MCROS: A Multimodal Collaborative RObot System for Human-Centered Tasks

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***Abstract*—Collaborative robots play a significant role in the Industry 5.0 revolution. In this work, we present the development of a new dual-arm all-terrain Multimodal Collaborative RObot System (MCROS), which has dynamic decision-making capabilities in addition to a physical capacity to be controlled and directed for human-centered tasks. MCROS consists of two UR10e collaborative robots, an all-terrain mobile base, a computing and control unit, and a set of multimodal sensory systems for human-robot interaction. These sensory systems include 3D LIDARs, Force-Torque sensors, 3D/security cameras, an inertial measurement unit, and a global position system. Such a design merits a broader range of applications for MCROS. The Robot Operating System is employed for MCROS programming and control, which enables MCROS to be an open-source agent to seamlessly integrate with other cyber-physical systems in different tasks. A specification discussion of MCROS and other existing systems is illustrated. We carry out several applications and analyze the results of MCROS in different real-world work contexts. The scalability of MCROS is also discussed.**

***Keywords*—robotics, human-robot collaboration, sensors, control, dual-arm, multimodal, autonomous system**

I. Introduction

In the Industry 5.0 revolution, collaborative robots have become increasingly significant in advancing manufacturing intelligence and efficiency [1, 2]. Different from traditional industrial robots, which are fenced off from human workers on production lines, collaborative robots make a tremendous shift to coexist and cooperate with workers in open environments for human-centered tasks [3-6]. This makes robots capable of democratizing manufacturing sectors with dynamic customer demands and low cost. Successful human-robot interactions involve flexibility in the robot's skills and its ability to grow and learn. Although the use of collaborative robots in real-life work environments is increasing, these robots remain underdeveloped in human-centered tasks necessitating human-robot collaboration.

The increased use of artificial intelligence (AI)-embedded systems and smart sensors in robots correlates with higher integration of humans and robots in the workplace [7]. As human-robot collaborative situations become increasingly complex, robot systems need to evolve with changing tasks and specialized needs. For instance, in interactions where objects are passed between a human and robot collaborator, the use of multimodal sensing systems and multiple arms helps to avoid accidents and allows for increased mobility and efficiency. The embedding of AI into a robot system enhances the robots' operational capacity to analyze situations then derive the best course of action needed to successfully complete tasks [8]. In conjunction with a sophisticated computing system, a robot's array of capabilities broadens as it is equipped with parts that allow it to function in various environments.

These challenges and requirements motivate us to develop a new dual-arm all-terrain multimodal collaborative robot system (MCROS) for human-centered tasks [9-11]. In this study, we survey existing robot systems and outline qualities that have the potential to bolster the performance of the proposed system and human-robot interaction. These identified qualities are all-terrain bases and multiple manipulators capable of working both independently and in collaboration with each other. Such configurations allow for the robot to freely move in diverse environments and be applied to a variety of human-centered tasks. The developed system is integrated with multimodal sensory systems including, 3D LIDARs, Force-Torque sensors, 3D/ security cameras, an inertial measurement unit (IMU), and a global position system (GPS) to enhance the capacity of MCROS. The Robot Operating System (ROS) is employed in MCROS programming and control to enable seamless integration with other cyber-physical systems in diverse environments. In this work, we present a specification discussion of MCROS and other existing systems. Several applications and results of MCROS in different real-world contexts are conducted and analyzed.

II. State of the Field

Robot systems that include a movable base and a controllable robotic arm are known as mobile manipulators. What makes mobile manipulator systems unique is their ability to multitask and collaborate in a variety of tasks with humans as well as with other robots. As some robots are equipped with wheeled bases, their actions are not restricted to a single region and they can traverse a broader area (e.g. pick up an object and bring it to the other side of a room). Mobile manipulators are able to move autonomously or teleoperated by a human user. This allows for them to be used in environments that are unsafe or inaccessible to humans. Additionally, mobile manipulator systems are available in a variety of forms and sizes; for example, robots such as the NEXTAGE Fillie OPEN [12] and PAL Robotics TIAGo++ [13] have payloads of under 5kg and are applicable to object-handling interactions. Other robot systems, such as the KUKA KMR iiwa with LBR iiwa 14 R820 arm [14] are designed for use in a warehouse setting and are capable of handling heavier loads of up to about 180kg. Some large mobile manipulators work in all-terrain environments and thus have large wheels or geared bases. The L3HARRIS T4 Robotic System [15], Robotnik Rising [16], and AgileX Cobot Kit with Bunker chassis and AUBO i5 arm [17] are among such adaptive robot systems. A large, sturdy base allows for a manipulator to safely be used to its maximum payload [18].

However, when the robot system's base is not all-terrain, this limits the system's application to environments with a flat, smooth surface. MCROS addresses this problem by integrating all-terrain tires in its robotic base. In our development, any delicate electrical components, motors, or wiring are secured within the mobile base or otherwise enclosed in the robot; this design allows for MCROS to safely work in wet and even semi-aquatic environments without the risks of damaging the robot. The stable, streamlined design of MCROS also allows for the use of UR10e manipulators in more complex tasks, as the robotic arms retain all their degrees of freedom when mounted onto the mobile base. Another benefit of MCROS is that it uses two UR10e manipulators rather than just one robotic arm attached to the robot base. With multiple arms, a collaborative robot system such as MCROS can hold objects in multiple ways for concurrent tasks. These arms have greater reach and a wider set of capabilities with the all-terrain base, which allows MCROS to move as it picks up objects, instead of remaining stationary on an immobile base. With GPS and OutdoorNAV capabilities as well as other sensors, the precise motions and location of MCROS can be autonomously maneuvered and tracked.

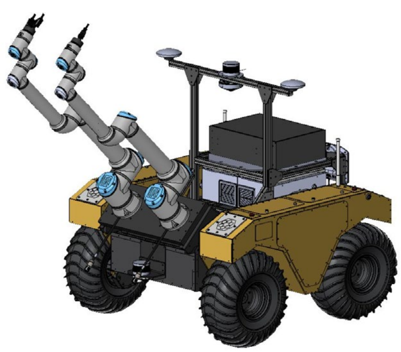


Fig. 1. The MCROS 3D model.

III. System Overview

As it is designed with consideration for a wide range of possible applications, MCROS is built from several commercial robot parts and sensors that suit its unique multifunctionality. Fig. 1 presents the 3D model design of MCROS, which has an all-terrain autonomous mobile robot base that can withstand rough terrains and partial submergence in water. The central computing unit is enclosed within the mobile base for safety and security reasons. The sensor systems of MCROS are accessible via ethernet connections. Attached to the front of MCROS are two collaborative arms that aid in the operating and carrying of objects/tasks. Each arm is configured with a Force-Torque sensor as well as a Robotiq gripper. Connected to the base of MCROS is a GPS Waypoint Navigation system, which has applications in steering MCROS to a set of coordinates as well as collecting location data. A Stereolabs Zed 3D Smart Camera, placed high on the front of the robot for the widest possible field of view, is able to provide real-time feedback and 3D vision information via image/video processing or motion-tracking methods. The embedded IMU will output the internal accelerometer, gyroscope, and magnetometer information of the mobile base. Two Velodyne VLP-16 LIDARs, attached to the top and front of MCROS base, can be used to produce maps of the area surrounding the all-terrain robot through approaches such as simultaneous localization and mapping (SLAM).

IV. Hardware System

A. All-terrain Mobile Base

Though extensive research exists on mobile manipulators, a significant portion of mobile manipulator systems have wheels that are only suitable for flat or paved surfaces. This limits the applicability of mobile manipulator systems to controlled settings where paths are level, e.g. the inside of buildings and pavements. As most mobile manipulators do not have the capacity to work in rugged environments, a challenge lies in developing such a system using a direct and cost-effective approach [19]. The introduction of all-terrain wheels to a mobile manipulator robot system greatly enhances the system's ability to function in more challenging places, including rugged terrain and semi-aquatic locations. All-terrain robot systems are ready for unpredictable settings and unexpected changes in the environment, which makes them suited for applications that require quick decision-making [20]. The inclusion of all-terrain platforms in mobile manipulator robot systems promotes their resilience and adaptability to environmental challenges.

Therefore, MCROS is integrated with a Clearpath Robotics Unmanned Ground Vehicle (UGV) Warthog all-terrain base [21], which can function and carry out tasks in complex environments. Because of the hardware's versatility and resilience to natural elements, it is safe to use in studies involving natural science, agriculture, and any human-robot collaboration that takes place outside [9]. These qualities also have the potential to enhance the performance of MCROS in indoor tasks or manufacturing settings, as the autonomous base can move as fast as 18km/hour and can carry a payload of up to 272kg. The Warthog UGV base can integrate with robotic arms while keeping delicate electronics secure inside the base, maintaining its amphibious qualities.

B. Collaborative Arms

The integration of collaborative arms in mobile robot systems further extends their applicability in the field of human-robot interactions. Research in this field has focused on the applicability of robotic arms in collaborative tasks as well as their teleoperation, resistance to outdoor climates, and ability to avoid collisions [22]. The widespread availability of collaborative manipulators and their compatibility with other robot parts build a compelling argument for their continued and evolving use in human-robot collaborative tasks. Stationary robotic arms can assist in tasks such as picking up and handing over objects only while the object is in reach, whereas arms attached to a wheeled all-terrain base such as in MCROS system can retrieve and handle a wider array of objects across different terrains and settings. Thus, the integration of collaborative manipulators with an all-terrain mobile base is a powerful combination that makes a robot system suitable for many new types of tasks.

MCROS is equipped with two Universal Robots UR10e arms [23] that are connected to a pair of Robotiq 2-fingered gripper attachments, which enable MCROS to pick up objects faster and with ease. Each of these robotic appendages has 6 degrees of freedom (DoF), amounting to 12 DoF for the entire system. This is important as a high DoF allows a given robot system the potential of increased movement and task operations. Since each of MCROS's UR10e arms can carry up to 12.5kg and can function independently from each other, they can complete separate tasks simultaneously or co-carry one large object together.

C. *Multimodal Sensory Systems*

MCROS is integrated with a set of multimodal sensors, including a 3D smart camera, an IMU, security cameras, LIDARs, GPS, and F/T sensors. These additional sensing capabilities enhance the system's ability to understand its surroundings and act according to them. One type of sensor contained in MCROS is the Stereolabs Zed 3D Smart Camera, which is placed above the mobile robot base and provides visual feedback from a wide field of view in front of the robot. The Zed 2 Smart Camera can use AI to monitor the distance of moving and static objects and take in surroundings from a 120-degree radius [24].

Two Velodyne VLP-16 LIDAR sensors are located on MCROS. LIDAR sensors generate feedback on obstacles using laser scanning technology and can create maps of the environment using this data [25]. This helps MCROS to gain familiarity with its environment while it is carrying out experiment responsibilities. The VLP-16 LIDARs have a range of 100m, are equipped with dual returns for a clearer and more accurate image, and have a 360-degree sensing capability [26]. Their placement at the front and back ends of MCROS allows the robot system to perceive its surroundings from all directions. This competency is particularly useful in situations where MCROS needs to be steered backward, at an angle, or work in an unfamiliar environment.

MCROS is equipped with a GPS unit which allows it to steer itself to a given set of coordinates at the human operator's commands [27]. The GPS can lead the robot to its destination with a heading accuracy of within $\pm 0.5°$ and a positioning accuracy of ± 0.75m. Since one application of the all-terrain MCROS is driving long distances across rugged terrains that may be inaccessible to humans, the GPS allows for MCROS to drive autonomously and reach its destination without the need for constant teleoperation by a human operator.

MCROS includes two 6-axis force-torque sensors Robotiq F/T 300-S [28], with each one connected to a UR10e arm. These sensors can be used to track the force and torque whenever MCROS uses its grippers in tasks involving the carrying of objects and handover interactions. F/T sensors are particularly important when robots are working in proximity to humans as these types of sensors measure physical pressure and resistance in an interaction. The Robotiq FT 300-S sensors have a data output rate of 100 Hz, allowing for the human operator of MCROS to perceive data in real-time.

V. Electrical System

MCROS integrates compatible robot parts and sensors into a fully symbiotic system that is controllable and versatile. The electrical system is critical to MCROS operations. It includes four main sections: the central chassis, mobile base, sensors, and collaborative arms. MCROS is equipped with a 105Ah @ 48V Lithium battery bank and the batteries are connected in a 4S1P configuration as well as a single Battery Management System (BMS) control unit. When MCROS is running, the BMS will protect the individual modules from being over-charged or over-discharged and from operating outside of their acceptable temperature range. The computing and control unit of MCROS is developed on a Mini ITX system featuring Intel i7-9700, Coffee Lake 8 Core processor, and Geforce GTX 1650 Ti. The Mini ITX is also deployed with a 5-port network switch and a wireless gigabit router. It handles system input, output, and battery monitoring as well as provides an interface to the CAN-controlled motor drivers for the mobile base. In addition, the computing and control unit is connectable with Ethernet, USB, and RS232 Serial ports that are used to communicate with the UR10e robots and sensors. The unit will be in charge of processing multimodal data collected from the sensors and planning robot motions and actions in different tasks.

VI. Control and Software System

A. *Control Modes for MCROS*

As MCROS is developed for a wide range of applications, it can be reliably maneuvered and is compatible with multiple forms of navigation and control modes. The local control mode of MCROS entails the use of hardware and controllers that are fully integrated with the robot system. The human operator can use the Futaba controller to manually and locally control and navigate MCROS system. A wireless key is also available for initiating an emergency stop to halt MCROS operations in urgent situations. This allows for flexibility in the ways in which MCROS is given instructions and enhances the quality of the connection between the human and the robot. The remote control model of MCROS can be conducted using a ROS-configured computer that the human operator connects to MCROS onboard computing and control unit. To run MCROS with this method, a ROS package is developed on the Ubuntu operating system. Other packages such as MoveIt! and RViz as well as necessary dependencies for virtually projecting and controlling MCROS are configured through the Ubuntu terminal and the ROS framework. ROS is also used for building a mesh of nodes corresponding to the sensors and functions of MCROS. Altogether, the merging of this control model and MCROS hardware allows the user to virtually interact with the robot system and remotely operate it through a computer.

B. *ROS-based MCROS-V Development*

As presented in Fig. 2, we develop a full-size virtual MCROS (MCROS-V) using ROS. MCROS-V can run on the onboard or client computers through ROS RViz for human operators to program, monitor, and control MCROS in both simulation and real-world contexts. ROS is an open-source framework for large-scale cross-platform communication and control [29-31]. It contains more than 2,000 packages that could support specialized functionality in different application areas. Another package MoveIt! that runs in the ROS framework is also used in MCROS-V development [32]. With MCROS-V, human operators can intuitively and easily maneuver each robot arm or the mobile base with a mouse to simulate the target tasks. All the robots in MCROS-V are full-size and configured in identical combinations and connections with the real-world MCROS. When MCROS-V works, a collision-aware plug-in provided by MoveIt! is invoked for the collaborative arms and the mobile base to actively avoid obstacles during the task execution process. The sensor data and communication messages of different subsystems are managed through a set of ROS nodes, by which MCROS operating information, such as robot joint angles, end effector poses, and sensor data streams, is published/subscribed to/from a developed ROS workspace via different types of messages topics. Additionally, MCROS-V supports diverse programming languages with friendly interfaces, which can easily integrate the robot control and path planning algorithms that are coded on other platforms into MCROS. This will highly bolster the scalability of MCROS.

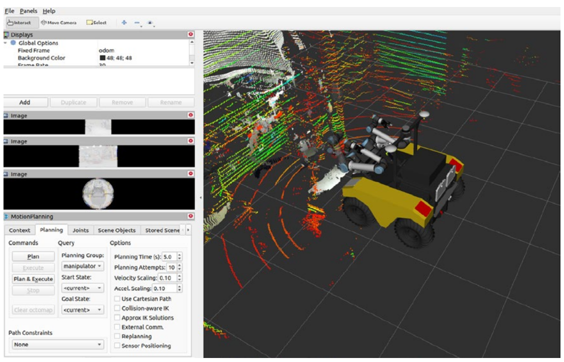
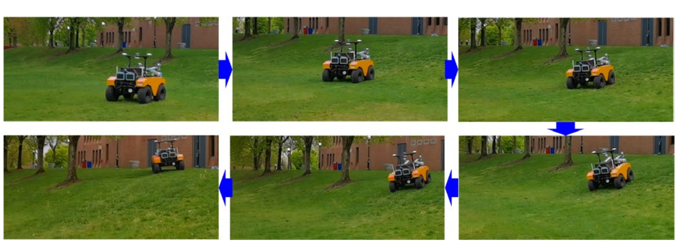


Fig. 2. The MCROS-V in RViz.

VII. Application Cases and Results Analysis

A. *Specifications*

Table I shows the specifications of MCROS and other mobile manipulators. MCROS has the maximum number of arm DoF. These collaborative arms provide an efficient and versatile way to thoroughly perform tasks and leave great potential for future work in the collaborative robotics field. In addition, all-terrain mobile robot systems such as MCROS can take on tasks that present physical and safety challenges to humans in different environments and can work alongside humans in all kinds of activities without barriers. This is important because as the demand for human-robot collaboration rises, it is critical for robots to be able to accommodate humans and not the other way around. Among the all-terrain mobile bases in Table I, MCROS has a waterproof chassis and is capable of performing tasks in water. It can work in tough environments such as vegetation, steep grades, thick mud, and soft soils. For example, in Fig. 3, MCROS is stably locomoting on sloping grasses. As presented in Table I, MCROS has the largest payload, which means it has a wider range of applications, especially in manufacturing environments, such as heavy automotive or airplane parts transportation and manipulation between assembly lines.



(a)

(b)

Fig. 3. MCROS is stably locomoting on sloping grasses. (a) Climbing. (b) Moving down.

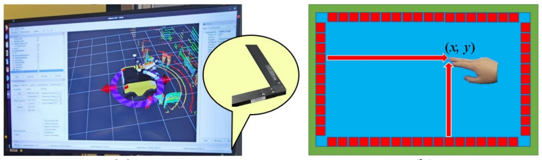
TABLE I. Specifications of MCROS and Other Mobile Manipulators

Robot System	Dimensions	Payload	Arm DoF	All-terrain
MCROS	1520mm x 1380mm x 830mm	272kg	12	Yes
MMO-500	986mm x 662mm x 804mm	42kg	6	No
KMR iiwa	700mm x 1080mm x 630mm	184kg	7	No
Robotnik Rising	967mm x 537mm x 252mm	20kg	6	Yes
AgileX Cobot Kit	1023mm x 778 mm x 400mm	85kg	6	Yes
CARLoS	1127mm x 747mm x 554mm	135kg	6	Yes
ER-FLEX UR10e	800mm x 560 mm x 540mm	186kg	6	No

B. *CASE 1: Robot Programming and Operation via MCROS-V for Human Workers in Manufacturing Contexts*

Generally, to efficiently use robot systems for manufacturing tasks, especially in industry sectors, human workers must be well trained to operate them. This process is time-consuming and costly. To mitigate this challenge, we develop an infrared-matrix-based immersive robot programming and operation approach using MCROS-V. As shown in Fig. 4, for the human-robot interface development, we employ a 58” Samsung TV with a 58” Infrared Multi-Touch Panel (IRMTP) attached to it for MCROS-V. The IRMTP is constructed by 4 infrared matrices including two transmitting tubes and two receiving tubes. When the human workers operate the robots on MCROS-V, their touch actions on the screen will be detected and located by the IRMTP (Fig. 4(b)).

In this application, the developed approach is able to enable human workers to manipulate specific parts and program each robot of MCROS intuitively by touching the corresponding component and function on the human-robot interface. This solution can therefore provide easy-to-use operations allowing workers to program and maneuver the robots for different customized tasks with minimal training or without robotics expertise and coding skills. We conduct different kinds of experiments to test this approach in real-world contexts such as object grasping and robot motion planning. As presented in Fig. 5, the human is able to easily program MCROS and maneuver it to move using MCROS-V through the human-robot interface. These implementation results suggest that the developed approach can effectively assist humans in robot programming and operation in customized tasks while reducing human coding effort and minimizing professional expertise requirements.



(a) (b)

Fig. 4. The infrared-matrix-based human-robot interface for MCROS-V.

Fig. 5. Robot maneuvering through MCROS-V.

C. CASE 2: Robot Spatial Awareness Development in Human-Robot Interaction

Spatial awareness is a critical trait for robots to effectively work and navigate in new and dynamic environments. It is usually characterized as the ability of robots to be aware of the objects, human partners, or robot peers in the environment and their positions in relation to the respective environment. In this application, we develop a spatial awareness model for MCROS based on the Simultaneous Localization And Mapping (SLAM) algorithms to effectively reconstruct its 3D work environments, identify its real-time 3D positions, and plan its paths when it works with humans in interactive tasks. As shown in Fig. 6, the 3D LIDARs on MCROS are used to collect the surrounding information when the robot is working. Mapping and localization are the two primary components in MCROS spatial awareness development. During the mapping phase, the robot uses information gathered from LIDARs to create a thorough map of its surroundings. Then the robot evaluates its orientation and position within the mapped area in the localization phase.

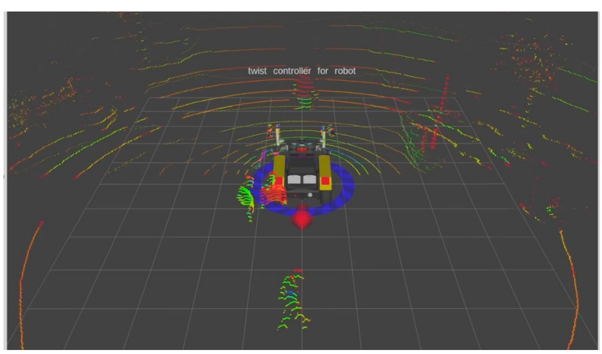


Fig. 6. MCROS surrounding information detected by LIDARs.

The built spatial awareness model is implemented and evaluated in an outdoor human-robot interactive environment. As shown in Fig. 7, MCROS moves to a desired location with a human walking towards it on its way to the destination. We utilize a laptop as the host machine to receive data from the LiDARs on MCROS, while also publishing movement commands to the robot's controller. As MCROS gets closer to the human, it will detect that there is a moving obstacle in its path using its created spatial awareness. The robot will turn and move to avoid the collision. Once the human has passed, the robot will course-correct back onto its original path. As described in Fig. 7, MCROS effectively navigates around the human going in a predictable direction through the developed spatial awareness model.

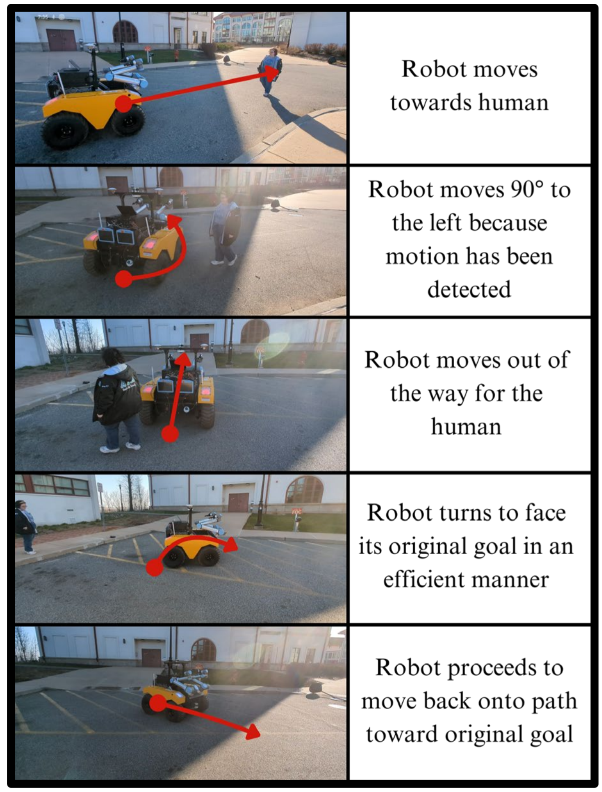
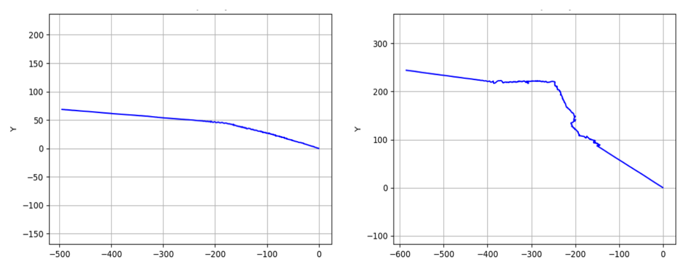


Fig. 7. MCROS moving with spatial awareness in human-robot interaction.



(a) (b)

Fig. 8. MCROS trajectory planning in human-robot interaction. (a) Without spatial awareness. (b) With spatial awareness.

We also compare the trajectory planning of MCROS with and without spatial awareness in the human-robot interaction process by using the robot's rotation information evaluated from the IMU. Fig. 8(a) demonstrates the MCROS trajectory without spatial awareness. It is apparent in the trajectory that the robot chooses the shortest route for itself with a lack of consideration for the humans around it. In fact, during this test, a human was standing in the path and the robot would not waiver in its goal to get to its destination. Obviously, the human may get injured if there are no safety measures (e.g., emergency stops) manually controlled by the human. From the trajectory planning in Fig. 8(b), it can be seen that MCROS moves around the human with spatial awareness to avoid collision in the dynamic interaction. This comparison further indicates that the developed approach is capable of enabling MCROS to safely and effectively interact with dynamic environments and human partners via spatial awareness. In addition, this would have impactful applications in numerous settings such as healthcare, wherein we could enable high-quality collaboration in human-robot or robot-robot partnerships.

VIII. Conclusion and Scalability

In this work, we have developed a new dual-arm all-terrain multimodal collaborative robot system for human-centered tasks. MCROS is constructed with an all-terrain mobile robot, two collaborative robots UR10e, a computing and control unit, and a set of multimodal sensory systems. It can be controlled locally and remotely in two modes. We have presented several applications and analyzed the results of MCROS in different real-world human-robot interactive contexts. The flexibility of MCROS reflects the continuously changing and dynamic state of cooperation between humans and robots. In addition, the design of MCROS grants a broader spectrum of applications for it over other existing mobile manipulators. With the unlocking of new functions and skills for MCROS, it will be scaled to more kinds of tasks in human-centered collaborative contexts.

Acknowledgment

This work is supported by the National Science Foundation under Grants CNS-2117308 and CMMI-2138351.

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