Development of a Collaborative Wheeled Mobile Robot: Design Considerations, Drive Unit Torque Control, and Preliminary Result

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***Abstract*— Nowadays, wheeled mobile robots constitute a considerable portion of robots in industrial applications. Generally, regardless of their purpose, these systems are not designed to physically interact with humans, other robots, or the environment. In this study, we present a novel safe autonomous mobile – SAM – robot, which is a torque-controlled compliant robot that is conceived for safe human-robot interaction. This work provides an overview of the development philosophy of the system, its mechanical and mechatronics structure along with control and navigation architecture. Preliminary results show the advantages of the proposed mobile robot while interacting with its surroundings. We believe that this study will bring the wheeled mobile robots one step closer to the proactive interaction with their environment and humans surrounding them.**

I. Introduction

Robots, once dangerous and non-cooperative machines are becoming co-workers of humans. State-of-the-art works on robot safety and physical human-robot interaction (pHRI) put some effort to remove the boundaries between humans and robots, especially in the area of robotic manipulation [1]. Robotic arms with custom hardware and high fidelity torque control, allow the users to program, teach and use robots as never seen before. By contrast, the same cannot be said for wheeled mobile robots (WMRs). Usually, during the collaboration with humans, WMRs are kept at a safe distance and the interaction between the robots and humans is reduced to remote communication methods like gesture control and eye tracking [2]–[5]. Besides some rare studies, physical contact between WMRs and humans is avoided [6]–[8]. However, once WMRs manage to safely interact with humans and their environment, collaborative wheeled robots (CWRs) will replace standard WMRs in many applications. As the parent field of CWR, WMRs are one of the most commonly used robotic systems with many alternatives in terms of size, architecture, loading capacity and applications [9]. On the other hand, WMRs which interact with their environment are also not a new concept [10] but the force interaction (push, pull, task share) is generally implemented with the help of additional components such as manipulators (equipped with torque/force sensing) [6], [11], [12]. Conversely, CWRs could be seen as "natural" extension to collaborative manipulators. We believe many new systems can emerge from the combination of CWRs and Cobots. These systems can be used in places such as hospitals for medical assistance [13], at households for elderly care [14], and in factories as labour support [15].

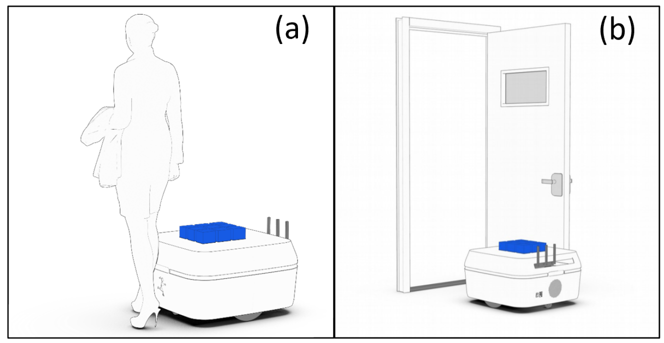

Fig. 1. Conceptual idea of CWR: (a) CWR collides with a human without any harm, (b) CWR safely pushes the door to create enough space for its motion.

Although each potential application area has different requirements, they share an essential point: CWRs need to be ready to be challenged by uncontrolled environments, as illustrated in Fig. 1. Therefore, CWRs cannot rely on virtual safe cages, perfectly designed roads (clear surfaces, no artefact on the surface, and lower inclination), surveillance sensors, complex user interfaces, and many more controlled measures that make their environment routinized and sanitized.

By taking into account the aforementioned points, a list of seven requirements was created for a novel CWR. The first requirement for a robot to become a collaborative system is to be able to perform *physical interaction with its environment*. In other words, CWRs should have a sense of touch and be able to not only passively comply with their environment but also engineer it, e.g., be able to move objects around. For a robot with a sense of touch, haptic gestures can also be used as part of the user interface, e.g., for teaching the robot a skill, or for starting/stopping the execution of a program/skill. While interacting with the environment, CWRs will require an *accurate perception and understanding of the environment*. In other words, CWRs

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should perform accurate indoor mapping and localization, intelligent and autonomous navigation, and path planning in dynamic environments. They should detect objects and understand human gestures. Since the performance of any CWR relies on the quality of its mobility, a *robust mobility* is a property that any CWR should have. In other words, a well-designed CWR should be able to move over obstacles and ramps without losing the performance. In addition, since CWRs operate in an uncontrolled environment, they must be easy to use or program. Thus, CWRs should have *intuitive programming and easy interaction* capability, meaning that CWRs should be accessible to everyone including non-experts (such as line workers in industrial settings or nurses in hospitals). Nevertheless, the most crucial requirement for CWRs is *safety*. Since CWRs will share a common space with humans, they must be able to safely interact with their environment. Finally, CWRs should be both *affordable* and *scalable*. The former property means they should be accessible to everyone including small companies, hospitals, and households; while the latter means their skills should improve when collectively sharing knowledge. For example, CWRs should learn from each other and humans as well.

The main goal of this study is to propose a stand-alone torque-controlled WMR system. By considering the aforementioned challenges, a CWR system – SAM (Safe Autonomous Mobile) robot, depicted in Fig. 2, was designed and developed from scratch. SAM is equipped with two drive units with integrated torque sensors and the entire robot is designed around this characteristic. Concerns caused by this characteristic are overcome with an integrative design approach which is presented in this study. In addition to the design effort, software architecture and programming are developed to be used by both researchers and non-experts. Torque control property also created new ways to use the robot therefore new characteristics like guiding, teaching, and gravity compensation are also applied to the system.

In the following sections of the paper, the criteria which are taken into account in each development stage of the SAM platform are explained. In Section II, the mechanical and mechatronics structure of the SAM and the design requirements are described. The control approach of the system is given in Section III. In Section IV, the software of the system is presented. The experimental results are presented in Section V. Finally, the manuscript is concluded with the conclusion and future work in Section VI.

II. Hardware Design

The primary development challenge of a pHRI-oriented WMR – safe interaction – can be solved, if the hardware components (drive system, force/torque measurements, perception sensors, mechanical and electronic designs of WMR) are precisely designed to support this purpose. During this development process, industrial standards and previous studies are used. For example, since the indoor areas are selected as main application environment of the system the barrier-free norm DIN 18040-1 [16] is used for defining the specifications such as maximum gate width and ramp slope.

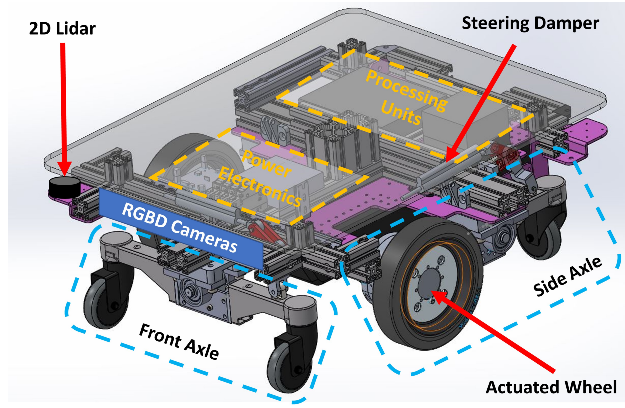

Fig. 2. The CAD model of SAM shows the side and front bogie axles, positions of the lidar and RGBD cameras and embedded electronics.

CAD model of SAM is shown in Fig. 2 to emphasize the structure of the system; while the system specifications of SAM are given in Table I.

A. Mechanical Design

As a WMR, the most dominant structure of SAM is the chassis and suspension design. The design was developed on three main criteria which helped to shape the boundaries for the design parameters (size, stiffness, mass, DoF). These criteria are torque control strategy, environmental needs for use cases, and integrability with other systems, such as mobile manipulators and humanoid robots.

Being torque controlled, the most distinct feature of SAM creates a challenge for the design, especially when considering the conflicting relation between manoeuvrability and constant torque-sensing. Even though torque control is an established research area for robotic manipulators, similar works with mobile systems are scarce and limited to safe lab environments [6], [7]. The final structure of SAM was selected from multiple interim designs. These designs were tested under three main topics: control (gravity compensation and impedance control), suspension and chassis performance, and navigation.

Another challenging decision was the selection of the wheel types. Due to high manoeuvrability, mechanum wheels have been favoured by many researchers [6], [17], [18]. However, since these systems consist of multiple moving parts, the contact with the ground fluctuates throughout the motion by creating changing ground forces. In this case, torque estimation becomes complicated [19], especially for

TABLE I

Physical parameters of SAM robot.

Property	Unit	Value
Size ($l \times h \times w$)	mm	$750 \times 600 \times 340$
Weight	kg	70
Battery	$\mathrm{V-Ah}$	LiPo $24 - 22.5$ LiPo $48 - 14.5$
Payload	kg	70
Operation Duration	min	180
Max. Slope	deg	20
Max. Obstacle	mm	30
Towing capacity	kg	180
Max. Speed	m/s	0.3

low speed and close to static motions. Therefore, solid rubber-like wheels were used on SAM.

Following our criteria for cost-effective robust navigation over obstacles, we used a fluid damper (steering damper) supported, three Degrees-of-Freedom (DoF) suspension system as shown in Fig. 2. As previously mentioned DIN 18040-1 is used to define the potential obstacle and motion path. Suspension design is extensively tested with interim prototypes and it was proved to be sufficient for the designated use case with three DoF architecture. In general, a mechanical design not only helps with robustness and cost-effectiveness but also reduces the effective inertia and consequently kinetic energy, therefore makes the robot safer in case of collision.

On the other hand, all the previous considerations should be focused on the main advantage of the proposed system, the drive unit torque control. Two main sources of external forces are defined as the contact between human-robot and robot-robot (like in the case of mobile manipulator architecture). By considering these interactions, the chassis was designed with high stiffness values so that there will be no considerable change in the force between the contact point and the actuated wheels. Therefore no additional sensor is required to observe the intermediary nodes. The final aspect of the design was safety. Since SAM should be able to work in close proximity to humans, a potential hazard, which can be caused by the motion of individual parts, had to be addressed. Therefore, SAM is designed within the limits of its perimeter meaning that no moving part can pass the side cover on any occasion. Thus, the user cannot contact the wheels and bogie axles. Another potential risk was the impact stress as a varying point from the other WMR systems, since SAM can perform tasks in close proximity. Therefore, while collisions are considered, the worst-case scenarios must be taken into account. Even though the torque control feature of the system helps to avoid any high-force contacts during a collision case, as a secondary safety measure SAM is designed to have wide faces to increase the contact area and decrease the contact stress.

B. Mechatronics Design

Mechatronics structure of SAM is grouped under three main category as, actuation, sensing, and communication.

1) Actuation: As force-based interaction is the core criteria, we needed a precise torque measurement and control system integrated with the actuators. Current based sensing would be a barrier to our full state control algorithms. The actuator concepts such as pseudo-direct-drive and series elastic actuators [20] have the main benefit of durability against the impact forces, while it is a major problem for strain wave gear systems. However, thanks to its suspension design, SAM is not subject to big impacts on the joints. All the aforementioned criteria make a full state-controlled joint, such as the one used in Panda robotic manipulator [21], a suitable actuator for our system. Following our criteria for cost-effectiveness, we decided to use the mass-produced modular Panda joint and do small modifications to enable unlimited rotation of the joints. The only drawback of these actuators is the speed, which is limited to $0.3\mathrm{m/s}$ due to high gear ratios used in the actuators enabling them to handle higher torques and as a trade-off in velocity.

2) Sensing: The following three types of sensors are installed on the structure of SAM:

a) Accelerometers: Accelerometers were integrated into the modular joints. Since the joints are integrated into moving frames of the robot, information from accelerometers can be used to observe the state of moving planes (side axles). Additionally, a third accelerometer is embedded into the chassis next to the power electronics so that the orientation of the three DoF can be readable.

b) Cameras: The platform is equipped with four RGBD cameras (three in front and one on the back) used for the 3D perception of the environment. The cameras are mounted vertically with an angle toward each other to optimized the visibility by covering maximum environment within the field of view. Cameras are used to capture obstacles on the ground, which are not capturable with Lidars, for 2.5D navigation (differentiate between ramps and obstacles, for details see Section IV-D) and gesture recognition.

c) Lidars: Two 2D lidars are also installed into the system, on the front-right and the back-left sides with 270° coverage per lidar so that combined the lidars can see the complete periphery of the system.

3) Communication: The communication was split between two different computers as low-level control and high-level navigation. A realtime computer is responsible for the $1\mathrm{kHz}$ control of the joints, installed for the low-level control. All other components are connected to the non-realtime computer, for high-level tasks, such as navigation and perception. Two communication methods can be used for exchanging information with SAM: through network protocols, e.g., TCP/IP, or a high level App-based interface called ”desk” connection. Other robots and devices (manipulators, other WMRs) can also be connected to SAM via the desk. Thus, for example, Panda robotic arm and SAM can process a sequence of commands in relation to one another. The communication design of the platform can be seen in Fig. 3.

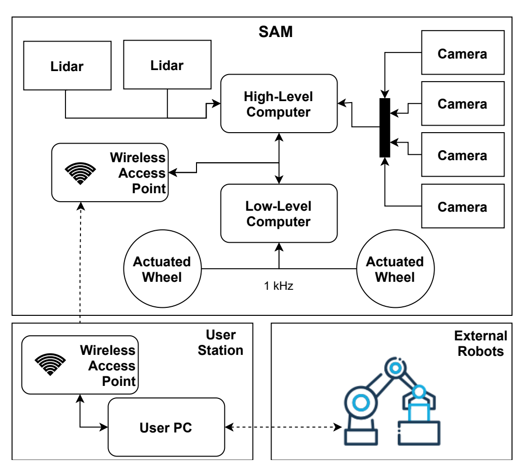

Fig. 3. Communication flow of SAM with user station and external robots.

III. Control Approach

From kinematic modelling point of view, SAM is a differential drive WMR. The Cartesian coordinates of the midpoint of the segment joining the two wheel centres can be denoted by $\mathbf{p} = \begin{bmatrix} x & y \end{bmatrix}^T$, while the orientation of the vehicle body by θ. Consequently, SAM's full pose can be described by $\mathbf{x} = \begin{bmatrix} x & y & \theta \end{bmatrix}^T$ [22], as depicted in Fig. 4. If $\mathbf{x}^* = \begin{bmatrix} x^* & y^* & \theta^* \end{bmatrix}^T$ is the desired pose of the robot, then the pose error is

$$\mathbf{e_x} = \mathbf{x}^* - \mathbf{x}. \tag{1}$$

To provide a feasible solution to the aforementioned use cases, SAM needed to have precise torque sensing and control. Therefore, an extension of the unified impedance control structure for robot joints which suggested in [23] was implemented to control the two drive units with a rate of 1kHz. Based on this interface, different controllers such as Cartesian impedance control, force control, and joint impedance control are implemented on SAM, as can be seen in Fig. 5. Friction observation and joint torque control are implemented on the joint level and run at high frequencies; while the impedance law is implemented on the control computer and runs at 1kHz frequency. For the sake of simplification in the first version of the control, the robot is modelled as a rigid body (the motion of the suspension system is neglected) and no inertia shaping is implemented although the unified impedance control framework allows these future improvements. The contact between wheels and floor is assumed to be rigid contact with only static friction.

Due to the nonholonomic constraints [24], the Cartesian impedance structure of SAM consist of two DoF: one translational x and one rotational θ, as depicted in Fig. 4. Therefore, the error in (1) is redefined as

$$\mathbf{e}' = \begin{bmatrix} x^* - x & \theta^* - \theta \end{bmatrix}^T. \tag{2}$$

By using the error in (2) and its time derivative, the impedance torque $\boldsymbol{\tau}_I \in \mathbb{R}^3$ is given by

$$\boldsymbol{\tau}_I = \mathbf{J}^T(\mathbf{k}^T\mathbf{e}' + \mathbf{d}^T\dot{\mathbf{e}}'), \tag{3}$$

where $\mathbf{J} \in \mathbb{R}^{2\times 2}$ is the Jacobian matrix of the system, $\mathbf{k} = \begin{bmatrix} k_T & k_R \end{bmatrix}^T$ and $\mathbf{d} = \begin{bmatrix} d_T & d_R \end{bmatrix}^T$ are the stiffness and damping coefficients, respectively. The impedance torque $\boldsymbol{\tau}_I$

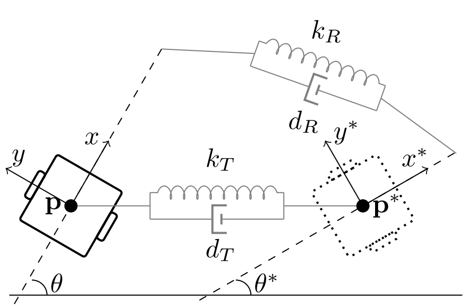

Fig. 4. Illustration of the actual position $\mathbf{p}$ and orientation θ of SAM, and its desired position $\mathbf{p}^*$ and orientation θ^*. The Cartesian impedance control is represented by two mass-spring-damper systems with translational stiffness k_T and damping d_T, and rotational stiffness k_R and damping d_R.

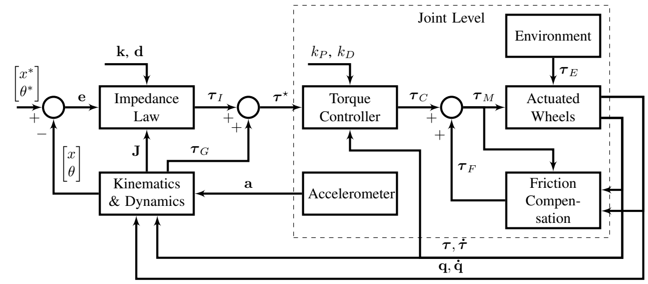

Fig. 5. Overview of the control scheme.

along with the gravity compensation torque $\boldsymbol{\tau}_G$ provide the desired torque τ^*. Then, a PD controller computes the commanded torque $\boldsymbol{\tau}_C$:

$$\boldsymbol{\tau}_C = k_P(\boldsymbol{\tau}^\star - \boldsymbol{\tau}) - k_D\dot{\boldsymbol{\tau}}, \tag{4}$$

where k_P and k_D are the proportional and derivative gains, respectively. By using the friction compensation suggested in [25], the estimated frictional torque $\boldsymbol{\tau}_F$ is combined with the control torque $\boldsymbol{\tau}_C$ to calculate the torques $\boldsymbol{\tau}_M$ of each actuated wheel:

$$\boldsymbol{\tau}_M = \boldsymbol{\tau}_C + \boldsymbol{\tau}_F = \begin{bmatrix} \tau_L & \tau_R \end{bmatrix}^T, \tag{5}$$

where τ_L and τ_R are commanded torques for the left and right wheels, respectively.

Impedance model is used for several application strategies such as guiding of the robot with minimum required force (see Section IV-B), safety features of the robot, virtual spring implementation for human following mode, and for interaction with the environment.

IV. Framework Architecture

SAM is designed not only for the end-users but also with the goal of enabling researchers to study pHRI with WMRs by providing them with an experimental reference platform, similar to the Panda robot [21].

A. User Interface

We implemented an intuitive programming interface to SAM using different methods. SAM can be programmed and controlled through the following three methods:

a) Desk: a browser-based application, originally developed for the Panda robot which can be used to program and control SAM via SAM apps, such as move, turn etc. Since this application is browser-based, this control can be carried out from any internet-enabled device, e.g., laptop, smartphone or tablet [21]. Fig. 6 depicts how the architecture introduced in [21] is extended to add SAM as a service to the platform.

b) Vision based gesture control: an RGBD camera on the front recognizes two types of gestures which are interpreted as stop and start. As soon as one of these gestures is recognized, the commanded action is executed, additionally the command list can be increased in the future.

c) Haptic communication: by measuring the torques in the joints, external forces can be interpreted as commands. For example, SAM can recognize an abrupt change in forces as a collision and issue a stop command.

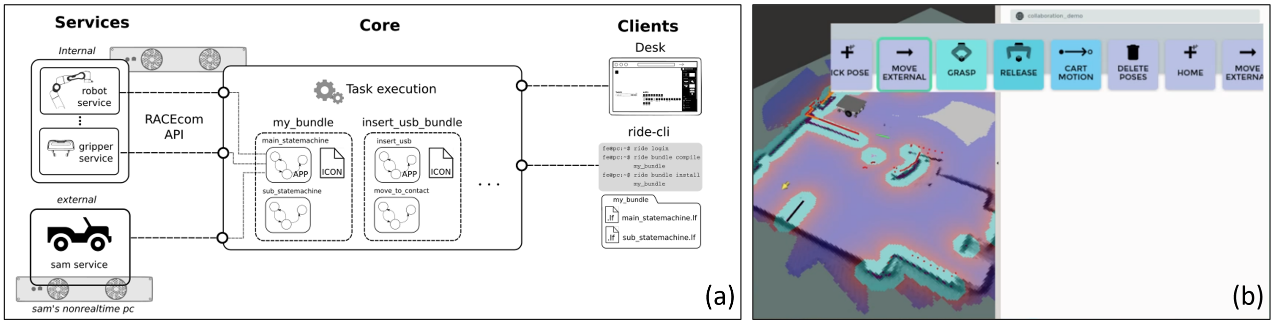

Fig. 6. (a) SAM application interface, (b) Desk Programming User Interface, on Desk Panda and SAM can be programmed in the same timeline, to generate a task, previously defined low-level apps such as Cartesian Motion, Grasp, Wait can be arrange consecutively.

B. Guiding Mode

The programming of the SAM platform is skill-based. This means that the end-user can use the implemented parameters for a specific use case but also has the option of changing high-level parameters themselves (stiffness and damping coefficients). Thus, no programming ability is required and, at the same time, the greatest possible variability in use is given. The challenging tasks like parameter tuning can be carried out by the user as well as a learning algorithm in order to optimize applications. In addition, the localization was optimized through key positions in connection with stored map data. Thanks to the stored map, SAM has stable localisation and understanding of the surrounding environment which are updated using a SLAM algorithm. This enabled the entire localization process to be accelerated and optimized. With SAM model aware control (impedance control with gravity and friction compensation) the user can guide the robot, for example, over ramps, without any effort.

C. Safety

Performing a task by a WMR with a human or while a human is in close proximity are undesired cases. Therefore, usually, robots either operate in a virtual cage with a space limit between them and humans or distant safety measures, such as remote safety buttons. However, as mentioned previously, one of the main goals of this study is to remove these boundaries by still keeping safety of paramount importance. The integrated force observation in SAM enables it to react safely with the environment in a case of collision. Additionally if required, a virtual spring can be created between the human and the robot.

D. Navigation

SAM not only can navigate passively (without any contact with the environment) in the environment but also if needed interact with objects around using its precise force observation and control. This potentially can help when navigation cannot plan any path and the robot needs to move an object, such as a chair, to be able to continue its defined task. The sides of the robot are fully covered to enable this interaction with the environment.

E. Perception

The perception system of the robot fuses all relevant sensory measurements into one coherent source of information, as depicted Fig. 7. Based on these measurements, the robot generates a 2D map, internally used for localization, and a 2.5D map, so-called height-map, for path planning and obstacle avoidance. The height-map is projected down into a 2D accounting for the robot's rotation and height in the world. Slopes in this projection greater than a configurable threshold are interpreted as obstacles which are registered in a costmap. Consequently, this costmap is used for path planning and safe navigation to the destination.

V. Experimental Validation

The control and sensing performance of SAM is validated with two experiments. In the first experiment, the robustness of two DoF (rotational and translational) impedance control of SAM against external disturbances is tested. In the second one, the step response of the impedance control to initial displacement is measured.

A. Repeatability and Stiffness Test

For measuring the performance of the impedance control, we designed the following experiment. As illustrated in Fig. 8, the Panda robot is used for applying precise static forces to SAM. In the first experiment, robot translational displacement is measured, while applying different static forces using Panda. Panda is specifically selected due to its force sensing quality [26]. SAM stiffness k_T is adjusted to $4000.0\mathrm{N/m}$, and consecutively $30\mathrm{N}$ to $50\mathrm{N}$ forces are given at an increased rate of $5\mathrm{N}$ per step, while each step continues for $15\mathrm{s}$, experiment ranges are selected based

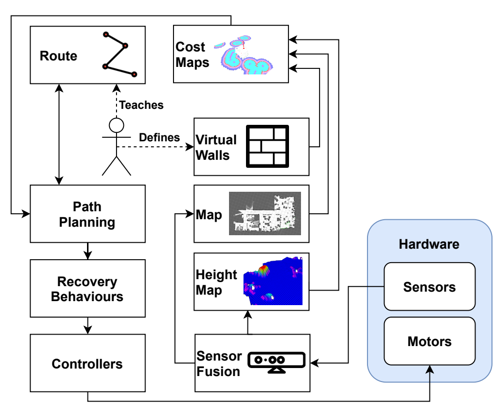

Fig. 7. System overview of 2.5D navigation concept.

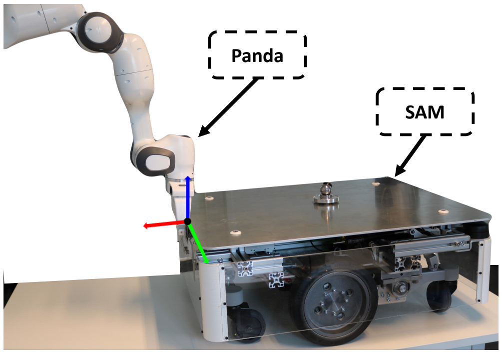

Fig. 8. SAM robot during interaction with Franka Emika Panda robot manipulator. As a genuine source of force and positioning, Panda robot is used for testing purposes. Please note that, on this picture, SAM is demonstrated with transparent side covers to showcase the internal components.

on the minimum visible effected motion threshold and the maximum applicable force by the manipulator.

The results of this experiment are shown in Fig. 9. It is possible to observe that the displacement is a linear function of the force for impedance control with different values $k_T = \Delta F / \Delta x$. We repeated the experiment with $2000.0 \mathrm{N/m}$ and $3000.0 \mathrm{N/m}$. During the experiments, a maximum of 4% force error is observed. On the other hand, as seen on the final two trials of the scenario, where $k_T = 4000.0 \mathrm{N/m}$, an extreme increase in the displacement is observed, this may be caused due to the accumulated, normally ignored, tiny slips, which create a small gap between the manipulator end-effector and the robot. Thus, the manipulator has an initial momentum which creates this error. Additionally, by using the steady-state force and position readings for each external force and position, resultant stiffness values are calculated (presented with dashed lines in Fig. 9), for $2000.0 \mathrm{N/m}$, $3000.0 \mathrm{N/m}$, and $4000.0 \mathrm{N/m}$ set stiffness consecutively read stiffness are $1947.5 \mathrm{N/m}$, $2934.3 \mathrm{N/m}$, and $4022.5 \mathrm{N/m}$ with average of 1.4% error.

B. Step Response Test

In this experiment, SAM is pushed, then hold in a steady-state and drastically released to have a sharp change of the position. To make a comparison, a mass-spring-damper system is simulated with friction. Comparing to the previous experiment, damping coefficients are kept lower to see oscil-

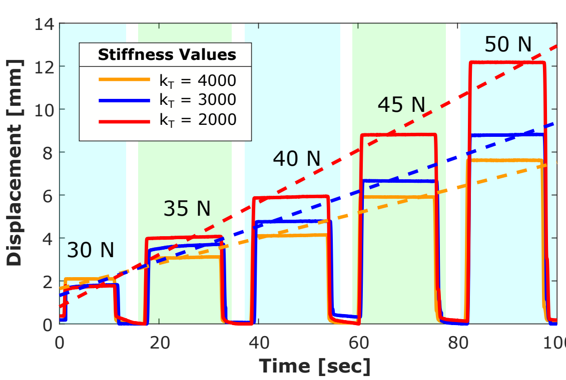

Fig. 9. Displacement response to increasing step forces with three different stiffness value. Linear regression for the experimental results are shown with dashed lines.

lating characteristics better. As seen in Fig. 10, even though the peak time and max overshoot of the system show similar characteristics, the settling time of the system is longer.

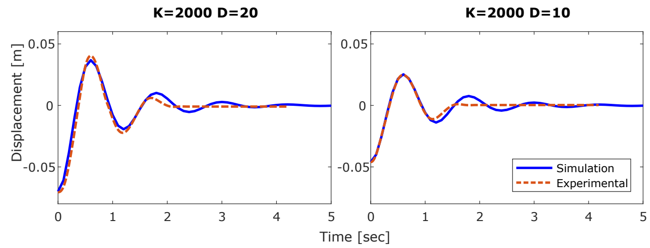

Fig. 10. Comparison between position responses to the step input of the simulated mass-spring-damper system and the actual robot. The experiment was performed for two different damping coefficients $d_T = 20$ and $d_T = 10$.

VI. Conclusions and Future Work

In this study, development and preliminary results of a CWR are represented. To achieve this system, we set the goal to have a torque and impedance controlled WMR system. We explained the design process for mechatronics, software and user interfaces of SAM based on a set of high-level requirements. Our experiments show how an impedance controlled platform behaves in different scenarios. Throughout the development process, some challenges were overcome but there is still huge room for improvement. We believe that force control helps the transition from WMRs to CWRs which can safely operate next to humans not only for carrying the objects around but also for haptic interaction with people and their environment.

This study is a starting point to propose a safe WMR that can cooperate with humans and other robots. Thus, there are many research questions that need to be addressed in future studies. As previously mentioned, the developed system is slow which reduce the potential error on the system and makes the model easier. However, if the goal is to move outside the controlled environments this issue must be improved. Besides, the developed system currently relies on a simplified model. More complex models will help to compensate for the impacts of other external effects, such as ground forces, contact forces and other second-order forces. In addition to this, safety protocols which will be valid while the CWR is in physical interaction with the human must be further researched, if necessary additional passive safety measures like back-drivability can be applied.

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