Safe Cooperating Cyber-Physical Systems using Wireless Communication

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Revision History

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001	2018-03-16	Document created, main content added following specifications of the SafeCOP Project Management Team (PMT).	M. Juelsgaard	K. Jeppesen C. Pilgrim
002	2018-03-22	Minor updates based on reviewer comments.	M. Juelsgaard	K. Jeppesen C. Pilgrim

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1 Introduction

This document represents the written contribution for SafeCOP deliverable D5.1, documenting the progress of the first use case (UC1) associated with T5.1 within WP5.

This document is in support of the physical demonstration documented through a video to be published via the Danish Technological Institute (DTI) youtube channel [1] early April, 2018.

The scope of D5.1 has been limited to completing T5.1 for demonstration in a lab setting, and so further work still remains within the overall scope of UC1, as outlined in Section 5.

In the following, Section 2 elaborates the overall details about UC1, whereafter Section 3 outlines the technical details concerning the framework developed for the demonstrator. Subsequently, Section 4 provides a detailed explanation of the physical demonstration and the technical achievments documented therein. Further work to be conducted within the remainder of the project is outlined in Section 5, before elaborating on exploits and end-user values in Section 6.

2 Use Case Elaboration

The following elaboration is largely an excerpt from [2] and may be illustrated as in Figure 1.

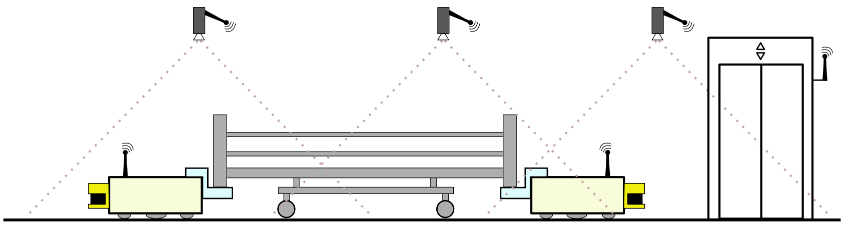

Figure 1: Conceptual outline of UC1.

The purpose of UC1 is to develop a two-robot autonomous bed mover which can wheel ordinary hospital beds through the cluttered and populated corridors without mishap. Neither the robots nor the un-instrumented bed between them will hit anything. In case of safety assurance violation or external emergency, the system must decide whether to stop, pull to the side, or proceed to a safe stop-zone.

The robots are given a target destination for the bed and must autonomously plan a transport path from their origin, to the destination.

Each robot is individually instrumented with sensors allowing detection of obstacles breaching safety zones. This allows the robot to react appropriately when moving around on its own, *e.g.* by slowing, driving around obstacles, or by stopping. This safety needs to be maintained also when two robots collaborate on moving a bed. For this, reliable Vehicle-To-Vehicle (V2V) communication is essential for both the basic task of synchronous movement, as well as safety functionality in terms of *e.g.* synchronous safety stop.

In addition to V2V communication among the robots, UC1 also encompass Vehicle-To-Infrastructure (V2I) communication with distributed sensors to warn the robot-train about obstacles, safety hazards, *etc.* beyond the Field of View (FOV) of the robots. This allows the robot-train to account for safety hazards that are yet out of sight for the robots, *e.g.*

when moving around a sharp corner of a corridor, or when approaching an intersection. By the extended FOV provided by external sensors, the robots may plan accordingly ahead of time, *e.g.* by

a) Identifying a local safe-place where the robots can wait,

b) Find a safe mode of travel *e.g.* at half speed or using extra-wide cornering.

The use and importance of both V2V and V2I communication requires strict monitoring of the communication integrity. This implies *e.g.* that it must be detected if a communication link breaks down so that appropriate measures may be taken. If the V2V link drops, proper movement of the robot-train may not be guaranteed and the fallback strategy could be emergency stop, safe docking, *etc.* If a V2I link is lost, it may be required to avoid navigation in part of the hospital where the affected sensors are installed, since the benefits of an extended FOV is not available if communication with the sensors is out of order.

The overall concept described above can be graphically illustrated by Figure 2.

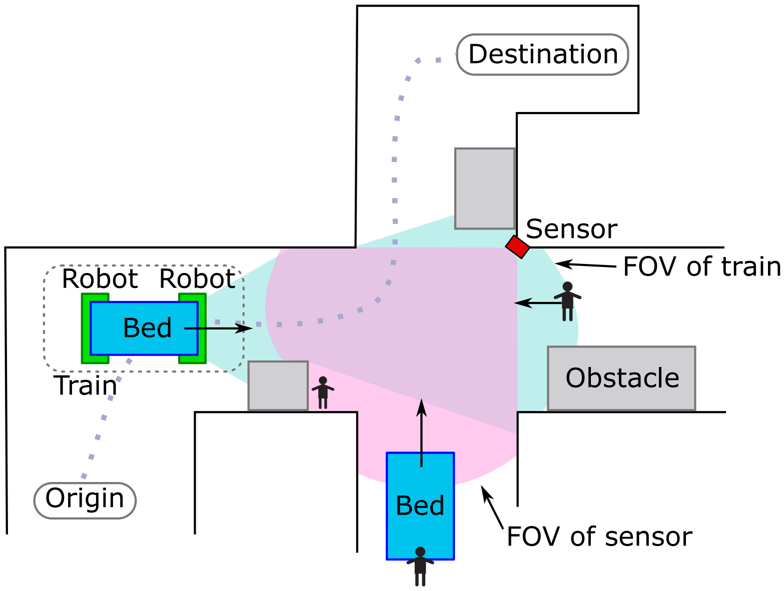

Figure 2: The robot-bed train must move from the origin position to the provided destination, without hitting obstacles or people along the way. The FOV of the robot-train is extended by external sensors along the corridors.

The intended behavior of the fully commercialized system is that the robots travels to a hospital ward when called, latches onto the bed indicated by staff and drives it safely to the Central Bed Washing Facility (CBWF) via hospital corridors, elevators, doors, *etc.* Compared to the fully commercialized system, the scope of the use-case is limited to navigating a bed through service-corridors and doorways only.

Service corridors are more cluttered than public corridors but have fewer vulnerable people in them (but do have fast service vehicles). For the commercialized system, travel through public areas will be unavoidable, but to limit human traffic UC1 seeks to focus on service corridors.

2.1 Use-Case Requirements

Based on the use-case description [2] and the work in [3, 4] conducted by WP1, the SafeCOP requirements related to UC1 are summarized in Table 1. The leftmost column indicates the party responsible for providing ways of satisfying the requirement within the project. As shown, the requirements to be governed solely by UC1 are UC1004, UC1007, UC1008 and UC1010. The material provided in the Section 3 and 4 is to indicate our approach and progress for accommodating these.

Req.	Title	Text	Resp.
UC1004	Detect communication loss and degradation	Detection of communication loss or degradation for V2V and V2I communication.	UC1
UC1005	Real time V2V communication	Communication between vehicles with a guaranteed latency.	WP3
UC1006	Error detection	Error detection on all communication channels for V2V and V2I.	WP3
UC1007	Connection establishment [V2I].	Fast and reliable connection establishment between vehicles and infrastructure.	UC1
UC1008	Communication range [V2I]	Minimum range of 25 m for V2I connection and communication.	UC1
UC1009	Communication encryption [V2I]	Data transfer must be encrypted due to video recordings of people (sensitive data	WP3
UC1011	Communication encryption [V2V]	Data transfer must be encrypted to prevent unauthorized manipulation or control.	WP3
UC1010	Connection graph scalability [V2I and V2V]	Connecting to multiple nodes at the same time must be possible in a dynamic fashion so that nodes may join or leave during runtime.	UC1
UC1003	Internal safety envelope	Detect and warn of malfunctioning software applications or hardware modules so the system can take precautions or degrade safely.	WP4
UC1010	Sharing of safety states	Reliable propagation of safety states both V2I and V2V.	WP4

Table 1: Project requirements identified for UC1.

3 Technical Framework

The technical framework of UC1 is entirely provided by DTI in the following sense:

- The robot platforms are constructor by DTI:
  - All hardware, mechanical or electrical, has either been designed and constructed by DTI or acquired as off-the shelf components

  - All tasks pertaining to assembly and system integration is conducted by DTI
- All software is provided by DTI:
  - Either written by DTI specifically or found as readily available open-source components
  - All integration and configuration is conducted by DTI

In the following, Section 3.1 and Section 3.2 elaborates on the hardware (HW) and Software (SW) structure respectively. Since the V2V and V2I communication plays a significant role of UC1, Section 3.3 elaborates further on the particulars of the communication framework.

3.1 Hardware Overview

The HW components of the robot platforms is conceptually illustrated in Figure 3 and summarized below:

- **Batteries**
  The source of power for the robot
- **Power management**
  Additional components to transform the direct battery voltage into other voltage levels supplied to various components.
- **Motors and gears**
  The actuators responsible for moving the robot. The speed of the motors is regulated by a motor controller.
- **Motor controller**
  The motor controller regulates the the speed of the motor based on a speed reference provided by either the Main Computer (MC) or Single Board Computer (SBC), as well as the actual speed measured by the encoders.
- **Encoders**
  The encoders are attached to the motors and measures the actual speed with which the motor rotates.
- **Inertial Measurement Unit (IMU)**
  An IMU measures the orientation of the robot and is used for the robot to navigate and position itself.
- **Cameras**
  Cameras are used both for navigation similar to the IMU, as well as for obstacle detection.
- **Main Computer (MC)**
  The main computer governs the entire software infrastructure of the robot and handles the data collection and transport to and from all hardware components of the robot.
- **Single Board Computer (SBC)**
  An SBC is a smaller and lighter computer that is used to support the MC with computations or data communication, e.g. for time critical data transport. The SBC is further part of the V2V communication an is able to control the motors as well as issuing a safety stop, based on data collected from the partner robot via the communication hardware.
- **Laser scanner**

The laser scanner uses optical measurements to detect the distance from the robot to walls, people and other obstacles. This information is both collected by the MC to be used for navigations, as well as it is used to issue a safety stop through the safety system.

- **Safety system**
  The safety system is comprised of a safety Programmable Logic Controller (PLC) and safety contactors. The PLC takes input from different sources such as a manual breaker switch, the laser scanner and the SBC, and determines whether a safety stop is required. If so the power to the motors is cut of using the contactors.
- **Interface components**
  For various purposes, different interface components have been installed on the robot to give a user the opportunity for manually moving the robot. The interface components include joystick, force sensors for haptic control, etc.
- **Communication**
  The communication hardware manages all data transfer for both V2V and V2I communication. Several different communication protocols are used and tested such as WiFi and ZigBee.

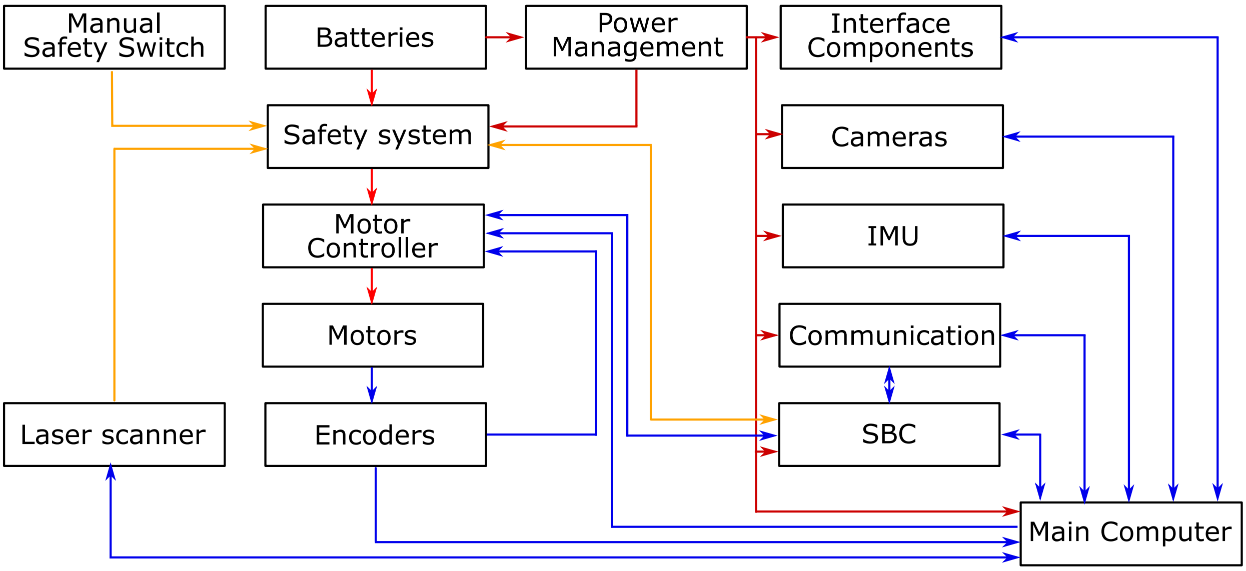

Figure 3: The different hardware components of the robots, along with interconnections. Here, power connections are represented in red, data connections in blue and safety connections in orange.

We remark that since the robots are under continuous development, the above description is subject to change, although the main components are reasonably fixed.

3.2 Software Overview

The SW of the constructed robots relies heavily on Robot Operating System (ROS) which is a middle-ware message passing infrastructure running inside the Operating System (OS) of the MC. The following provides a brief overview of the general use of ROS within UC1 - For a more detailed description of ROS, the reader is referred to [5].

The conceptual software structure of ROS is illustrated in Figure 4.

Conceptually speaking, ROS contains a master and a multitude of nodes, which are able to communicate and transfer data between each other. This data transfer is coordinated by the master, which keeps track of which nodes are running, what data type is shared between nodes, time synchronization between nodes and so on.

The nodes may be hardware specific, *e.g.* a driver for a specific sensor, and may be used for instance to conduct sensor readings, and to provide a way of making the sensor data available to other parts of the robot software.

A ROS node could also be purpose specific, *e.g.* to run the localization algorithm of the robot, in which case the node could potentially subscribe to data provided by *e.g.* laser scanner, IMU and wheel encoders, through their respective nodes.

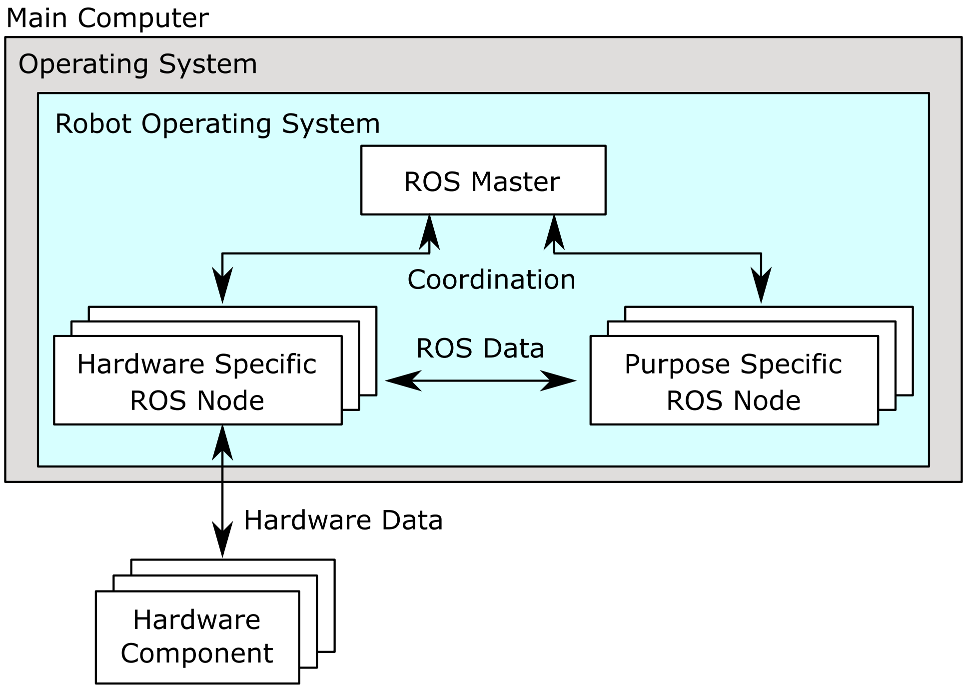

Figure 4: The ROS middle-ware runs inside the MC OS and provides a multitude of nodes for *e.g.* interfacing sensors, actuators, SBC, or running for instance localization or control algorithms. The data transfer between nodes is coordinated by the ROS master.

3.3 Communication Framework

To outline the communication framework, Figure 5 illustrates the V2V and V2I communication architecture, along with the subset of the HW subsystems from Figure 3 directly influenced by the communication.

As reported for [6], different communication structures have been, and are still being considered. The outline in Figure 5 represent the architecture upon completion of D5.1, but is likely to undergo modifications onwards.

As indicated by Figure 5, both V2V and V2I communication is conducted through a dedicated cloud network, presently realised as a shared WiFi network.

The dedicated network is used to transfer the following information:

- V2V data:
  - Laser scan information in order to conduct shared navigation and localization.
  - Intended movement of the train for each robot to calculate its individual motor speed.
    (In praxis, one of the robots conducts a centralized planning of the path that the train should follow, wherefrom each robot may individually calculate their respective motor rotation)
  - Safety information, *i.e.* whether one or the other robot imposes a safety stop which must be propagated to the other robot so that the entire train is brought to stop.
- V2I data:
  - Obstacle information as detected by the external sensors
  - Position and orientation information of the sensors *w.r.t.* the robots.

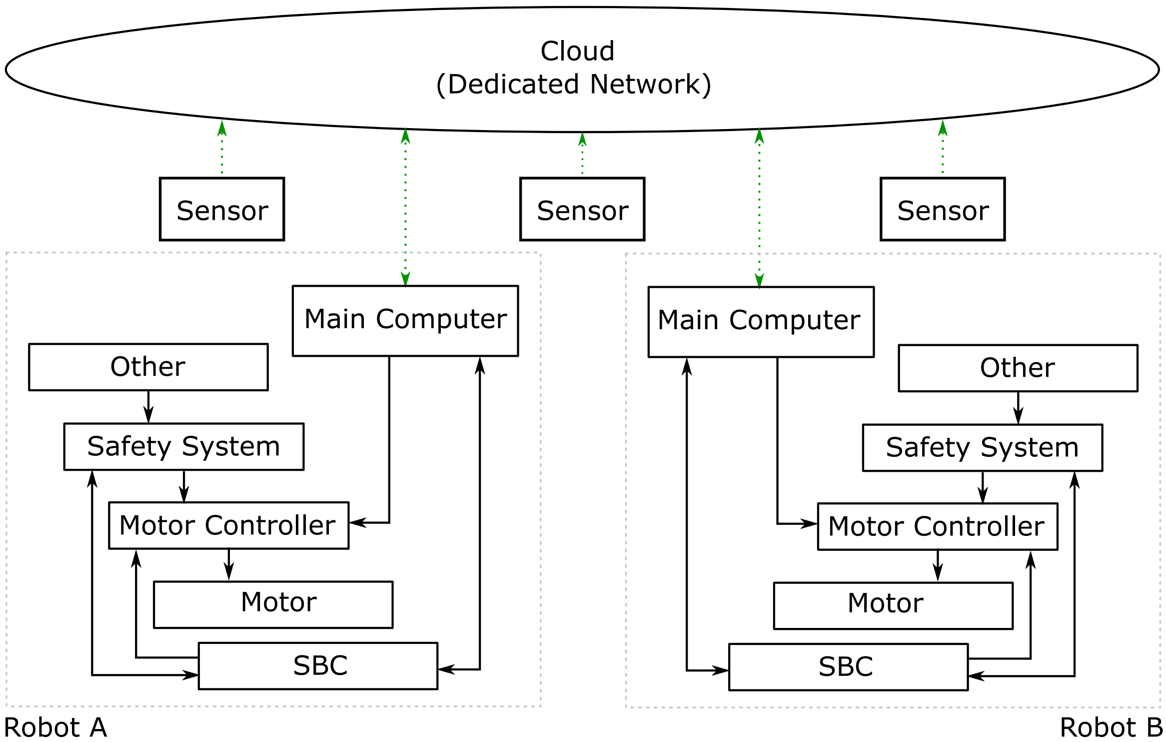

Figure 5: The communication structure used for D5.1. Both V2V and V2I communication is passed along a dedicated network.

4 Physical Demonstration

The video of the physical demonstration documents the technical achievements obtained so far for UC1, as described in the following.

4.1 Technical Achievements

The main achievements demonstrated are:

- **Independent movement and navigation**
  DTI has constructed two robots that are individually able to operate similar to other autonomous mobile robots available in the market. The robots are shown Figure 6. The robots are able to localize themselves within a map, and navigate through the map using continuous path planning.
- **Independent safety**
  When in the individual mode of Figure 6, the robots developed by DTI are operationally safe, in the sense that they are each instrumented and operated in concordance with safety regulations for mobile robotics. This entails that the robots are able to move and navigate individually without hitting people, walls or other obstacles. Sudden obstacles, *e.g.* objects being dropped or people rushing in front of the robots, are detected, and causes the robot to stop.

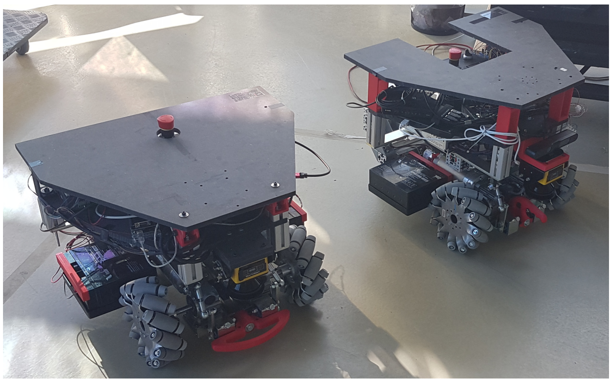

Figure 6: When the robots operate individually, no data is transmitted between them.

- **Switch to joint movement and navigation**
  Besides their individual mode of operation, the robots developed by DTI are able to dock together around a hospital bed and change their respective kinematic configuration and mode of operation to function not as separate units, but as a whole single train consisting of the two robots and the bed. The train may subsequently move, navigate and behave autonomously as a single unit. The joint mode of operation is illustrated in Figure 7.
- **Distributed safety**
  When the robots are joined into a unified train as in Figure 7, the safety mode is similarly updated so that safety information is shared between the robots, and safety critical events are shared among both robots and not just the one experienced the event. For instance, if an object or person is rushed in front of on of the robots, thus

posing a safety critical situation, the obstacle detection is shared among the robots so that the entire train is brought to stop.

Figure 7: In the joint mode of operation the robots shares information concerning movement, navigation and safety.

- **Software initiated latching**
  When docking against the hospital bed, the robots exploit the iron in the bed-frame and attaches themselves using electromagnets, as illustrated in Figure 8. The magnets are automatically activated through software, thus removing the need for manual efforts in the latching process. The latching mechanism is however under continuous development, and may be replaced at a later stage in the project.

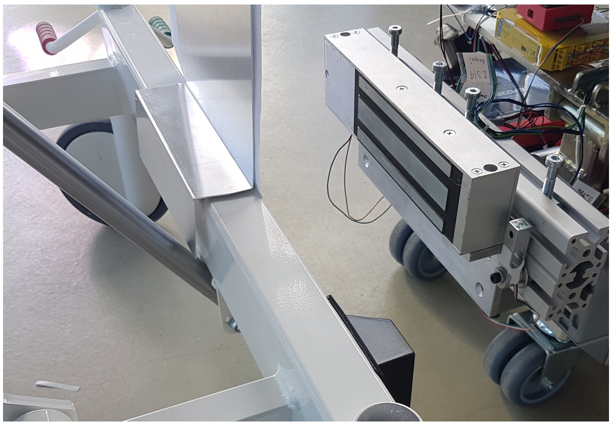

Figure 8: The robot latches on to the bed frame using electromagnets automatically activated by the robots through software.

- **Improved operation using external sensors**
  The external sensors used for extending the Field of View (FOV) of the robots, reports any obstacles detected in the map, as well as their position, to the robots so that they may act accordingly.

  For instance if multiple paths exists for reaching the destination, the sensors may report blockages so that obstructed paths are avoided. This use of external sensors for improved planning and navigation is illustrated in Figure 9.

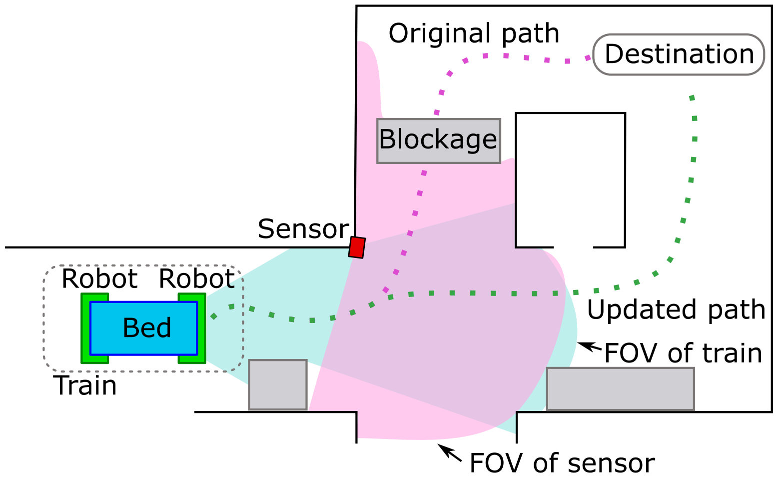

Figure 9: The external sensors reports blockages to the robots beyond their own FOV, so that infeasible paths may be updated ahead of time.

The obstacle detection by external sensors may also be used for improving safety, for instance when a sensor detects a person, the robots will slow down and plan around that person *e.g.* when moving towards a sharp bend.

4.2 Relation to other Work Packages

The technical achievements outlined above are related to the Work Packages (WPs) outside WP5 through the requirements listed in Table 1, in that the requirements poses an interface the remaining project. The work of UC1 has been coordinated with the project partners Danish Technological University (DTU) and SINTEF in capacity of their engagement in WP3 and WP4, respectively.

Given the nature of both the WP3 and WP4 related requirements of UC1, as well as the technical commitment of DTU and SINTEF, the mutual coordination has largely been related to the communication and distributed safety aspects of UC1.

Concretely, it has been discussed how to implement a shared communication protocol between the robots, in a way that is suitable for transfer of time- and safety critical data. As part of this, extensive work has been put in deriving safety analysis of UC1 to allow developing an application specific safety framework for communication.

The details about the collaboration between DTI, DTU and SINTEF are further elaborated in the periodic status summary of UC1/WP5.

5 Further Work

Despite the substantial technical achievements described in Section 4, significant work still remains for improving the use-case towards the end of the project. The following summarizes some of the eminent tasks to consider within UC1.

Although the latching process for joining the bed and robots is autonomous, the docking process leading up to the latching still requires manual input. Ongoing efforts are exploring ways for extending the level of autonomy in the docking process.

As an addition to extending the autonomy of the docking procedure, the switch in mode of operation for the robots will also require an increased level of automation. In their present state, some manual efforts are required when the robots are to transition from individual to joint operation. Ongoing work focus on both how the mode transition should be automated in a safe manner, but also how to detect when the transition is appropriate/desired.

The communication infrastructure is still quite crude, although it does accommodate the required functionalities. Ongoing work will focus on further exploring the technical details concerning implementation of the communication infrastructure *w.r.t.* improving robustness and safety. This will also be a concern in relation to onwards implementation of technical contributions from other work packages outside the use-case.

The above largely concerns improvements to the robots themselves, however some efforts are also required in terms of using the external sensors for V2I communication. Presently, the approach for adding external sensors, and enabling the V2I data-link, is somewhat cumbersome, static and rigid. A more flexible way of dynamically adding external sensors will be a subject for increased focus onwards.

6 Exploits and End-User Value

The immediate end-user values of a fully commercialized system of appropriate Technology Readiness Level (TRL), based on the work of UC1, may be summarized from [2] as follows:

- **Staff savings**
  It is estimated that up 15 minutes of staff time could be saved pr. bed using robots to automate the process. This is equivalent to 5.4 full time employments with the present bed-washing needs of Odense University Hospital (OUH).
- **Reduction in staff muscular strain injuries**
  Due to the time required for moving beds to and from the CBWF, much of the cleaning is presently conducted manually in the wards. The task of properly cleaning the bed requires a lot of work in uncomfortable non-ergonomic positions. The time-savings incurred by using robots would remove the need for in-ward cleaning thus reducing the appertaining discomfort and muscular stress of staff.
- **Reduction in hospital-borne infections by not stripping beds in the ward**
  The present practice of in-ward cleaning, implies that bed linen is changed within the ward as well. Changing the bedlinen may lifts pathogens into the air where they can more easily infect both staff and patients. Allowing a more substantial use of the CBWF reduces this risk.
- **Improvement in the environment on the ward**
  Reducing the need for in-ward cleaning further reduces the exposure of patients and staff for residue of the cleaning chemicals.
- **Potential savings in water and cleaning chemicals**
  Relying more on the using the CBWF as opposed to in-ward cleaning potentially allows for better recycling of water/detergent/heat thus providing both a financial as well as environmental benefit.

In addition to the end-user values directly related to the SafeCOP demonstrator, a number of additional exploits may be envisaged by various elements of UC1:

- **Moving generalized objects**
  The derived framework for using two robots to solve a logistics task need not be

focused on moving beds. The robots could in principle be used to move any wheeled object with an appropriate surface for the robots to latch onto. Within the hospital industry, this could also be carts storing clean or dirty bed linen, garbage carts, carts with clean or dirty tableware, carts with medicine, *etc*.

- **Including several robots**
  The work in UC1 is limited to consider two robots, but it would be an obvious extension to render the system scalable to even more robots, thus allowing transport of items which are larger or heavier, to an extent not manageable by only two robots.
- **Distributed safety**
  The aspects of having a safety system wirelessly distributed across several agents is applicable to multiple industries. For instance in production facilities it would of significant value to be able to wirelessly link manual or automatic safety-stops across the entire production-floor such that an emergency switch at one end of the production line, could relive a hazardous situation in the other end, without needing to hardwire the entire system.

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Abbreviations

CBWF Central Bed Washing Facility p.: 5, 14

DTI Danish Technological Institute p.: 4, 6, 7, 11, 13
DTU Danish Technological University p.: 13

FOV Field of View p.: 4, 5, 12, 13

HW hardware p.: 7, 9

IMU Inertial Measurement Unit p.: 7, 9

MC Main Computer p.: 7–9

OS Operating System p.: 8, 9
OUH Odense University Hospital p.: 14

PLC Programmable Logic Controller p.: 8
PMT Project Management Team p.: 2

ROS Robot Operating System p.: 8, 9

SBC Single Board Computer p.: 7–9
SW Software p.: 7, 8

TRL Technology Readiness Level p.: 14

V2I Vehicle-To-Infrastructure p.: 4–10, 14
V2V Vehicle-To-Vehicle p.: 4–10

WP Work Package p.: 13

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