations of human-robot relative motion and to other relevant features of typical production environments.

Given the complexity of the real world, continuous or purely quantitative descriptions of context-aware HRSI are either infeasible or computationally inefficient. We therefore adopt a discrete and qualitative motion representation based on a theoretically-sound Qualitative Trajectory Calculus (QTC) [253], which was already used in our previous work to model simple human-robot encounters in narrow corridors and other indoor scenarios [103, 57]. QTC state transitions and sensor observations were embedded in probabilistic Markov models to deal with uncertainties and missing data. However, only 2D-trajectories were previously considered.

In this task, will extend the QTC-based representations of HRSI to explicitly model the relative motion of the robot and nearby humans with respect to other static (e.g. door, pallet) or dynamic (e.g. forklift) objects, initially based on existing datasets [267] and then using the perception and localisation input from WP2–WP3. The increased complexity of these models, which are no more limited to a robot and a single human, requires new algorithmic solutions for dealing with uncertainties and possible lack of information. We will make use of additional QTC operators, namely Conceptual Neighbourhood Diagrams (CNDs) and Composition Tables (CTs) [253], which were not exploited in previous robotics literature, to embed stronger priors in our Markov models. We will further extend these representations to consider 3D spatial relations between objects, which cannot be captured by simpler 2D models, by integrating a more recent extension of the calculus, called QTC_{3D} [169]. These new qualitative models will provide an interface between the sensor-level perception of objects (T2.1), humans (T2.5, T5.1), and robot position (T3.4), and the more abstract perception required by the reasoning system in T5.4 to understand human-human and human-robot spatial interactions. These models can also be used to infer the safest robot motion behaviour in proximity to people (T6.1) and to provide a human-readable description of HRSIs for post hoc analyses and risk assessment (WP7).

Task 5.4: Causal reasoning for safe HRSI **UoL,** Bosch, ORU

In our previous work we investigated the use of qualitative models for generating more socially-acceptable HRSIs, either by hardcoding the robot intended behaviours [18] or by learning them from a human demonstrator [58]. In these models, however, the robot could only cope with relatively simple scenarios of human-robot encounters in corridors and similar walking paths, for example to decide whether to pass on the left or right of a pedestrian, or to stop when the latter was met at an intersection. Dealing with more complex situations, where human trajectories can be affected by other agents and objects in the environment, requires a deeper understanding of human motion intentions and possible factors that influence them, besides the robot's presence. In other words, we need to reason on the causes of these spatial interactions.

Inspired by recent developments in causal inference and machine learning [194, 197], this task will develop new algorithms to learn and reason on causal models of HRSI, enabling the computation of intervention (e.g. "what happens if I move the robot in this way?") and counterfactual probabilities (e.g. "what would have happened if I moved it in that way instead of this?"). Such probabilities are necessary to choose the most appropriate robot behaviour in proximity of a single person or multiple people, and to facilitate safer and more efficient HRSIs. The output of this task is also useful for local planning (e.g. move the robot left or right during a human encounter; T6.1), robot intent communication (e.g. tell a person to overtake the robot; T5.2) and human safety (T6.4). The research work carried out in this task consists of two parts:

Learn causal models of (multiple) human trajectories based on their QTC representations from T5.3, which consider also the context. Previous work learned causal graphs from static cameras [71]. Here we address the more challenging problem of a multi-modal mobile sensor (i.e. the robot) in a dynamic human environment, where people and objects position might change depending on the current location and on the robot's presence.

Reason on causal models of the above trajectories to understand human intents and infer the most suitable robot behaviour, taking also into account possible risks (WP7). Recent work on robot imitation for manipulation [122] proposed a causal inference systems that estimates the intentions of the users to replicate their actual plans, rather than merely copying their actions. In this tasks, a similar concept will be developed for HRSI to infer how the mobile robot should move (e.g. overtake or follow a slow pedestrian?), based on its original plans (WP6) and estimated human intentions (T5.1).

Deliverables

D5.1 Report on prediction of human motion and intents Bosch / M36
The deliverable will report on the system for prediction of human motion and intents developed in T5.1, including its scientific results and an initial software prototype that will be providing input to other components in DARKO (e.g. motion planning and control in WP6).

D5.2 Report on system for communication of robot intent ORU / M36
This deliverable will report on the final system for communication of robot intent developed in T5.2, including its scientific evaluation and the final software prototype (the first prototypes will be available in M24).

D5.3 Representations and reasoning algorithms for HRSI UoL / M42
The deliverable consists of a report presenting the final implementation and evaluation of the solutions developed in T5.3 and T5.4 for HRSI.

Measures for Success and Benchmarking

- For Task T5.1: Prediction of human motion and intents

  For trajectory prediction, we will adopt the most relevant geometric and stochastic metrics [213] such as Average Displacement Error (ADE), Final Displacement Error (FDE) and Negative-Log-Likelihood (NLL). For intent prediction, we will measure classification accuracy. We aim to achieve an improvement over the state of the art of 5%. We will use existing benchmarks [4] and newly recorded domain-specific data for evaluation.

- For Task T5.2: Communication of robot intent

  For this task we will assess how communication of robot intent improves the interaction with humans. In addition to the analysis of post-experiment interviews where subjective impressions are reported against Likert scales (where we aim to obtain significant improvements), we will analyse the human trajectories, measuring path length and smoothness compared to where the improved means of intent communication are not used.

We will further evaluate the collected eye-tracking data comparing different intent communication strategies in terms of their efficiency operationalized as total visual attention required or average illumination-adjusted pupil dilation during an interaction (aiming at a decrease by 20% compared to current state-of-the-art).

- For Task T5.3: Context-aware representations of HRSI

  For this task we will measure the efficiency of the models in capturing all the 3D qualitative spatial relations among agents (i.e. robot, humans) and surrounding objects/locations, aiming to cover at least 90% of the elements currently detected by the robot.

- For Task T5.4: Causal reasoning for safe HRSI

  For this task we will measure the effectiveness of the causal inference system in computing a predefined set of HRSIs from previous literature [67], increasing the possible scenarios to more than one person and aiming to approach nearly real-time (i.e. $\leq$ 100ms) performance.

Risk Assessment and Problem Resolution

- Highly inaccurate human motion prediction. *Impact: medium, Risk: medium*

  We expect short term human motion prediction to work relatively well and to suffice to our accuracy requirements. Long-term human motion prediction may present a high uncertainty, novel machine learning techniques and the usage of additional priors such as MoD could help in reducing it. In the worst case, the system will keep its safe operation but it will behave cautiously, e.g. going slower while passing nearby a group of people.

- Slow computation of desired HRSIs. *Impact: low, Risk: medium*

  If the environment is particularly challenging (i.e. large number of objects and agents) the complexity of the inference models might render the computation of particular HRSIs too slow for real-time execution. Efficient pruning strategies will be implemented to maintain the computational requirements within feasible limits. In the worst case, the system will simply fall back to standard motion planning.

3.1.6 Work Package 6: Predictive and Safe Motion Planning

WP6		Predictive and Safe Motion Planning							
Type:	RTD	Part.no.:	1	2	**3**	4	5	6	7
Start:	M01	Part.:	ORU	TUM	**Bosch**	UNIPI	EPFL	UoL	ACT
End:	M42	Effort:	6 PM	11 PM	**24 PM**	20 PM	4 PM	2 PM	4 PM
Task T6.1: Predictive local planning									
Task T6.2: Risk-aware planning and control for mobile robots									
Task T6.3: Efficient and context-aware global planning									
Task T6.4: Safety for wheeled mobile robots									

Objectives

Following the ambition for *safe and predictive planning* described in Sec. 1.4, in this work package we implement several tasks to overcome the detailed limitations by extending the state-of-the-art of autonomous decision making systems in several directions. Specifically, this work package will contribute to the improvement of the overall task efficiency of the DARKO robot, its safe functioning (DARKO 's objective **O3** and **O4**) and guarantee an efficient human-robot collaboration (objective **O2**), by leveraging the inputs of WP2, WP3, WP5 and WP7. In particular, in T6.1, we will investigate methods for *planning and controlling the robot in dynamic environments by considering pro-actively predicted future human states*. Considering the results of WP7, in T6.2 we will propose novel *methods for risk-aware planning and control* that minimise the overall risk of the robot operation. In T6.3, we will address the following research question: *Can we further improve current global planning approaches by considering more environmental contextual information?* Safety is a crucial component in today's robotic systems, particularly in settings where robots co-operate with humans. In T6.4, we will study and develop *novel safe planning concepts* for wheeled mobile robots in agile production settings.

Task 6.1: Predictive local planning **Bosch,** EPFL, UoL, TUM, ACT

Computing safe control policies for mobile robots operating in densely cluttered and crowded spaces is a difficult task due to several factors, i.e. perception noise, system models mismatch and high uncertainty of human future behaviours. In these settings, classical reactive approaches [207, 214, 204, 73, 199, 174, 210] often result in an overly cautious robot that fails to produce a feasible, safe path in the crowd, or plans a large, sub-optimal, perhaps oscillating, detour to avoid humans. Moreover a robot un-aware of future human movements may end up in the so-called *"freezing"* robot problem [251] (i.e. robot blocked by continuous unpredicted human encounters). In this task we address these issues by considering predictions of human behaviour from T5.1 and contextual information from T2.1 to plan short and safe robot motion. Intuitively, exploiting both predictions and semantic information might improve robot's ability to predictively plan and reason, in a way similar to what humans naturally do [34]. To overcome the limitations of short-sighted reactive approaches, we will develop *safe and robust nonlinear model predictive control (NMPC)* techniques that jointly optimise robot motion and human motion predictions along a predictive horizon. The NMPC framework would allow the DARKO robots to plan with a larger predictive time horizon than common reactive methods, thus planning in a pro-actively manner to avoid foreseeable collisions. Starting from our previous work [225], we will study learning-based MPC solutions [107] to combine safe MPC with learned augmented system dynamics (i.e. considering a joint human-robot state space) or learned controller design (i.e. predictions-aware cost function). We will augment the controller capabilities by combining it we deep generative models [84]. The combination would allow the DARKO robots *to embed learned contextual and semantic cues of the environment and proactively consider human motion predictions* directly in the inexpensive MPC optimisation step.

Classical MPC-based approaches solve the motion planning and control problem by using ad-hoc efficient numerical solvers. State-of-the-art solvers [126, 130] are highly efficient when the problem to solve has particular properties, i.e. convex, smooth or differentiable formulation. Problems with high non-linearities or complex non-convex cost functions may be hard to solve in a real-time fashion. Based on this insight we plan to further enhance Information Theoretic sampling-based MPC strategies for model-based reinforcement learning by combining them with learned generative models [140, 262, 84]. In our previous work [140] we show that learned generative models allow to guide the controller towards promising areas of the solution space. We will extend these approaches to also include human motion prediction, Maps of Dynamics, localisation reliability and environmental semantic information (as also explored in [152]) obtained from T5.1, T5.3, T5.4, T3.3 and T3.4.

Task 6.2: Risk-aware planning and control for mobile robots **UNIPI,** ACT, TUM

Navigating in an unstructured environment where there are moving obstacles, humans or other robots usually leads to potential risks (undesired interactions, damage to fragile objects or the robot itself, or even harming humans). In this task, we will study the problem of planning and control in *risk space* to cope with external risk factors that might affect the robot status or the possibility to complete a given task. Taking as inputs the risk modelling developed within T7.1 and the risk map developed in T7.2, existing planning methods based on anytime sample based algorithms will be extended to find optimal or sub-optimal (but readily feasible) motion plans to guarantee task-accomplishment while avoiding collisions in the risk space. The severity of external risks will be considered, when available. In this respect, we will also comply with the most recent safety recommendations for collaborative robots (ISO/TS 15066:2016). Methods based on convex optimisation, or branch-and-bound, or task-based probabilistic algorithms will be developed to exploit information about the correlation between different risk factors: for instance, throwing an object does not pose a risk for the robot safety, but throwing an object from an unstable position of the mobile base can cause an unexpected imbalance with a consequent possible impact with the surrounding and a severe damage to the robot. Methods that will be developed in this task will leverage upon well-established previous work on safe physical human robot interaction UNIPI [47, 25, 100].

Task 6.3: Efficient and context-aware global planning **Bosch,** ORU, ACT

Planning considering a large portion of the cluttered and crowded environment (i.e. several dozens of meters per side), and nonholonomic system constraints is a demanding task in terms of computation efficiency and quality of obtained solution. This is even more demanding in dynamic environments, where the final path quality must be assessed not only against usual geometric and temporal aspects [106], but also intrinsic elements of the dynamic environment, for instance adherence of usual behaviours of people or risk of collisions. In today's state-of-the-art sampling-based approaches [106], computation efficiency and improved path quality is often obtained by providing heuristics that could focus the planning exploration towards promising areas of the solution space. Often those heuristics are computed from only geometric properties of the environment [185, 77, 76]. Our prior works suggest that planning considering maps of dynamics (T3.3) improve the overall quality of the resulting paths and the social behaviour of the robot [187, 243], by allowing it to produce paths adhering to the learned human-flow motion patterns. In DARKO we will further enhance those methods by exploring the possibility to inform planning methods with more contextual information [152], such as semantics provided by T2.1, human intents and predictions from T5.1, T5.3, T5.4, and additional uncertainty information coming from maps of dynamics (T3.3) and localisation reliability maps (T3.4).

In sampling-based planners, heuristics are used predominantly to focus the drawn samples towards promising areas of the configuration space. A common approach to generate those samples is to draw them from a defined probability distribution (i.e. often uniform [224, 121]). Randomly distributed samples are beneficial for achieving a good exploration of the state space, but they do not allow a quick exploitation or quality improvement of the current found solution, thus resulting often with a sub-optimal control policy. To overcome those limitations, recently a number of works adopt deterministic sampling schemes [186, 118, 270]. These approaches offer deterministic properties for the planning algorithms, such as bounding the final path quality and the number of iterations for converging to a good solution. In particular they also offer the possibility to precisely define the minimum clearance to the obstacles, thus enforcing the safe robot operation. In DARKO we will research how to improve efficiency of those methods by also considering more contextual information provided by T2.1 into the deterministic sampling set generation.

Task 6.4: Safety for wheeled mobile robots **TUM,** UoL

The objective of this task is to ensure human safety via safe coordinated motion control of the mobile base and the manipulator for preventing risk of human injury during unforeseen collisions. Previously, the so-called Safe Motion Unit (SMU) was introduced for fixed-base manipulators [100]. The SMU relies on a human injury database and the instantaneous robot dynamic and surface properties and shapes the robot velocity so as to avoid human injury upon a dynamic collision between a human and robot. The SMU concept was extended to the Safety Map as a tool for global robot safety evaluation that may serve for safer robot design and motion planning [165]. The concept of the *vehicle Safe Motion Unit* (vSMU) was introduced in the ILIAD project, which can be applied to mobile robots and other vehicles such as forklifts. In DARKO, we follow this line of research and develop a human-aware vSMU and Safety Map framework for mobile platforms with elastic-joint manipulators.

Potentially, whenever a human is approaching a mobile robot, the vSMU can impose constraints on velocity to avoid any injuries in case of a collision. To increase the efficiency and avoid unnecessary velocity reduction, we exploit the concept of risk space (T7.1) and the short- and long-term predictions (T5.1) as well as the information about human tracking (T2.5) and intention prediction in HRSI (T5.4) to trigger the vSMU. The idea is to present a risk- and human-aware framework that relies not only on injury biomechanics data but also on predictive low-level motion interpolator to enable shaping the vehicle velocities for preventing any risks of human injury in case of unforeseen collision. The knowledge about potential current and upcoming risks, human position and intention will avoid unnecessary velocity reduction and increase efficiency. The estimated safe velocity will be used by T6.1 and T6.2 to generate dynamically feasible and safe trajectories in real time.

Deliverables

D6.1 Report on techniques for predictive local planning — Bosch / M42
This deliverable will report on scientific results obtained by the predictive planning techniques developed in T6.1 and their integration aspects into the DARKO motion planning system showed in deliverable D6.3.

D6.2 Report on risk-aware planning and control — UNIPI / M42
Report on motion planning and control strategies developed in T6.2 for limiting external risk factors.

D6.3 First prototype of the DARKO motion planning system — Bosch / M21
In this deliverable we will show the first prototype of the DARKO motion planner system. The first prototype will be able to properly plan considering static and semi-static environments (i.e. considering also the map of dynamics provided by T3.3). The system will be also tested during integration events and used for first experiments of the DARKO robots.

D6.4 Report on safe dynamic mobile platform planning — TUM / M35
The deliverable will describe the results of T6.4. More specifically, the concept of vSMU and the calculation of reflected inertia will be presented and we demonstrate how the knowledge about risks, human position and intention trigger vSMU implementation to increase the efficiency.

Measures for Success and Benchmarking

- For Task T6.1: Predictive local planning

  The results of T6.1 will be measured against a set of metrics that can report the efficiency of the techniques and their human-awareness. Spatial and temporal metrics of interest for dynamic environments are path length and smoothness, time to achieve the goal, clearance to the humans or obstacles. The novel approaches will be compared against a set of baselines including also the ones that plan merely in a reactive manner (i.e. not considering environmental cues and human motion predictions).

- For Task T6.2: Risk-aware planning and control for mobile robots

  We will assess the robot performance degradation to have risk guarantees in a deterministic or probabilistic way. Concrete KPIs are the reduction of failure rate in presence of external risk factors. Depending on the task, these could be the reduction of the average speed, the time to reach the waypoint or time to accomplish a task w.r.t. the risk-unaware case.

- For Task T6.3: Efficient and context-aware global planning

  Results of T6.3 will be benchmarked using different metrics such as planning cycle time, path length, path smoothness, time to completion and adherence to the expected flow behaviours learned in T3.3.

- For Task T6.4: Safety for wheeled mobile robots

  The developed vehicle safe Motion Unit (vSMU) should be able to guarantee human safety and avoid any kind of injury in case of unforeseen collision during physical human-robot interaction. Moreover, we show how our proposed method for triggering vSMU based on risk- and human-aware method increases efficiency.

Risk Assessment and Problem Resolution

- Planning efficiency scales poorly with complexity and size of the environment *Impact: medium, Risk: low*

  Planning in crowded and densly cluttered environments is known to reduce the computational efficiency of planning algorithms. Based on our previous works [186, 185, 187] we will reduce this risk by implementing accurate heuristics (i.e. deterministic sampling, flow-awareness).

- Local planner cannot cope with complexity of highly dynamic environments *Impact: medium, Risk: medium*

  In the past, different partners of the consortium, e.g. BOSCH, ORU, have deployed state-of-the-art reactive planning solutions on robots operating in crowded environments and developed planning techniques that consider learned motion patterns or short-term predictions of human walking in the environment. In DARKO we will further enhance those techniques by exploiting also more contextual information and long-term human motion prediction. In the worst case the robot will behave according to the background state-of-the-art approaches.

- The vSMU doesn't function properly and human safety is endangered *Impact: high, Risk: low*

  We set a minimum allowed safety distance between human and robot regardless of the vSMU functionality. The robot will be stopped if it traverses through the dangerous zone. Moreover since the robot velocity should be adapted to ensure human safety, a swift reduction by vSMU may cause jerk and unexpected robot movements. To avoid this situation, we will set proper control limits on the vSMU (while human safety has been guaranteed) to avoid unexpected movements.

- Planning and control algorithms ineffective in preventing damage to robot *Impact: medium, Risk: medium*

  Tests will be performed in controlled environments. In presence of high uncertainty in the robot state with respect to hazards, human operator will be prompted to provide guidance.

3.1.7 Work Package 7: Risk Representation and Operations Scheduling

WP7		Risk Representation and Operations Scheduling							
Type:	RTD	Part.no.:	1	2	3	4	5	6	**7**
Start:	M04	Part.:	ORU	TUM	Bosch	UNIPI	EPFL	UoL	**ACT**
End:	M42	Effort:	2 PM	1 PM	0 PM	10 PM	0 PM	0 PM	**41 PM**
Task T7.1: Multi-dimensional risk space definition and metrics									
Task T7.2: Continuous learning and forecasting of risk trajectories									
Task T7.3: Risk-optimal scheduling of operational tasks									

Objectives

This work package is mainly responsible for DARKO Objective **O4**, and is conceived to *develop a methodological and technological framework* that will enable a *comprehensive representation and dynamic assessment of risks* encountered by DARKO's robots, unleashing its operational scheduling and feeding the other project modules with *risk forecasting services*. The establishment of a "multi-dimensional risk space", together with its metrics, allows to quantitatively evaluate the probability of undesired outcomes, hence scheduling the operations of robots according to risk-minimisation, while satisfying functional constraints (e.g., productivity objectives). Integrating with WP2, WP3 and WP6, this work package will support solving the challenges of risk minimisation across multiple layers of supervision and control, by providing all the other modules of DARKO with risk assessment and forecasting services.

In particular, we will i) define the theoretical foundation of the DARKO approach to dynamic risk management (T7.1), ii) investigate where and how continuous learning of the (multi-dimensional) models for risks assessment can be implemented (T7.2); iii) implement asynchronous risk-optimising techniques for operational scheduling of robot tasks coherently with the presence of human operators (T7.3).

Task 7.1: Multi-dimensional risk space definition and metrics **ACT,** UNIPI, ORU

Human-robot collaboration aims to realise an environment where humans can work side by side with robots in close proximity, sharing the same work-space and resources. The goal is to integrate the best of two worlds: strength, endurance, repeatability and accuracy of the robots with the intuition, flexibility and versatile problem solving and sensory skills of the humans.

Endowing autonomous agents with a keen sensitivity to uncertainty and risk of failure then becomes a key in enabling them to reliably complete complex operations in real-world environments. In safety-critical applications, optimising performance alone is not enough, but must be combined with awareness of certain risks, both for the environment (humans included) and for the robot itself. Risk awareness results from the fact that a robot complies with or refines its "risk understanding" at run-time. Consequently, our main questions are: What constitutes a powerful risk model to make autonomous robots risk-aware? How can we systematically engineer a consistent and valid risk model for an autonomous robot?

The conceptual approach proposed in T7.1 to tackle this challenge is to formalise a so-called "Risk Space", i.e., a multi-dimensional space of Risk Factors, each one classifying the current state of the autonomous agent according to a fuzzy definition of risk levels (e.g., from "red" = high to "green" = low risk), based on the severity and probability of undesired outcomes (hazardous states). The most relevant risk factors will be detailed, cataloguing them within the following families: i) Risks of not accomplishing the operational needs (e.g. missed temporal deadline, unsatisfactory quality, etc.); ii) Risks for human safety, in compliance with the *Machinery Directive* 2006/42/EC; iii) Risks for robot's own "health" (e.g. locked or overheated joints, low energy) and for that of other robots/machines.

In addition to defining the "dimensions" of the Risk Space, T7.1 needs to establish the corresponding metrics: a set of analytical rules to actually classify the condition a robot is in, based on the value of the variables that defines its state but also considering its currently *planned intentions*. For instance, the same state of proximity to a human operator might be classified as high or low risk, depending on the type of planned robot motion activities. This means that the models for quantitative assessment will be strongly intertwined with the runtime layers of a DARKO's robot, i.e. fed by their decisions and actions.

T7.1 will therefore study how the position of an autonomous agent within the Risk Space (i.e. its risk-level with respect to the previously defined factors) is a direct consequence, statically and dynamically, of its current and future state. The task will distinguish between functional dependency on the geometrical trajectory (hence linked to the modules of WP3 and WP6) and on non-Cartesian variables, such as those coming from the conditions monitoring of a robot (coming from WP2, WP4, and WP5).

Task 7.2: Continuous learning and forecasting of risk trajectories **ACT,** UNIPI

The definition of a Risk Space in T7.1 and the corresponding establishment of risk classification rules, triggers in T7.2 the need to develop a method to dynamically localise the "position" of an agent within its Risk Space, as much as to predict its movement in it, with different reliability over the short-, mid- and long-term. Our goal is to provide a globally available functional layer, where the aggregation of data from multiple sources and the implementation of dedicated risk forecasting models will allow to compute a risk trajectory and feed it back to the requesting module, that will eventually adapt its decisions to reduce/compensate for unacceptably high risks.

The development in this task will be focused on on-line identification of the "risk models", usable as directly interfaced to the perception and mapping functionalities of WP2 and WP3. These models should be capable of capturing major dynamics of risk for each of the robotic systems, and they will be used as basis for DARKO's risk forecasting engine. Deriving from the macroscopic distinction among risk factors done in T7.1, the development activities in T7.2 will tackle differently the corresponding learning and forecasting requirements.

Considering the data-intense nature of risk assessment, the task will study the adoption of deep learning techniques to deal with the accumulated large amount of information that will come from the different agents' state, both during normal operations and also generated during unwanted events. Due to the fuzzy definition of risk levels (established in T7.1), a certain and automatic assignment will not be possible via machine learning, hence leading to the need for an expert supervision. Once the model has learned risk categorisation, it uses its knowledge to evaluate real-time risk from the state of the monitored robots.

Finally, a specific part of T7.2 will be devoted to developing those software functions for the data collection, filtering (e.g. de-trending, bandwidth based filtering, etc.) and structuring needed to feed the machine learning algorithms of the risk models. Such interface will be used during run-time data collection for iterative on-line self-learning, to guarantee model compensations under process variations thus progressively improving robustness of forecasting.

All the predictive models of T7.2 will be deployed inside an instance of ACT's Ublique runtime framework, as always accessible software services for WP4, WP3 and WP6 to access whenever needed for their specific purposes.

Task 7.3: Risk-optimal scheduling of operational tasks **ACT,** UNIPI

In T7.3 we focus on the design and asynchronous optimisation phase of shop-floor operations, where DARKO's robots must operate in presence of human operators, to satisfy the requirements of a specific task and then reach, at execution stage, the corresponding objectives. This will be achieved by developing both the algorithms used to optimally distribute duties and responsibilities among the different entities needed at shop floor level to execute certain operations (e.g. robots, machine and humans) and to embed them in a simple engineering tool that supports the creation of the corresponding run-time applications. Clearly, the task will use the theoretical foundation of WP7 to define a corresponding risk-based Pareto frontier to guide the optimisation of tasks planning and temporal scheduling.

To find the best task assignment, the problem will be formalised considering that risk represents either a constraint not to be violated or a minimisation criterion for determining an optimal plan, with the machine-learnt models of T7.2 used to allow the per-state estimation of risk. The notion of multi-dimensional (Risk Factors) and multi-level classification of risk introduced in T7.1 will add another possibly helpful uncertainty factor to such approaches and allow the per-state estimation of an expected risk range. Since several algorithms are available to tackle this type of problems, a screening phase to select those that are most suitable for the specific application will be done.

To guarantee the needed flexibility and adaptability of robotic agents in dealing with risk management in presence of humans, continuous adaptation of orchestrated tasks will be achieved through a dedicated scheduling layer, with on-line risk minimisation functionalities (WP4 and WP6). The intrinsic uncertainty of activities where human operators are involved will guide algorithm selection, based on statistic behavioural forecasting and exploiting results of WP2.

The scheduling tool of T7.3, whose results will be fed to the underlying execution and ability layers of motion planning and control (WP4 and WP6), will also integrate a distributed approach to partial re-scheduling. In fact, in case of relevant local deviations of a robot from its planned behaviour (e.g. to react to an unexpected risk), each agent needs to make its own decisions about how to at least partially change its scheduling, cooperating with other robots but also machines to maximise the overall reaction of the whole process. In DARKO, we intend to explore the possibility of using an automated negotiation of re-scheduling between robots based on game theory and its most recent developments with respect to Artificial Intelligence (e.g. General Game Playing).

Deliverables

D7.1 Risk-space modelling and assessment metrics. UNIPI / M13
This deliverable will formalise the definition of a multi-dimensional risk space, its composing factors and how they relate to the variables defining the state of a robot.

D7.2 Learning and forecasting tools for risk assessment. ACT / M23
This deliverable will provide the algorithmic modules needed to learn from continuous data sources the forecasting models for multi-dimensional risk.

D7.3 Off-line nominal scheduling and decentralised re-scheduling module – v1 ACT / M35
The initial version of this deliverable will provide the software layers needed for off-line scheduling and runtime re-scheduling of risk-optimal operational tasks.

D7.4 Off-line nominal scheduling and decentralised re-scheduling module – v2 ACT / M42
Second release of deliverable with SW module for scheduling.

Measures for Success and Benchmarking

- For Task T7.1: Multi-dimensional risk space definition and metrics

  Complete definition of the risk space dimensions and of its state-mapping metrics will be checked against traditional risk assessment techniques applied to the project use-case, assessing their level of coverage.

- For Task T7.2: Continuous learning and forecasting of risk trajectories

  The reliability of the risk forecasting models will be checked by artificially creating anomalous situations for the robots and measuring the error between the expected error level and that assessed by a supervisor.

- For Task T7.3: Risk-optimal scheduling of operational tasks

  The effectiveness of scheduling layer(s) will be tested by comparing the predicted optimised performance with the actual one, achieved during experimental testing.

Risk Assessment and Problem Resolution

- Incomplete definition of risk space. *Impact: low, Risk: medium*

  The results of T7.1 governs the details of the subsequent ones and the risk of not being totally comprehensive in defining risks dimensions is not non-existent. Still, the approach of WP7 does not require to consider all possible type of risk to enable the development of its tools; a progressive improvement of the risk space, with iterative inclusion of new factors, is a reasonable and acceptable approach.

- Unsatisfactory learning of predictive models for risk. *Impact: medium, Risk: medium*

  Machine learning applied to risk assessment is still a very young field whose effectiveness of results cannot be fully guaranteed at proposal stage. To compensate for the occurrence of this risk, T7.2 will implement also heuristic rules and simpler stochastic models to compute the levels of risk, hence allowing for the other developments to not be too impacted by a partially unsuccessful result.

3.1.8 Work Package 8: Requirements and Evaluation

WP8		Requirements and Evaluation							
Type:	RTD	Part.no.:	**1**	2	3	4	5	6	7
Start:	M01	Part.:	**ORU**	TUM	Bosch	UNIPI	EPFL	UoL	ACT
End:	M48	Effort:	**5 PM**	4 PM	9 PM	5 PM	7 PM	3 PM	6 PM
Task T8.1: Requirements and evaluation metrics									
Task T8.2: System architecture development									
Task T8.3: Evaluation and system demonstrations									

Objectives

This work package will address requirements engineering, development and maintenance of the overall software architecture, as well as testing and validation of the DARKO demonstrator. Thorough and dependable integration of all software systems together with hardware tests will ensure a reliable system for long-term application. (Note that hardware and close-to-hardware integration, including mounting, cabling, and driver software is managed in WP1).

The elicitation of application-related requirements and relevant evaluation metrics will be performed in Task T8.1. Task T8.2 manages the implementation of a modular and easily maintainable software architecture, for efficient development and to maximise the impact and uptake of its outcomes. This task also contains the development of tools for unit and system testing. Real-world evaluation and system validation is performed in T8.3.

Task 8.1: Requirements and evaluation metrics — **ORU,** ALL

The consortium has a long experience of working with autonomous systems for intra-logistics. Several previous and current projects (ILIAD, SAUNA, MALTA, etc.) have provided deep knowledge of what are the requirements that a step-changing system should present and what are the relevant evaluation metrics. To ensure that the DARKO objectives remain strongly tied to the most recent, real-world requirements, we will set out to formulate the use cases and system requirements based on our previous experience as well on survey of the current industrial landscape.

To achieve this goal we will follow a two step strategy. In the first step we will complete a focus group consisting of representatives of hardware manufacturers, integrating companies and end-users across different industries. The insight from the focus group will be used to develop the system requirements and evaluation metrics. The second step is to assess the output of the first step. To execute it we will utilise our connection to DIH networks (DIH^2 http://www.dih-squared.eu and TRINITY https://trinityrobotics.eu/trinity-network/), which will be used to collect feedback on the system requirements and evaluation metrics. The final version of the document will be based on it.

Task 8.2: System architecture development — **ORU,** Bosch, TUM, UoL

In this task we will be developing a system architecture, mostly based on the open-source Robot Operation System (ROS) middleware. As a consequence DARKO's system architecture will be an inherently component-based architecture, built around the principles of re-usability and low coupling. The consortium can build on extensive experience in robotic system integration and software architecture, gathered in projects like STRANDS (UoL), SPENCER (Bosch, ORU) and ILIAD (ORU, Bosch, TUM, UoL).

Given the nature of the project, on top of the middleware, we will devise a distributed system architecture composed of functional layers: At the bottom, an *ability-level* is foreseen, encapsulating the basic robot functionalities like sensing, control, localisation, path planning, pick and place operations, etc. Hence, this layer is closely developed in conjunction with WP1, WP2, WP4 and WP6, facilitating low-latency, closed-loop control of individual lower level abilities of the robots.

On top of this, we envision an *execution layer* that encompass the shared, context-specific knowledge and abilities enabling robots for safe and efficient operation in shared environments. This layer will enable platforms to jointly collect, refine and share knowledge about the environment they are operating in as well as functionalities allowing to utilise this knowledge. Hence, this layer comprises modules developed in WP2, WP3, WP5 and partially WP6. This layer will provide a necessary toolkit for robots to operate in shared, industrial environment.

Finally, to assure that the system will execute its tasks in a safe way in WP7 we will develop a *risk monitoring layer* with a methodological and technological framework that will enable the planning and execution of shop floor tasks by both robots and humans under a common and analytic definition of risk.

In order to ensure high software quality and ease of software deployment (and to maximise uptake of DARKO's outcomes), a *continuous integration and deployment* paradigm is facilitated through a build farm (e.g., existing Jenkins instances available in the consortium), tight integration with git (using an institutional account at GitHub) and an internally hosted GitLab installation, and automatic deployment of ROS packages overseen by ORU and UoL.

Task 8.3: Evaluation and system demonstrations **Bosch,** ALL

Prior to demonstration of the integrated DARKO system, all components will be evaluated individually by benchmarking key performance indicators and success measures described within each work package. These tests will be conducted using datasets recorded specifically at the end-user site, the BSH spare part commissioning department in Fürth, Germany, or using parts provided by BSH, or using similar existing datasets where available.

The DARKO work plan comprises three major demonstrations of the functionalities of the DARKO demonstrator, which are aligned with the yearly milestones MS2, MS3 and MS4. As motivated in Sec. 1.3, this will take place on the ARENA2036 platform. In this location, closely located to the Bosch Research campus, we will prepare a designated testing and demonstration area for the DARKO use-case which we will obtain from ARENA2036 (see also Letter of Intent). We will build a near-real replica of the BSH commissioning use-case with a relevant quantity and quality of difficulties: we will set up shelf structures in the same geometry, the same spare part boxes with the original parts, the same target tray, conveyor belts if needed, and other relevant objects. In addition, we will observe and replicate typical motion behaviours of workers. This setup will be integrated into the existing Bosch Factory of the Future showcase at ARENA2036, and the overall ARENA2036 environment. Due to the large extents of the hall (ca. 1000 m^2) and the regular presence of other external parties, this environment provides sufficient challenges e. g. for mapping, localisation and motion planning also over longer distances, and enough potential for interaction with humans and other robotic agents.

During demonstrations at milestones MS2 and MS3, the DARKO contributors will show individual or partly integrated components at TRL 5 and 6. A final demonstration at MS4 will showcase the fully integrated system at TRL 6 over an extended period of time. We will use both qualitative observations and quantitative measurements from these deployments to assess progress towards the central objectives of DARKO listed in Sec. 1.1.

Deliverables

D8.1 Report on software and functional requirements, evaluation metrics ORU / M6
This report will summarise the elicitation of application-related requirements, from the software and functional point of view. It will also detail the metrics that are to be used in evaluation.

D8.2 System architecture ORU / M11
Overall system architecture that will be used throughout the project. The implementation will include mock-up modules in lieu of functionalities still to be developed. The deliverable document will detail guidelines on using the software architecture, on deployment of components, and on testing procedures, also using the simulation environment. This document will be mainly for internal use. See also MS1 description in Sec. 3.2.2.

D8.3 First demonstration Bosch / M23
See MS2 description in Sec. 3.2.2.

D8.4 Second intermediate demonstration Bosch / M35
See MS3 description in Sec. 3.2.2. As an additional demonstration show-case contributing to **O3** and **O5**, we will present a user interface to facilitate easy deployment of robots in intralogistics settings, which leverages some of the key results of T2.1, T2.5, T5.1 and T5.2 by allowing the user to easily define pick-up/drop-off points through pointing his hands to areas/objects of interest.

D8.5 Final demonstration TUM / M47
See MS4 description in Sec. 3.2.2.

Measures for Success and Benchmarking

- For Task T8.3: Evaluation and system demonstrations

  Assessment criteria for the demonstrations are given in Table 3.

Risk Assessment and Problem Resolution

- Difficulties completing a focus group for requirements elicitation. *Impact: medium, Risk: low*

  If we will not be able to collect enough participants for a focus group (at least one representative from each relevant industry) we will focus on requirements by end user BSH.

- Some system components are not ready for demonstrator deployment. *Impact: high, Risk: medium*

  If despite our software evaluation and integration efforts in preparation of the milestones, and the continuous integration and deployment as implemented by T8.2, we find that a component is not ready for demonstration, we will carefully analyse and decide if dropping, simplifying or replacing the component by an existing baseline component, where applicable, can ensure or improve overall system performance during demonstration.

3.1.9 Work Package 9: Management

WP9		Management							
Type:	MGT	Part.no.:	**1**	2	3	4	5	6	7
Start:	M01	Part.:	**ORU**	TUM	Bosch	UNIPI	EPFL	UoL	ACT
End:	M48	Effort:	**14 PM**	6 PM	2 PM	0 PM	0 PM	5 PM	2 PM
Task T9.1: Administrative and financial management									
Task T9.2: Technical management									
Task T9.3: Project status monitoring									

Objectives

This work package accounts for all activities at the management level aiming to ensure that the overall objectives of the project are achieved. This will be accomplished through an effective project management and administration structure. The management structure consists of two main bodies, the Steering Board and the Technical Board. The Project Coordinator heads the Executive Team and the Steering Board and is the single point of contact with the EU. The Project Coordinator and the two bodies further maintain contact to consortia of related projects and the international Advisory Board.

The management structures and procedures necessary to accomplish these tasks are further described in Sec. 3.2.

Task 9.1: Administrative and financial management **ORU,** ALL

Administrative and financial project management is addressed by the first task of this work package and spans the entire duration of the project. This task is concerned with: i) Legal, administrative, financial, and ethical management of the consortium during the project. ii) Providing the necessary liaisons between the consortium, the EU and other consortia. iii) Gathering, compiling and delivering progress reports and cost statements. iv) Ensuring smooth progress of the work plan and fulfilment of the consortium's contractual obligations. v) Promoting gender equality and a family environment in the project. vi) Ensuring the quality and timeliness of the deliverables. vii) Conflict resolution.

Task 9.2: Technical management **ORU,** ALL

Technical project management also spans the whole duration of the project and includes the following sub-tasks: i) Coordinating the consortium's technical efforts during the execution of the project. ii) Fostering effective technical exchange, communication and cooperation within the consortium. iii) Ensuring timely and complete specification and design. iv) Managing research data distribution, storage and dissemination within the project. v) Monitoring all integration efforts. vi) Ensuring the quality and timeliness of the technical work and all other technical deliverables.

The responsibility for the technical management will be carried by the Steering Board, which is supported by the Technical Board and, on request, the Advisory Board in technical matters related to DARKO.

Task 9.3: Project status monitoring **ORU,** ALL

Successful project management requires constant knowledge of the current status of the project. Yearly progress reports are insufficient tools for providing quick reaction to upcoming problems, conflicts or delays. Hence, each partner is requested to report *every three months* on progress and deployed resources. We plan to monitor the progress of the beneficiaries also based on informal status reports provided to the Project Coordinator. This methodology will ease the assessment of progress, allows to raise warnings immediately, and take respective reactions. In particular, this task is dedicated to: i) Facilitating effective internal and external communication and cooperation procedures.

ii) Anticipating, managing, and reporting changes related to the project. iii) Resolving conflicts encountered in the consortium. The Project Coordinator is thus able to provide an overview of the current project status to the members of the Steering Board as well as to the European Commission.

Risk Assessment and Problem Resolution

- Risk assessment for the management is provided in Section 3.2.3.

3.1.10 Work Package 10: Dissemination and Exploitation

WP10	Dissemination and Exploitation								
Type:	MGT	Part.no.:	**1**	2	3	4	5	6	7
Start:	M01	Part.:	**ORU**	TUM	Bosch	UNIPI	EPFL	UoL	ACT
End:	M48	Effort:	**6 PM**	3 PM	3 PM	3 PM	3 PM	5 PM	4 PM
Task T10.1: DIH Networks Task T10.2: Scientific dissemination Task T10.3: Communication plan Task T10.4: Exploitation									

Objectives

The objective of all dissemination and exploitation activities is to achieve high impact of DARKO during and beyond the life-time of the project. To this end, this work package aims at collecting the knowledge and the results of all technical work packages and to arrange for the appropriate exploitation of such results as well as the dissemination of non-confidential knowledge. We will setup and maintain a plan for dissemination and exploitation that coordinates, records and reports all activities in this area.

Task 10.1: DIH Networks **ORU,** ALL

The DARKO consortium is heavily dedicated to strong mutual interaction with stakeholders and end-users throughout the project: in eliciting the initial requirements and evaluation criteria (T8.1); dissemination of results / eliciting constructive feedback regarding goals and achievements at regular stakeholder meetings at the three yearly milestone demonstrations, with a particular focus on maximising exploitation in the final year at MS4 and MS5.

To further interact with relevant stakeholders beyond what we could do as an individual consortium, we will exploit the DIH actions arising from DT-ICT-02-2018 (DIH-HERO, DIH^2, TRINITY, RIMA and agROBOfood). Of these, DIH^2 and TRINITY are especially relevant for DARKO. Concretely, we will seek *input from* the DIHs in requirement solicitation, regarding end user needs, input from additional use cases, advise on regulation and standards for exploitation, and will connect to DIH members and their contacts for the stakeholder meetings at the milestone demonstrations. We expect to *contribute to* the DIHs by providing technologies developed in DARKO as modules to the DIH digital access point.

Task 10.2: Scientific dissemination **ORU,** ALL

Dissemination will be achieved through publications of papers and attendance of conferences and workshops. All publications will reference the project. Following H2020's open access policy, all results selected for dissemination will be published with open access and will be linked with all the bibliographical data on the project website.

While DARKO is not part of the Open Research Data Pilot of H2020, all parts of the generated research data that is interesting for large parts of the community and possible to distribute from a public safety viewpoint will be made accessible and hosted at trusted and professionally maintained storage facilities (e.g., Zenodo), using IEEE or ISO standard formats where possible.

The policy with respect to data generated in the project will be described in the plan for exploitation and dissemination of results (PEDR), see D10.2 and D10.3.

Task 10.3: Communication plan **ORU,** ALL

This tasks concerns public dissemination through the implementation of the communication plan that is detailed in Sec. 2.2.2, including web and social media, interaction with the press etc.

Task 10.4: Exploitation **ORU,** ALL

A plan for exploitation and dissemination of results (PEDR) will be prepared and revised throughout the project, in communication with DARKO's industrial partners and its advisory board, participants at stakeholder meetings, and DIH networks. A preliminary version will be prepared with input from the first stakeholder meeting at MS2 (see D10.2). It will be further revised for the demonstrations and stakeholder meetings at MS3 and MS4. The final exploitation plan will be generated at the end of the project (see D10.3). It will summarise information on exploitable technologies developed in the project and identify target applications, markets and suitable exploitation partners.

By integrating stakeholder meetings throughout the project, in addition to communications with the advisory board, we will not only raise awareness of the project's activities, but also be able to incorporate insights from the invited stakeholders in the development of all the tasks in the work plan. The stakeholder meetings will be aligned to the planned milestone demonstrations to achieve the maximum impact.

Deliverables

D10.1 Communication plan ORU / M06

D10.2 Initial plan for exploitation and dissemination of results ORU / M30

D10.3 Final plan for exploitation and dissemination of results ORU / M48

D10.4 Report on success of dissemination and communication activities ORU / M48

Risk Assessment and Problem Resolution

- Lack of archival storage resources *Impact: low, Risk: low*

  If the amount of data exceeds the archival storage space that is available to the partners, we will have to make a more strict selection of which data to include in public archival storage. Since we will have several terabytes of archival storage available, the risk of having to leave out essential data is low.

3.2 Management structure, milestones and procedures

3.2.1 Management structure

The Project Coordinator, Achim J. Lilienthal from ORU, will be responsible for ensuring that all beneficiaries know exactly what is expected of them (as described in the individual work packages), that all milestones are met and that use of resources and all costs are in line with the budgets and the provided Gantt chart (Fig. 7). Any deviation will be immediately communicated to the consortium members and the EC Project Officer.

The Project Coordinator will appoint an Administrative Project Manager and a Scientific Manager. Together with the Project Coordinator, the Administrative Project Manager will take care of the management of the project and will ensure the execution of the contract. The Scientific Manager will be responsible for technical coordination and supervision of the work packages, planning and control of activities, and preparation of deliverables. These roles are further described in Sec. 3.2.1.

The overall goal for project management is to achieve the project's mission in the given time frame, within the limits of the budget and with the best possible results. This includes dealing with the inherent risks of research and development projects, communicating internally and with external stakeholders, and actively initiating problem solving and decision making procedures when progress (or the lack of it) demands it. It also includes monitoring of quality and progress of each work package as well as of the project as a whole.

DARKO will have the flexible and efficient management structure shown in Fig. 8 to manage knowledge in the consortium, the flow of information and the execution of the work plan aligned with the objectives. All actions will be aimed to facilitate collaboration between beneficiaries, enhance the exchange of information between project components, and to enable joint efforts involving different competencies.

The individuals and committees listed in Fig. 8 are described in detail in Secs. 3.2.1 and 3.2.1. Overall, the Executive Team (Project Coordinator, Scientific Manager, and Administrative Project Manager) acts on an operational level where the daily management affairs are conducted. The Steering Board acts on a strategic level where the overall strategic orientation of the project is determined, plans are decided, milestones are monitored and results are approved. The Technical Board acts on a technical level. It steers the technical activities of the project towards its goals and

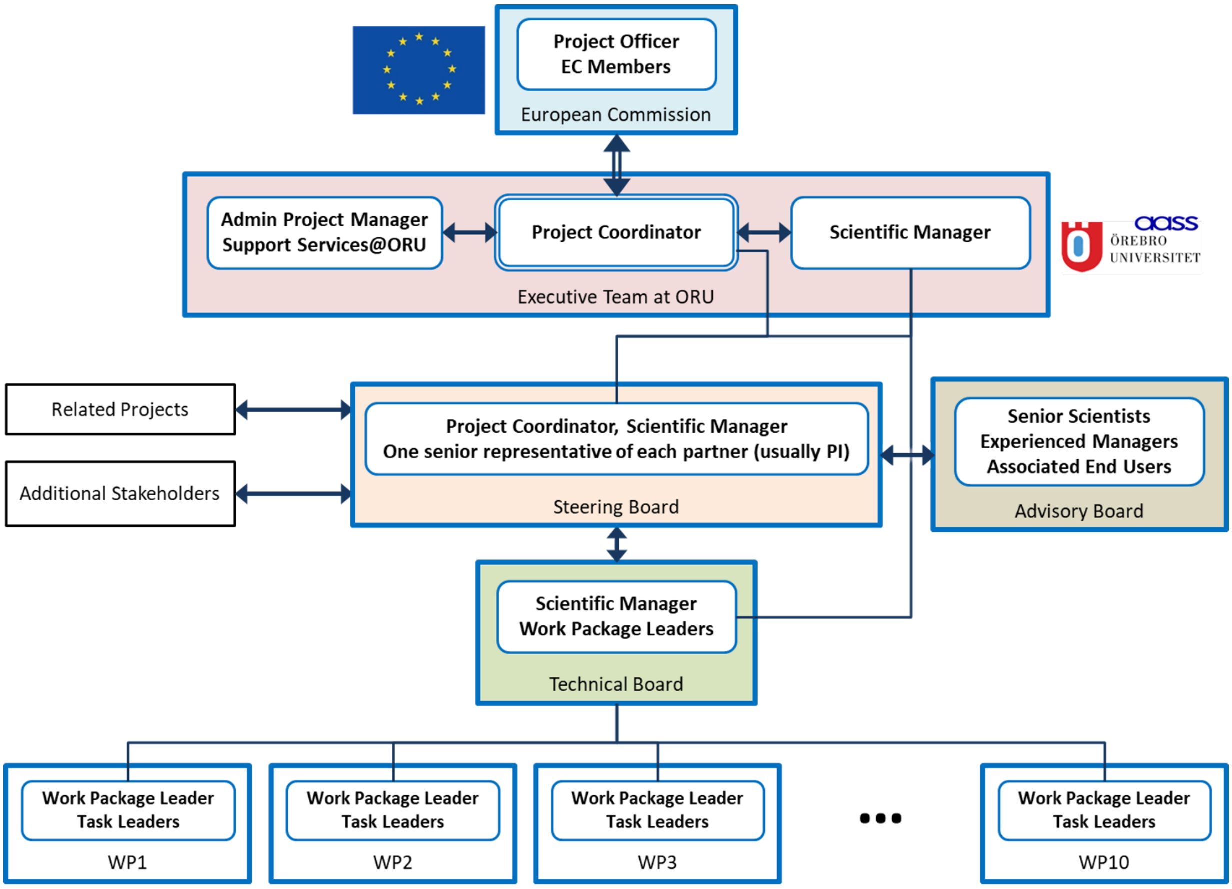

Figure 8: DARKO management structure.

ensures the technical quality of the deliverables of the project. The Work Package Leaders and Task Leaders act on an operational level where the daily technical affairs are conducted.

Key Individuals *The Project Coordinator.* ORU, represented by Professor Achim J. Lilienthal, will coordinate the project in relation to the European Commission. The Project Coordinator will be accountable for day-to-day management of the project in terms of legal, contractual, financial and administrative matters. He will act as single point of contact with the European Commission, but will not be entitled to act or make legally binding declarations on behalf on any other partner within the consortium. The Project Coordinator will also be responsible for preparation of meetings and decisions, will chair the Steering Board, and will manage communication channels. English will be used for communication between members within the project. The main tasks of the Project Coordinator will be to: ensure that the contract with the European Commission and other official project documents are timely signed by the ORU representatives; ensure accession to the contract by the other partners; monitor administration and distribution of project funds to each partner; collect from all partners cost and other statements for submission to the European Commission; organise meetings with the European Commission as necessary; organise and chair Consortium, Steering Board and Advisory Board meetings; plan and guide the project according to decisions made in the Steering Board; prepare, with the support of the Scientific Project Manager and the members of the Steering Board, the reports and project documents required by the European Commission; ensure that reports are of high quality and are delivered on time to the European Commission; monitor, with the support of the Administrative Project Manager, managing and updating of web-based communication actions; act as a mediator and attempt to settle potential differences or conflicts between partners. The mandate of the Project Coordinator will be defined in the Consortium Agreement.

The Administrative Project Manager. The Administrative Project Manager will be appointed by the Project Coordinator. Together with central administrative, financial and legal representatives at Örebro University, the Administrative Project Manager will support the Project Coordinator on a daily basis and will be responsible for management of the project and execution of the contract.

The Grants Office and the Central Finance Department at ORU will support the Project Coordinator and the Administrative Project Manager in their day-to-day business and in handling additional legal, financial, administrative and organizational issues. In this sense, the Administrative Project Manager will act as an interface to the local services at Örebro University, between technical and administrative coordination and among the partners, ensuring smooth collaboration.

The following activities belong to the responsibilities of the Administrative Project Manager: contact management;

preparing project documents for the Coordinator including contracts, meeting minutes, etc.; maintaining documentation on standards and document control procedures in the project; monitoring of important dates and deadlines; day-to-day management activities; organisation of meetings; verifying implementation of decisions made by the Coordinator and the Steering Board; monitoring preparation and coordination of project documents such as progress and final reports, management reports, technical reports, and publishable summary; overseeing the promotion of gender equality in the project; monitoring and illustration of the Project status and data of the beneficiaries; maintaining the project calendar.

Further responsibilities of the Administrative Project Manager are to moderate the following tasks in collaboration with central ORU administration: overall legal, contractual, and administrative management of the project; financial management for the Project Coordinator; cost calculations for personnel, travel, meetings, and equipment; juridical advice and administrative advice of the Coordinator; preparing, updating, and managing the Consortium Agreement between the beneficiaries; obtaining audit certificates (as and when required) by each of the contractors; collection of financial reports; preparation and coordination of project documents such as Form C.

The Scientific Manager. The Scientific Manager will be appointed by the Coordinator and will support the Project Coordinator in all technical aspects of the project, primarily the supervision of project objectives and timeliness of the work plan. The Scientific Manager will have a seat in the Steering Board, will chair the Technical Board, and must be aware of relevant technical developments inside and also outside the project.

The Work Package Leaders. All work packages are under the responsibility of a Work Package Leader. They will be supported by Task Leaders and are responsible for keeping the time schedule and the appropriate implementation related to their work package. They will also monitor the status of milestones and expenditure of effort in their respective work packages. Work Package Leaders are member of the Technical Board and (via the Technical Board) will keep the Executive Team informed of developments and progress status on a regular basis.

The Work Package Leaders will make sure for their work package that the individual members can carry out their tasks. They will be the first contact person in case of irregularities or arising problems in technical work. In this case, they will try to resolve the issue. If this is not possible, they will bring the issue to the attention of the Technical Board and make suggestions for its resolution. In summary, the Work Package Leaders will monitor the quality and progress in their work package, the timely delivery of documents defined for their work package in the work plan, and report to and alert if needed the Technical Board and the Steering Board.

Task Leaders. The Task Leaders cooperate with the Work Package Leaders and are responsible for the technical management of their task as defined in the work plan. Each Task Leader will report to the Work Package Leader and cooperate with the partners of the task in order to achieve its goals.

Committees *The Steering Board.* The Steering Board is the core organisational and decision-making body and has the obligation to ensure that the consortium functions properly. It will be responsible for the successful completion of the project and exploitation of its results. The Steering Board will be chaired by the Project Coordinator. Further members of the Steering Board will be the the Scientific Manager, and one representative of each beneficiary, typically the Principal Investigator (PI) of each beneficiary. Decisions regarding the project will be made by vote with each beneficiary having a single vote. A majority of voting members (at least half of the members of the Steering Board) is required to conduct a meeting. In cases of a tie, the Project Coordinator will have a casting vote. A majority of 2/3 is required to make formal decisions. A European Commission Representative may participate as an observer at the meetings of the Steering Board. Non-voting members and external experts from the Advisory Board can be invited to the Steering Board by the Chair.

The duties of the Steering Board – and thus also of the Coordinator as the head of the Steering Board – are of strategic nature and include, but are not limited to: steering of the consortium; all budget-related matters; structure and restructuring of work plan and work packages (if needed); alteration of the Consortium Agreement (if needed); premature completion/termination of the project (if needed); management of knowledge and preparation of all documents (financial, reporting, audit, etc.); communication between the Consortium and third parties (e.g., related projects and additional stakeholders); and establishment and overview of intellectual property procedures.

The Technical Board. The Technical Board is the technical central body of DARKO. It consists of the Project Coordinator, the Scientific Manager, and the work package leaders. For beneficiaries that are not leading a work package, another person is designated to sit on the Technical Board so that all beneficiaries are represented. It brings together expertise in the various technical fields relevant to the DARKO work packages, and can provide scientific guidance to guarantee successful advancement. The Technical Board will be chaired by the Scientific Manager.

The duties of the Technical Board include, but are not limited to: coordination of activities covering more than one technical area, contribution to the overall technical affairs of the consortium, and responsibility for the integration of the individual developments stemming from the work packages.

The Technical Board decides with a majority of 2/3 about modifications due to unexpected findings during the course of the project. The Technical Board will meet (via tele-conference) at least once every three months.

The Advisory Board. The Steering and Technical Board will be supported by an Advisory Board, which comprises highly qualified individuals in disciplines related to the scientific objectives of the project and its innovation goals. The Advisory Board will also accommodate *associated end-users* that endorse the project, can provide input in the initial requirement elicitation phase as well as during the project run time. Upon request of the Steering or the Technical Board, the Advisory Board will provide expert opinions on scientific, ethical, management or exploitation procedures.

- **Prof. Dr. Tamim Asfour (confirmed), Karlsruhe Institute of Technology, Germany.** Tamim Asfour is full professor at the Institute for Anthropomatics and Robotics, where he holds the chair of Humanoid Robotics Systems and is head of the High Performance Humanoid Technologies Lab (H2T). He is developer and the leader of the development team of the ARMAR humanoid robot family and his research interests include manipulation and learning of motor skills, which are directly relevant to the DARKO project. Tamim Asfour has been active in a number of relevant projects, including SecondHands, IMAGINE, and WALK-MAN.
- **Prof. Sören Kerner (confirmed), Fraunhofer Institute for Material Flow and Logistics, Germany.** Sören Kerner is Head of the Department Automation and Embedded Systems at the Fraunhofer Institute for Material Flow and Logistics in Dortmund. His research interests include Robotics / Automated Guided Vehicles, Artificial Intelligence / Machine Learning and Logistics, which are all directly relevant to the DARKO project.
- **Prof. Thorsteinn Rögnvaldsson (confirmed), Halmstad University, Sweden.** Thorsteinn Rögnvaldsson is professor in computer science, with research interests in AI and robotics. He is director of CAISR, the Centre for Applied Intelligent Systems Research, which is a long-running strategic research investment at Halmstad University, backed by external grants from the Swedish Research Council, among others. He is also experienced in logistics projects, e.g. in the EU EP7 project Cargo-ANTS.
- **Prof. Bruno Siciliano (confirmed), University of Naples Federico II, Italy.** Bruno Siciliano is head of the PRISMA Lab at the Department of Electrical Engineering and Information Technology and Director of the ICAROS Center. He is IEEE fellow, ASME fellow, IFAC fellow, past president of the IEEE Robotics & Automation Society, co-editor of the award-winning Springer Handbook of Robotics, member of the Board of Directors of the European Robotics Association, Rudolf Kálmán honorary professor at Óbuda University, Hungary, to name only a few of his honours. His research interests include dynamic manipulation, human-robot interaction and service robotics, which are directly relevant to the DARKO project. Bruno Siciliano has been active in a number of relevant research projects, including RoDyMan (Robotic Dynamic Manipulation, ERC PI), REFILLS (Robotics Enabling Fully-Integrated Logistics Lines for Supermarkets, coordinator), EuRoC (European Robotics Challenges, coordinator), RockEU and RockEU2 (Robotics Coordination Actions for Europe), SAPHARI (Safe and Autonomous Physical Human-Aware Robot Interaction), euRobotics (European Robotics Coordination Action), ECHORD (European Clearing House for Open Robotics Development, co-coordinator), PHRIENDS (Physical Human-Robot Interaction: De-pENDability and Safety), EURON 2 and EURON (European Robotics Research Network).

3.2.2 List of Milestones

The DARKO work plan is structured around five milestones. They represent the main control points of the work plan and will be used to monitor the progress of the project and ensure progress on the intense integration effort (**O5**). The milestones are also designed to include *measures to ensure exploitation activities* during and after the project, as three of them involve live demonstrations for the public and designed stakeholder meetings for decision makers and interested users from the industry.

Milestone 1: Architecture & Initial Integration. This milestone assesses the first full development of the overall system architecture that will be used throughout the project (T8.2, D8.2). The implementation will include mock-up modules in lieu of functionalities still to be developed. All layers of the architecture will be considered in the implementation. Communications infrastructure will be available to connect modules from all relevant work packages in the architecture (e.g., using ROS messages, topics and services), and basic simulation infrastructure will be provided.

Milestone 2: First Demonstration. The second milestone measures the achievement of physical deployment on the initial platform and demonstrated in a limited use-case replica at ARENA2036. The mock-up modules deployed at MS1 will be substituted with the first prototypes of real functionalities. This milestone is aligned with the release of the first prototype of the novel gripper (still mounted on an off-the-shelf manipulator), and initial releases of software modules for perception for manipulation and human tracking, reliability-aware mapping and localisation, control and planning for manipulation and throwing, global motion planning for the platform, and the final module for a learning and forecasting risk assessment. This milestone coincides with the first stakeholder meeting, including interaction with the DIHs designated in T10.1.

Table 3: List of milestones

Milestone nr	Milestone name	Related WPs	Due date	Means of verification
MS1	Architecture & Initial Integration	WP2, WP3, WP4, WP5, WP6, WP7, WP8	M11	The entire system can be run in simulation, with scriptable mock-up modules replacing real functionality where necessary. The simulation can be used to exhibit the desired behaviour of the system under different circumstances through hard-coded scripts emulating the behaviour of the live system.
MS2	First Demonstration	WP1, WP2, WP3, WP4, WP5, WP6, WP7, WP8, WP10	M23	Relevant mock-up modules have been substituted with initial prototypes implementing real functionalities. The system can, to a limited extent and in a limited use-case replica, run on a physical platform. Missions can be posted that include both motion and manipulation, missions can be subject to induced risk factors, articulated 3D poses of humans can be tracked, basic integration of perception and manipulation can be demonstrated.
MS3	Intermediate Demonstration	WP1, WP2, WP3, WP4, WP5, WP6, WP7, WP8, WP10	M35	The system can run in a real environment, including all key aspects of the use-case concept, exhibiting partial ability to integrate data from qualitative map sources, learning maps of dynamics during live operation and using them in planning, predict long-term human motion, perform mutual communication of intents, communicate risk constraints to planning modules. Novel gripper and manipulator hardware is included. Metrics defined in the technical development workpackages will also contribute in the assessment of this milestone.
MS4	Final Demonstration	WP1, WP2, WP3, WP4, WP5, WP6, WP7, WP8, WP10	M47	The system can run in a real environment, including all key aspects of the use-case concept, and adheres to the requirements stipulated in WP8. This includes final versions of all system functionalities, notably including throwing of goods, mobile manipulation, perception, online map and localisation verification subject to induced faults, causal reasoning for safe HRSI, predictive local planning, planning and navigation modules that respond to risk-optimal scheduling under a number of scenarios.
MS5	Release of Exploitable Results	WP8, WP10	M47	Visit counters on download pages, and any product development initiative or scholarly citations stemming from the released results.

Milestone 3: Intermediate Demonstration. The intermediate integration and demonstration at ARENA2036 will focus on achieving integration of the novel gripper and elastic manipulator, which are the main components of the final platform developed in T1.4. While their full capabilities are still being developed in WP4, this milestone will include the functionality in the live system. This milestone will also achieve a full integration of on-line learning of maps of dynamics, heterogeneous map merging, safe motion planning and control with a vSMU, and the first version of risk-optimal scheduling, and results from human motion prediction and intent communication. This milestone coincides with the second stakeholder meeting.

Milestone 4: Final Demonstration. The final technical milestone assesses the results of the project based on the requirements stipulated in WP8. The capabilities of the entire system will be showcased in a final demonstration to occur near project completion. The demonstrator will include refined versions of all layers of the system. We will actively engage with stakeholders and members of the DIHs designated in T10.1 before and during the milestone demonstration and stakeholder meeting in order to maximise exploitation potential.

Milestone 5: Release of Exploitable Results. In order to maximise the exploitability of DARKO results, selected technologies will be packaged and made public as public repositories (e.g., via GitHub), publicly available ROS stacks and/or ready-to-install software packages. The attainment of these activities will be measured through visit counters on download pages, and any product development initiative stemming from the released results (e.g., forks of code).

3.2.3 Procedures

Key Project Meetings In addition to the Review Meetings, we will organise four five types of consortium-wide meetings throughout DARKO: the Steering Board and Technical Board meetings mentioned in Sec. 3.2.1, integration

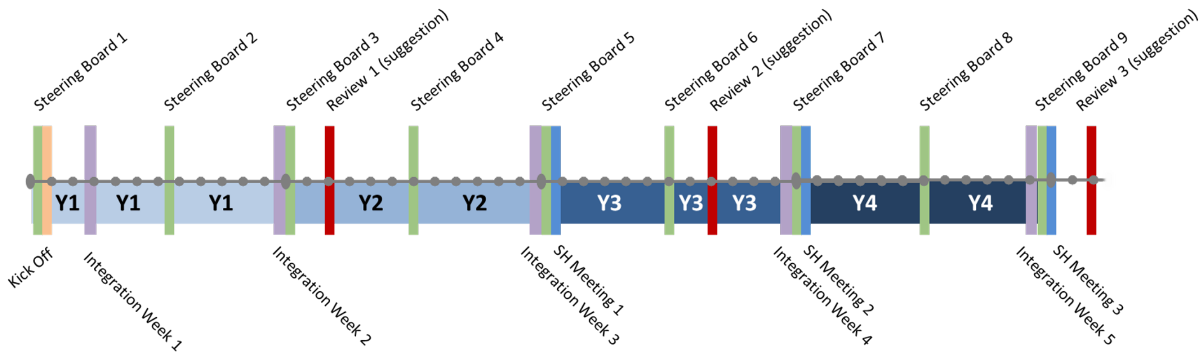

Figure 9: DARKO meeting schedule assuming project start in January 2021 and $12+18+18$ month reporting periods. Orange: kick-off meeting, green: Steering Board (SB) meetings, purple: integration weeks, red: review meetings, blue: stakeholder meetings. Technical Board meetings are not shown.

sprints in preparation of the milestone demonstrations, and stakeholder meetings to maximise impact. A tentative meeting schedule is shown in Fig. 9.

Meetings will be organized either physically or by teleconference. Meeting agendas will be sent out in advance to allow partners to prepare their input, and the results of the communication will be captured and stored for reference.

Kick Off Meeting. The Coordinator will hold a Kick-Off Meeting with all beneficiaries and the EU Commission's representative (if possible). The purpose of the project Kick-Off Meeting is to check the effective beginning of the work, detecting and preventing possible problems in the very beginning.

Steering Board Meetings. Only the members of the Steering Board, the Project Coordinator, the Scientific Manager and members of the Advisory Board (on request) participate in the Steering Board meetings. The Steering Board will meet at the Kick-Off and at strategic intervals distributed over the project runtime, nine times in total.

Technical Board Meetings. Members of the Technical Board, the Coordinator, the Scientific Manager are required to participate in Technical Board meetings. Other consortium members are invited to participate. Should voting be needed, members of the Technical Board have one vote each. Quarterly meetings are held over video or telephone.

Both Steering and Technical Board may also meet exceptionally in case of problems or delays in the implementation of the work plan that cannot be resolved by the usual communication procedures outlined in Sec. 3.2.3.

Integration Weeks. A key objective of DARKO and one of its most challenging aspects is the integration of cutting edge project results in a prototype of a working system, to be demonstrated live. This requires a holistic system integration approach in which all individual components are put together to a working system. Building upon experience from past projects (e.g. SPENCER and ILIAD), we will take a hierarchical integration approach in DARKO. We will have four *integration weeks* with all required partners. Additionally, separate integration sprints will be organised with a subset of the partners, as needed.

Stakeholder Meetings. To inform end users, technology providers and other interested parties we will arrange stakeholder meetings in conjunction with the demonstrations at MS2, MS3 and MS4.

Management Procedure Tools The Executive Team will establish the following management procedure tools.

Continuous, internal risk assessment. This procedure is concerned with an early identification of partners risks via a protocol of continuous communication with all the beneficiaries. In case of partner risks with a high impact on the results of DARKO, the procedure indicates that the Steering Board has to take appropriate actions.

Collaborative tools. To foster collaboration between all partners at all levels we will use several state-of-the-art management tools such as: Slack, shared calendars, GitLab document and source versioning systems, internal mailing lists, or online shared storage space.

Intellectual Property Rights When signing the Consortium Agreement, based on the DESCA 2020 model consortium agreement v 1.2, all partners must declare their background (immaterial rights generated outside of the project). The consortium agreement further specifies the conditions for using background and foreground (joint or individual). While this agreement can only be signed and legally binding after the project has been approved, the following text outlines the intended strategy for handling immaterial rights.

In general, non-background results generated within the project will be owned by the partner that generates them. Where results are generated from work carried out jointly by two or more partners and it is not possible to separate such work for the purpose of obtaining or maintaining relevant intellectual property rights, the partners shall have joint ownership of this work. The joint owners shall establish a written separate joint ownership agreement regarding the allocation of ownership and terms on a case by case basis. Unless otherwise agreed, each of the joint owners shall be entitled to use their jointly owned results for non-commercial research activities and without requiring the prior consent of the other joint owner(s), and each of the joint owners shall be entitled to otherwise exploit the results if the other joint owners are given reasonable compensation and advance notice.

General Risk Analysis A systematic and comprehensive approach to risk analysis is essential in an ambitious and complex project like DARKO. This section describes how the Project Coordinator and the Steering Board will deal with potential problems. These could be problems within the consortium, technical risks, or exploitation risks.

Consortium Risks:

- **Potential issue**: Consortium has no harmony. **Risk and Resolution**: The key people know and trust each other. In the unlikely case of quarrels that cannot be resolved in the consortium, external help will be sought according to a procedure described in the Consortium Agreement.
- **Potential issue**: Poor quality of deliverables. **Risk and Resolution**: The Executive Team will monitor the quality of the deliverables and will immediately react in case of low quality deliverables.
- **Potential issue**: Delay in meeting the deadlines. **Risk and Resolution**: The progress of the project will be assessed frequently to predict possible delays and to act accordingly.

Technical Risks. The consortium is confident that the overall technical goals defined in the project are reasonable and can be achieved within the project scope. Due to the ambitious goals of DARKO, however, technical problems could occur during the project. A detailed description of the technical risks and their handling is given in the work package descriptions. In general, the major technical risks we may face concern:

- **Potential issue**: Important technical components may not work as expected. **Risk and Resolution**: Our detailed risk analysis on a work package-level is dedicated to mitigating this risk. If, however, some components would not work as expected at some point in the project, we can exploit the modular structure of DARKO to contain the issue or temporarily lower the requirements with respect to the under-performing component so that the integrated system can still be tested.
- **Potential issue**: Risk plans as identified in the work package descriptions may be missing important points. **Risk and Resolution**: To assure that the work packages will be executed correctly, the risk plans for each of the work packages will assessed in the Kick Off meeting and, on request, at Steering Board meetings.
- **Problem**: Delivery delays of the hardware components. **Risk and Resolution**: Delivery times of hardware can vary as a function of unforeseeable factors (e.g., global economy or supply chain). This risk is addressed by a particularly tight schedule for platform specification, design and production in the beginning of the project.
- **Potential issue**: Integration weeks may be inefficient and miss their goals. **Resolution**: Due to the experience of the consortium in several EU projects, this risk is low. We will strive for bi- or trilateral integration sprints well ahead of the consortium-wide integration weeks that are planned before each Milestone. Together with a Continuous Integration service and automated system-level testing, we will ensure that components are made available deployment-ready in a timely manner. Should we still experience inefficient integration meetings, we can also consult the Advisory Board to get guidance for improved organisation.

In cases where problems such as the above cannot be handled adequately, the Technical Board will issue a proposal how to handle them. The Steering Board will consider the proposal for changes and decide whether the changes would be within the current contract or not. Modification of project tasks or rearrangement of the man-power in the project are examples of measures that might be taken to guarantee that the objectives will still be achieved. The EC Project Officer will immediately be informed about identified issues and any proposed major changes.

Innovation and Exploitation Risks. DARKO is a highly innovative project, which aims at improving the key technologies for intralogistics robots operating in warehouse applications with a high demand on flexibility. One outcome of DARKO will be a significant improvement of logistics robots and a corresponding extension of the market for these robots, backed up by the expertise of the technology providers and end users in the consortium. Nonetheless, there could be risks related to exploitation.

- **Potential issue**: Low correspondence with market demand. **Risk**: DARKO has been planned together with the Bosch, including the BSH group, as well as technology provider ACT, to answer specific and true market needs that have been proactively exposed to us. This is a market-pull situation, ideal to diminish this risk.
- **Potential issue**: IPR issues. **Risk and Resolution**: When signing the Consortium Agreement, all partners must declare their background (immaterial rights generated outside of the project). The consortium agreement further specifies the conditions for using background and foreground (joint or individual). IPR issues will be addressed according to a procedure described in the Consortium Agreement.
- **Potential issue**: A market player releases a competing product making the planned work obsolete. **Risk**: This is a small risk since DARKO is a highly innovative project carried out by very skilled research partners that work at the forefront of their fields. It is very unlikely that somebody else has the same unique spectrum of competences

as the DARKO consortium.

Communication Procedures The Executive Team and the Steering Board will set up instruments for successful communication at the beginning of the project; e.g., a Mattermost or Slack discussion board in combination with mailing lists. We will provide infrastructure to keep all consortium participants informed about meetings, reporting, minutes, finances, results and other day-to-day issues in the project. Privacy will be guaranteed by the definition of public and private spaces, for individual project members, groups, work packages, EC staff, or reviewers.

Supported by the consortium the Executive Team will facilitate communication not only on a consortium level but also with other relevant bodies such as the Advisory Board, other related EU-funded projects, industrial stakeholders, and end-users. In order to avoid communication overflow, information that is of specific interest for a subset of the consortium only will be communicated in a targeted manner.

Quality Control Quality control requires the Project Coordinator and the consortium to constantly inspect the accomplished work and to ensure that it is aligned with the work plan. Quality control is supported by the management infrastructure in DARKO, which establishes a clear decision tree from the Executive Team over the Steering Board, the Technical Board, the Work Package Leaders to the Task Leaders. This structure will allow for a clear overview on ongoing activities, and thus for effective quality control. In addition to monitoring of the quality of documents and reports through the Executive Team, quality is the responsibility of every member participating in DARKO. Everybody commits to the goal to meet the very highest quality standards in all the work conducted for the project.

Progress Monitoring and Measures of Success Work progress in DARKO will be constantly monitored by the Executive Team. Each partner is requested to report *every three months* on progress and deployed resources. The documentation standard designed to support efficient reporting will be provided by the Project Coordinator. All information will be summarised by the Executive Team and distributed to the partners with remarks and countermeasures in case of major deviations.

A basis for measuring the quality of the conducted work are the measures of success specified in the descriptions of the individual work packages. Furthermore, the status of the academic dissemination plan in terms of publications in journals and international conferences will be taken as a measure of success for the involved research teams. For important deliverables, internal peer reviews will be performed for the documents produced.

3.3 Consortium as a Whole

The DARKO consortium brings together a unique combination of partners with highly complementary, world-leading expertise to tackle the application needs for robots that operate in intralogistics applications of agile production in environments shared with humans.

The "market pull" for the research and innovations in DARKO is represented firstly by partners Bosch and ACT, both having strong commercial ties to end users in agile production, and in particular the intralogistics aspects of these operations. The main guide for the DARKO use case comes from Bosch subsidiary BSH (Bosch Siemens Hausgeräte). ACT provide modelling, scheduling, and simulation products to clients in manufacturing and logistics. As such, in addition to their technical competences, they also bring to the consortium well-grounded and up-to-date insights of present market needs.

The "science push" for DARKO comes from recent break-throughs in component technologies, in which the academic partners are already world-leading. The academic partners in the consortium have been selected on the basis of two criteria: the excellence of their research track record in the complementary areas necessary to achieve the project aims, and their track record of delivering the results of their research in the context of integrated robot systems, ensuring a balance to the engineering load across the consortium. The distribution and complementarity of the partners' scientific competences can be glanced from the efforts listed in Table 4. Coordinating partner **ORU** will contribute primarily to mapping and localisation in WP3, and also to perception for manipulation in WP2, with expertise from their newly formed Autonomous Mobile Manipulation Lab. Partner **TUM**, building on the world-renown expertise in safe manipulation of Prof. Sami Haddadin, leads the work on the design and control of a novel and efficient elastic manipulator in WP1, and contributes to safe planning in WP6. **Bosch** leads WP2 (3D Perception and Scene Understanding) and WP6 (Predictive Motion Planning), which manifests their expertise in robot perception and social navigation, proven also in their previous leading work in the SPENCER and ILIAD projects. **UNIPI** has a strong record in manipulation, and in particular end-effector design. They will contribute design and control of novel flexible end-effectors, and lead WP4 (Safe Dynamic Manipulation), in addition to novel contribution of risk-aware manipulation in WP7. **EPFL** joins the consortium under the lead of Prof. Aude Billard. Although not designated leader of a work package, EPFL would be indispensable in a project with DARKO's ambitions of including throwing for greater efficiency in logistics and production.[25] They will contribute greatly to manipulation in WP4 as well as WP2. **UoL** will contribute particularly in social navigation in the presence of humans, through its L-CAS research centre, and lead WP5, Human-Robot Spatial Interaction. **ACT**, in addition to the market connections outlined above, leads the technical WP7 (Risk and Scheduling), where they contribute a risk assessment and forecasting framework to ensure both efficient and safe operation in a human-robot shared environment.

The consortium thus precisely matches DARKO's objectives, bringing together Europe's leading expertise in the aspects related to its goals, through the value chain from academic researchers to technology providers. In addition to scientific and technical competence, the consortium is also well connected to end-users from several market domains. We have included partners well suited for maximising exploitation of project results, as also described in Sec. 2.2.

Together, the partners in DARKO have close ties already since previous projects and have many areas of complementary expertise. Furthermore, the numerous intersections between the research areas of the partners, together with their shared history of working together (e.g., in EU projects SPENCER, ILIAD, STRANDS, I.AM) will enable seamless cooperation, a close understanding of each other's work and accelerated performance in systems integration. The balance of academic partners with technology providers further provides the consortium with multiple dissemination routes and routes to market, ensuring maximum exposure to end-users across many market domains and sectors.

3.4 Resources to be committed

Table 4 shows the number of person months required per partner. Table 5 details the "other direct costs" for beneficiaries where those costs exceed 15% of the personnel costs. The other partners do not exceed the 15% limit.

Table 4: Summary of staff effort in person months. Bold numbers represent the work package leader.

Partic. no.	**Partic.**	WP1	WP2	WP3	WP4	WP5	WP6	WP7	WP8	WP9	WP10	**Sum**
1	ORU	6	38	**80**	4	38	6	2	**5**	**14**	**6**	199
2	TUM	**91**	3	0	15	1	11	1	4	6	3	135
3	Bosch	2	**44**	3	0	9	**24**	0	9	2	3	96
4	UNIPI	39	10	5	**59**	0	20	10	5	0	3	151
5	EPFL	0	24	0	54	4	4	0	7	0	3	96
6	UoL	2	7	4	0	**54**	2	0	3	5	5	82
7	ACT	0	0	2	0	4	4	**41**	6	2	4	63
Total		140	126	94	132	110	71	54	39	29	27	822

References

[1] H. Admoni and S. Srinivasa. "Predicting user intent through eye gaze for shared autonomy". In: *Proceedings of the AAAI Fall Symposium Series: Shared Autonomy in Research and Practice (AAAI Fall Symposium)*. 2016, pp. 298–303.

[2] N. Akai et al. "Misalignment Recognition Using Markov Random Fields With Fully Connected Latent Variables for Detecting Localization Failures". In: *IEEE Robotics and Automation Letters* 4.4 (2019), pp. 3955–3962.

[3] O. Akman and P. Jonker. "Object Recognition and Localisation for Item Picking". In: *Automation in Warehouse Development*. Ed. by R. Hamberg and J. Verriet. Springer London, 2012, pp. 153–162.

[4] A. Alahi. *Trajnet++*. URL: https://www.aicrowd.com/challenges/trajnet-a-trajectory-forecasting-challenge.

[5] A. Albu-Schäffer et al. "Dynamic modelling and control of variable stiffness actuators". In: *2010 IEEE International Conference on Robotics and Automation*. IEEE. 2010, pp. 2155–2162.

[6] H. Almqvist et al. "Learning to detect misaligned point clouds". In: *Journal of Field Robotics* 35.5 (Aug. 2018), pp. 662–677.

[7] F. Amigoni et al. "A Standard for Map Data Representation: IEEE 1873-2015 Facilitates Interoperability Between Robots". In: *IEEE Robotics & Automation Magazine* 25.1 (2018), pp. 65–76.

[8] J. S. Andersen and T. Christensen. "Apparatus for handling layers of palletized goods". Pat. 6802688. Oct. 2004.

[9] H. Andreasson et al. "Autonomous Transport Vehicles: Where We Are and What Is Missing". In: *IEEE Robotics & Automation Magazine* 22.1 (2015), pp. 64–75.

[10] H. Andreasson et al. "Incorporating Ego-motion Uncertainty Estimates in Range Data Registration". In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. Sept. 2017, pp. 1389–1395.

[11] F. Angelini et al. "SoftHandler: An Integrated Soft Robotic System for Handling Heterogeneous Objects". In: *IEEE Robotics and Automation Magazine* PP (Feb. 2020). DOI: 10.1109/MRA.2019.2955952.

[12] Y. Aoki et al. "PointNetLK: Robust & Efficient Point Cloud Registration Using PointNet". In: *IEEE Conf. on Comp. Vis. and Pat. Recog. (CVPR)*. June 2019.

[13] V. Arapi et al. "To grasp or not to grasp: an end-to-end deep-learning approach for predicting grasping failures in soft hands". In: *IEEE Int. Conf. on Soft Robotics (ROBOSOFT)*. In press. Apr. 2020.

[14] G. Averta et al. "A technical framework for human-like motion generation with autonomous anthropomorphic redundant manipulators". In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2020.

[25] https://actu.epfl.ch/news/ultra-fast-the-robotic-arm-can-catch-objects-on-th/

Table 5: “Other direct cost” items for partners exceeding the 15% limit.

ORU / 1		
Travel	93,200 €	Key project meetings, conferences, DIH and stakeholder workshops, ARENA2036 meetings.
Equipment	74,000 €	Clearpath mobile base + Franka Panda, for ARENA2036 demo (60,000 €), 2× Ouster OS0-64 lidar for perception (14,000 €).
Other	13,500 €	Consumables (4 000 €), audit (4 500 €), objects for picking and throwing (5 000 €).
Total	180,700 €	
TUM / 2		
Travel	50,000 €	Key project meetings, conferences, DIH and stakeholder workshops.
Equipment	260,000 €	Clearpath mobile base + Franka Panda (60,000 €), hardware for constructing 2× elastic manipulator (200,000 €).
Other	8500 €	Consumables (4 000 €), audit (4 500 €).
Total	318,500 €	
UNIPI / 4		
Travel	40,000 €	Key project meetings, conferences, DIH and stakeholder workshops.
Equipment	0 €	
Other	218,500 €	Clearpath mobile base + Franka Panda (60,000 €), assorted hardware for constructing 2× end-effector (150,000 €). consumables (4 000 €), audit (4 500 €).
Total	258,500 €	
UoL / 6		
Travel	51,480 €	Key project meetings, conferences, DIH and stakeholder workshops.
Equipment	10,626 €	PAL TiaGo robot upgrade (5986 €), 2× hi-spec. laptops (4640 €).
Other	8500 €	Consumables (4 000 €), audit (4 500 €).
Total	70,606 €	

[15] G. Averta et al. “Exploiting upper-limb functional principal components for human-like motion generation of anthropomorphic robots”. In: *J. on euroEngineering Rehabil.* 17.63 (2020).

[16] T. Başar and G. Olsder. “Dynamic Non-Cooperative Game Theory”. In: 160 (Jan. 1999).

[17] J. C. Beck and N. Wilson. “Proactive algorithms for job shop scheduling with probabilistic durations”. In: *Journal of Artificial Intelligence Research* 28 (2007), pp. 183–232.

[18] N. Bellotto et al. “Qualitative Design and Implementation of Human-Robot Spatial Interactions”. In: *Proc. of Int. Conf. on Social Robotics (ICSR)*. 2013, pp. 331–340.

[19] N. Bellotto et al. “Human Detection and Tracking”. In: *Encyclopedia of Robotics*. Ed. by M. H. Ang et al. Berlin, Heidelberg: Springer Berlin Heidelberg, 2018.

[20] M. Ben-Daya. “Failure Mode and Effect Analysis”. In: *Handbook of Maintenance Management and Engineering*. Ed. by M. Ben-Daya et al. London: Springer London, 2009, pp. 75–90.

[21] B. Berenguel-Baeta et al. “OmniSCV: An Omnidirectional Synthetic Image Generator for Computer Vision”. In: *Sensors* 20.7 (Apr. 2020), p. 2066.

[22] K. Bernardin and R. Stiefelhagen. “Evaluating Multiple Object Tracking Performance: The CLEAR MOT Metrics”. In: *Journal on Image and Video Processing* 2008.1 (May 2008), p. 246309.

[23] L. Beyer et al. “Deep Person Detection in Two-Dimensional Range Data”. In: *IEEE Robotics and Automation Letters* 3.3 (July 2018), pp. 2726–2733.

[24] M. Bianchi et al. “Touch-Based Grasp Primitives for Soft Hands: Applications to Human-to-Robot Handover Tasks and Beyond”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2018, pp. 7794–7801.

[25] A. Bicchi and G. Tonietti. “Fast and "soft-arm" tactics [robot arm design]”. In: *IEEE Robotics Automation Magazine* 11.2 (2004), pp. 22–33.

[26] J. Bidot et al. “A theoretic and practical framework for scheduling in a stochastic environment”. In: *Journal of Scheduling* 12.3 (2009), p. 315.

[27] R. Bischoff et al. “The KUKA-DLR Lightweight Robot arm-a new reference platform for robotics research and manufacturing”. In: *ISR 2010 (41st international symposium on robotics) and ROBOTIK 2010 (6th German conference on robotics)*. VDE. 2010, pp. 1–8.

[28] A. Bochkovskiy et al. “YOLOv4: Optimal Speed and Accuracy of Object Detection”. In: *arXiv preprint arXiv:2004.10934*. 2020.

[29] F. Boniardi et al. “Robust LiDAR-based localization in architectural floor plans”. In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. Sept. 2017, pp. 3318–3324. DOI: 10.1109/IROS.2017.8206168.

[30] M. Bonilla et al. “Grasp planning with soft hands using bounding box object decomposition”. In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. IEEE. 2015, pp. 518–523.

[31] C. Borst et al. “A humanoid upper body system for two-handed manipulation (Video)”. In: *Robotics and Automation, 2007 IEEE International Conference on*. 2007.

[32] M. Breteler et al. “End-point constraints in aiming movements: effects of approach angle and speed”. In: *Biological Cybernetics* 85 (July 2001), pp. 65–75. DOI: 10.1007/PL00007997.

[33] D. Brščić et al. “Person tracking in large public spaces using 3-D range sensors”. In: *IEEE Transactions on Human-Machine Systems* 43.6 (2013), pp. 522–534.

[34] A. Bubic et al. “Prediction, cognition and the brain”. In: *Frontiers in human neuroscience* 4 (2010), p. 25.

[35] B. Busch et al. "Evaluation of an Industrial Robotic Assistant in an Ecological Environment". In: *2019 IEEE International Workshop on Robot and Human Interactive Communication (Ro-Man)*. IEEE. 2019.

[36] C. Cadena et al. "Past, Present, and Future of Simultaneous Localization and Mapping: Toward the Robust-Perception Age". In: *IEEE Transactions on Robotics* 32.6 (Dec. 2016), pp. 1309–1332.

[37] F. Camara et al. "Pedestrian Models for Autonomous Driving. Part II: High Level Models of Human Behaviour". In: *IEEE Transactions on Intelligent Transportation Systems* (2020).

[38] N. Carion et al. "End-to-End Object Detection with Transformers". In: *arXiv preprint arXiv:2005.12872*. 2020.

[39] J. L. Castellanos et al. "Using machine learning based on eye gaze to predict targets: An exploratory study". In: *Computational Intelligence (SSCI), 2017 IEEE Symposium Series on*. IEEE. 2017, pp. 1–7. DOI: 10.1109/SSCI.2017.8285207.

[40] M. G. Catalano et al. "VSA-CubeBot: A modular variable stiffness platform for multiple degrees of freedom robots". In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2011, pp. 5090–5095.

[41] R. T. Chadalavada et al. "Bi-directional navigation intent communication using spatial augmented reality and eye-tracking glasses for improved safety in human–robot interaction". In: *Robotics and Computer-Integrated Manufacturing* 61 (2020), p. 101830.

[42] R. T. Chadalavada et al. "Empirical evaluation of human trust in an expressive mobile robot". In: *Robotics Science and Systems (RSS), Workshop on Social trust in Autonomous Robots*. 2016.

[43] R. T. Chadalavada et al. "That's on my Mind! Robot to Human Intention Communication through on-board Projection on Shared Floor Space". In: *ECMR*. 2015, pp. 1–6.

[44] C. C. Cheah et al. "Feedback control for robotic manipulator with uncertain kinematics and dynamics". In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. Vol. 4. 1998, 3607–3612 vol.4.

[45] Y. F. Chen et al. "Decentralized non-communicating multiagent collision avoidance with deep reinforcement learning". In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2017, pp. 285–292.

[46] C. Choi et al. "Learning Object Grasping for Soft Robot Hands". In: *IEEE Robotics and Automation Letters* 3.3 (2018), pp. 2370–2377.

[47] E. Colgate et al. "Safety for Physical Human-Robot Interaction". English. In: *Springer Handbook of Robotics*. Springer, 2008, pp. 1335–1348.

[48] C. Coppola et al. "Social Activity Recognition on Continuous RGB-D Video Sequences". In: *International Journal of Social Robotics* 12 (2020), pp. 201–215.

[49] H. Coskun et al. "Long Short-Term Memory Kalman Filters: Recurrent Neural Estimators for Pose Regularization". In: *IEEE Int. Conf. on Computer Vision (ICCV)*. 2017, pp. 5525–5533.

[50] R. Dabral et al. "Learning 3D Human Pose from Structure and Motion". In: *Eur. Conf. on Computer Vision (ECCV)*. 2018, pp. 679–696.

[51] K. Dautenhahn. "Socially intelligent robots: dimensions of human–robot interaction". In: *Philosophical transactions of the royal society B: Biological sciences* 362.1480 (2007), pp. 679–704.

[52] Y. Dawen and S. Ji. "Grid Based Spherical CNN for Object Detection from Panoramic Images". In: *Sensors* 19 (2019), p. 2622. DOI: 10.3390/s19112622.

[53] A. De Luca et al. "Collision detection and safe reaction with the DLR-III lightweight manipulator arm". In: *2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE. 2006, pp. 1623–1630.

[54] X. Deng et al. "Self-supervised 6D Object Pose Estimation for Robot Manipulation". In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2020.

[55] A. Dietrich et al. "Reactive Whole-Body Control: Dynamic Mobile Manipulation Using a Large Number of Actuated Degrees of Freedom". In: *IEEE Robotics and Automation Magazine* 19.2 (2012), pp. 20–33.

[56] K. Doherty et al. "Probabilistic Data Association via Mixture Models for Robust Semantic SLAM". In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2020.

[57] C. Dondrup et al. "A Probabilistic Model of Human-Robot Spatial Interaction Using a Qualitative Trajectory Calculus". In: *AAAI Spring Symposium on Qualitative Representations for Robots*. 2014, pp. 18–25.

[58] C. Dondrup and M. Hanheide. "Qualitative constraints for human-aware robot navigation using Velocity Costmaps". In: *IEEE Int. Symposium on Robot and Human Interactive Communication (RO-MAN)*. 2016, pp. 586–592.

[59] C. Dondrup et al. "A Computational Model of Human-Robot Spatial Interactions Based on a Qualitative Trajectory Calculus". In: *Robotics* 4.1 (2015), pp. 63–102.

[60] B. R. Duffy. "Anthropomorphism and the social robot". In: *Robotics and Autonomous Systems* 42.3 (2003). Socially Interactive Robots, pp. 177 –190.

[61] C. R. Duguay et al. "From mass production to flexible/agile production". In: *International Journal of Operations & Production Management* (1997).

[62] O. Eiberger et al. "On joint design with intrinsic variable compliance: Derivation of the DLR QA-joint". In: *2010 IEEE International Conference on Robotics and Automation*. IEEE. 2010, pp. 1687–1694.

[63] F. Engelmann et al. "3D-MPA: Multi Proposal Aggregation for 3D Semantic Instance Segmentation". In: *IEEE Conf. on Comp. Vis. and Pat. Recog. (CVPR)*. 2020.

[64] C. Eppner and O. Brock. "Grasping unknown objects by exploiting shape adaptability and environmental constraints". In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. IEEE. 2013, pp. 4000–4006.

[65] G Fantoni et al. "Grasping devices and methods in automated production processes". In: *CIRP Annals - Manufacturing Technology* 63 (2014), pp. 679–701.

[66] D. Feng et al. "Deep Multi-modal Object Detection and Semantic Segmentation for Autonomous Driving: Datasets, Methods, and Challenges". In: *arXiv:1902.07830*. 2019.

[67] M. Fernandez-Carmona et al. "Making the Case for Human-aware Navigation in Warehouses". In: *Towards Autonomous Robotic Systems (TAROS)*. 2019.

[68] N. Figueroa et al. "A Dynamical System Approach for Adaptive Grasping, Navigation and Co-Manipulation with Humanoid Robots". In: *2020 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE. 2020.

[69] N. M. Filatov and H. Unbehauen. "Survey of adaptive dual control methods". In: *IEE Proceedings - Control Theory and Applications* 147.1 (2000), pp. 118–128.

[70] R. Filippini et al. "Toward soft robots you can depend on". In: *IEEE Robotics Automation Magazine* 15.3 (2008), pp. 31–41.

[71] A. Fire and S.-C. Zhu. "Learning Perceptual Causality from Video". In: *ACM Trans. Intell. Syst. Technol.* 7.2 (2015).

[72] F. Flacco and A. De Luca. "A reverse priority approach to multi-task control of redundant robots". In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. IEEE. 2014, pp. 2421–2427.

[73] D. Fox et al. "The dynamic window approach to collision avoidance". In: *IEEE Robotics & Automation Magazine* 4.1 (1997), pp. 23–33.

[74] C. Gabellieri et al. "Grasp It Like a Pro: Grasp of Unknown Objects With Robotic Hands Based on Skilled Human Expertise". In: *IEEE Robotics and Automation Letters* 5.2 (2020), pp. 2808–2815.

[75] A. Gabriel and P. Baxter. "Towards Intention Recognition for Human-Interacting Agricultural Robots". In: *UK-RAS Conference*. 2020.

[76] J. D. Gammell et al. "Batch informed trees (BIT*): Sampling-based optimal planning via the heuristically guided search of implicit random geometric graphs". In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2015, pp. 3067–3074.

[77] J. D. Gammell et al. "Informed RRT*: Optimal sampling-based path planning focused via direct sampling of an admissible ellipsoidal heuristic". In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. 2014, pp. 2997–3004.

[78] M. Garabini et al. "Optimality principles in stiffness control: The VSA kick". In: *2012 IEEE International Conference on Robotics and Automation*. 2012, pp. 3341–3346.

[79] M. Garabini et al. "Optimality principles in variable stiffness control: The VSA hammer". In: *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2011, pp. 3770–3775.

[80] M. Garabini et al. "Optimality principles in variable stiffness control: The VSA hammer". In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. 2011, pp. 3770–3775.

[81] G. M. Gasparri et al. "Efficient Walking Gait Generation via Principal Component Representation of Optimal Trajectories: Application to a Planar Biped Robot With Elastic Joints". In: *IEEE Robotics and Automation Letters* 3.3 (2018), pp. 2299–2306.

[82] A. Geiger et al. "Are we ready for autonomous driving? The KITTI vision benchmark suite". In: *IEEE Conf. on Comp. Vis. and Pat. Recog. (CVPR)*. June 2012, pp. 3354–3361. DOI: 10.1109/CVPR.2012.6248074.

[83] S. Gholami Shahbandi et al. "Nonlinear Optimization of Multimodal 2D Map Alignment with Application to Prior Knowledge Transfer". In: *IEEE Robotics and Automation Letters* 3 (July 2018), pp. 2040–2047.

[84] S. Gomez-Gonzalez et al. "Real Time Trajectory Prediction Using Deep Conditional Generative Models". In: *IEEE Robotics and Automation Letters* 5.2 (2020), pp. 970–976.

[85] M. Grebenstein et al. "The DLR hand arm system". In: *2011 IEEE International Conference on Robotics and Automation*. IEEE. 2011, pp. 3175–3182.

[86] M. Grebenstein et al. "The hand of the DLR hand arm system: Designed for interaction". In: *The International Journal of Robotics Research* 31.13 (2012), pp. 1531–1555.

[87] J. Guerrero-Viu et al. "What's in my Room? Object Recognition on Indoor Panoramic Images". In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2020.

[88] V. Guizilini et al. "3D Packing for Self-Supervised Monocular Depth Estimation". In: *IEEE Conf. on Comp. Vis. and Pat. Recog. (CVPR)*. June 2020.

[89] Y. Guo et al. "Deep Learning for 3D Point Clouds: A Survey". In: *arXiv preprint arXiv:1912.12033*. 2019.

[90] A. Gupta et al. "Learning dexterous manipulation for a soft robotic hand from human demonstrations". In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. 2016, pp. 3786–3793.

[91] S. Haddadin et al. "Safety Evaluation of Physical Human-Robot Interaction via Crash-Testing." In: *Robotics: Science and Systems*. Vol. 3. Citeseer. 2007, pp. 217–224.

[92] S. Haddadin et al. "Soft-tissue injury in robotics". In: *2010 IEEE International Conference on Robotics and Automation*. IEEE. 2010, pp. 3426–3433.

[93] S. Haddadin and E. Croft. "Physical human–robot interaction". In: *Springer handbook of robotics*. Springer, 2016, pp. 1835–1874.

[94] S. Haddadin et al. "Robot collisions: A survey on detection, isolation, and identification". In: *IEEE Transactions on Robotics* 33.6 (2017), pp. 1292–1312.

[95] S. Haddadin et al. "Optimal control for exploiting the natural dynamics of variable stiffness robots". In: *2012 IEEE International Conference on Robotics and Automation*. IEEE. 2012, pp. 3347–3354.

[96] S. Haddadin et al. "Collision detection and reaction: A contribution to safe physical human-robot interaction". In: *2008 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE. 2008, pp. 3356–3363.

[97] S. Haddadin et al. "Exploiting elastic energy storage for "blind" cyclic manipulation: Modeling, stability analysis, control, and experiments for dribbling". In: *IEEE Transactions on Robotics* 34.1 (2018), pp. 91–112.

[98] S. Haddadin et al. "Intrinsically elastic robots: The key to human like performance". In: *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE. 2012, pp. 4270–4271.

[99] S. Haddadin et al. "Kick it with elasticity: Safety and performance in human–robot soccer". In: *Robotics and Autonomous Systems* 57.8 (2009), pp. 761–775.

[100] S. Haddadin et al. "On making robots understand safety: Embedding injury knowledge into control". In: *The International Journal of Robotics Research* 31.13 (2012), pp. 1578–1602.

[101] S. Haddadin et al. "Optimal control for maximizing link velocity of robotic variable stiffness joints". In: *IFAC Proceedings Volumes* 44.1 (2011), pp. 6863–6871.

[102] K. Hang et al. "Pre-grasp sliding manipulation of thin objects using soft, compliant, or underactuated hands". In: *IEEE Robotics and Automation Letters* 4.2 (2019), pp. 662–669.

[103] M. Hanheide et al. "Analysis of Human-Robot Spatial Behaviour applying a Qualitative Trajectory Calculus". In: *Proc. of the IEEE Int. Symposium on Robot and Human Interactive Communication (RO-MAN)*. 2012, pp. 689–694.

[104] M. M. Hayhoe and C. A. Rothkopf. "Vision in the natural world". In: *Wiley Interdisciplinary Reviews: Cognitive Science* 2.2 (2011), pp. 158–166. DOI: 10.1002/wcs.113.

[105] Y. He and C. Lee. "An Improved ICP Registration Algorithm by Combining PointNet++ and ICP Algorithm". In: *2020 6th International Conference on Control, Automation and Robotics (ICCAR)*. 2020, pp. 741–745.

[106] E. Heiden et al. "Experimental Comparison of Global Motion Planning Algorithms for Wheeled Mobile Robots". In: *arXiv preprint arXiv:2003.03543* (2020).

[107] L. Hewing et al. "Learning-Based Model Predictive Control: Toward Safe Learning in Control". In: *Annual Review of Control, Robotics, and Autonomous Systems* 3 ().

[108] D.-C. Hoang et al. "Panoptic 3D Mapping and Object Pose Estimation Using AdaptivelyWeighted Semantic Information". In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)* (May 2020).

[109] T. Hodaň et al. "BOP: Benchmark for 6D Object Pose Estimation". In: *European Conference on Computer Vision (ECCV)* (2018).

[110] J. Hoffman et al. "CyCADA: Cycle-Consistent Adversarial Domain Adaptation". In: *Proceedings of the 35th International Conference on Machine Learning*. Ed. by J. Dy and A. Krause. Vol. 80. Proceedings of Machine Learning Research. Stockholmsmässan, Stockholm Sweden: PMLR, July 2018, pp. 1989–1998.

[111] J Hore et al. "Braking of elbow extension in fast overarm throws made by skilled and unskilled subjects". In: *Experimental brain research* 164.3 (2005), pp. 365–375.

[112] M. B. Horowitz and J. W. Burdick. "Combined grasp and manipulation planning as a trajectory optimization problem". In: *2012 IEEE International Conference on Robotics and Automation*. 2012, pp. 584–591.

[113] R. Hou et al. "Real-Time Panoptic Segmentation from Dense Detections". In: *IEEE Conf. on Comp. Vis. and Pat. Recog. (CVPR)*. June 2020.

[114] Q. Hu et al. "RandLA-Net: Efficient Semantic Segmentation of Large-Scale Point Clouds". In: *IEEE Conf. on Comp. Vis. and Pat. Recog. (CVPR)*. June 2020.

[115] R. Hu et al. “Learning to Segment Every Thing”. In: *IEEE Conf. on Comp. Vis. and Pat. Recog. (CVPR)*. 2018, pp. 4233–4241.

[116] C.-M. Huang and B. Mutlu. “Anticipatory robot control for efficient human-robot collaboration”. In: *The Eleventh ACM/IEEE International Conference on Human Robot Interaction*. IEEE Press. 2016, pp. 83–90. DOI: 10.1109/HRI.2016.7451737.

[117] L. Huber et al. “Avoidance of convex and concave obstacles with convergence ensured through contraction”. In: *IEEE Robotics and Automation Letters* 4.2 (2019), pp. 1462–1469.

[118] L. Janson et al. “Deterministic sampling-based motion planning: Optimality, complexity, and performance”. In: *Int. Journal of Robotics Research (IJRR)* 37.1 (2018), pp. 46–61.

[119] J. Jovancevic-Misic and M. Hayhoe. “Adaptive gaze control in natural environments”. In: *The Journal of Neuroscience* 29.19 (2009), pp. 6234–6238. DOI: 10.1523/JNEUROSCI.5570-08.2009.

[120] A. Kanazawa et al. “Learning 3D Human Dynamics from Video”. In: *IEEE Conf. on Comp. Vis. and Pat. Recog. (CVPR)*. 2019.

[121] S. Karaman and E. Frazzoli. “Sampling-based optimal motion planning for non-holonomic dynamical systems”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2013, pp. 5041–5047.

[122] G. Katz et al. “A Novel Parsimonious Cause-Effect Reasoning Algorithm for Robot Imitation and Plan Recognition”. In: *IEEE Trans. on Cognitive and Developmental Systems* 10.2 (2018), pp. 177–193.

[123] S. M. Khansari-Zadeh and A. Billard. “Learning stable nonlinear dynamical systems with gaussian mixture models”. In: *IEEE Transactions on Robotics* 27.5 (2011), pp. 943–957.

[124] O. Khatib et al. “Whole-Body Dynamic Behavior and Control of Human-like Robots.” In: *International Journal of Humanoid Robotics* 10 (Mar. 2004), pp. 29–43.

[125] M. Khoramshahi and A. Billard. “A dynamical system approach to task-adaptation in physical human–robot interaction”. In: *Autonomous Robots* 43.4 (2019), pp. 927–946.

[126] S.-J. Kim et al. “An interior-point method for large-scale l1-regularized least squares”. In: *IEEE journal of selected topics in signal processing* 1.4 (2007), pp. 606–617.

[127] S. Kim et al. “Catching objects in flight”. In: *IEEE Transactions on Robotics* 30.5 (2014), pp. 1049–1065.

[128] K. Kleeberger and M. F. Huber. “Single Shot 6D Object Pose Estimation”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2020.

[129] H. S. Koppula and A. Saxena. “Anticipating Human Activities Using Object Affordances for Reactive Robotic Response”. In: *IEEE Transactions on Pattern Analysis and Machine Intelligence* 38.1 (2016), pp. 14–29.

[130] D. Kouzoupis et al. “Recent advances in quadratic programming algorithms for nonlinear model predictive control”. In: *Vietnam Journal of Mathematics* 46.4 (2018), pp. 863–882.

[131] T. Krajník et al. “FreMEn: Frequency Map Enhancement for Long-Term Mobile Robot Autonomy in Changing Environments”. In: *IEEE Transactions on Robotics* 33.4 (Aug. 2017), pp. 964–977. DOI: 10.1109/TRO.2017.2665664.

[132] H. Kretzschmar et al. “Socially compliant mobile robot navigation via inverse reinforcement learning”. In: *Int. Journal of Robotics Research (IJRR)* 35.11 (2016), pp. 1289–1307.

[133] K. Kronander et al. “Incremental motion learning with locally modulated dynamical systems”. In: *Robotics and Autonomous Systems* 70 (2015), pp. 52–62.

[134] R. Krug et al. “The next step in robot commissioning: Autonomous picking and palletizing”. In: *IEEE Robotics and Automation Letters* 1.1 (2016), pp. 546–553.

[135] T. P. Kucner et al. “Enabling flow awareness for mobile robots in partially observable environments”. In: *IEEE Robotics and Automation Letters* 2.2 (2017), pp. 1093–1100.

[136] T. P. Kucner et al. *Probabilistic Mapping of Spatial Motion Patterns for Mobile Robots*. Cognitive Systems Monographs 40. Springer International, 2020.

[137] T. P. Kucner et al. “Robust Frequency-Based Structure Extraction”. In: *arXiv:2004.08794*. 2020.

[138] J. Kuhn et al. “Towards Semi-Autonomous and Soft-Robotics Enabled Upper-Limb Exoprosthetics: First Concepts and Robot-Based Emulation Prototype”. In: *2019 International Conference on Robotics and Automation (ICRA)*. IEEE. 2019, pp. 9180–9186.

[139] W. Kuo et al. “ShapeMask: Learning to Segment Novel Objects by Refining Shape Priors”. In: *IEEE Int. Conf. on Computer Vision (ICCV)*. 2019.

[140] R. Kusumoto et al. “Informed Information Theoretic Model Predictive Control”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2019, pp. 2047–2053.

[141] A. Kuznetsova et al. “The Open Images Dataset V4: Unified image classification, object detection, and visual relationship detection at scale”. In: *International Journal of Computer Vision* (2020).

[142] A. H. Lang et al. “PointPillars: Fast Encoders for Object Detection from Point Clouds”. In: *IEEE Conf. on Comp. Vis. and Pat. Recog. (CVPR)*. 2019.

[143] L. Leal-Taixé et al. *Tracking the Trackers: An Analysis of the State of the Art in Multiple Object Tracking*. arXiv: 1704.02781v1 [cs.CV].

[144] S. Li and X. Zhang. “Implicit Intention Communication in Human–Robot Interaction Through Visual Behavior Studies”. In: *IEEE Transactions on Human-Machine Systems* 47.4 (2017), pp. 437–448. DOI: 10.1109/THMS.2017.2647882.

[145] S. Li et al. “Attention-aware robotic laparoscope based on fuzzy interpretation of eye-gaze patterns”. In: *Journal of Medical Devices* 9.4 (2015), p. 041007. DOI: 10.1115/1.4030608.

[146] X. Li et al. “Putting humans in a scene: Learning affordance in 3D indoor environments”. In: *IEEE Conf. on Comp. Vis. and Pat. Recog. (CVPR)*. IEEE Computer Society, June 2019, pp. 12360–12368. DOI: 10.1109/CVPR.2019.01265.

[147] Y. Li et al. “Visual Grounding of Learned Physical Models”. In: *arXiv preprint arXiv:2004.13664* (2020).

[148] T.-Y. Lin et al. “Microsoft COCO: Common Objects in Context”. In: *Eur. Conf. on Computer Vision (ECCV)*. 2014, pp. 740–755.

[149] T. Linder et al. “Accurate Detection and 3D Localization of Humans Using a Novel YOLO-Based RGB-D Fusion Approach and Synthetic Training Data”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2020.

[150] T. Linder et al. “On Multi-Modal People Tracking from Mobile Platforms in Very Crowded and Dynamic Environments”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2016, pp. 5512–5519.

[151] T. Linder et al. “Towards Training Person Detectors for Mobile Robots using Synthetically Generated RGB-D Data”. In: *Computer Vision and Pattern Recognition (CVPR) Workshop on 3D Scene Generation*. 2019.

[152] K. Liu et al. “Learned Sampling Distributions for Efficient Planning in Hybrid Geometric and Object-Level Representations”. In: (2020).

[153] L. Liu et al. “Deep Learning for Generic Object Detection: A Survey”. In: *International Journal of Computer Vision* 128 (2019), pp. 261 –318.

[154] S. Liu and D. Sun. “Minimizing Energy Consumption of Wheeled Mobile Robots via Optimal Motion Planning”. In: *IEEE/ASME Transactions on Mechatronics* 19.2 (2014), pp. 401–411.

[155] F. Lombai and G. Szederkényi. “Throwing motion generation using nonlinear optimization on a 6-degree-of-freedom robot manipulator”. In: *2009 IEEE International Conference on Mechatronics*. IEEE. 2009, pp. 1–6.

[156] M. Lombardi et al. “Robust scheduling of task graphs under execution time uncertainty”. In: *IEEE transactions on computers* 62.1 (2011), pp. 98–111.

[157] C. Loughlin et al. “The DLR lightweight robot: design and control concepts for robots in human environments”. In: *Industrial Robot: an international journal* (2007).

[158] L. Lukic et al. “Learning coupled dynamical systems from human demonstration for robotic eye-arm-hand coordination”. In: *2012 12th IEEE-RAS International Conference on Humanoid Robots (Humanoids 2012)*. 2012, pp. 552–559.

[159] M. Luperto et al. “Exploiting Inaccurate A Priori Knowledge in Robot Exploration”. In: *Proceedings of the 18th International Conference on Autonomous Agents and MultiAgent Systems*. AAMAS ’19. Montreal QC, Canada: International Foundation for Autonomous Agents and Multiagent Systems, 2019, 2102—2104.

[160] M. Magnusson et al. “Scan Registration for Autonomous Mining Vehicles Using 3D-NDT”. In: *Journal of Field Robotics* 24.10 (Oct. 2007), pp. 803–827.

[161] M. Magnusson et al. “Beyond Points: Evaluating Recent 3D Scan-Matching Algorithms”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2015, pp. 3631–3637.

[162] A. Makadia et al. “Fully Automatic Registration of 3D Point Clouds”. In: *IEEE Conf. on Comp. Vis. and Pat. Recog. (CVPR)*. Vol. 1. June 2006, pp. 1297–1304. DOI: 10.1109/CVPR.2006.122.

[163] S. Manivasagam et al. “LiDARsim: Realistic LiDAR Simulation by Leveraging the Real World”. In: *IEEE Conf. on Comp. Vis. and Pat. Recog. (CVPR)*. 2020.

[164] Manolis Savva* et al. “Habitat: A Platform for Embodied AI Research”. In: *IEEE Int. Conf. on Computer Vision (ICCV)*. 2019.

[165] N. Mansfeld et al. “Safety Map: A Unified Representation for Biomechanics Impact Data and Robot Instantaneous Dynamic Properties”. In: *IEEE Robotics and Automation Letters* 3.3 (2018), pp. 1880–1887.

[166] N. Mansfeld et al. “Improving the performance of biomechanically safe velocity control for redundant robots through reflected mass minimization”. In: *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE. 2017, pp. 5390–5397.

[167] N. Mansfeld et al. “Safety map: A unified representation for biomechanics impact data and robot instantaneous dynamic properties”. In: *IEEE Robotics and Automation Letters* 3.3 (2018), pp. 1880–1887.

[168] R. Martín-Martín et al. *JRDB: A Dataset and Benchmark for Visual Perception for Navigation in Human Environments*. 2019. arXiv: 1910.11792 [cs.CV].

[169] N. Mavridis et al. “QTC3D: Extending the Qualitative Trajectory Calculus to Three Dimensions”. In: *Information Sciences* 322 (2015), pp. 20–30.

[170] Y. Mei et al. “Energy-efficient mobile robot exploration”. In: *Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006*. IEEE. 2006, pp. 505–511.

[171] D. Meike et al. “Increasing the energy efficiency of multi-robot production lines in the automotive industry”. In: *2012 IEEE International Conference on Automation Science and Engineering (CASE)*. IEEE. 2012, pp. 700–705.

[172] M. Mielle et al. “The Auto-Complete Graph: Merging and Mutual Correction of Sensor and Prior Maps for SLAM”. In: *Robotics* 8.2 (2019). DOI: 10.3390/robotics8020040.

[173] M. Mielle et al. “URSIM: Unique Regions for Sketch map Interpretation and Matching”. In: *Robotics* 8.2 (2019). DOI: 10.3390/robotics8020043.

[174] J. Minguez and L. Montano. “Nearness diagram navigation (nd): A new real time collision avoidance approach”. In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. Vol. 3. 2000, pp. 2094–2100.

[175] S. Mirrazavi et al. “A unified framework for coordinated multi-arm motion planning”. In: *The International Journal of Robotics Research* 37.10 (2018), pp. 1205–1232.

[176] A. Mohamed et al. “Social-STGCNN: A Social Spatio-Temporal Graph Convolutional Neural Network for Human Trajectory Prediction”. In: *arXiv preprint arXiv:2002.11927* (2020).

[177] S. Molina et al. “Modelling and Predicting Rhythmic Flow Patterns in Dynamic Environments”. In: *Towards Autonomous Robotic Systems*. Ed. by M. Giuliani et al. Cham: Springer International Publishing, 2018, pp. 135–146.

[178] I. Mordatch et al. “Interactive Control of Diverse Complex Characters with Neural Networks”. In: *Advances in Neural Information Processing Systems 28*. Ed. by C. Cortes et al. 2015, pp. 3132–3140.

[179] R. Mur-Artal and J. D. Tardós. “ORB-SLAM2: an Open-Source SLAM System for Monocular, Stereo and RGB-D Cameras”. In: *IEEE Transactions on Robotics* 33.5 (2017), pp. 1255–1262. DOI: 10.1109/TRO.2017.2705103.

[180] T. Nishimura et al. “Thin plate manipulation by an under-actuated robotic soft gripper utilizing the environment”. In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. 2017, pp. 1236–1243.

[181] *NVIDIA Isaac SDK and Simulator*. https://developer.nvidia.com/isaac-sdk. 2019.

[182] A. Ošep et al. “4D Generic Video Object Proposals”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2020.

[183] A. Palleschi et al. “Time-Optimal Path Tracking for Jerk Controlled Robots”. In: *IEEE Robotics and Automation Letters* 4.4 (2019), pp. 3932–3939.

[184] A. Palleschi et al. “Time-Optimal Trajectory Planning for Flexible Joint Robots”. In: *IEEE Robotics and Automation Letters* 5.2 (2020), pp. 938–945.

[185] L. Palmieri et al. “RRT-based nonholonomic motion planning using any-angle path biasing”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2016, pp. 2775–2781.

[186] L. Palmieri et al. “Dispertio: Optimal Sampling For Safe Deterministic Motion Planning”. In: *IEEE Robotics and Automation Letters* 5.2 (2019), pp. 362–368.

[187] L. Palmieri et al. “Kinodynamic motion planning on Gaussian mixture fields”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2017, pp. 6176–6181.

[188] J.-J. Park et al. “Safe robot arm with safe joint mechanism using nonlinear spring system for collision safety”. In: *2009 IEEE International Conference on Robotics and Automation*. IEEE. 2009, pp. 3371–3376.

[189] M. Parsley and S. Julier. “Exploiting prior information in GraphSLAM”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2011, pp. 2638–2643.

[190] A. E. Patla and J. N. Vickers. “How far ahead do we look when required to step on specific locations in the travel path during locomotion?” In: *Experimental brain research* 148.1 (2003), pp. 133–138. DOI: 10.1007/s00221-002-1246-y.

[191] A. E. Patla and J. N. Vickers. “Where and when do we look as we approach and step over an obstacle in the travel path?” In: *Neuroreport* 8.17 (1997), pp. 3661–3665. DOI: 10.1097/00001756-199712010-00002.

[192] D. Pavllo et al. “3D Human Pose Estimation in Video With Temporal Convolutions and Semi-Supervised Training”. In: *IEEE Conf. on Comp. Vis. and Pat. Recog. (CVPR)*. June 2019.

[193] J. Pearl and D.Mackenzie. *The Book of Why*. Penguin Books, 2019.

[194] J. Pearl et al. *Causal Inference in Statistics – A Primer*. Wiley, 2016.

[195] A. Pekarovskiy and M. Buss. “Optimal control goal manifolds for planar nonprehensile throwing”. In: *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE. 2013, pp. 4518–4524.

[196] X. Peng et al. “Terrain-adaptive locomotion skills using deep reinforcement learning”. In: *ACM Transactions on Graphics* 35 (July 2016), pp. 1–12. DOI: 10.1145/2897824.2925881.

[197] J. Peters et al. *Elements of Causal Inference*. The MIT Press, 2017.

[198] M. Pfeiffer et al. “Predicting actions to act predictably: Cooperative partial motion planning with maximum entropy models”. In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. 2016, pp. 2096–2101.

[199] R. Philippsen and R. Siegwart. “Smooth and efficient obstacle avoidance for a tour guide robot”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. Vol. 1. 2003, pp. 446–451.

[200] C. Piazza et al. “A Century of Robotic Hands”. In: *Annual Review of Control, Robotics, and Autonomous Systems* 2.1 (2019), pp. 1–32.

[201] S. Pirk et al. “Online Learning of Object Representations by Appearance Space Feature Alignment”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2020.

[202] A. Ponsich et al. “A Survey on Multiobjective Evolutionary Algorithms for the Solution of the Portfolio Optimization Problem and Other Finance and Economics Applications”. In: *IEEE Transactions on Evolutionary Computation* 17.3 (2013), pp. 321–344.

[203] C. R. Qi et al. “Frustum PointNets for 3D Object Detection from RGB-D Data”. In: *IEEE Conf. on Comp. Vis. and Pat. Recog. (CVPR)*. 2018.

[204] S. Quinlan and O. Khatib. “Elastic bands: Connecting path planning and control”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 1993, pp. 802–807.

[205] H. Ravichandar et al. “Recent Advances in Robot Learning from Demonstration”. In: *Annual Review of Control, Robotics, and Autonomous Systems* 3 ().

[206] S. Riazi et al. “Energy optimization of multi-robot systems”. In: *2015 IEEE International Conference on Automation Science and Engineering (CASE)*. 2015, pp. 1345–1350.

[207] J. Rios-Martinez et al. “Understanding human interaction for probabilistic autonomous navigation using Risk-RRT approach”. In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. 2011, pp. 2014–2019.

[208] A. Robicquet et al. “Learning social etiquette: Human trajectory understanding in crowded scenes”. In: *European conference on computer vision*. Springer. 2016, pp. 549–565.

[209] A. Rosinol et al. “3D Dynamic Scene Graphs: Actionable Spatial Perception with Places, Objects, and Humans”. In: *Robotics: Science and Systems (RSS)*. 2020.

[210] C. Rösmann et al. “Integrated online trajectory planning and optimization in distinctive topologies”. In: *Robotics and Autonomous Systems* 88 (2017), pp. 142–153.

[211] A. Rudenko et al. “Joint long-term prediction of human motion using a planning-based social force approach”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2018, pp. 1–7.

[212] A. Rudenko et al. “Human motion prediction under social grouping constraints”. In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. IEEE. 2018, pp. 3358–3364.

[213] A. Rudenko et al. “Human motion trajectory prediction: A survey”. In: *Int. Journal of Robotics Research (IJRR)* (2020).

[214] M. Rufli et al. “Reciprocal collision avoidance with motion continuity constraints”. In: *IEEE Transactions on Robotics* 29.4 (2013), pp. 899–912.

[215] J. Saarinen et al. “Normal distributions transform Monte-Carlo localization (NDT-MCL)”. In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. 2013, pp. 382–389.

[216] S. S. Sajjan et al. “ClearGrasp: 3D Shape Estimation of Transparent Objects for Manipulation”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2020.

[217] S. S. M. Salehian et al. “A Dynamical System Approach for Softly Catching a Flying Object: Theory and Experiment”. In: *IEEE Transactions on Robotics* 32.2 (2016), pp. 462–471.

[218] S. S. M. Salehian et al. “Coordinated multi-arm motion planning: Reaching for moving objects in the face of uncertainty”. In: *Robotics: Science and Systems (RSS)*. June 2016.

[219] A. Sanchez-Gonzalez et al. “Learning to simulate complex physics with graph networks”. In: *arXiv:2002.09405* (2020).

[220] C. D. Santina et al. “Learning From Humans How to Grasp: A Data-Driven Architecture for Autonomous Grasping With Anthropomorphic Soft Hands”. In: *IEEE Robotics and Automation Letters* 4.2 (2019), pp. 1533–1540.

[221] I. Sárándi et al. “Synthetic Occlusion Augmentation with Volumetric Heatmaps for the 2018 ECCV PoseTrack Challenge on 3D Human Pose Estimation”. In: *European Conference on Computer Vision Workshops (ECCVW)*. 2018. Winner of ECCV 2018 PoseTrack 3D Challenge.

[222] I. Sárándi et al. “Metric-Scale Truncation-Robust Heatmaps for 3D Human Pose Estimation”. In: *IEEE Int. Conf. on Automatic Face and Gesture Recognition*. 2020.

[223] Schmalz. *Vacuum gripping systems*. URL: http://us.schmalz.com/produkte/vakuumgreifsysteme/.

[224] E. Schmerling et al. “Optimal sampling-based motion planning under differential constraints: the driftless case”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2015, pp. 2368–2375.

[225] T. Schoels et al. “An NMPC Approach using Convex Inner Approximations for Online Motion Planning with Guaranteed Collision Freedom”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2020.

[226] S. Schwertfeger and A. Birk. “A short overview of recent advances in map evaluation”. In: *IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*. 2012, pp. 1–2.

[227] L. Sentis and O. Khatib. “Synthesis of whole-body behaviors through hierarchical control of behavioral primitives”. In: *International Journal of Humanoid Robotics* (2005), pp. 505–518.

[228] S. Seok et al. “Design principles for energy-efficient legged locomotion and implementation on the MIT cheetah robot”. In: *Ieee/asme transactions on mechatronics* 20.3 (2015), pp. 1117–1129.

[229] A. Settimi et al. “Motion primitive based random planning for loco-manipulation tasks”. In: *IEEE/RAS International Conference on Humanoid Robots (Humanoids)*. 2016, pp. 1059–1066.

[230] A. Shukla and A. Billard. “Coupled dynamical system based arm–hand grasping model for learning fast adaptation strategies”. In: *Robotics and Autonomous Systems* 60.3 (2012), pp. 424–440.

[231] L. Silva et al. “Precision Range Image Registration Using a Robust Surface Interpenetration Measure and Enhanced Genetic Algorithms”. In: *IEEE Transactions on Pattern Analysis and Machine Intelligence* 27.5 (May 2005), pp. 762–776.

[232] A. Sintov et al. “Learning a State Transition Model of an Underactuated Adaptive Hand”. In: *IEEE Robotics and Automation Letters* 4.2 (2019), pp. 1287–1294.

[233] *Social Signal Processing*. Cambridge University Press, 2017. DOI: 10.1017/9781316676202.

[234] S. Song et al. “SUN RGB-D: A RGB-D Scene Understanding Benchmark Suite”. In: *IEEE Conf. on Comp. Vis. and Pat. Recog. (CVPR)*. 2015.

[235] T. Stoyanov et al. “No More Heavy Lifting: Robotic Solutions to the Container Unloading Problem”. In: *IEEE Robotics Automation Magazine* 23.4 (2016), pp. 94–106.

[236] T. Stoyanov et al. “Fast and Accurate Scan Registration through Minimization of the Distance between Compact 3D NDT Representations”. In: *Int. Journal of Robotics Research (IJRR)* 31.12 (12 2012), pp. 1377–1393. DOI: 10.1177/0278364912460895.

[237] T. Stoyanov et al. “Grasp envelopes: Extracting constraints on gripper postures from online reconstructed 3d models”. In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. IEEE. 2016, pp. 885–892.

[238] T. Stoyanov et al. “Normal Distributions Transform Occupancy Map fusion: Simultaneous mapping and tracking in large scale dynamic environments”. In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. 2013, pp. 4702–4708. DOI: 10.1109/IROS.2013.6697033.

[239] Y. Su and K. Grauman. “Kernel Transformer Networks for Compact Spherical Convolution”. In: *IEEE Conf. on Comp. Vis. and Pat. Recog. (CVPR)*. 2019, pp. 9442–9451. DOI: 10.1109/CVPR.2019.00967.

[240] L. Sun et al. “3DOF Pedestrian Trajectory Prediction Learned from Long-Term Autonomous Mobile Robot Deployment Data”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2018, pp. 5942–5948.

[241] X. Sun et al. “Explicit Spatiotemporal Joint Relation Learning for Tracking Human Pose”. In: *IEEE/CVF International Conference on Computer Vision Workshops*. IEEE, 2019, pp. 2825–2835.

[242] M. Sundermeyer et al. “Multi-path Learning for Object Pose Estimation Across Domains”. In: *IEEE Conf. on Comp. Vis. and Pat. Recog. (CVPR)*. 2020.

[243] C. S. Swaminathan et al. “Down The CLiFF: Flow-aware Trajectory Planning under Motion Pattern Uncertainty”. In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. 2018, pp. 7403–7409.

[244] J. Tang et al. “GCNv2: Efficient Correspondence Prediction for Real-Time SLAM”. In: *IEEE Robotics and Automation Letters* 4.4 (2019), pp. 3505–3512.

[245] T. Y. Tang et al. “RSL-Net: Localising in Satellite Images From a Radar on the Ground”. In: *IEEE Robotics and Automation Letters* 5.2 (2020), pp. 1087–1094.

[246] B. W. Tatler et al. “Eye guidance in natural vision: Reinterpreting salience”. In: *Journal of vision* 11.5 (2011), pp. 5–5. DOI: 10.1167/11.5.5.

[247] R. Thandiackal et al. “Exploiting passive dynamics for robot throwing task”. In: *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE. 2012, pp. 2443–2448.

[248] Z. Tian et al. “FCOS: Fully Convolutional One-Stage Object Detection”. In: *IEEE Int. Conf. on Computer Vision (ICCV)*. 2019.

[249] A. Tödtheide et al. “Antagonistic impedance control for pneumatically actuated robot joints”. In: *IEEE Robotics and Automation Letters* 1.1 (2015), pp. 161–168.

[250] G. Tonietti et al. “Optimal Mechanical/Control Design for Safe and Fast Robotics”. In: *Experimental Robotics IX*. Ed. by M. H. Ang and O. Khatib. Berlin, Heidelberg: Springer Berlin Heidelberg, 2006, pp. 311–320.

[251] P. Trautman and A. Krause. “Unfreezing the robot: Navigation in dense, interacting crowds”. In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. 2010, pp. 797–803.

[252] N. Vahrenkamp et al. “Simultaneous Grasp and Motion Planning: Humanoid Robot ARMAR-III”. In: *IEEE Robotics Automation Magazine* 19.2 (2012), pp. 43–57.

[253] N. Van de Weghe. “Representing and Reasoning about Moving Objects: A Qualitative Approach”. PhD thesis. Ghent University, 2004.

[254] B. Vanderborght et al. “Variable impedance actuators: A review”. In: *Robotics and autonomous systems* 61.12 (2013), pp. 1601–1614.

[255] B. Vanderborght et al. “Variable impedance actuators: moving the robots of tomorrow (Video)”. In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. 2012.

[256] A. Velasco et al. “Soft actuation in cyclic motions: Stiffness profile optimization for energy efficiency”. In: *2015 IEEE-RAS 15th International Conference on Humanoid Robots (Humanoids)*. 2015, pp. 107–113.

[257] A. Velasco et al. “Soft-actuators in cyclic motion: Analytical optimization of stiffness and pre-load”. In: *2013 13th IEEE-RAS International Conference on Humanoid Robots (Humanoids)*. 2013, pp. 354–361.

[258] O. Vysotska and C. Stachniss. “Improving SLAM by Exploiting Building Information from Publicly Available Maps and Localization Priors”. In: *PFG – Journal of Photogrammetry, Remote Sensing and Geoinformation Science* (2017).

[259] D. Wang et al. “3D Object Detection Algorithm for Panoramic Images With Multi-Scale Convolutional Neural Network”. In: *IEEE Access* 7 (2019), pp. 171461–171470.

[260] Z. Wang et al. *Geometric Pose Affordance: 3D Human Pose with Scene Constraints*. 2019. arXiv: 1905.07718 [cs.CV].

[261] B. Wen et al. “Robust, Occlusion-aware Pose Estimation for Objects Grasped by Adaptive Hands”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2020.

[262] G. Williams et al. “Information theoretic MPC for model-based reinforcement learning”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2017, pp. 1714–1721.

[263] Z. Wu et al. “A Comprehensive Survey on Graph Neural Networks”. In: *arXiv:1901.00596*. 2019.

[264] B. Xu et al. “Interact as You Intend: Intention-Driven Human-Object Interaction Detection”. In: *IEEE Transactions on Multimedia* 22.6 (2020), pp. 1423–1432.

[265] S. Yan et al. “Spatial temporal graph convolutional networks for skeleton-based action recognition”. In: *Proc. of the AAAI Conf. on Artificial Intelligence*. 2018.

[266] Y. Yan et al. “SECOND: Sparsely Embedded Convolutional Detection”. In: *Sensors* 18.10 (2018).

[267] Z. Yan et al. “Online Learning for 3D LiDAR-based Human Detection: Experimental Analysis of Point Cloud Clustering and Classification Methods”. In: *Autonomous Robots* 44 (2020).

[268] Z. Yan et al. “Online Learning for Human Classification in 3D LiDAR-based Tracking”. In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. 2017.

[269] Z. Yan et al. “Multisensor Online Transfer Learning for 3D LiDAR-based Human Detection with a Mobile Robot”. In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. Oct. 2018.

[270] A. Yershova and S. M. LaValle. “Deterministic sampling methods for spheres and SO (3)”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. Vol. 4. 2004, pp. 3974–3980.

[271] A. Zaganidis et al. “Integrating Deep Semantic Segmentation Into 3-D Point Cloud Registration”. In: *IEEE Robotics and Automation Letters* 3.4 (Oct. 2018), pp. 2942–2949.

[272] A. Zaganidis et al. “Semantic-assisted 3D Normal Distributions Transform for scan registration in environments with limited structure”. In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. Sept. 2017, pp. 4064–4069.

[273] A. Zaganidis et al. “Semantically Assisted Loop Closure in SLAM Using NDT Histograms”. In: *IEEE Int. Conf. on Intell. Rob. and Systems (IROS)*. 2019.

[274] A. Zeng et al. “Robotic pick-and-place of novel objects in clutter with multi-affordance grasping and cross-domain image matching”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. IEEE. 2018.

[275] A. Zeng et al. “TossingBot: Learning to Throw Arbitrary Objects with Residual Physics”. In: *Robotics: Science and Systems (RSS)*. 2019.

[276] J. Zhang and S. Singh. “Visual-lidar odometry and mapping: low-drift, robust, and fast”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2015, pp. 2174–2181.

[277] J. Zhang and S. Singh. “LOAM: Lidar Odometry and Mapping in Real-time”. In: *Robotics: Science and Systems (RSS)*. Berkeley, USA, July 2014. DOI: 10.15607/RSS.2014.X.007.

[278] Y. Zhang et al. “Sampling-based motion planning with dynamic intermediate state objectives: Application to throwing”. In: *2012 IEEE International Conference on Robotics and Automation*. IEEE. 2012, pp. 2551–2556.

[279] X. Zhou et al. “Objects as Points”. In: *arXiv:1904.07850*. 2019.

[280] C. Zimmermann et al. “3D Human Pose Estimation in RGBD Images for Robotic Task Learning”. In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2018.

[281] Z. Zou et al. “Object Detection in 20 Years: A Survey”. In: *arXiv:1905.05055*. 2019.

[282] A. Zunino et al. “Predicting Human Intentions from Motion Cues Only: A 2D+3D Fusion Approach”. In: *Proc. ACM Int. Conf. on Multimedia*. ACM, 2017, 591–599.

4 Members of the Consortium

4.1 Participants

4.1.1 ORU

The DARKO project will be carried out at the Centre for Applied Autonomous Sensor Systems (AASS) at Örebro University (ORU). The coordinator, Professor Achim J. Lilienthal, will have the full support of central resources of Örebro University in running this project.

AASS organises research and graduate studies in Autonomous Systems at Örebro University and is one of the appointed research environments of the Swedish Knowledge Foundation (KKS). The AASS centre currently has around 70 senior researchers and PhD students as well as several visiting researchers and associated PhD students from other Swedish universities. Due to the prominence of AASS in the AI and Robotics landscape, Örebro University has been included in the prestigious privately funded WASP-AI programme, which is Sweden's largest individual research programme. The university has been involved in many FP7 and H2020 projects. Of particular interest here are the previous H2020 ICT projects ILIAD and SmokeBot, both of which were coordinated by Achim J. Lilienthal.

The university Grants Office has considerable additional experience of involvement as a coordinator of Framework Programme projects and can thus provide invaluable advice. The central finance department is experienced in the financial reporting of EU projects and can lend necessary support to AASS. Further, the university has offices to support innovation and exploitation, including the Alfred Nobel Science Park and Inkubera company incubator, as well as a holding company for assisting exploitation opportunities. ORU also leads an "AI Impact Lab" that is connected to the "AI Innovation of Sweden" hub (http://ai.se). These services will provide advice and action regarding the potential exploitation research findings, and will ensure that research findings are handled in the optimal way.

The research effort at the AASS Mobile Robotics & Olfaction Lab has a pronounced interdisciplinary character. Research topics are characterised by a need for learning and fusion of information from different sensor modalities. Major themes are 3D perception, navigation, human-robot interaction, mobile robot olfaction, and lifelong learning by autonomous systems, demonstrated through long-term experiments in robot-environment interaction, and aiming to establish the necessary representations and algorithms for continuous operation of autonomous systems in a dynamic environment.

Role in the project The researchers involved in DARKO from the AASS Mobile Robotics & Olfaction Lab have substantial expertise and track record in efficient mapping and localisation in large-scale environments, rich 3D perception, and are leaders in the emerging field of maps of dynamics. As coordinator of the project ORU will naturally be involved in the management and dissemination work packages (WP9, WP10). ORU are leading WP3 (Mapping and Localization) and are substantially involved in WP2 (especially, perception for manipulation), WP6 (especially, planning on maps of dynamics), WP7 (providing reference-free estimates of map and localisation accuracy for better risk assessment), as well as spatially augmented reality for communication of robot intents in WP5. ORU will also substantially contribute to WP8 (Requirements and Evaluation), leveraging previous experience from previous and ongoing international and national projects.

Key people involved

Achim J. Lilienthal[26] (male) is full professor of Computer Science at Örebro University where he leads the AASS Mobile Robotics & Olfaction (MRO) lab. His research interests concern perception systems in unconstrained, dynamic environments. Typically based on approaches that leverage domain knowledge and Artificial Intelligence, his research work addresses rich 3D perception, autonomous navigation, human robot interaction (with a strong view on professional service robots in logistics applications), mobile robot olfaction (with applications in inspection robots), and mathematics education research. Achim J. Lilienthal is a senior member of IEEE and has co-authored over 250 refereed conference papers and journal articles[27] ($h = 46$ on Google Scholar). Achim J. Lilienthal has participated in 6 EU projects and many national projects. He is currently coordinating the H2020 project ILIAD[28] and also coordinated the H2020 project SmokeBot[29]. He has been responsible as principal investigator (PI) for the EU projects SPENCER (STREP, FP7[30]), RobLog (IP, FP7[31]), Diadem (STREP, FP7[32]), and DustBot (STREP, FP6[33]). Achim J. Lilienthal will be the coordinator of DARKO.

[26] http://mrolab.eu/amll
[27] https://scholar.google.com/citations?hl=en&user=_CdZ5cgAAAAJ
[28] H2020-732737, from Jan 1, 2017 - Dec 31, 2020
[29] H2020-645101, from Jan 1, 2015 - Jun 30, 2018
[30] FP7-600877, from Apr 1, 2013 to Mar 31, 2016.
[31] FP7-270350, from Feb 1, 2011 to Jan 31, 2015.
[32] FP7-224318, from Sep 1, 2008 to Nov 30, 2011.
[33] FP6-045299, from Nov 1, 2006 to Jan 11, 2010.

Martin Magnusson[34] (male) is a associate professor (docent) at the MRO lab of AASS. He received his Master's degree in computer science from Uppsala University in 2004 and his Ph.D. degree from Örebro University in 2009. His main research area is maps for mobile robots, including 3D mapping and localisation, as well as heterogeneous map merging, constructing and using maps of dynamics, and map quality estimation. He is currently Scientific Manager of the ILIAD project and PI of the FIREM-II project. He also serves as deputy coordinator of the euRobotics Topic Group on Logistics and Transport, and is heavily involved in the IEEE working group for standardised robot map representations in 2D and 3D. Key contributions are the 3D-NDT representation for accurate and memory-efficient mapping and localisation as well as more recent work on learning motion patterns in dynamic environments and efficient handling of piled materials. He currently has 1872 citations and h-index 17 on Google Scholar. Within DARKO, he will contribute to the scientific management and WP3.

Tomasz Piotr Kucner[35] (male) is a postdoctoral researcher at the MRO lab of AASS. He received his B.Sc. in Computer Management Systems in Manufacturing (2011) and M.Sc. in Robotics (2012) at Wrocław University of Technology. In 2018, he received a Ph.D. degree from Örebro University. He is currently involved in the EU H2020 research project ILIAD, where he is working with methods for automatic map quality assessment and building spatio-temporal models of dynamics. He is also a vice-chair of IEEE working group for standardised robot map representations in 3D. Key contributions are CLiFF-map representation for representing motion patterns as flow maps and also his more current work on referecne free map qaulity assessment. He currently has 305 and h-index 7 on Google Scholar. Within DARKO, he will contribute to WP3 and WP8.

Todor Stoyanov[36] (male) is associate professor (docent) with the AASS research center where he leads the Autonomous Mobile Manipulation lab. Todor received a Ph.D. degree in computer science from Örebro University, Örebro, Sweden, in 2012. His main interests include perception and motion generation for mobile manipulation. Major contributions over the past five years include: map building and range data fusion in the context of NDT-OM and SDF maps, grasp planning and grasp execution control in the context of the EU FP7 IP project RobLog, as well as learning for manipulation control. Todor Stoyanov is currently the PI for two national projects, a Vinnova project within deep learning for articulated object tracking, and a WASP-AI project within reinforcement learning for manipulation. He has coauthored 16 journal and 38 peer reviewed conference articles and holds a Google scholar h-index of 21. Todor Stoyanov will be involved in DARKO in particular with respect perception for manipulation in WP2.

Key relevant publications

1. T. P. Kucner et al. *Probabilistic Mapping of Spatial Motion Patterns for Mobile Robots*. Cognitive Systems Monographs 40. Springer International, 2020.

2. M. Magnusson, A. J. Lilienthal, and T. Duckett. "Scan Registration for Autonomous Mining Vehicles Using 3D-NDT". in: *Journal of Field Robotics* 24.10 (Oct. 2007), pp. 803–827.

3. D.-C. Hoang, A. J. Lilienthal, and T. Stoyanov. "Panoptic 3D Mapping and Object Pose Estimation Using AdaptivelyWeighted Semantic Information". In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)* (May 2020).

4. M. Mielle, M. Magnusson, and A. J. Lilienthal. "The Auto-Complete Graph: Merging and Mutual Correction of Sensor and Prior Maps for SLAM". in: *Robotics* 8.2 (2019). DOI: 10.3390/robotics8020040.

5. R. T. Chadalavada et al. "Bi-directional navigation intent communication using spatial augmented reality and eye-tracking glasses for improved safety in human–robot interaction". In: *Robotics and Computer-Integrated Manufacturing* 61 (2020), p. 101830.

Related projects

ILIAD (H2020-732737; Jan 2017 – Dec 2020) The focus of ILIAD (Intra-Logistics with Integrated Automatic Deployment: safe and scalable fleets in shared spaces) is to enable the transition to automation of intralogistics services, particularly focusing on the food distribution sector. The project aims at overcoming limitations in the state of the art in tracking and analysing humans; quantifying map quality and predicting future states depending on activity patterns inferred from long-term observations; planning of socially normative movements using learned human models; integration of task allocation, coordination and motion planning for heterogeneous robot fleets; and systematically studying human safety in mixed environments, providing a foundation

[34] http://mrolab.eu/mnmn
[35] https://mro.oru.se/people/tomasz-kucner/
[36] https://amm.aass.oru.se/people/todor-stoyanov/

for future safety standards. ORU coordinates the ILIAD project and leads the work on mapping & localisation and fleet management, also contributing to long-term learning of flow-aware maps, object perception, and robot intent communication.

SmokeBot (H2020, Jan 2015 – June 2018) SmokeBot was driven by the application needs for robots that operate in domains with restricted visibility. The focus was on civil robots supporting fire brigades in search and rescue missions, e.g. in post-disaster management operations in response to tunnel fires. Existing sensor technology and the related cognitive approaches cannot cope with such demanding conditions. SmokeBot worked to address this shortcoming, delivering software and hardware components which facilitate robot systems to perform under harsh conditions of smoke, dust or fog. ORU coordinated this project.

Semantic Robots (KKS 2014, Sep 2014 – Aug 2020) Building upon previous experience in EU-funded research projects and other KKS-funded initiatives, this six-year profile targets a unified development of "Semantic Robots", i.e., robots that can reason about rich symbolic and metric models of their environment and capabilities to automatically derive and execute action plans that achieve given goals. The profile is heavily co-funded by industrial partners Epiroc, CNet, Hothouse Studios, Husqvarna, Kollmorgen, Optronic, SAAB Dynamics and Volvo CE. More information can be found at semanticrobots.oru.se.

SPENCER (FP7-600877, Apr 2013 – Mar 2016) "Social situation-aware perception and action for cognitive robots" (SPENCER) dealt with cognitive systems in populated environments by addressing basic problems in making robots more socially aware. Research in SPENCER broke new ground for cognitive systems in populated environments covering key areas of interactive intelligent systems such as perception of people and groups of people in sensory data, normative human behaviour learning and modelling, socially-aware mapping, and socially-aware task, motion and interaction planning in unstructured real-world environments and from mobile platforms. In a final demonstration scenario, SPENCER has very successfully deployed a fully autonomous mobile robot for smart passengers flow management at the Amsterdam Schiphol Airport in March 2016.

AIR (KKS 2014/0220, Apr 1, 2015 – Mar 31, 2019) AIR was a distributed research environment[37] on Action and Intention Recognition in human interaction with autonomous systems. The project investigated the role of mutual action and intention recognition for safety and public acceptance of autonomous systems. ORU's contribution was particularly to investigate human interaction with autonomous transport vehicles in industrial environments. The goal has been to make operation of autonomous transport vehicles unobtrusive and transparent to the humans interacting with them, and to develop cognitive abilities for autonomous systems that allow humans to intuitively and effortlessly communicate their intentions and desired actions.

4.1.2 TUM

The Technical University of Munich (TUM) is one of Europe's top universities. It is committed to excellence in research and teaching, interdisciplinary education and the active promotion of promising young scientists. The university also forges strong links with companies and scientific institutions across the world. TUM was one of the first universities in Germany to be named a University of Excellence and regularly ranks among the best European universities in international rankings. TUM promotes both basic research, aimed at furthering scientific knowledge and insights in general, and applied research, focused on concrete solutions to defined problems. These mutually complementary research strands both shape the transfer of knowledge and technology to society through collaboration with industry partners. Every year, TUM signs more than 1,000 research agreements with partners in both the scientific and business communities.

The Chair of Robotics and Systems Intelligence (RSI) is a member of the newly founded TUM Munich School of Robotics and Machine Intelligence directed by Prof. Sami Haddadin. The goal of RSI is to significantly advance the scientific foundations for intelligent machines capable of autonomous acting in our world and in close interaction with their human creators. The research focus of RSI is the development of control algorithms, mechatronics, intelligent robotics and prosthetics, robot learning algorithms, foundations of machine intelligence, as well as nonlinear control and systems theory. Prof. Haddadin and his team contributed in the research domains of physical human-robot interaction, nonlinear robot control, real-time motion planning, real-time task and reflex planning, robot learning, optimal control for elastic systems, human motor control, variable impedance actuation as well as safety in robotics.

Role in the project TUM has significantly contributed to the field of compliant actuator and compliantly controlled systems within various national and European projects. Among other contributions, Sami Haddadin and his team has significantly contributed to the development of DLR lightweight robot LWR III [157, 27], where parts of the concepts

[37] Partners are Viktoria institute and the Universities of Skövde (coordinator) and Halmstad.

and technologies were successfully transferred to the lightweight robot KUKA LBR. Also, they were responsible for development and commercialisation of FRANKA EMIKA ® lightweight robot. In DARKO, TUM will lead WP1 and significantly contribute to selecting and customising an initial platform, developing an elastic manipulator and preparing the final integrated system. Due to TUM's profound knowledge and experience in safe physical human-robot interaction (e.g. involvement in various projects such as ILIAD and ranging back to projects like Phriends and Sappharie) TUM will lead safety-related tasks in WP4 and WP6 to ensure human safety in DARKO.

Key people involved

Sami Haddadin [38] (male) is the director of the Munich School of Robotics and Machine Intelligence at the Technical University of Munich (TUM) and holds the Chair of Robotics and System Intelligence. He received his PhD from RWTH Aachen University. Prof. Haddadin was Chair of the Institute of Automatic Control at Gottfried Wilhelm Leibniz Universität Hannover from 2014 to 2018. Prior to that, he was head of the DLR research group "Human-Centered Robotics" and the program "Terrestrial Assistant Robotics" and participated or coordinated several research and industrial projects. He was strongly involved in the development and technology transfer of the DLR Lightweight robot to KUKA and is the founder of FRANKA EMIKA GmbH. He has received numerous awards for his scientific work, including the George Giralt PhD Award (2012), the RSS Early Career Spotlight (2015) and IEEE/RAS Early Career Award (2015), the Alfried Krupp Award for Young Professors (2015), the German Future Prize of the Federal President (2017) and the Leibniz Prize (2019). He contributed to various national and EUfunded projects including SoftPro, ILIAD, I.AM. and ReconCycle (Horizon 2020), SAPHARI and VIACTORS (FP7), SMERobot™, PHRIENDS and NEUROBOTICS (FP6). Prof. Haddadin has published more than 200 scientific articles in international journals and conferences. His research interests include intelligent robot design, robot learning, task and reflex planning, collective intelligence, human-robot interaction, nonlinear control, realtime planning, optimal control, human neuromechanics and prosthetics, and robot safety.

Saeed Abdolshah (male) received his PhD degree in Mechatronics Engineering from the University of Padova, Italy, in 2016. He was a visiting scholar in The Robotics And Rehabilitation (RoAR) Lab at Columbia University, US. From 2016 to 2018 he was a post-doctoral fellow at Safety Intelligence Group of Nagoya University, Japan. Since 2018, he is a post-doctoral researcher at The Chair of Robotics Science and Systems Intelligence (RSI). Currently, He has been involved as a senior researcher in various projects including ILIAD, I.AM., ReconCycle (H2020).

Nico Mansfeld (male) studied Robotics, Cognition, Intelligence (M.Sc.) at the Technical University of Munich. From 2012 to 2019, he worked as a research associate at the Institute of Robotics and Mechatronics at the German Aerospace Center (DLR). Since 2020 he is working with the Munich School of Robotics and Machine Intelligence at the Technical University of Munich. His research interests include safety in human-robot interaction, human injury biomechanics, and control of flexible joint and variable compliance robots.

Alexander Tödtheide completed his Diploma degree in mechanical engineering at Leibniz University of Hanover in 2015. Thereafter, he started his PhD at the Insitut für Regelungstechnik. Since 2018 he has been continuing his PhD at the Munich School of Robotics and Machine intelligence, which is a department of Technical University of Munich. His research deals mainly with the identification of mechanical systems, pneumatically driven structures as well as prostheses and exoskeletons.

Key relevant publications

1. J. Kuhn et al. "Towards Semi-Autonomous and Soft-Robotics Enabled Upper-Limb Exoprosthetics: First Concepts and Robot-Based Emulation Prototype". In: *2019 International Conference on Robotics and Automation (ICRA)*. IEEE. 2019, pp. 9180–9186

2. N. Mansfeld et al. "Safety map: A unified representation for biomechanics impact data and robot instantaneous dynamic properties". In: *IEEE Robotics and Automation Letters* 3.3 (2018), pp. 1880–1887

[38] **Declaration regarding possible Conflict of Interest Professor Sami Haddadin and Franka Emika**
Sami Haddadin, the director of the Munich School of Robotics and Machine Intelligence (MSRM) at the Technical University Munich (TUM) is one of the founders and a minority shareholder of the company Franka Emika. He does not hold any operational position at the company. Professor Sami Haddadin uses robots sold from the company Franka Emika within his research activities because of the technological specifications and interfaces provided by the robots.
All project partners have taken notice of the declared potential conflict of interest and raise no objections concerning the project.

3. S. Haddadin and E. Croft. "Physical human–robot interaction". In: *Springer handbook of robotics*. Springer, 2016, pp. 1835–1874

4. B. Vanderborght et al. "Variable impedance actuators: A review". In: *Robotics and autonomous systems* 61.12 (2013), pp. 1601–1614

5. S. Haddadin et al. "Intrinsically elastic robots: The key to human like performance". In: *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE. 2012, pp. 4270–4271

Related projects

I.AM. (H2020-871899; Jan 2020 – Dec 2023) I.AM. focuses on impact aware manipulation in logistics, a new area of application for robotics, which will grow exponentially in the coming years. In this project, the technology of torque-controlled robots will be leveraged to exploit intentional impacts for manipulation. I.AM.'s goal is to substantially reduce the cycle time by making a robot aware of the effects of impacts on its structure and its surrounding. TUM as a partner of I.AM. focuses on developing aim aware robot-object state estimation, contact monitoring, a systematic fault recovery framework, reflexes to handle undesirable events and robustify the execution of dynamic manipulation tasks.

ReconCycle (H2020-871352; Jan 2020 – Dec 2023) ReconCycle introduces the concept of robotic self-reconfiguration for disassembly of electronic devices based on a reconfigurable robotic cell. TUM will be the coordinator of WP3 with the focus on the development of control layer in the software architecture. This includes the derivation of new motion generation policies and adaptive control laws that can achieve project goals. Moreover, based on the sensory data, TUM will set up an error handling and learning framework in the control layer.

ILIAD (See description in Sec. 4.1.1.) TUM has been leading the work package on "Human Safety". Within this project TUM contributes on ensuring human-safety during mobile system motions in dynamic environment as well as robotic grasping and manipulation. For this, TUM extends already existing data on human injury in robotics by a thorough risk analysis followed by crash-testing simulations and experiments. With the help of these data, TUM provides methods for shaping the vehicles velocity in order to prevent human injuries even in the case of collisions.

SoftPro (H2020-688857; Mar 2016 – Feb 2020) SoftPro project studies and designs soft synergy-based robotics technologies to develop new prostheses, exoskeletons, and assistive devices for upper limb rehabilitation, which will greatly enhance the efficacy and accessibility to a greater number of users. Building on solid methodological bases, SoftPro produces a significant social impact, promoting advanced robot prosthetic and assistive technology "from bench to bedside"; but it also introduces disruptively new, admittedly risky but potentially high-impact ideas and paradigms.

KoBo34 (BMBF (Bundesministerium für Bildung und Forschung); July 2018 – Jun 2021) Due to demographic and epidemiological changes, more and more older people are in need for care in everyday life. The project KoBo34 focuses on the multi-professional development of intuitive interaction with a cooperative assistive robot as a complex intervention to support participation and autonomy in older individuals in geriatric care. The project is carried out by the TUM Munich School of Robotics and Machine Intelligence (MSRM), the University of Applied Sciene Rosenheim, robot manufacturerer Franka Emika and the Center for Cognitive Sciences at TU Darmstadt. The subproject managed by the TUM RSI aims to work on following research and technology fields:

- Collision detection and classification in Human-Robot-Interfaction.
- Safe Human-Robot-Interaction.
- Robot Whole-Body Control and Interaction.
- Bi-manual manipulation control.
- Independent learning of robotic skills.

Major technical equipment and facilities Several (>20) 7-DoF Franka Emika Panda arms with joint torque sensors and (two-finger) grippers, Schmalz vacuum gripping system, one URe10 Robot and a Vicon motion capture system with 12 cameras.

4.1.3 Bosch

The Bosch Group is a leading global supplier of technology and services. Its roughly 400,000 associates generated sales of 77 billion euros (2019).[39] Its operations are divided into four business sectors: Automotive Technology, Industrial Technology, Consumer Goods, and Energy and Building Technology. The Bosch Group comprises Robert Bosch GmbH and its more than 360 subsidiaries and regional companies in some 50 countries. If its sales and service partners are included, then Bosch is represented in roughly 150 countries. This worldwide development, manufacturing, and sales network is the foundation for further growth. In 2013, Bosch applied for some 5,000 patents worldwide. The Bosch Group's products and services are designed to fascinate, and to improve the quality of life by providing solutions which are both innovative and beneficial. In this way, the company offers technology worldwide that is "Invented for life". The new Strategic Programme Robotics and Autonomous System in the corporate sector Research and Advance Engineering, mainly situated in Renningen close to Stuttgart (Germany), is engaged with future robotics products developed under the above premise. One research focus lies on socially compliant and intelligent autonomous systems building on year-long in-house expertise in robotics, machine learning, and user technologies.

Role in the project Bosch will lead WP2 on 3D perception and scene understanding, where it will lead tasks on object-level semantics and perception of humans and their poses. We will further collaborate with UoL in WP5 to provide human motion prediction, intentions and contextual information to other work-packages. Bosch will also lead WP6 on predictive and safe motion planning, which takes contextual and social constraints as input and develops methods to plan and execute quantitative human and flow-aware vehicle motion. Finally, Bosch with its business unit BSH Household Appliances group, provides the spare part commissioning target-use case of the project, as well as access to the ARENA2036 integration, testing and demonstration site in Stuttgart-Vaihingen.

Key people involved

Kai O. Arras (male) is the head of robotics reasearch and Chief Expert robotics at Robert Bosch GmbH. Until May 2015 he was assistant professor for social robotics and HRI at the University of Freiburg where he was awarded a DFG Junior Research Group Leader Grant. He obtained his Dr. degree from EPFL and was a post-doctoral researcher at KTH Stockholm and at the University of Freiburg. He published around 120 peer-reviewed papers, articles, editorials and book chapters on robot navigation, perception, planning, or system integration and was member of various international program committees in robotics, AI, HRI, computer vision, and member of the HRI steering committee. Kai Arras was PI for the German Research Centre SFB/TR8, the coordinator of FP7-project SPENCER (2013-2016), PI during the H2020 ILIAD project (2016-2020) and will act as PI for DARKO.

Timm Linder (male) is a research scientist at Robert Bosch GmbH – Corporate Research with research focus on multi-modal robot perception. He earned his PhD degree on human detection, tracking and analysis using mobile robots from the University of Freiburg, Germany. Besides his research in the EU FP7 project SPENCER, he was also heavily involved in the system integration, safety aspects and deployment of a mobile robot in a crowded airport environment. In the subsequent ILIAD project, he led the work package on human-aware AGV fleets. He has co-authored publications at various robotics and computer vision conferences with focus on traditional and deep learning-based human detection and tracking, 3D human pose estimation, and 3D scene generation for sim-to-real transfer.

Luigi Palmieri (male) is a senior expert at Robert Bosch GmbH – Corporate Research. His research focuses currently on kinodynamic motion planning in dynamic and crowded environments, control of non linear dynamic systems, hybrid systems of learning-planning-control, MPC and numerical-optimization techniques, planning considering human motion predictions and social constraints. He earned his PhD degree in robot motion planning from the University of Freiburg, Germany. During his PhD he was responsible for the motion planning task of the EU FP7 project Spencer. Since then, he has the same responsibility in the EU H2020 project ILIAD. He has co-authored multiple papers at RA-L, ICRA, IROS, FSR on the combinations of motion planning with control, search, machine learning, and human motion prediction.

Narunas Vaskevicius (male) is a research scientist at Robert Bosch GmbH – Corporate Research. His current research interests include multi-modal 3D scene understanding for robotic applications covering topics of 3D object detection, object pose estimation and semantic segmentation. Before joining Robert Bosch GmbH, he received his PhD degree with distinction in 3D robot perception from Jacobs University Bremen, Germany in 2017. During his academic career, he was involved in several EU projects and co-authored more than 30 publications in robotics and computer vision conferences and journals.

[39] https://www.bosch.com/company/our-figures/

Jens Hofele (male) is a research engineer at Robert Bosch GmbH – Corporate Research. He has a background in mechanical engineering and robotics with a specialization in special machinery, plant engineering and construction. He will support the project with requirements analysis and the design, construction and integration of the BSH use-case replica at ARENA2036 and will also contribute to the integration of the DARKO demonstrator into existing installations and show-cases at ARENA2036.

Key relevant publications

1. T. Linder, K. Y. Pfeiffer, N. Vaskevicius, R. Schirmer, and K. O. Arras. "Accurate Detection and 3D Localization of Humans Using a Novel YOLO-Based RGB-D Fusion Approach and Synthetic Training Data". In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2020.

2. I. Sárándi, T. Linder, K. O. Arras, and B. Leibe. "Metric-Scale Truncation-Robust Heatmaps for 3D Human Pose Estimation". In: *IEEE Int. Conf. on Automatic Face and Gesture Recognition*. 2020.

3. T. Stoyanov, N. Vaskevicius, et al. "No More Heavy Lifting: Robotic Solutions to the Container Unloading Problem". In: *IEEE Robotics Automation Magazine* 23.4 (2016), pp. 94–106.

4. A. Rudenko, L. Palmieri, M. Herman, K. M. Kitani, D. M. Gavrila, and K. O. Arras. "Human motion trajectory prediction: A survey". In: *Int. Journal of Robotics Research (IJRR)* (2020).

5. L. Palmieri, L. Bruns, M. Meurer, and K. O. Arras. "Dispertio: Optimal Sampling For Safe Deterministic Motion Planning". In: *IEEE Robotics and Automation Letters* 5.2 (2019), pp. 362–368.

Related projects

SPENCER (See description in Sec. 4.1.1.) Bosch PI Kai O. Arras, while still head of the Social Robotics Lab at the University of Freiburg, coordinated the SPENCER project. Timm Linder and Luigi Palmieri were responsible for the development of the the human tracking and motion planning systems, as well as many integration and safety tasks that prepared the robot for deployment in a crowded airport terminal.

ILIAD (See description in Sec. 4.1.1.) Bosch has been leading the work-package on human-aware AGV fleets and developed the ILIAD flow-aware motion planning system.

OFERA is an EU-funded innovation action from 2018 to 2021 and brings ROS 2 onto microcontrollers in an open-source project named micro-ROS. Bosch is leading Work Package 4: APIs and Core Libraries.

Major technical equipment and facilities On the new Bosch corporate research campus in Renningen, opened in fall 2014 and unifying most research activities at Bosch on over 100 hectares, there are two dedicated robotics labs and a number of test environments. The labs are equipped with high-end servers for computationally intense tasks and a high-performance Qualisys motion capture system that can be used, for example, to obtain tracking ground truth in Bosch's human detection and tracking tasks. A large collection of sensors and robots is available, ranging from autonomous lawnmowers over mobile transportation platforms to robots with manipulation capabilities. Examples include two robots based on the Robotino platform, the SPENCER robot, Franka Emika Panda arms, two KUKA YouBot platforms, one Turtlebot, one Aethon TUG, several BOSCH Indegos and ActiveShuttles. Bosch will also provide the consortium with access to the ARENA2036 demonstration site in Stuttgart-Vaihingen (see Sec. 1.3 and T8.3), where the DARKO system can be integrated with the existing intralogistics demonstrator by Bosch Rexroth.

4.1.4 UNIPI

The Università di Pisa (UNIPI), founded in 1343, is among the oldest and most prestigious universities in Europe, with alumni such as Galilei, Volterra and Fermi. The Research Centre "Enrico Piaggio", founded in 1962 and recently promoted to the status of Centro di Ateneo, organises interdisciplinary research among engineering, medicine, and biological scientists towards applications in Bioengineering and Robotics. Centre "E. Piaggio" has a longstanding experience in managing contracts with international, EC, and industrial partners, and currently hires four professional project managers. The Robotics Group of the Research Centre "Enrico Piaggio" focuses on robotics and embedded automation. The group is among the originators of the modern approach to physical human-robot interaction, where it has been advocating intrinsic safety via the codesign of mechanics and control, oriented towards performance maximization within rigid safety constraints. Particular attention has been focused on the study of hands and haptics since at least 20 years. Recent work has proposed a synergy-based approach to hand design and control for grasp and manipulation that is producing interesting results from both a theoretic and a design point of view.

Role in the project UNIPI will significantly contribute on the whole design of real time motion planning and control for robotic grasping and manipulation. UNIPI will also contribute in the design of a general-purpose gripper for the grasping and manipulation of the objects envisaged in DARKO. UNIPI will also contribute to the problem of planning in the risk space by closely working with ACT in WP7.

Key persons involved

Antonio Bicchi (male) is Professor of Robotics at the Università di Pisa, and Senior Scientist at the Italian Institute of Technology in Genoa. He graduated from the University of Bologna in 1988 and was a postdoc scholar at M.I.T. Artificial Intelligence lab in 1988–1990. He teaches Control Systems and Robotics in the Department of Information Engineering (DII) of the Università di Pisa. He leads the Robotics Group at the Research Centre "E. Piaggio" of the Università di Pisa since 1990, where he was Director from 2003 to 2012. He is the Head of the SoftRobotics Lab for Human Cooperation and Rehabilitation at IIT in Genoa. Since 2013 he serves as Adjunct Professor at the School of Biological and Health Systems Engineering of Arizona State University. His main research interests are in Robotics, Haptics, and Control Systems in general. He has published more than 400 papers on international journals, books, and refereed conferences. In 2016 he was the founding Editor in Chief of the IEEE Robot. Autom. Lett., which in 2 years became the largest Journal in the field. He has organized and chaired the first WorldHaptics Conference (2005). He is Editor of the book series “Springer Briefs on Control, Automation and Robotics”, and has served in the Int.l J. Robotics Research, the IEEE Trans. on Robotics and Automation, IEEE Trans. Automation Science and Engineering, and IEEE RAS Magazine. He was Program Chair of the IEEE Int. Conf. Robotics and Automation (ICRA’16), Robotics Science and Systems (RSS2019), and General Chair of the Int. Symposium on Robotics Research (ISRR’ 2015) and Hybrid Systems: Computation and Control (HSCC 2007). He was Editor in Chief of the Conference Editorial Board for the IEEE Robotics and Automation Society (RAS), Vice President for Publications (20132014), for Membership (2006-2007), and as Distinguished Lecturer (2004-2006) of IEEE RAS. He served as the President of the Italian Association or Researchers in Automatic Control (2012-2013). He is the recipient of several awards and honors, among which the IEEE RAS George Saridis Leadership Award in Robotics and Automation (2018). His 2012-2017 ERC Advanced Grant “SoftHands” established the basis for the theory of soft synergies in human manipulation, led to the design of a new generation of robotic and prosthetic hands, and contributed to establishing the new field of “soft manipulation”. In 2017 he ran an ERC Proof of Concept project to explore the applicability of advanced soft robotics solutions to prosthetics. In 2018 his proposal “Natural BionicS” has been funded in the highly selective ERC Synergy framework. In 2018 he was awarded with another ERC Proof of Concept project on soft articulated robots applied to industrial picking. Antonio Bicchi is a Fellow of IEEE since 2005.

Lucia Pallottino (female) is Associate Professor in Robotics and Automation at the Università di Pisa in the Research Centre “E. Piaggio” and the Department of Information Engineering (DII). She received the Laurea degree in Mathematics and the Ph.D. degree in Robotics and Industrial Automation from the Università di Pisa, Italy in 1997 and 2002, respectively. She is, or has been, Deputy Director of Centro di Ricerca “E. Piaggio” (since Jan. 2017), Chair of the IEEE Robotics & Automation Society Italian Chapter (I-RAS) (Jan. 2015-Dec 2018), Associate Editor of the IEEE Robotics and Automation Letters and of the IEEE Transaction on Robotics. She currently is Principal Investigator of the ILIAD European project. Her main research interests within Robotics are in motion planning and control of complex systems such as humanoids or systems of autonomous vehicles, optimal control of constrained systems, distributed control of multi-robot vehicles and quantised control.

Matteo Bianchi (male) received from the Università di Pisa the B.S degree and the M.S degree in Biomedical Engineering (both cum laude), and the PhD in Automatics, Robotics, Bioengineering, in 2004, 2007 and 2012, respectively. From January to June 2011, he was visiting student at the Johns Hopkins University. Currently, he is a tenure track Assistant Professor of Automatic Controls and Robotics at the Research Centre “E. Piaggio” and the Department of Information Engineering of the Università di Pisa, and clinical research affiliate at Mayo Clinic. His research interests include robotic/human hands and manipulation; haptic interfaces and tactile sensing for advanced Human-Machine Interaction. He is author of more than 100 peer-reviewed contributions and serves as member of the editorial/organizing board of international conferences and journals. He is editor of the book “Human and Robot Hands”, Springer. He is recipient of several awards, including the JCTF novel technology paper award (IROS 2012) and the Best Paper Award (IEEE-RAS Haptics Symposium 2016). He serves as co-Chair of the IEEE RAS Technical Committee (TC) on Robotic Hands, Grasping and Manipulation, and Vice Chair for Information Dissemination for the IEEE RAS TC on Haptics. He acts as PI for UNIPI of EU grants and research contracts (funds > 1.2 M€).

Manolo Garabini (male) received the Laurea degree and the Ph.D. both from the Università di Pisa, in 2010 and 2014, respectively. He is currently an Assistant Professor at the Research Centre “E. Piaggio” and at the Department of Information Engineering of the Università di Pisa. His main research interests lie in the field of design, planning, control and optimal control of soft robots. He is co-founder of qbrobotics s.r.l., a spin-off company of the Research Centre "E. Piaggio" and the Italian Institute of Technology of which the mission is to foster the diffusion of soft-robots. He is currently Principal Investigator in the EU Project THING (780883) for the Research Centre “E. Piaggio”.

Paolo Salaris (male) received the M.Sc. degree in Electrical Engineering in 2007 and his PhD in Automation and Bioengineering in 2011, both from the university of Pisa. He has been Visiting Scholar at Beckman Institute for Advanced Science and Technology, University of Illinois, Urbana-Champaign in 2009. He has been a PostDoc at the Research Center “E.Piaggio” from March 2011 to January 2014 and at LAAS-CNRS in Toulouse from February 2014 to July 2015. From October 2015 to August 2019 he has been a permanent researcher (CRCN) at Inria Sophia Antipolis Méditerranée. From September 2019 he is an assistant professor at the Department of Information Engineering and the research Center "E. Piaggio", University of Pisa. His main research interests are optimal motion planning and control, active sensing, optimal sensors placements and optimal estimation, multi-robot and nonholonomic systems.

Danilo Caporale (male) received the Bachelor and Master of Science degrees in Automation and Control Engineering in 2009 and 2011, respectively, from the Politecnico di Milano. In 2015 he received the Ph.D. degree in Information Technology from the same institution, with a thesis on robust control devices for railway traction and braking, with the collaboration of Alstom Transport Italy and the support of Associazione Eugenio e Germana Parizzi. During his Ph.D. studies, he spent visiting periods at Imperial College, UK, at University of Newcastle, NSW, Australia, and, as a Rocca Fellow, at Massachusetts Institute of Technology, USA. Since 2015 he is a Post-Doc Researcher at Research Centre “E. Piaggio”, Università di Pisa, where he collaborated on the EU Project Walk-Man and is now working on the Project ILIAD.

Alessandro Settimi (male) received a Master Degree in Robotics and Control engineering and the Ph.D. in Information Engineering from the Università di Pisa in 2013 and in 2017, respectively. He is currently a PostDoc researcher at the Centro di Ricerca "E. Piaggio" of Università di Pisa and CEO and co-founder of Proxima Robotics s.r.l.. He works in planning and control of humanoid robots and autonomous vehicles and robots software architecture.

Key relevant publications

1. Gabellieri Chiara, Angelini Franco, Arapi Visar, Palleschi Alessandro, Catalano Manuel, Grioli Giorgio, Pallottino Lucia, Bicchi Antonio, Bianchi Matteo and Garabini Manolo. Grasp It like a Pro: Grasp of Unknown Objects with Robotic Hands based on Skilled Human Expertise. IEEE Robotics and Automation Letters, vol. 5, no. 2, pp. 2808-2815, April 2020.

2. Palleschi Alessandro, Mengacci Riccardo, Angelini Franco, Caporale Danilo, Pallottino Lucia, De Luca Alessandro and Garabini Manolo, "Time-Optimal Trajectory Planning for Flexible Joint Robots," in IEEE Robotics and Automation Letters, vol. 5, no. 2, pp. 938-945, April 2020.

3. Angelini Franco, Petrocelli Cristiano, Catalano Manuel, Garabini Manolo, Grioli Giorgio and Bicchi Antonio. "SoftHandler: An Integrated Soft Robotic System for Handling Heterogeneous Objects". IEEE Robotics & Automation Magazine. Feb. 2020.

4. Bianchi Matteo, Salaris Paolo, Bicchi Antonio. "Synergy-based hand pose sensing: Optimal glove design". The International Journal of Robotics Research, 32(4), 407–424, 2013.

5. Catalano Manuel, Grioli Giorgio, Farnioli Edoardo, Serio Alessandro, Piazza Cristina and Bicchi Antonio, “Adaptive Synergies for the Design and Control of the Pisa/IIT SoftHand”, International Journal of Robotics Research 2014.

Related projects

ILIAD (See description in Sec. 4.1.1.) UNIPI leads WP4 (Efficient and Safe Dynamic Manipulation), contributes novel end-effector hardware as well as control and planning software, and makes a large contribution to the risk framework in WP7.

SoMa (H2020-645599) Soft-bodied intelligence for Manipulation (Partner). SOMA explores a new avenue of robotic manipulation, exploiting the physical constraints imposed by the environment to enable robust grasping and manipulation in dynamic, open, and highly variable contexts.

Sophia (H2020-871237) Socio-physical Interaction Skills for Cooperative Human-Robot Systems in Agile Production. SOPHIA project aims to develop a new generation of socially cooperative human-robot systems in agile production. The objectives are to achieve a reconfigurable and resource-efficient production and to improve human ergonomics and trust in automation, in hybrid human-plus-robot manufacturing environments.

Saphari (H2020-688857) Safe and Autonomous Physical Human-Aware Robot Interaction. Saphari project aimed at taking a big step further along the human-centred roadmap by addressing all essential aspects of safe, intuitive physical interaction between humans and complex, human-like robotic systems in a strongly interconnected manner. The project developed and validated key perceptive and cognitive components that enable robots to track, understand and predict human motions in a weakly structured dynamic environment in real-time.

THE (FP7-248587) THE Hand Embodied. THE aimed at advancing the state of the art in artificial system architectures for the "hand" as a cognitive organ. The scientific goals of the project concerned the reciprocal linkages between the physical hand and its high-level control functions, and about the way that the embodiment enables and determines its behaviours and cognitive functions. The idea was to study how the embodied characteristics of the human hand affect and determine the learning and control strategies people use for such fundamental cognitive functions as exploring, grasping and manipulating. The ultimate goal of the project was to learn from human data how to devise improved system architectures for the hand as a cognitive organ, and eventually how to better design and control robot hands, haptic interfaces and hand prostheses.

Major technical equipment and facilities UNIPI will commit several hardware facilities, robotic systems, and prototypes which will be fully accessible to the consortium and will be used in experimental tests during the overall project. These include: an integrated variable stiffness actuated modular platform; two KUKA lightweight robots; a phaseSpace motion capture facility for human motion tracking; ten PISA/IIT SoftHands; a soft gripper integrated in the SoftHandler; three Panda manipulators by Franka Emika.

4.1.5 EPFL

The Ecole Polytechnique Fédérale de Lausanne (EPFL) is one of the two Swiss Federal Institutes of Technology and is located in Lausanne, Switzerland. The Learning Algorithms and Systems Laboratory (LASA) at the EPFL was founded on the 1st of January, 2006. LASA has a long-standing expertise at developing robots and adaptive control architectures to realise skilful robot motions in a variety of robotic platforms. Research at LASA combines engineering, computer science and computational neuroscience methods for the development of learning control system to enable flexible human-robot interactions. The LASA laboratory is composed of around 20 people with 5 postdocs and 10 PhD students. LASA is funded primarily by research grants from the EPFL, the European Community and the Swiss National Science Foundation, and, secondarily through private foundations and industry. It has led to the creation of two start-ups (Pomelo in 2011 and AICA in 2019). The research at LASA focuses on the development of novel approaches in the field of robot control and machine learning. Such approaches enable robots to adapt adequately and on-the-fly to a variety of environments and compensate for sudden perturbations through motions which are safe for the robot's embodiment, environment and humans. The key personnel involved in the project have wide research experience from participating in EU and nationally funded projects which aim to apply safe robotic systems in real life manufacturing applications (SecondHands,I.AM., Cogimon EU H2020).

Role in the project EPFL will mainly contribute to the activities of WP4 and particularly will lead T4.4 by developing robot controllers for object throwing. Furthermore, it will be involved in other tasks of the WP4 (T4.3, T4.2) where it will provide methods for safe robot control during picking and placing moving objects.

Key persons involved

Aude Billard (female) is Full Professor and Head of the LASA Laboratory at the School of Engineering at the Swiss Federal Institute of Technology in Lausanne. She received her B.Sc. (1994) and M.Sc. (1995) in Physics from EPFL, with specialisation in Particle Physics at the European Centre for Nuclear Research (CERN), a M.Sc. in Knowledge-based Systems (1996) and a Ph.D. in Artificial Intelligence from the Department of Artificial Intelligence at the University of Edinburgh. Since 2002, A. Billard (PI at LASA) has participated in numerous EU projects of various sizes, including STREPs, IP, NEST and Marie-Curie grants. She is the recipient of an ERC Advanced Grant.

Athanasios Polydoros (male) is a postdoctoral researcher at the LASA Laboratory at the School of Engineering at the Swiss Federal Institute of Technology in Lausanne. He holds a Dip. Eng (2011) in Production Engineering from Democritus University of Thrace (DUTH), a M.Sc. with Distinction (2013) in Artificial Intelligence from

University of Edinburgh and a Ph.D. in Robot Learning (2017) from Aalborg University. He has participated in multiple EU and nationally funded projects.

Relevant publications

1. S. S. M. Salehian, M. Khoramshahi, and A. Billard. "A Dynamical System Approach for Softly Catching a Flying Object: Theory and Experiment". In: *IEEE Transactions on Robotics* 32.2 (2016), pp. 462–471
2. S. Kim, A. Shukla, and A. Billard. "Catching objects in flight". In: *IEEE Transactions on Robotics* 30.5 (2014), pp. 1049–1065
3. A. Shukla and A. Billard. "Coupled dynamical system based arm–hand grasping model for learning fast adaptation strategies". In: *Robotics and Autonomous Systems* 60.3 (2012), pp. 424–440
4. S. Mirrazavi, N. Figueroa, and A. Billard. "A unified framework for coordinated multi-arm motion planning". In: *The International Journal of Robotics Research* 37.10 (2018), pp. 1205–1232
5. N. Figueroa et al. "A Dynamical System Approach for Adaptive Grasping, Navigation and Co-Manipulation with Humanoid Robots". In: *2020 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE. 2020

Related projects

I.AM. (H2020-871899) focuses on impact aware manipulation in logistics, and relies on four scientific and technological research lines that will lead to breakthroughs in modeling, sensing, learning and control of fast impacts. This integrated paradigm, I.AM, brings robots to an unprecedented level of manipulation abilities. By incorporating this new technology in existing robots, I.AM focuses on enabling shorter cycle time (10%) for applications requiring dynamic manipulation in logistics which is validated in three realistic scenarios: a bin-to-belt application demonstrating object tossing, a bin-to-bin application object fast boxing, and a case depalletizing scenario demonstrating object grabbing.

CogIMon (H2020-644727) Compliant control in humans is exploited in a variety of sophisticated skills. These include solitary actions such as soft catching, sliding, pushing large objects as well as joint actions performed in teams such as manipulation of large scale objects or mutual adaptation through physical coupling for learning, in walking or in execution of joint tasks. We refer to this advanced ability of organizing versatile motion under varying contact and impedance as cognitive compliant interaction in motion. The CogIMon project aims at a step-change in human-robot interaction toward the systemic integration of robust, dependable interaction capabilities for teams of humans and compliant robots, in particular the compliant humanoid COMAN. We focus on interaction that requires active and adaptive regulation of motion and behavior of both the human(s) and the robot(s) and involves whole-body variable impedance actuation, adaptability, prediction, and flexibility.

SAHR (ERC-2016-EDG-741945) We design controllers that can plan at run time and adapt to new environmental constraints. We offer a novel approach to robot learning that follows stages of skill acquisition in humans. To inform modelling, we conduct a longitudinal study of the acquisition of dexterous bimanual skills in craftsmanship. We study how humans exploit task uncertainty to overcome their sensory-motor noise, and how humans learn bimanual synergies to reduce the control variables. This study informs the design of novel learning strategies for robots that exploit failures as much as successes. We combine planning and ML to learn feasible control laws, retrievable at run time with no need for further optimization. We exploit properties of dynamical systems (DS), which have received little attention in robot control, and use ML to identify characteristics of DS, in ways that were not explored to date. The approach is assessed in live demonstrations of coordinated adaptation of a multi-arm/hand robotic system engaged in a fast-paced industrial task, in the presence of humans.

SecondHands (EUH2020-643950) The topic addressed by SecondHands is to advance abilities and key technologies relevant to industrial robotics and to improve the technology readiness level in the areas of cognition, human-robot interaction, mechatronics, and perception. SecondHands aims to develop a robot assistant that is trained to understand maintenance tasks so that it can either pro-actively, or as a result of prompting, offer assistance to automation maintenance technicians performing routine and preventative maintenance. Conceptually the robot's task is to provide a second pair of hands to the maintenance technician, such that once the robot has been trained, it can predict when it can usefully provide help and knows which actions to take to provide it. To operate within environments designed primarily for industrial efficiency, but centred around a human workforce, a robot should possess a rich repertoire of human-like skills, and probably a humanoid or human-like form, specifically in order to use the same methods of access.

Significant infrastructure and major items of technical equipment The LASA laboratory will put at the disposal of the project its robotics and computing facilities. This includes 4 KUKA light weight robots, two iCub robots, one mobile platform mounted with a UR10 arm, two Franka Emika robots and several dexterous robotic hands and grippers. It has also at its disposal a large set of real-time visual tracking monitoring through IR-based and RBGD cameras.

4.1.6 UoL

The *University of Lincoln* is one of the fastest rising institutions in the UK. It has established an international reputation based on world-class research, high student satisfaction, and excellent graduate employment. Research funding within the University is obtained from a variety of external sources. During the past decade the University has been involved in a great number of projects funded by various European agencies and many others with national government, charity or industrial funding. These include the European Commission, the UK Research Councils, Government Departments (UK and Overseas), Charities and other similar organisations. Within the University there is significant involvement in funded European and international projects across a number of different Schools and departments, often involving collaboration across disciplines to deliver innovative, user-engaged results. Within the last year the University has secured multi-million funded projects for research and innovation, and in many cases it is playing a lead role or coordinating the management of the work.

The *Lincoln Centre for Autonomous Systems Research (L-CAS)*, in particular, is currently a major research centre within the College of Science, comprising 15+ full-time academic staff, 10+ post-doctoral researchers, 25+ PhD students, 2 dedicated technicians, and a large number of associated or international visiting researchers. The Centre is organised internally into several research groups and projects, including human-centred robotics, agri-food technology and computational intelligence. L-CAS pursues several major lines of fundamental research into autonomous systems, including (i) human-centred mobile robotics, (ii) long-term autonomy and adaptation in changing environments, (iii) machine perception and sensor fusion, and (iv) bio-inspired embedded systems. These developments share a common need to robustly process and interpret large-volumes of real-world sensory data from different modalities in real time, as well as intelligent spatiotemporal decision-making on where and when to acquire these data. The Centre further specialises in systems integration, bringing together these technologies with other state-of-the-art supporting components, to tackle challenging real-world applications, especially in food and agriculture, security, assistive care, and intelligent transportation, particularly through external partnerships. Our joint facilities include dedicated robotics research labs, a demonstration farm, an experimental food factory, a fleet of diverse mobile and social robots, advanced compliant robotic manipulators, a swarm of microrobots, and state-of-the-art agricultural robots.

Role in the project UoL will lead WP5 on Human-Robot Spatial Interaction, including tasks for context-aware modelling and causal reasoning. It will also contribute to other tasks in the same and related WPs, especially for human perception and motion prediction, where UoL has strong expertise from previous projects.

Key persons involved

Nicola Bellotto (male) is an Associate Professor in the School of Computer Science at the University of Lincoln, UK, and a member of the Lincoln Centre for Autonomous Systems. His main research interests are in machine perception, especially for human detection, tracking, identification and activity recognition with mobile robots for applications in healthcare, industrial services and agri-food technology. He has a Master in Electronic Engineering from the University of Padova, Italy, and a PhD in Computer Science from the University of Essex, UK. Before joining the University of Lincoln, he was a researcher in the Active Vision Lab at the University of Oxford. Dr Bellotto is the recipient of a Google Faculty Research Award and was a PI of the H2020 projects ENRICHME and FLOBOT.

Marc Hanheide (male) is a Professor of Intelligent Robotics & Interactive Systems in the School of Computer Science at the University of Lincoln, UK. He received the Diploma in computer science from Bielefeld University, Germany, in 2001 and the Ph.D. degree (Dr.-Ing.) also in computer science also from Bielefeld University in 2006. In 2001, he joined the Applied Informatics Group at the Technical Faculty of Bielefeld University. From 2006 to 2009 he held a position as a senior researcher in the Applied Computer Science Group. From 2009 until 2011, he was a research fellow at the School of Computer Science at the University of Birmingham, UK. Prof. Hanheide is a Principle Investigator in many national and international research projects, funded by H2020, EPSRC, InnovateUK, DFG, industry partners, and others. The STRANDS, ILIAD, RASberry, and NCNR projects are among the bigger projects he is involved with. In all his work, he researches on autonomous robots, human-robot interaction, interaction-enabling technologies, and system architectures. Prof. Hanheide specifically focuses on aspects of long-term robotic behaviour and human-robot interaction and adaptation. His work contributes to robotic applications in care, logistics, nuclear decommissioning, security, agriculture, museums, and general service robotics. He features regularly in public media, has published more than 100 peer-reviewed articles, and is actively engaged in promoting the public understanding of science through appearances in dedicated events, media appearances, and public lectures.

Tom Duckett (male) is a Professor of Robotics and Autonomous Systems at the University of Lincoln, UK, where he leads the Lincoln Centre for Autonomous Systems. His research focuses on perception systems for autonomous mobile robots that operate in unconstrained, dynamic environments. He worked previously at the Centre for Applied Autonomous Sensor Systems, Örebro University, Sweden, where he led the Learning Systems Laboratory. He obtained his PhD in the AI Group at the University of Manchester, UK. Prior to becoming an academic, he worked as a programmer, developing and supporting software solutions for the fresh food industry. Prof. Duckett has co-authored over 140 scientific publications and held peer-reviewed research grants of £10.2 million at the University of Lincoln (£9.1 m as PI), including the new EPSRC Centre for Doctoral Training in Agri-Food Robotics (AgriFoRwArdS) and the European-funded collaborative projecsts BACCHUS, ILIAD, FLOBOT and STRANDS. He played a major role in securing a further award of £6.3 m from the UK Government's Expanding Excellence in England (E3) Fund to create Lincoln Agri-Robotics, a centre of excellence in agricultural robotics that will look at how robots can tend, harvest and quality control high-value crops with minimum human intervention.

Relevant publications

1. Z. Yan, T. Duckett, and N. Bellotto. "Online Learning for 3D LiDAR-based Human Detection: Experimental Analysis of Point Cloud Clustering and Classification Methods". In: *Autonomous Robots* 44 (2020).
2. F. Camara et al. "Pedestrian Models for Autonomous Driving. Part II: High Level Models of Human Behaviour". In: *IEEE Transactions on Intelligent Transportation Systems* (2020).
3. C. Coppola et al. "Social Activity Recognition on Continuous RGB-D Video Sequences". In: *International Journal of Social Robotics* 12 (2020), pp. 201–215.
4. L. Sun et al. "3DOF Pedestrian Trajectory Prediction Learned from Long-Term Autonomous Mobile Robot Deployment Data". In: *IEEE Int. Conf. on Rob. and Autom. (ICRA)*. 2018, pp. 5942–5948.
5. C. Dondrup et al. "A Computational Model of Human-Robot Spatial Interactions Based on a Qualitative Trajectory Calculus". In: *Robotics* 4.1 (2015), pp. 63–102.

Related projects

ILIAD (See description in Sec. 4.1.1.) UoL role: Leader of WP2 on "Long-Term Operation". The main role of the UoL team in ILIAD is coordination of activities on long-term operation, exploiting the team's expertise on long-term mapping and spatio-temporal representations for mapping, planning and search. UoL contributes also to the tasks on human-robot interaction. UoL's experience from related EU projects is employed for the integration and deployment activities in ILIAD. The team's unique expertise in food manufacturing and professional links with the food industry is further exploited in dissemination activities.

FLOBOT (H2020-645376) Floor Washing Robot for Professional Users, http://www.flobot.eu/. UoL role: contribution to WP5 on "Software development and Integration". This project developed a floor washing robot for industrial, commercial, civil and service premises, such as supermarkets and airports. Floor washing tasks have many demanding aspects, including autonomy of operation, navigation and path optimization, safety with regards to humans and goods, interaction with human personnel, easy set-up and reprogramming. FLOBOT addressed these problems by integrating existing and new solutions to produce a professional floor washing robot for wide areas. UoL's research contribution in this project focused in the area of robot perception, based on laser range-finder and RGB-D sensors, for human detection, tracking and motion analysis in dynamic environments. Primary tasks included developing novel algorithms and approaches for enabling the acquisition, maintenance and refinement of multiple human motion trajectories for collision avoidance and path optimization, as well as integration of the algorithms with the robot navigation and on-board floor inspection system.

STRANDS (H2020-600623) UoL role: leader of WP1 on "Long-term mapping and localisation". STRANDS (http://strands.acin.tuwien.ac.at/) produced intelligent mobile robots that are able to run for months in dynamic human environments. The project provided robots with the longevity and behavioural robustness necessary to make them truly useful assistants in a wide range of domains. Such long-lived robots are able to learn from a wider range of experiences than has previously been possible, creating a whole new generation of autonomous systems able to extract and exploit the structure in their worlds. In STRANDS, UoL investigated long-term mapping and localisation, and contributed to activities for human-robot interaction.

Major technical equipment and facilities PAL Robotics TiaGo platform, to be used as an economical alternative to the main platform envisioned in WP1 – with less focus on throwing.

4.1.7 ACT

ACT Operations Research IT is specialized in advanced decision support systems by standing on optimisation, simulation, forecasting and process control expertise built on the breadth of skills within its cross-engineering background team; their products are based on a strong scientific foundation. Company core-competencies includes: math optimisation and statistical forecasting; discrete event dynamic simulation; software design and implementation. The key competencies of ACTOR correspond to the tasks of the project proposal because it will be necessary to design and develop optimisation, simulation and forecasting tools to support the risk-aware scheduling of robots, activities that describe the core competencies of ACTOR. The distinctive features of ACTOR products are linked to the strong mathematical content at the base of decision support software products. The integration of forecasting, simulation and optimisation for optimised process management is a feature that distinguishes the ACTOR approach, which therefore does not qualify for being a software house but an engineering company, in particular a math engineering company that with own products can optimise the performance of various processes. Based on the power of artificial intelligence, predictive analytics, simulations, and mathematical optimisation techniques ACT Operations Research offers robust and innovative solutions to cut costs, improve productivity and service levels, predict trends and behaviours, improve safety, support the care of patients, reduce risks and manage crises. ACT OR innovates the way in which operational research, statistics and control theory are used in companies and plants. The company carries out R&D activities on a continuous basis and all personnel involved in the design and development of company products are actually involved in R&D activities. All company personnel have a minimum degree qualification (engineering, IT, automatics, economics) and most of them have a PhD degree (operational research, engineering, IT). R&D is also carried out in participation with public research facilities (universities, CNR) and the topics are in the field of operations research and management science, with the design and development of decision support models for effective and efficient management of processes in manufacturing, logistics, revenue management and control of large industrial plants.

Role in the project In DARKO, ACT's role is mostly related to the development of the risk assessment and forecasting framework (WP7), with a specific focus on the design of an operational scheduling layer capable of managing both the off-line optimisation (with respect to risks) of the robotic tasks to be accomplished in presence of humans, and the on-line decentralised re-scheduling intelligence that each agent will be able to manifest. Leader of WP7, ACTOR will guarantee the progressive deployment of the corresponding algorithmic modules, contributing to the integration of the project reference architecture into the selected use-cases.

Key persons involved

Eng. Raffaele Maccioni (male) master of engineering, CEO and co-founder of ACTOR, is head of the R&D and Optimization and Simulation Divisions; he is the main contact and responsible of all project activities at ACTOR. Professional highlights:

- Business Software Technology (Vertical: supply chain management & Revenue Management);
- Co-Invented and led the development of 5 innovative optimization products suites including a multi-paradigma forecasting platform. The products constitute a set of math-based decision support systems to be used in multiple industries (Retail, Fashion & luxury, Supply Chain and Logistics, Manufacturing);
- Executed 200+ projects improving customers business processes delivering 7-15% range savings from inventory reductions, network and transportation optimization across manufacturing and services vertical markets;

Eng. Alessandro Pinzuti (male) engineering PhD, Team Leader and Product Engineer at ACTOR. The main activities concerned the design and development of IT systems for decision support, with the use of operational research techniques in the optimization of complex systems, statistical forecasting and simulation.

Relevant products and services

1. **BEFORE! Predictive Analytics** (Product) - Demand and promotion forecasting: Before! empowers forecasting while drastically reducing both the time to draw up well-rounded models as well as its integration and maintenance costs. ACT Operations Research BEFORE! Predictive Analytics invokes embedded intelligent models continuously learning the behaviour of forces like i.e., seasonality, trends, weather and cross influences

while improving their accuracy without human intervention. Before! Predictive Analytics includes two modules: (1) Before! Forecasting predicts the demand at aggregate level as well as at store-item level, considering multiple variables affecting the demand (holiday, meteo, price, etc). (2) Before! Promo Forecasting predicts the demand for future promotion events associated with temporary price reductions and/or media and advertising pressure.

2. **BEFORE! Market Analytics** (Product) - Before! Market Analytics empowers forecasting while drastically reducing both the time to draw up well-rounded models as well as its integration and maintenance costs. Before! Market Analytics includes three modules: (1) Before! Value Items helps you spot the customer sensitive items while giving you recommendations on how to manage their regular and promotional prices so to keep your reputation high. (2) Before! Competitive Analysis has the ability to make meaning by assembling necessary figures from stores and market sources and to add value by conveying patterns and trends in data. (3) Before! Category Efficiency let you look at the best-in-class stores so to learn and apply their management choices in other stores

3. **OPT Net** (Product) - Multi-level distribution network optimization and simulation: One of the most advanced multi-level distribution network optimization and simulation system, OPT Net finds the best geographic location for logistics resources (i.e., factories, warehouses, point of sales) while combining demand requests with supply sources.

4. **OPT WAREHOUSE** (Product) - Warehouse process optimization: A set of math-optimization models' libraries with excellent integration capabilities with WMS and advanced adding-value functionalities for picking and inventory management, make OPT Warehouse a really best-of-breed warehouse process optimization system. Faster process execution, optimized spaces and workforce, deliver higher productivity and cost savings while lifting service levels.

5. **NET SOLVER RTD** (Product) - Optimal load dispatching: This robust technology has been thought to deal with constant disturbances of logistics process such as devices break-down, congestions and arrests coming out within factory's handling areas. Net Solver is a powerful optimizer built on innovative algorithms providing a really high accuracy level. Capable to work in synch with field devices it interfaces well with other systems (e.g., PLC -programmable logic controllers, WMS).

Relevant projects

ILIAD (See description in Sec. 4.1.1.)

1-SWARM (H2020-871743) ACTOR role: Project Coordinator. 1-SWARM project focuses on the design-operations for CPSoS with the specific focus on industrial sector of large-scale distribution and logistics. The project aims at achieving industrially acceptable level of robustness of CPSoS whose operation emerges as "Swarm Intelligence". 1-SWARM's solution will span across different steps of the value chain, connecting intelligence through the digital domain to maximize their effectiveness and reliability. The objective is to provide a methodological and technological framework, modular and re-usable ("Swarm Intelligence DevOps Framework"), for the engineering of the three major aspects of CPSoS: i) The HW/SW runtime platform that sustains their operations; ii) The distributed and orchestrated Intelligence that guarantees their autonomic behavior; iii) The extension of their "existence" into the cyber-domain for a full life-cycle approach.

DEMETO (H2020-768573) ACTOR role: Developer of plant control. Based on an internationally patented technology, the project foresees to bring at industrial level (through a completely functional pilot plant) the usage of microwaves as Process Intensification approach (through an electromagnetic catalytical effect) of the well-known alkaline hydrolysis depolymerization reaction. Such reaction was, up to know, economically unfeasible due to a certain number of technological constraints that DEMETO finally solves.

Major technical equipment and facilities ACT Operational Research as distributor of discrete-event simulator systems – ARENA Simulation (by Rockwell Automation) and SIMIO (Simio LLC proprietary product) – will provide these graphical simulation environments within the project as well as its decennial experience in the design and implementation of discrete-event simulations. ARENA, developed by Rockwell Automation, is the most used tool for simulation of discrete-event systems. It is an integrated graphical simulation environment including resources for modelling, design, process visualization, statistical analysis. With simulation you create real systems' virtual copies to dynamically analyze their behaviours, testing management criteria, assessing mission-critical circumstances, comparing design choices as well as concurrent projects and their investment returns. Arena relies on SIMAN, a powerful language avoiding to write codes' lines as modelling is an integrated graphical and visual process. SIMIO, produced by Simio LLC, is built on the "Intelligent Object" paradigm. SIMIO has been thought and designed by Dennis Pegden (co-creator of Arena Simulation software and of Siman simulation language). SIMIO is particularly known for its modeling speed and 3D functionality. With simulation you can model real systems to analyze their behaviour while testing the assumptions either they are technical (e.g., mission-critical) or economic (e.g. return on investments in concurrent projects).

4.2 Third parties involved in the project

ORU 1

No third parties involved.

TUM 2

Professor Sami Haddadin, the director of the Munich School of Robotics and Machine Intelligence (MSRM) at the Technical University Munich (TUM) is one of the founders and a minority shareholder of the company Franka Emika. For further description refer to "Members of the Consortium" section.

Bosch 3

No third parties involved.

UNIPI 4

No third parties involved.

EPFL 5

No third parties involved.

UoL 6

No third parties involved.

ACT 7

No third parties involved.

5 Ethics and Security

5.1 Ethics

The activities deemed to give rise to ethical issues in DARKO fall into three categories including:

- Participation of humans
- Protection of personal data
- Environment protection and safety

Each of these issues will be addressed in this section to ensure full compliance with the ethical standards of H2020 projects and EU and international directives.

5.1.1 Participation of humans

In the first phase of the project, DARKO partners will use an autonomous platform indicatively consisting of a Franka Emika Panda robot, which is mounted on a mobile platform. The Franka Emika Panda will later be replaced by an elastic manipulator, which is developed during the project. Adult participants will be involved in the research during the validation and testing of the prototypes and the system developed as part of DARKO. They may participate in some experiments, but there will be no physical contact between the robot and human. Furthermore, in T4.2 and T6.4 dedicated studies and research involving humans will be carries out; however, physical intervention on the study participants is not in the scope of the project. As a part of T4.2 and T6.4, TUM intends to gather human injury data by conducting some impact experiments. Only crash-test dummies will be used for these tests.

Recruitment for the project's research activities will be carried out locally and apart from the consortium researchers. All adults who work within the premises and environments of the DARKO validation locations are allowed to be a candidate for participating in the research in case of providing informed consent. Each DARKO partner is allowed to select and recruit participants for their tests. Subjects may be recruited from the general public on a voluntary basis, using advertisement and publication. The minimum and maximum number of volunteers necessary in each scenario will be defined prior to the beginning of the field trials. The necessary number of volunteers will be reached on a first come-first serve basis. All partners are committed to treat test participants respectfully and with honesty while subjects' safety will never put at risk during the tests.

Partners in communication with the project's Ethics Board will prepare informed consent forms stating all relevant information clearly so that all participants understand at all stages of their involvement. The participants should be informed about their right to withdraw from the study without providing any explanation for their withdrawal. The research team should always obtain a written consent regarding study participation; however, withdrawal can be communicated orally. The participants will be informed about DARKO, the details of trials, procedure to be followed, duration, outcome, risks and benefits without any deception about the objectives and the procedures related to the trials and evaluations.

5.1.2 Protection of personal data

All necessary procedures to ensure that data is collected, stored and used in compliance with related EU (Directive 95/46/EC and the General Data Protection Regulation) and national law (including privacy and data protection laws) are followed by the DARKO consortium. DARKO partners will only collect adequate, relevant and limited data, which is necessary in relation to the purposes of the project. Appropriate safeguards are used in processing of data for research purposes to enhances the data protection. Informed consent will be collected during all DARKO studies from all participating researchers and volunteers. All subjects will be clearly informed about the use and storage of any data recorded. No personal data will be recorded without explicit informed consent.

Furthermore, the sensors used in DARKO do not collect particularly sensitive data such as biometrics, medical or genetics information. Consequently, a national ethics approval is not necessary and the partners will seek guidance from local legal offices and ethics committees at their institutions (e.g., The Ethics commission at the Technical University of Munich[40]) We will also seek advise from the Data Protection Officer at coordinating partner ORU when necessary in questions of privacy and data integrity.

5.1.3 Environment protection and safety

DARKO does involve robot platforms that could, in principle, cause harm to humans (research staff), although driving speeds are low, and the robots are equipped with certified safety sensors and emergency stops. Furthermore, DARKO has dedicated WP7 to investigate risks and establish a multi-dimensional risk space and follow a risk-minimisation principle. Moreover, T4.2 and T6.4 focus on human safety. The core concept of these tasks is based on developing Safe Motion Units (SMU) for the fixed base and mobile manipulator in the environments shared between human and robots. Regardless, all national guidelines and standards will be followed throughout the project to ensure the safety of staff and subjects involved. More specifically the consortium will refer to ISO 10218 to determine collaborative requirements between humans and robots and limit the maximum of velocities and forces mobile robot operating in an industrial environment. Besides, technical experts from DARKO team will supervise the tests to ensure that safety procedures are respected.

5.2 Security

- DARKO will not involve activities or results raising security issues.
- DARKO will not involve "EU-classified information" as background or results.

[40] The Ethics commission at the Technical University of Munich is composed of 17 members from a wide range of disciplines including internists, surgeons, nuclear medicine specialists, paediatricians, anaesthetists and pharmacologists, statisticians, lawyers, a medical ethicist and a pastor. They protect participants and patients against irresponsible treatments through scientific research activities. Every clinical study with a leader from TUM should be approved by the ethical committee before the study begins. There are some general questions, which are not directly related to medical laws and should be replied for submitting an application including scientific significance, study design, ratio between benefits and risks, fairness, necessity of insurance, data protection, resources, finances and conflicts of interest. A decision period of up to 60 days applies to an application. Meetings take place every two weeks and the critical aspects of studies are discussed among the members.

A Letters of intent

ARENA2036

ARENA2036 e.V.
Pfaffenwaldring 19
70569 Stuttgart, Germany
Phone +49 711 685 68361
www.ARENA2036.de

ARENA2036 – Pfaffenwaldring 19 – 70569 Stuttgart

Prof. Dr.-Ing. Achim Lilienthal
Örebro University
SE-701 82 Örebro

29.05.20

Subject: EU-Proposal DARKO

Dear Prof. Dr. Lilienthal,

Following up on our recent correspondence, I would like to underline our interest in your proposal and to confirm the support of ARENA2036 for the H2020 ICT-46 project **DARKO – D**ynamic **A**gile Production **R**obots That Learn and Optimize **K**nowledge and **O**perations.

As a federally funded Research Campus that unites the innovation endeavors of industry and science alike, ARENA2036 runs a number of projects that deal with questions adjacent to those of yours. I am confident that DARKO would not only inspire the researchers on site at ARENA2036 but that it would be a nucleus for further activities at our Research Campus. Especially, since ARENA2036 offers the opportunity to quickly link science and industry in so-called speedboat projects that would allow to pursue specific questions emerging from your work done in DARKO.

We see DARKO as a visionary project with high disruptive potential that complements our portfolio of ongoing activities. In particular, and along the lines of our ambition to actively shape work, mobility, digitalization, and production of the future, we are interested in the DARKO contributions for easy-to-deploy, self-learning, socially and semantically aware AGVs as well as high-performance dynamic manipulation and robotic throwing in shared man-machine environments.

We commit to host the DARKO project and offer our infrastructure, services and unique network of ARENA2036 members and partners. DARKO will receive a dedicated space for its demonstrator system, access for the DARKO team during integration weeks, project meetings and stakeholder events. The ARENA2036 platform is a uniquely ideal environment for stakeholder management for DARKO and we are happy to support the project in the goal to maximize and realize its exploitation potential. This shall include commonly organized workshops, demonstration or other events and the enable the possibility to integrate the DARKO demonstrator with systems and demonstrators of existing partners on the ARENA2036 platform.

Sincerely yours,

(Peter Froeschle)

ARENA2036 e.V.
info@arena2036.de
www.arena2036.de

Baden-Württembergische Bank
DE67 6005 0101 0001 2042 69
SOLADEST600

Geschäftsführer: Peter Froeschle, Vorsitzender: Andreas Friedrich, stellv. Vorsitzender: Wolfram Ressel

Steuer-Nr.: 990 150 731 9
USt-IdNr.: DE294963383
VR 721329 Stuttgart