Design and Implementation of Mobile Manipulator System

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***Abstract*— In this paper, we develop and implement a kind of mobile manipulator named Jupiter, which consists of a six-degree-of-freedom(DOF) manipulator and an omnidirectional mobile platform with four actively steerable wheels. In contrast to the omnidirectional mobile manipulator with Mecanum wheels, the proposed mobile manipulator can be adopted in rough terrains. Two laser scanners and a stereo camera are mounted in the system to perceive the environment. With the IMU and odometry data, Jupiter is capable of doing SLAM by Hector SLAM method and path planning. A manipulation frameworks with a single shot multibox detector (SSD) approach is used to detect and grasp the objects. Combining the two function, both the manipulator and the platform are integrated into a system which can execute mobile manipulation tasks autonomously. Our contribution includes a complete hardware construction and software pipeline of the mobile manipulator which is capable of autonomously doing SLAM, navigation, detecting and grasping objects. The performance of the system are tested and proved by autonomously executing an mobile manipulation mission including autonomous navigation with multi-sensors and apples grasping and placing.**

I. INTRODUCTION

A mobile manipulator system is normally combined by a mobile platform, one or more manipulators, tooling subsystems and sensor subsystems. Compared with the traditional stationary and pre-programmed manipulator, mobile manipulators can transfer the position of the base to provide highly flexible logistic services and dexterous manipulation in both structured and unstructured environments. Therefore, autonomous mobile manipulator are widely used in different scenarios, including industries [1], living apartments [2], [3], [4] and orchards [5].

The autonomous mobile manipulators was applied in industries, and normally had large mobile platform with high mobility and high load capacity to transport the goods quickly. The design of the mobile platform influenced the performance of transportation. There were different structural designs of mobile platform. A mobile manipulator with a railway guided vehicle (RGV) was applied to detect the electric energy meters [6]. The robot can only execute the manipulation tasks in a limited space, since the RGV can only move in a single dimension in a restricted area. Little Helper robots [7] which had a differential drive mobile platform, were implemented at a pump manufactory to assemble the rotors and transport finished rotors to the warehouse [1].

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Fig. 1. The prototype of the proposed mobile manipulator.

However, the mobility of the platform was limited and the bottom of the chassis was very low, it might be stuck when going over some irregular surfaces. To improve the mobility of the platform, the omnidirectional mobile manipulator, especially the one with Mecanum wheels, has the attention of the researchers. It can move with unrestricted motion in any direction when transports the goods, so that it can avoid the obstacles in a limited or unknown environment. Song et al.[8] designed and optimized a kind of omnidirectional mobile manipulator with four Mecanum wheels to drill and rivet for large-scale mechanisms. Chen et al. [9] proposed a framework to control mobile manipulation for industrial automation based on a mobile manipulator with four Mecanum wheels, KUKA MIIWA. Some platforms with Mecanum wheels are integrated with dual-arm structures with human-like morphologies [10], [11], which can deal with some complex manipulation tasks like humans.

The platform with Mecanum wheels has outstanding performance in an indoor environment, but it may fail on the rough terrain, like sandy and rocky surface, since the platform are highly sensitive to the irregularity of the surface. There was study on modification of Mecanum wheels [12], but the design does not widely used. Compared with the omnidirectional mobile platform with Mecanum wheels, the one with four actively steerable wheels can keep well performance on both the hard and flat surface and rough terrains because the conventional tires is not sensitive to the irregularity of the surface. The mobile platform design with four actively steerable wheels has been utilized in the field for weeding [13], [14]. Inspired by the studies with four actively steerable wheels, we design a new omnidirectional mobile manipulator.

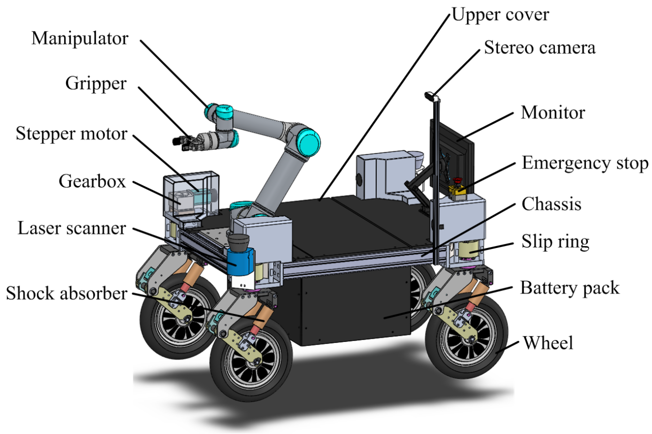

Fig. 2. The mechanism design of the mobile manipulator.

In this study, a generic omnidirectional mobile manipulator named Jupiter is developed, which consists of a six-DOF manipulator and a mobile platform with four actively steerable wheels as shown in Fig. 1. The contribution of our work can be listed as follows:

1) We present a generic omnidirectional mobile manipulator with four actively steerable wheels, which maintain the performance of mobility in both indoor and outdoor environments.
2) We integrate a set of implemented behavior including perception, SLAM, autonomously navigation and object grasping in to a single system. In object grasping module, a mobile manipulation framework with a deep learning method is proposed and successfully implemented.

In the remainder of this paper is organized as follows. In Section II, we demonstrate the hardware design of Jupiter and the connections among the subsystems. Several implemented behaviors of the mobile manipulator are proposed in Section III. To test and prove the performance of Jupiter, the experiments and the results are discussed in Section IV. The conclusion and the future work are presented in Section V.

II. HARDWARE AND SYSTEM DESIGN

In this section, we present the hardware setup of the mobile manipulator and the communication architecture among the subsystems. Jupiter was design in modular, since our goal is to develop a generic mobile manipulator which can be utilized in a variety of tasks, rather than tailored to a specific application. The design of Jupiter is shown as Fig.2. Jupiter is combined by a omnidirectional mobile platform, a six-DOF manipulator with a two-finger gripper and multiple sensors for environmental perception.

The key performance parameters of Jupiter are listed as follows.

TABLE I
KEY PERFORMANCE PARAMETERS OF JUPITER.

Total weight	238kg
Vehicle height of the mobile platform	825mm
Length with scanners of the mobile platform	1420mm
Width with scanners of the mobile platform	1100mm
Max. payload of the mobile platform	200kg
Max. velocity of the mobile platform	2m/s
Wheel diameter	390mm
Obstacle negotiation	50mm
Max. payload of UR5	5kg
Max. reach of UR5	850mm
Stroke of the gripper	90mm
Max. payload of the gripper	5kg
Max. force of the gripper	100N

A. Mobile platform

The omnidirectional mobile platform equips with four actively steerable wheels, which has full degree of mobility on the plane. Four wheels place in each corner of the chassis. For each actively steerable wheel, two actuators are utilized to drive the wheel and steer the direction independently. In contrast to the mobile manipulator with Mecanum wheels, our design have higher tolerance to surface irregularity and higher durability of tires. With the actuation of the stepper motors and gearboxes, each wheel can freely change the orientation without any limitation. To prevent the wiring problem, a slip ring is mounted in each wheel to maintain the wire connection while steering. Furthermore, in each wheel structure, two shock absorbers and aluminum bars are incorporated into a suspension to mitigate the effect of disturbances on robot body, so that obstacle negotiation and sensor stabilization are improved. As shown in Fig. 3 and 4, the mobile manipulator can move over a speed bump with 5cm height and keep maneuverable on the concrete surface with small gravels and the grass with irregular surface.

The mechanism of actively steerable wheels provide the best flexibility of motion. Four kinds of basic motion patterns are designed for the mobile manipulator, including stopping, the synchronous drive, rotation about any given instantaneous center of rotation (ICR) and the one about the reference coordinate of the mobile platform, as shown in Fig.5. As the orientations of all the four wheels point to the reference coordinate of the mobile platform, the wheels are restricted by each others, which generates the pattern of stopping. The synchronous drive pattern, which keeps all the four wheels in the same orientation and velocity, is used when the heading of the mobile manipulator is required to maintained in a narrow space. Moving straight is a special instant of the synchronous drive pattern. Rotation pattern (I) can be adapted to move along with an arc in any given radius. It is frequently used since a tiny segment of the path can be treated as an arc. Rotation pattern (II) can be treated as one of the instant of Rotation pattern (I), and it is specially designed as a pattern since it is used to adjust the heading without changing the position when the mobile platform arrives the destination. Jupiter is capable of implementing complex path by dividing the path into a series of the motion patterns.

B. Manipulator

For complex manipulation task, a six-DOF manipulator UR5, manufactured by Universe Robotics, is mounted on

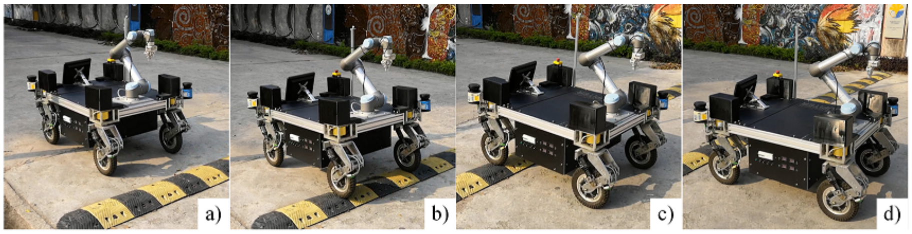

Fig. 3. The mobile manipulator moves over a speed bump with $5cm$ height.

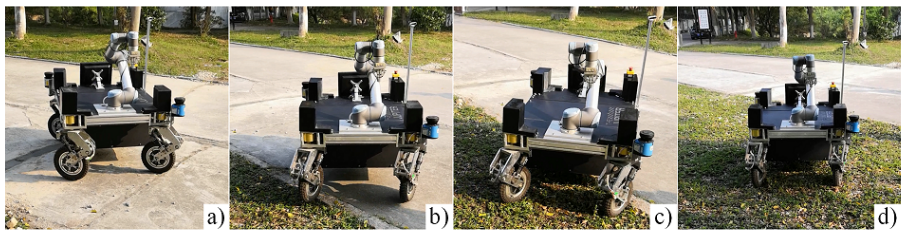

Fig. 4. The mobile manipulator keeps maneuverable on both the concrete surface with small gravels and the grass with irregular surface.

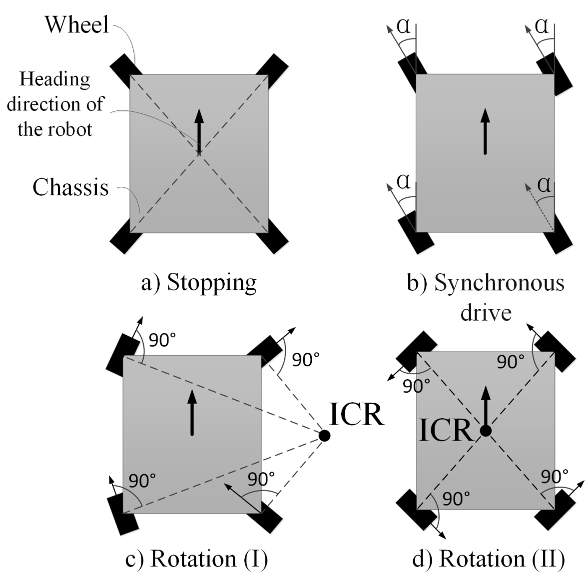

Fig. 5. Different motion patterns of the mobile manipulator.

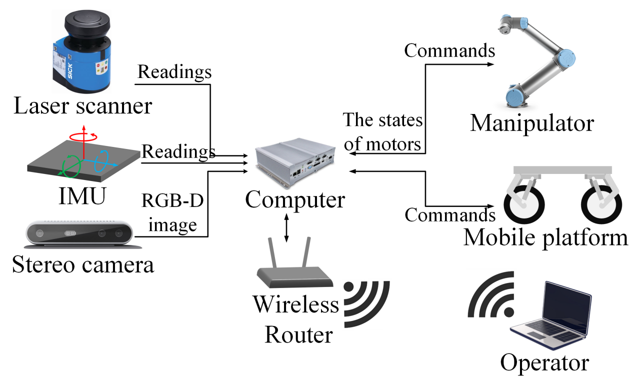

Fig. 6. The connection of the subsystems.

the mobile platform. The maximal reach of the manipulator is 850*cm* and the maximal payload is 5*kg*. We use a gripper with two fingers as an end-effector to grasping objects. The stroke is 90*mm*. The grip force can be adjusted under 100*N*, and the maximal payload is 5*kg*.

C. Computation unit and sensors

The sensors, computational unit and communication devices are all assembly in the chassis. A industrial grade computer is incorporated in the mobile manipulator, which allows to be accessed and remote controlled by an operator computer through a wireless network. The setup of our computational infrastructure is as shown in Fig.6.

The mobile manipulator is equipped with multiple sensors to perceive the environments and infer the states of the subsystems. Basically, the position, velocity and the torque of all the motor in the mobile manipulator are collected to figure out the current configure of the mobile manipulator. We also set an inertial measurement unit (IMU) for robot mapping and navigation. Two laser scanner are mounted at the front left and rear right corners of the chassis to perceive the 360-degree picture of surroundings and provide information to conduct SLAM and autonomously guided navigation. A stereo camera is set at the left side of the chassis to capture the depth images for objective detection and positioning.

The controller system of the mobile manipulator is consisted of two layers: the computer as the upper layer transmits the motion sequences to the lower layer which deals with the servo process of the actuator. For example, to execute the navigation of the mobile platform, the computer calculates the expected velocity and direction of the whole mobile manipulator and the commands are sent to the on-board controller of each wheel. Then the on-board controller figures out the specific motion of the motor and executes it with servo process.

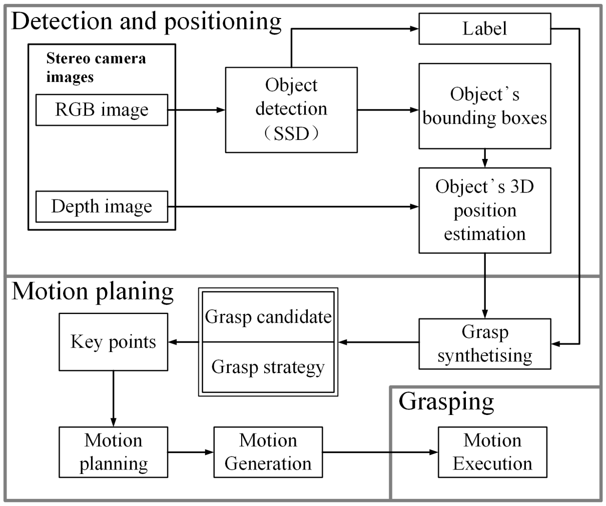

Fig. 7. The schema of the workflow for grasping and placing an object.

III. Implemented behaviors

One of the challenge to develop and implement mobile manipulators is that the high-dimensional spaces associated to systems with high number of actuators and sensors lead to complicate problem in perception and execution of the tasks [15]. Method of perception and motion planning play important roles to develop an integrated mobile manipulator. This section demonstrates the detailed method of the necessary implement behaviors, including SLAM and navigation with the laser scanners and IMU data, object detection and positioning, and object grasping with stereo camera images.

A. SLAM and navigation

SLAM is the a procedure to build up a map of the environment and localize the robot itself simultaneously. We use Hector SLAM [16] to implement SLAM, since it can estimate the full six-DOF state consisting of translation and rotation of the platform. The algorithm projects the endpoints of laser scanner on the 2D map, and aligns laser scans with each other or with an existing map with Gauss-Newton optimization. Then, the algorithm combines the reading from laser scanner and the data of attitude estimator from IMU with a navigation filter to form a full six-DOF solution.

With the grid map, the trajectory between the current position and the destination is solved by the Dijkstra algorithm [17]. The dynamic window approach (DWA) [18] is utilize for local path planning, which yields a motion vector for a next step.

B. Object detection and positioning

To grasp the objective, the robot needs to recognize the objects and locate them with respect to the mobile manipulator. A stereo camera is attached to the chassis to capture RGB-D images of the environment. The process consist of two step, the object detection and positioning. The schema of the workflow for grasping and placing an object is as shown in Fig. 7.

The main challenge of the object detection is that there might be more than one instance of objects in the scene simultaneously. The instances might vary in size, shape, pose and appearance. The object detection module should overcome the influence of the difference in visual, and locate all the objects in the image. In this study, we use the single shot multibox detector (SSD) approach, proposed by [19]. The mobile manipulation mission is a real-time task, we choose SSD approach since it is renowned for its performance of accuracy and speed.

The object detection module inputs RGB images and returns a list of the object proposals. For each of proposal, it contains a label and a 2D position of the object in the image. The proposals are sorted in the descending order of the confidences. The ranking of the proposal determines the order of being grasped. As a bounding box encloses an object, the center of the bounding box is treated as the estimation of the center of the object.

To grasp the object, the 3D position of the object with respect to the mobile manipulator is required. The 2D position of the object in the RGB images is transferred into a 2D position in the Euclidean coordinate respect to the base of the manipulator. The remaining dimension can be obtained by transferring the depth value.

The object detection module influences the ability of positioning the object of the mobile manipulator. The average precision (AP) metric is adopted to evaluate the performance of the object detection module. Average precision (AP) is a popular evaluation metric for object detection, where a detection is declared as a true positive if the detection box and the ground truth box overlaps with IOU (intersection-over union) greater than or equal to 0.5 (AP@0.5IOU) [20]. The AP@0.5IOU of the green apple is 0.99, while that of the red apple is 0.95, and the detection mean average precision (mAD) of both two labels is 0.97. The high AP values reflect that the module can detect the objective precisely. The examples of the results in Fig. 8 (A)-(D) verify that the module can precisely detects the all apples with complex background or being partly blocked.

C. Motion planning and grasping

The 3D position and the label are taken as input to the motion planing module. One of the main challenges is the motion strategies should be suitable to different objects, since the objects have different shape, size, position and should be placed to different places.

In our study, a series of parameterize templets of motion are designed for different categories of the objects. The motion instantiated from a templet of motion is combined by four segments: approach, contact, retreat and put down. The algorithm takes the 3D position and the label as input, then choose the grasping strategies base on the label of the candidate. The algorithm figures out four key points of the end-effector based on the parameterize templets, and the motion planning module generates a motion plan to connect the key points. In the beginning, the first key point is a special position, where the stereo camera can capture the

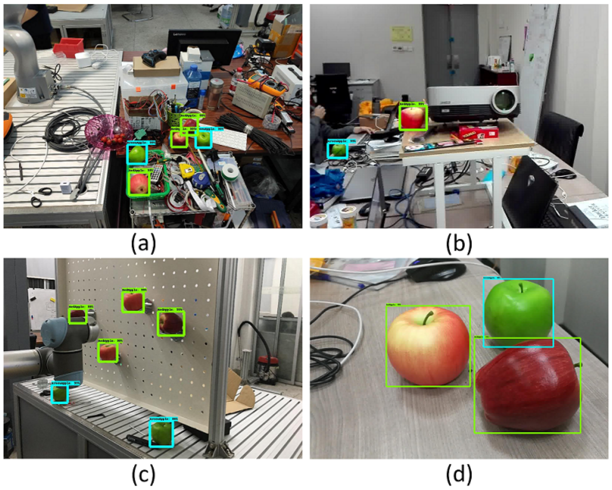

Fig. 8. Examples of the detection results.

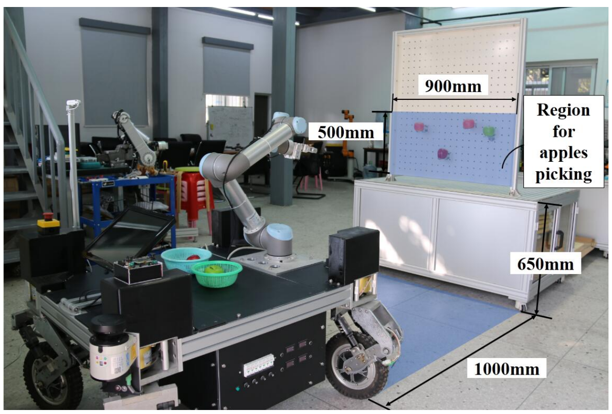

Fig. 9. The experimental setup in the lab for grasping and placing the apples.

view of the whole region without being blocked out by the manipulator. To grasp the object, the manipulator does not reach the 3D position of the object directly. The algorithm chooses a second key point next to the 3D position of the object with a given distance based on the grasping strategies and the gripper heads to the object. The third key point is the 3D position of the object. And the fourth key point is the right place to put down the object based on the grasping strategies. As the path is generated, the manipulator executes the path and at last returns to the first key point to wait for the next command.

IV. EXPERIMENT AND RESULT DISCUSSION

A. Mission

To test the performance of the integrated system, Jupiter is assigned to execute a complex mobile manipulation task of apples grasping and placing autonomously. The experimental setup is as shown in Fig. 9.

The mobile manipulator first autonomously navigate to a given position near the self. Then, the mobile manipulator begins to detect and grasp all the apples one by one based on the depth image data. It is worth mentioning that the position and the number of each kind of apples are setup randomly each time and the manipulator has no any prior information about the position and the numbers of apples. At last, the manipulator needs to sort the apples and place them into the corresponding calibrated baskets.

The scenario of the experiment is as shown in Fig. 10. To obtain the statistics for the cycle time and the success rate of the mission, we randomly put five apples on the self for each time. The numbers and the position of the two kinds of apples are stochastic and the mobile manipulator has no any prior information about the numbers and the position of apples. The missions are repeated for 10 times to test the performance of the mobile manipulator.

B. Performance and discussion

In statistic, the cycle time of the mission is averagely about $211s$. It takes averagely $13s$ to approach the shelf, $15s$ to move back to the starting point. The bottleneck in navigation process is the slow driving speed in approximately $0.3m/s$, which aims to limit the stopping distance to prevent Jupiter from hitting. The result is shown in Table II.

TABLE II

RESULTS OF THE EXPERIMENT.

Cycle time	$212s$
Time to approach	$13s$
Time to grasp and place an apple	$36.8s$
Time to retreat	$15s$
Success rate	98%

It takes approximately $36.7s$ to grasp and place one apple on average. Most of the apples are successfully detected, grasped and placed in the correct baskets, with 98% success rate. However, there is one failure in 50 trials of grasping. The failure happens when one of the finger push down the apple. The failure cause is that the apple is not completely enclosed by the bounding box, so that the center of the bounding box fail to reflect the position of the apple. The error position leads the gripper to the position with bias. The failure demonstrates that the center of bounding box sometimes is not reflect the position of the objects. To grasping the objects precisely, the performance of the proposed method should be improved and it is in the list of our future work.

V. CONCLUSION AND FUTURE WORK

In this paper, we propose the design and implementation of a generic omnidirectional mobile manipulator system named Jupiter. Jupiter consists of a six-DOF manipulator and a omnidirectional mobile platform with four actively steerable wheels, which is capable of executing mobile manipulation tasks autonomously in both indoor or outdoor environments. In the test, Jupiter successfully moves over a speed bump with $5cm$ height and keeps good performance on both the concrete surface with small gravels and the grass with irregular surface. Several implemented behaviors of the mobile manipulator are developed, including SLAM with multi-sensor, autonomous navigation, object detection

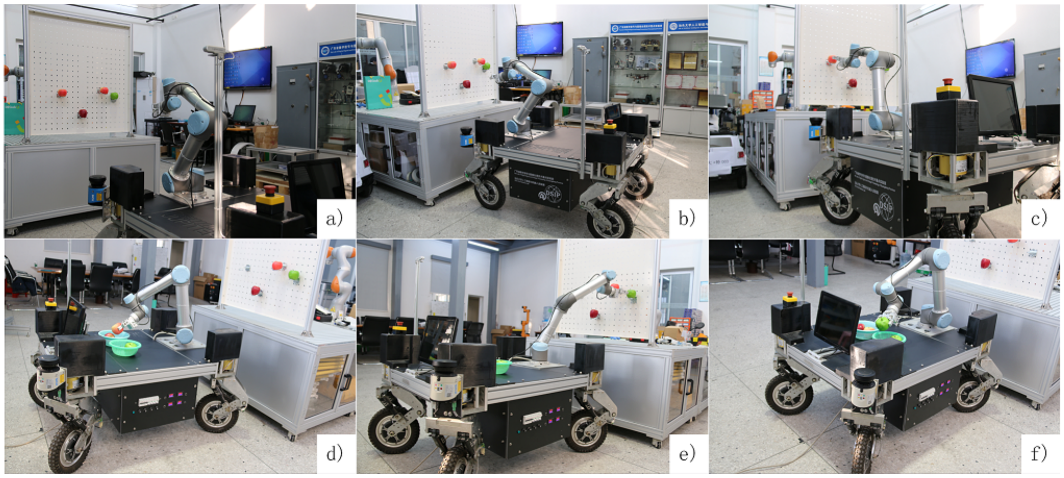

Fig. 10. The scenario of the experiment. a)-b) Jupiter approaches the self. c)-d) Jupiter grasps one of red apples and places it into the correct basket. e)-f) Jupiter picks a green apple and places it into the correct baskets.

and grasping, so that Jupiter can execute a complex mobile manipulation mission. We test and prove the performance of Jupiter by autonomously execution a complex mission, including autonomous navigation and grasping apples. Jupiter successfully complete the mission with 98% success rate, which demonstrates that Jupiter have strong abilities to complete mobile manipulation tasks.

We will continue to use the system as a research platform for further study of mobile manipulation and other real-world applications. Specifically, we plan to research further about autonomously decide the grasping strategy rather than generating the plan based on templets. To avoid the failure of grasping, we will have further study to improve the preciseness and robustness of positioning the objects. Moreover, in the current method, we make a strong assumption that there are no obstacles on air, without risks of hitting the manipulator while path planning. However, it is not the case in the real-world applications. Therefore, we will consider the manipulator pose when path planning to prevent the manipulator from being hit by the obstacles.

References

[1] O. Madsen, S. Bøgh, C. Schou, R. S. Andersen, J. S. Damgaard, M. R. Pedersen, and V. Krüger, "Integration of mobile manipulators in an industrial production," *Industrial Robot: An International Journal*, vol. 42, no. 1, pp. 11–18, 2015.

[2] Z. Li, P. Moran, Q. Dong, R. J. Shaw, and K. Hauser, "Development of a tele-nursing mobile manipulator for remote care-giving in quarantine areas," in *2017 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2017, pp. 3581–3586.

[3] C. Mucchiani, W. O. Torres, D. Edgar, M. J. Johnson, P. Z. Cacchione, and M. Yim, "Development and deployment of a mobile manipulator for assisting and entertaining elders living in supportive apartment living facilities," in *2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*. IEEE, 2018, pp. 121–128.

[4] T. Yamamoto, K. Terada, A. Ochiai, F. Saito, Y. Asahara, and K. Murase, "Development of the research platform of a domestic mobile manipulator utilized for international competition and field test," in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2018, pp. 7675–7682.

[5] A. Silwal, J. R. Davidson, M. Karkee, C. Mo, Q. Zhang, and K. Lewis, "Design, integration, and field evaluation of a robotic apple harvester," *Journal of Field Robotics*, vol. 34, no. 6, pp. 1140–1159, 2017.

[6] X. Shao, J. Liu, Q. Xu, Q. Huang, W. Xiao, W. Wang, and C. Xing, "Application of a robotic system with mobile manipulator and vision positioning," in *Advanced Intelligent Mechatronics (AIM), 2015 IEEE International Conference on*. IEEE, 2015, pp. 506–511.

[7] M. Hvilshøj and S. Bøgh, "little helper-an autonomous industrial mobile manipulator concept," *International Journal of Advanced Robotic Systems*, vol. 8, no. 2, p. 15, 2011.

[8] T. Song, F. J. Xi, S. Guo, and Y. Lin, "Optimization of a mobile platform for a wheeled manipulator," *Journal of Mechanisms and Robotics*, vol. 8, no. 6, p. 061007, 2016.

[9] F. Chenf, B. Gao, M. Selvaggio, Z. Li, D. Caldwell, K. Kershaw, A. Masi, M. Di Castro, and R. Losito, "A framework of teleoperated and stereo vision guided mobile manipulation for industrial automation," in *2016 IEEE International Conference on Mechatronics and Automation*. IEEE, 2016, pp. 1641–1648.

[10] E. Dean-Leon, B. Pierce, F. Bergner, P. Mittendorfer, K. Ramirez-Amaro, W. Burger, and G. Cheng, "Tomm: Tactile omnidirectional mobile manipulator," in *2017 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2017, pp. 2441–2447.

[11] R. Suárez, L. Palomo-Avellaneda, J. Martinez, D. Clos, and N. García, "Development of a dexterous dual-arm omnidirectional mobile manipulator," *IFAC-PapersOnLine*, vol. 51, no. 22, pp. 126–131, 2018.

[12] A. Ramirez-Serrano and R. Kuzyk, "Modified mecanum wheels for traversing rough terrains," in *2010 Sixth International Conference on Autonomic and Autonomous Systems*. IEEE, 2010, pp. 97–103.

[13] T. E. Madsen and H. L. Jakobsen, "Mobile robot for weeding," *Unpublished MSc. thesis Danish Technical University*, 2001.

[14] T. Bakker, J. Bontsema, J. Müller *et al.*, "Systematic design of an autonomous platform for robotic weeding," *Journal of Terramechanics*, vol. 47, no. 2, pp. 63–73, 2010.

[15] M. A. Roa, D. Berenson, and W. Huang, "Mobile manipulation: toward smart manufacturing [tc spotlight]," *IEEE Robotics & Automation Magazine*, vol. 22, no. 4, pp. 14–15, 2015.

[16] S. Kohlbrecher, O. Von Stryk, J. Meyer, and U. Klingauf, "A flexible and scalable slam system with full 3d motion estimation," in *2011 IEEE International Symposium on Safety, Security, and Rescue Robotics*. IEEE, 2011, pp. 155–160.

[17] E. W. Dijkstra, "A note on two problems in connexion with graphs," *Numerische mathematik*, vol. 1, no. 1, pp. 269–271, 1959.

[18] D. Fox, W. Burgard, and S. Thrun, "The dynamic window approach to collision avoidance," *IEEE Robotics & Automation Magazine*, vol. 4, no. 1, pp. 23–33, 1997.

[19] W. Liu, D. Anguelov, D. Erhan, C. Szegedy, S. Reed, C.-Y. Fu, and A. C. Berg, "SSD: single shot multibox detector," in *European Conference on Computer Vision*. Springer, 2016, pp. 21–37.

[20] G. Salton and M. J. McGill, "Introduction to modern information retrieval," 1986.