SafeLog

Safe human-robot interaction in logistic applications for highly flexible warehouses

Title: A simulation-based test environment for a heterogeneous warehouse system - version 1

Deliverable: D3.2

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Contents

1 Summary

To test the communication interfaces between different components of the warehouse, a simulation based test environment is being constructed. This environment can be also later used to support debugging, testing and verification of developed planning algorithms, simulation of agents moving inside the warehouse and monitoring system components. Since the project adds human workers into the planing infrastructure, the environment needs to innately support heterogeneous agents.

In this document we describe the first version of the test environments, the communication between components of the environment, the extension of the present systems with a human component, and finally the implementation of the warehouse in a Virtual Reality environment to extend the scope of possible test scenarios.

2 System architecture, communication and 2D vizualisation

The simulation is an important part of the project, as it allows us to test and troubleshoot components without the need for tests inside a test environment, or even an actual warehouse (a very costly and infeasible option). During the initial discussion regarding the simulation, the purpose of the test environment was first defined together with its main components (e.g. robot and human simulation, visualization, *CO005: Fleet Management System* simulator, *CO004: Warehouse Management System* simulator, etc.) and their basic functionalities. It was decided that the particular components will be realized as standalone programs which communicate with each other via defined interfaces (sockets, web services, etc). The implementation follows the architecture as defined in *D1.4 System Specification [M9]*, subsection 3.6. For a simplified diagram of the system refer to Fig. 1.

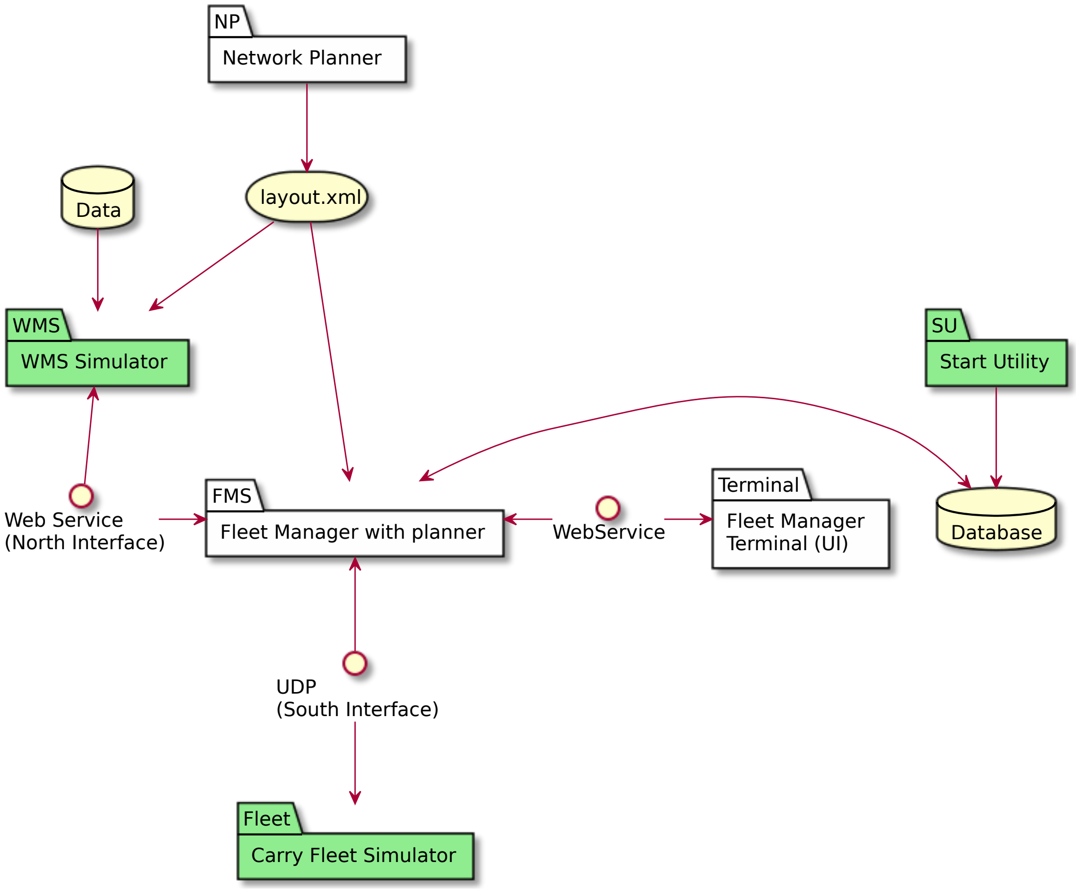

Figure 1: Simplified FMS Emulation System Architecture.

Presently the simulator consists of 5 components, with other diagram components added as the project progresses:

- the *CO005: Fleet Management System*
- the Carry fleet simulator
- the Fleet manager terminal (the UI)
- the Virtual reality simulator

Since a simulation of sensors and dynamics was not needed and since full robotic simulators (e.g. Gazebo) are too complex a decision was made that writing our own simulator and visualization environment for SafeLog is the best option. Moreover, all interactions of simulated components are event based and don't require physical simulation (e.g robot picks rack, humans picks object from rack etc.) Based on the made decision, several visualization libraries and game engines were considered and tested:

- Game Engines:
  - Oxygine
  - Spring
  - Cocos2d-x
  - GODOT
- Visualization libraries
  - Cinder
  - bgfx

The "Simple and Fast Multimedia Library" (SFML) was chosen and the development of the visualization module will be thus conducted in it. The first version of the simulation component was realized in C++ by implementing the South interface (the interface between *CO005: Fleet Management System* and *CO006: AGVs*) as described in *20160203-in-wuc-e-1-swisslog-fleetmanager-southinterface.pdf*. All of the components exchange JSON messages. The communication conducted through a serialised UDP protocol is currently being implemented to make the simulation component fully compatible with the SLA code. Finally, an application to allow visualization of the robots traversing the planned trajectories and the visualisation of loading and unloading racks was also created. This was further extended with the implementation of the human component as described in the next chapter. The visualisation of the *CO006: AGV* simulation is shown in Fig. 2.

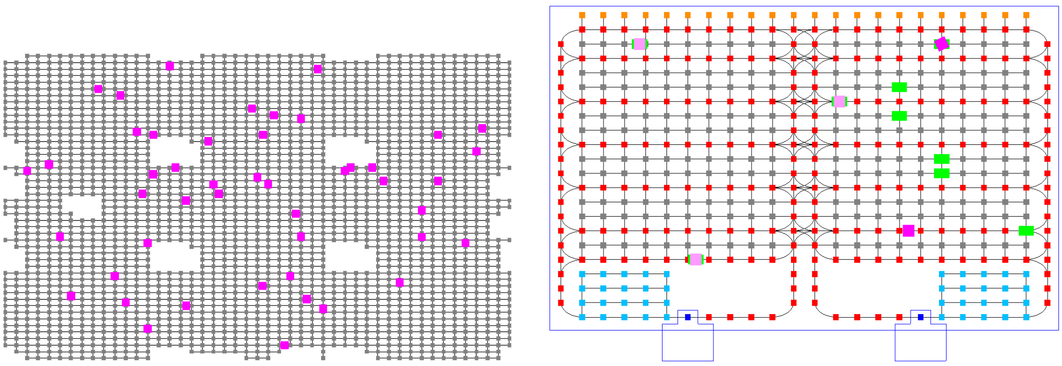

Figure 2: Visualization of simulated behavior of robots traversing planned trajectories.

3 Representation and Simulation of Humans

The base system was extended to incorporate "Human" as an element of the warehouse. In contrast to robots, which are required to follow commands from *CO005: Fleet Management System*, humans can behave differently. For example, humans can choose not to follow the path assigned to them, or accidently deviate from it, while robots can't. Additionally, the communication protocol for the robots defined as the south interface was not appropriate for the human since humans do not follow paths like splines, rather move directly to the target. For a detailed description of the interfaces please refer to *D6.1 System Framework Architecture [M18]*.

3.1 The communication protocol between human and FMS

To represent humans in the simulation, the south interface was extended to support communication between human and *CO005: Fleet Management System*:

- Similar to the "DriveAlongPath" command for the robot, the new command type "MoveAlongPath" for the human is designed. Rather than having complicated types of movements for the robot, the "MoveAlongPath" command simply contains a list of nodes to travel for the human. As long as the human arrives at the last node, the command is successfully executed. The command defines additionally the start and end angle for the movement, which can be visualized in the AR device to indicate the direction of travel.

Table 3.1: Humans "MoveAlongPath" command

Parameter	Type	Description	Unit	Range
NumberOfNodes	Int32	Number of nodes in the list		
NodeList	[]	List of Nodes human should move along		
StartAngle	UInt16	Absolute orientation	1/10	0..3599
EndAngle	UInt16	Absolute orientation	1/10	0..3599
PathLength	Int32	Length of the path from start to target node.	mm	

- A dedicated "StatusHuman" message is defined to let the human synchronize with the FMS. The localization algorithms will deduce the current position and orientation of the human, which will be sent back to the FMS. Similar to the robots' "Status" message, general system status like WLAN Quality and Battery are also synchronized with FMS.

Table 3.2: Humans "Status" command

Parameter	Type	Description	Unit	Range
StatusIndex (SI)	Int32	Consecutive number identifying each Status message.		
NodeId	Int32	The Id of the detected node. Zero if no node was detected.		
NodeOrientation	UInt16	The absolute orientation of the human on the currently detected node.	1/10	0..3599
MobileRackId	UInt16	Id of the mobile rack where human performs some operation.		
WLANQualityOfServiceIndicator	Byte	The WLAN quality experienced by the human on the current node.		
BatteryStatus	Byte	Linear interpolation of the battery capacity in percent.	%	0..100
ErrorSeverity	Byte	Message, Warning, Error, FatalError		
ErrorCode	Byte	Possible error code		
CRCFailureCounter	UInt16	Messages received by the Human with CRC errors since last power up of the SafetyVest (Human).		
ReadMarkerId		The marker id read when the operation was completed		
ReadMarkerQuality		The marker read quality		
ReadMarkerSubNodeId		The SubNodeId of the detected node. 255 if no sub node was detected.		

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Table 3.2: Humans "Status" command (... continued)

Parameter	Type	Description	Unit	Range
DeltaXPositionDeviation		The deviation of the human in x direction to the ideal node position when reading the current node id.	mm	
DeltaYPositionDeviation		The deviation of the human in y direction to the ideal node position when reading the current node id.	mm	
DeltaThetaRotationDeviation		The rotation deviation of the human in 0.1 degrees	degrees	
ReadMarkerDelay		The marker read delay in 10 ms.	ms	

3.2 Implementation of the simulated human

The described protocol has been implemented in the simulation software. Since the path planner is not integrated in the current implementation of the simulation, the system is not able to react to the behaviour of the human. Thus, the human receives a "MoveAlongPath" command at the beginning of the simulation, and follows the nodes in the given path. The following image (Fig. 3) demonstrates a running simulation with 4 robots and 3 humans.

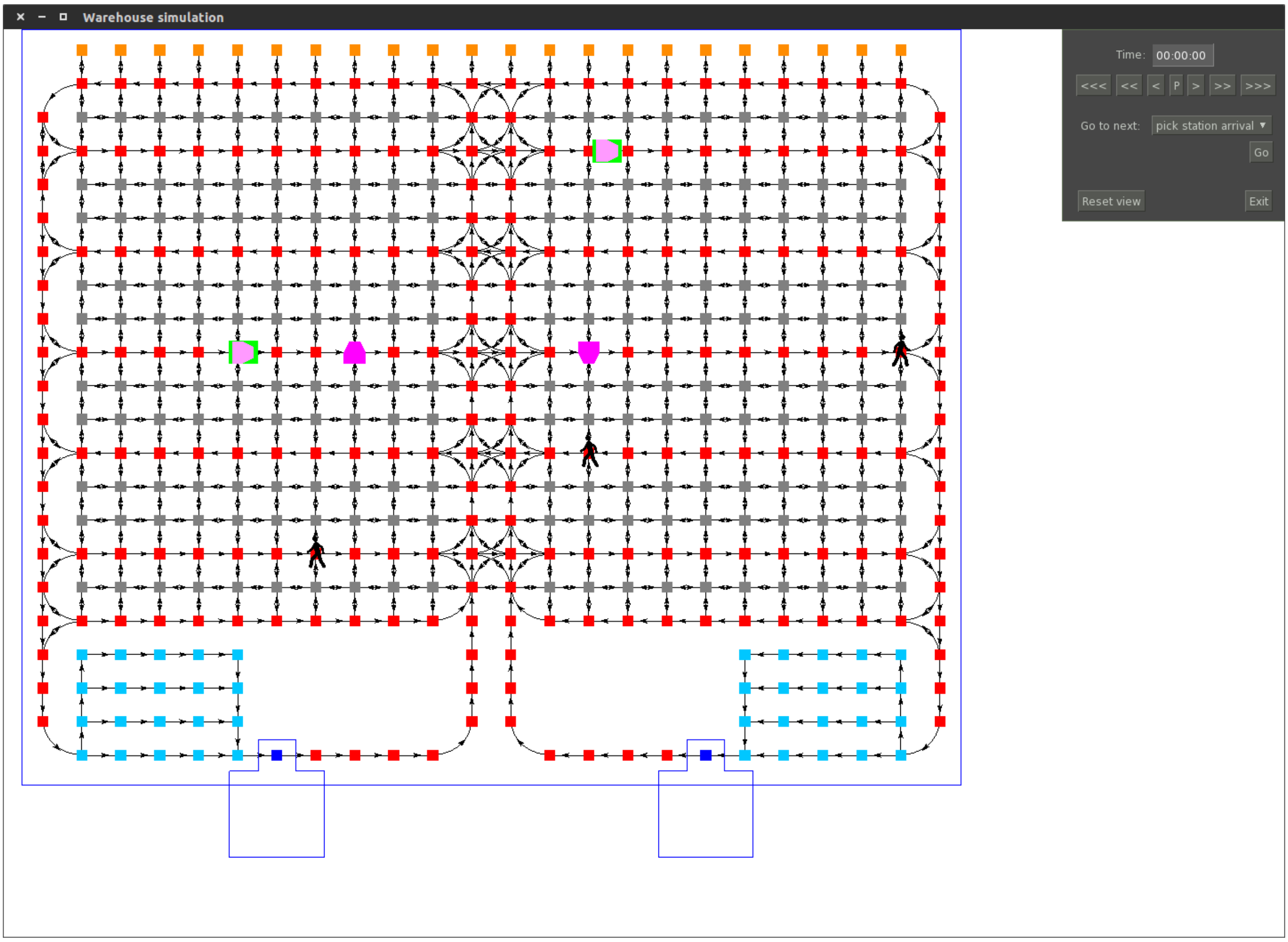

Figure 3: A visualisation of the warehouse with both humans and robots inside.

4 Virtual Reality implementation

The implementation of the Virtual Reality component was driven partially by the desire to test the system as accurately as possible in the sense of component interaction while still avoiding to close down an entire warehouse for tests. Unlike in the standard simulation mentioned before, here the behaviour of the human doesn't need to be simulated as there is a real human moving in a virtual warehouse. Testing this in virtual reality may allow us to see phenomena not evident from the normal simulator with simulated human behaviour. Presently the system communicates with the simulated *CO009: Fleet Manager Terminal* via JSON messages containing robot trajectories and orders. In this regard the robots can move in the 3D environment and pick up or deposit racks. The communication between other components and the worker in the warehouse is currently not yet implemented. Also, as of the time of writing this deliverable, safety levels A and B (slowing of the robot if in the safety radius B and stopping if in safety radius A) are in the process of implementation. The safety levels will need to be implemented modularly, with the ability to change the ranges normally (by changing the radius) or because obstructions, while avoiding to simulate the propagation of UWB waves used in ranging between the *CO001: Safety Vest* and the *CO006: AGVs* . This will allow us to consider worst case scenarios while leaving the simulation of wave propagation to specialised software. A screenshot of the present state of the VR simulator can be seen in the following figure (Fig. 4)

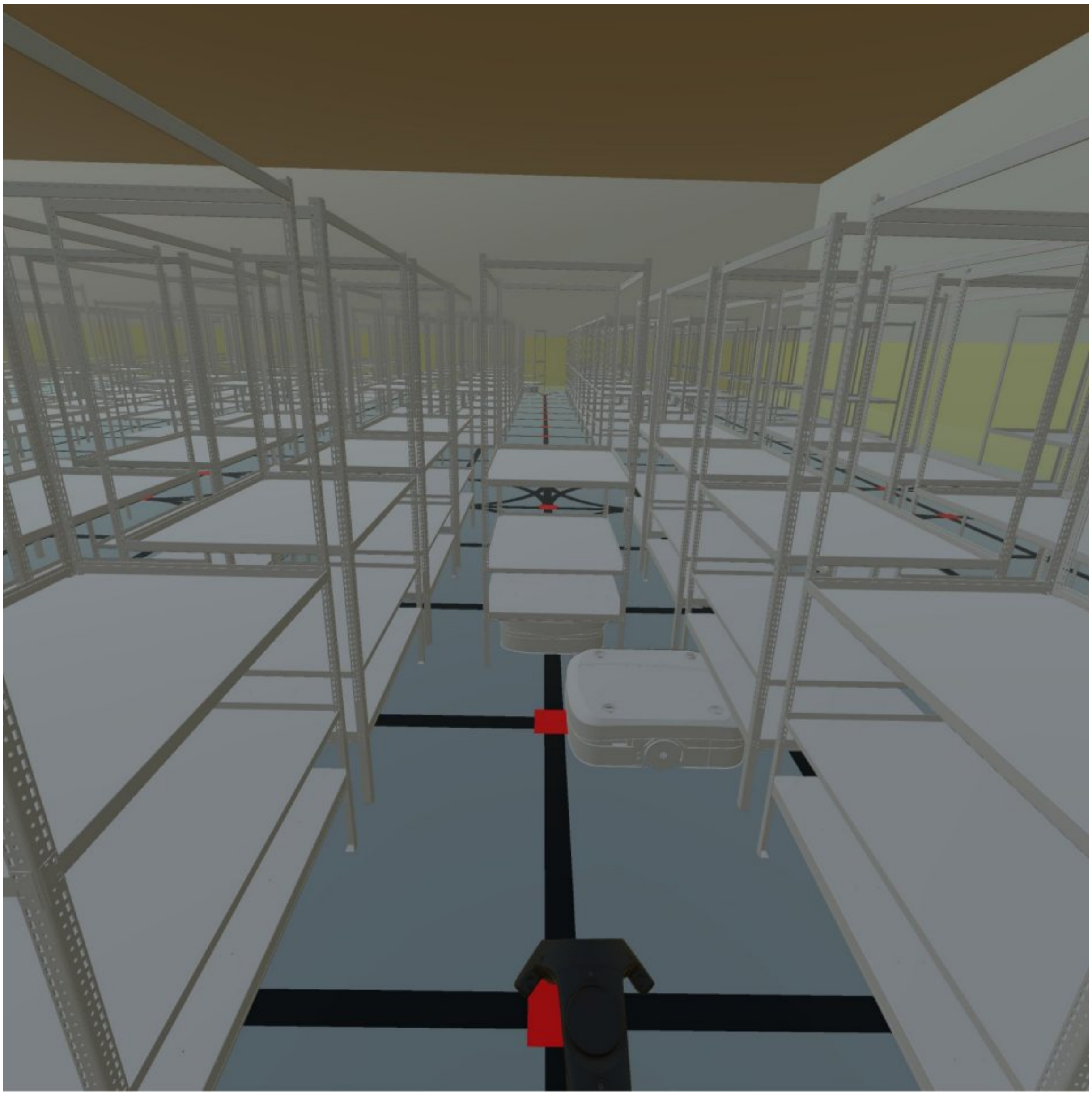

Figure 4: The simulated 3D environment in Unity3D from the human perspective; both a rack carying robot and an rackless one moving below the racks can be seen .

5 Consortium

5.1 Karlsruhe Institute of Technology

The Karlsruhe Institute of Technology (KIT) is a higher education and research organisation with about 10.000 employees, 25.000 students, and a total annual budget of about 750 million Euros. It bundles the missions of both precursory institutions: a university of the state of Baden-Württemberg with teaching and research tasks and a large-scale research institution of the Helmholtz Association conducting program-oriented provident research on behalf of the Federal Republic of Germany. Within these missions, KIT is operating along the three strategic fields of action of research, teaching, and innovation.

In establishing innovative research structures, KIT is pursuing joint strategies and visions. KIT is devoted to top research and excellent academic education as well as to being a prominent location of academic life, lifelong learning, comprehensive advanced training, exchange of know-how, and sustainable innovation culture. KIT's research profile is characterised by a strong focus on information and communication technology, energy technology and mobility. It has significant competencies in the fields of optics and photonics, climate and environment, and the inter-relations of humans and technology. It hosts a significant number of infrastructures of federal or European importance.

KIT builds on the extensive experience its predecessors have gained in EC-funded research from more than 1000 projects up to now.

The **Intelligent Process Control and Robotics Lab (IPR)** is part of the Institute for Anthropomatics and Robotics (IAR) and covers a vast variety of robotic and automation areas. Research in the field of industrial automation comprises conception and realisation of sensor based autonomous robots for typical tasks in production. Another area is safe human robot co-operation integrating multiple sensors and novel interaction techniques. Further activities consist of designing modular control and diagnosis systems for robots, robot cells and plants based on multi-agent architectures.

FORscience is the central Proposal and Project Management Service at KIT. Established in 2009, it pools KIT's many years of experience in project management. The Project Management Office thus offers professional expertise in all aspects of project management. Its members have substantial experience in supporting EU and other projects from proposal phase to execution, including for example the FP7-CP DACCIWA and the Horizon2020-FoF ProRegio, for both of which FORscience serves as the PMO.

Role

KIT has two roles:

1. KIT will be coordinator of SafeLog. Coordinating person will be Björn Hein. The department FORScience of KIT will handle all management issues (s. previous paragraph, section *Management structure and procedures* and **WP8** in document Part 1).

2. Regarding research and innovation KIT will mainly focus on the human-system interaction and assistive technologies in the envisioned flexible and collaborative warehouse **WP4** with the corresponding relations to the other work packages.

5.2 Swisslog Automation GmbH

Swisslog is one of the leading companies for automation and logistics solutions. For many years Swisslog has been a technological leader in many industrial sectors and has been exploiting innovative solutions for its customers. The portfolio of Swisslog comprises

swisslog
inspired solutions

- Intelligent material handling, production, and automation technologies
- Conveyor systems for light goods and pallets
- Shuttle systems and cranes
- Storage and Robot systems for automated case picking
- Automated Guided Vehicles
- Production lines and equipment for building materials
- Modular Warehouse Management and Control Systems

Swisslog is eager in participating in this project as Swisslog sees a big chance in exploiting the fast growing logistics automation market by state-of-the-art goods-to-man systems. Swisslog however wants to support European research to give this research an industrial platform.

Role

Swisslog provides expertise in automation and logistics ranging from industrial robot applications, electrical overhead monorails, transport AGVs and goods-to-man systems. Swisslog will handle the demonstrator based on a fleet of mobile goods-to-man robots. For this system prior work exists comprised of fleet-manager, standard safety infrastructure and also a 2D emulation environment. Swisslog will take the lead of WP1 and WP6.

5.3 Czech Technical University in Prague

The CZECH TECHNICAL UNIVERSITY IN PRAGUE (CVUT), founded in 1707, is one of the oldest technical universities and currently the leading technical university in the Czech Republic with approx. 23000 students enrolled in engineering courses. With over 1700 members of academic staff is also one of the largest research institutions in the Czech Republic. The Czech Institute of Informatics, Robotics, and Cybernetics (CIIRC) that will participate in the project is a new institute of CVUT founded in 2013 with the aim to concentrate an excellent research in the fields robotics, intelligent, distributed and complex systems, automatic control, computer-aided manufacturing, bioinformatics, biomedicine and assistive technologies. The key researchers of CIIRC have come from the Department of Cybernetics, Faculty of Electrical Engineering of CVUT this year, which is recognized as an outstanding research centre at the CVUT. In 2000 the department received the "EU Centre of Excellence"' award and in 2006 the prestigious European IST Prize by the European Commission. The Department includes over 80 academic staff and researchers, and over 30 Ph.D. students. The research focus covers the areas of intelligent mobile robotics, computer vision, artificial intelligence, biomedical engineering, and multi-agent systems. The department has been actively involved in scientific collaboration with international partners via various types of research programmes namely FP7/FP6/FP5 programmes. The Department has a strong industrial experience in providing research and development, training services and customized solutions to international industrial partners (e.g. Robert Bosch GmbH, Rockwell Automation, SKODA AUTO/Gedas CR, CADENCE, DENSO Automotive, BAE Systems). Additionally the department extensively collaborates with the defense industry (European Office for Aerospace Research and Development, US Air Force Research Laboratory, US Office for Naval Research and Army Research Laboratory).

CTU
CZECH TECHNICAL UNIVERSITY IN PRAGUE

Intelligent Mobile Robotics divison (IMR) (`http://imr.felk.cvut.cz`) will be involved in the project. This unique laboratory founded in 1993 and headed by Dr. Libor Preucil since, steadily builds excellence in mobile and intelligent systems and robots and stand for major stakeholders in the field in the Czech Republic. Recently, he co-founded **Center for Advanced Field Robotics (CAFR)** (http://lynx1.felk.cvut.cz/cafr) bringing together main robotics research labs and industry in the Czech Republic. Dr. Libor Přeučil is going to supervise herein suggested project and will assure the top level quality research within.

Role

CVUT will lead **WP3**. The target of the workpackage is to realize a planning module that will provide coordinated plans for robots and humans in the warehouse CVUT will also significantly contribute localization activities in **WP2** as well as specification and requirement analyzis **WP1** and integration **WP6**.

5.4 University of Zagreb, Faculty of Electrical Engineering and Computing

The **UNIZG-FER** (http://www.fer.unizg.hr/en) is the highest-quality member of the University of Zagreb, with a large and modern infrastructure devoted to research-based education. Currently UNIZG-FER participates in more than 20 projects financed by EU through various grant schemes (HORIZON 2020, FP7, IPA, COST, etc.). With 170 professors, 220 graduate teaching and research assistants, 4.000 students enrolled in various programs, and operating in facilities of more than 40.000 m2, UNIZG-FER is the largest and leading educational technical and R&D institution in the fields of electrical and computer engineering and computer science in Croatia. UNIZG-FER is organised in 12 Departments which represent the focal points of education and R&D. Research related to this project will be carried out at the Department of Control and Computer Engineering (DCCE) by the Autonomous Mobile Robotics group (AMOR group, http://act.rasip.fer.hr/groups_amor.php).

The AMOR group has a long tradition in research of advanced control strategies and estimation techniques and their application in autonomous navigation of ground and aerial robots in unknown and dynamic environments. The major research activities of the group include: Simultaneous Localization and Mapping (SLAM), Detection and Tracking of Moving Objects (DATMO) and Motion Planning and Control (MPAC). The Group currently consists of 3 Postdocs and 5 PhD students directed by Prof. Ivan Petrović. Laboratory of the AMOR group is equipped with state of the art ground mobile platforms, aerial vehicle, sets of advanced perception sensors, flying arena, etc. The group coordinated the major national robotic research program “Intelligent robotic systems and autonomous vehicles” (2007-2014), which involved 5 major robotic research groups in Croatia. The group has also a long tradition of collaboration with research centres in the EU and worldwide. Currently, Professor Petrović, the head of the AMOR group, is coordinating the EU project “ACROSS - Centre of Research Excellence for Cooperative Robotic Systems” (http://across.fer.unizg.hr), which involves 14 research groups from the University of Zagreb and 16 research institutions from 10 European countries. AMOR group recently successfully organised two robotic conferences: (1) the 4th European Conference on Mobile Robots - ECMR’09 (www.ecmr09.fer.hr) and (2) the 10th IFAC Symposium on Robot Control - SYOROCO 2012 (http://www.syroco2012.org).

Role

UNIZG-FER will lead **WP2**. The target of the workpackage is development of a holistic safety concept that will allow safe collaboration of humans and robots in the warehouse. UNIZG-FER will also contribute in human aware planning in **WP3**, localization and human intention recognition in **WP4**, specification and requirement analyzis in **WP1** and integration in **WP6**.

5.5 Fraunhofer IML

The Fraunhofer Institute for Material Flow and Logistics (IML) has been tackling logistic tasks, mainly the process, hardware and software development for internal and external logistics. The IML turnover consists of more than 50% of industrial contracts for software development in different logistical applications, supply chain consulting and R&D of novel logistical solutions. Knowledge acquired from funded projects is directly transferred in industrial contracts. So made-to-measure arranged teams create cross-industry and customer-specific solutions in the area of materials handling, warehouse management, supply chain management, simulation supported business and system planning and also traffic systems, closed loop economy, resources logistics, building logistics and e-business. IML is said to be first address for all questions with respect to holistic logistics, the employees work on all fields of internal and external logistics. At the Institute, founded in 1981, there are at the moment 200 employees as well as 250 post-graduates, supported by colleagues in workshops, laboratories and service areas.

Role

IML has a comprehensive knowledge about a multitude of interlogistic applications as well as a deep knowledge about development of embedded eletronic components and robotic solution.

In this position IML will contribute to the overal integration of the different concepts by leading the **WP6**. Furthermore IML will bring in the expert knowledge in embedded systems and communication technologies to contribute majorly to the safety concept and hardware development of the vest as part of **WP4**.

5.6 KONCAR - Electrical Engineering Institute Inc.

KONČAR – Electrical Engineering Institute (www.koncar-institut.com) is a leading Croatian industrial institute involved in R&D of equipment and technologies for efficient and reliable energy conversion and power transmission. As a result of a 50-year-tradition in applied R&D, KEEI has developed proprietary solutions for monitoring systems (transformers, electrical rotating machines, bay/switchyard, wind turbines), off-grid power supplies as well as platforms for design of demanding embedded HW/SW systems (including safety related SIL4 platforms). KEEI has been involved in several European and national R&D grant schemes (EUREKA, Proof of Concept (PoC), IPA, ERDF etc.) and has a lot of experience in implementation of various R&D projects. Currently there are 164 employees at KEEI, it is organized in 6 departments and its premises occupy 13.000 m2. In the frame of 6 departments there are specialised R&D sub-departments and 9 well-equipped laboratories which are used for R&D support, testing and diagnostics. In July 2014 KEEI became a Notified Body of the European Commission for several important EC directives (low voltage equipment, machinery, EMC, radio and telecommunications terminal equipment, appliances burning gaseous fuels, pressure equipment and personal protective equipment). Research related to the proposed project will be carried out by Control, Renewables & Power Electronics Department. This Department employs 30 experts and offers extensive knowledge in design, development and testing of industrial embedded control systems (HW and SW components), renewable energy solutions and power converters used in traction and energy applications.

Control, Renewables & Power Electronics Department: The Department is specialized in design, development and testing of industrial embedded control systems, renewable energy systems and power converters. It develops HW and SW components for industrial embedded control systems and complete systems for highly demanding applications such as rail vehicles and power engineering. Based on initial technical and functional requirements, the Department prepares complete production documentation, performs various tests (type/serial) and eventually provides product life-cycle management. The Department has successfully developed railway crossing safety platform SIL 4 which was positively assessed by TÜV according to EN50126, EN 50128 and EN50129.

Role

KEEI will lead **WP5**. The goal of this work package is to develop a Safety Vest which enables humans to safely enter and work in a flexible warehouse system with AGVs. Special attention shall be given to safety certification of the safety west and the Safety Concept developed in **WP2**. KEEI will contribute to the Project with its experience in embedded systems design and in development and certification of safety critical control systems for railway applications.

6 Glossary

Glossary

AGV
Automated Guided Vehicle: An Automated Guided Vehicle is a mobile robot that follows markers or wires in the floor, or uses vision, magnets, or lasers for navigation. They are most often used in industrial applications to move materials around a manufacturing facility or warehouse. Application of the automatic guided vehicle has broadened during the late 20th century.. 6, 9, 12, 15

AR
Augmented Reality: Augmented reality is a visualization technique where a direct (e.g through glasses) or indirect (through a camera and screen) view of the real world is supplemented by sensory input and data to achieve a better and more informative understanding of the scene.. 7

EMC
Electromagnetic compatibility: Electromagnetic compatibility is the branch of electrical sciences which studies the unintentional generation, propagation and reception of electromagnetic energy with reference to the unwanted effects (Electromagnetic interference, or EMI) that such energy may induce. The goal of EMC is the correct operation, in the same electromagnetic environment, of different equipment which use electromagnetic phenomena, and the avoidance of any interference effects - Wikipedia.. 14

FMS
Fleet Managment System: The Fleet Management System cares about scheduling and computing trajectories for mobile robots based on orders given by the WMS. The present system will be updated with real-time replanning, human avoidance planning, and heterogeneous fleet planning features.. 5, 7

PMO
The Project Management Office: The project Management Office consists of personnel from KIT FORScience (cf. description of KIT). 11

SIL
Safety Integrity Level: Safety integrity level is a relative level of risk-reduction provided by a safety function, or a targeted level of risk reduction. In other words, SIL is a measurement of performance required for a safety instrumented function.. 14, 15

UWB
Ultra-Wide-Band: UWB is a radio technology pioneered by Robert A. Scholtz and others that can use a very low energy level for short-range, high-bandwidth communications over a large portion of the radio spectrum. UWB has traditional applications in non-cooperative radar imaging. Most recent applications target sensor data collection, precision locating and tracking applications. Unlike spread spectrum, UWB transmits in a manner that does not interfere with conventional narrowband and carrier wave transmission in the same frequency band.. 9

References