Proceedings Paper:

Yang, M., Yang, E. F., Zante, R. C. et al. (2 more authors) (2019) Collaborative mobile industrial manipulator:a review of system architecture and applications. In: Proceedings of the 25th International Conference on Automation & Computing, Newcastle University, Newcastle upon Tyne, UK.

Proceedings of the 25th International Conference on Automation & Computing, Newcastle University, Newcastle upon Tyne, UK, 6-7 September 2019

Collaborative mobile industrial manipulator: A review of system architecture and applications

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Abstract—**This paper provides a comprehensive review of the development of Collaborative Mobile Industrial Manipulator (CMIM), which is currently in high demand. Such a review is necessary to have an overall understanding about CMIM advanced technology. This is the first review to combine the system architecture and application which is necessary in order to gain a full understanding of the system. The classical framework of CMIM is firstly discussed, including hardware and software. Subsystems that are typically involved in hardware such as mobile platform, manipulator, end-effector and sensors are presented. With regards to software, planner, controller, perception, interaction and so on are also described. Following this, the common applications (logistics, manufacturing and assembly) in industry are surveyed. Finally, the trends are predicted and issues are indicated as references for CMIM researchers. Specifically, more research is needed in the areas of interaction, fully autonomous control, coordination and standards. Besides, experiments in real environment would be performed more and novel collaborative robotic systems would be proposed in future. Additionally, some advanced technology in other areas would also be applied into the system. In all, the system would become more intelligent, collaborative and autonomous.**

Keywords- collaborative mobile industrial manipulator; architecture; hardware; software; industrial application

I. INTRODUCTION

With the coming of industry 4.0, robotic systems would significantly promote the manufacturing process, which means that more and more work would be done by robots [1]. It is also the key medium connecting cyber and physical space. Different types of industrial robots are shown in Figure 1, including robot with fence, mobile manipulator, stationary robot and mobile platform. On one hand, they could replace humans to carry out repetitive manual tasks. On the other hand, they could enter more hazardous environments to fulfill some dangerous tasks. To date, many aspects of industrial robots have been investigated. Chebab in 2015 overviewed and compared different forms of cooperative industrial robots (Mobile robots, Manipulation robots, Mobile manipulators, etc.). He summarized that more research concerning obstacle avoidance and creative mechatronic design needs to be carried out in future [2]. Among different kinds of industrial robots, mobile platform with manipulator has high demand because of its mobility, collaboration and flexibility. Mads in 2012 focused on mobile industrial manipulator applications and surveyed 12 general industrial application requirements, which combine academic research and industry. However, little emphasis was placed on the importance of system architecture [3]. Since then, some issues of CMIM proposed in previous literatures have been solved, and could be integrated with new technology to make it more intelligent. What is more, few of them combine the hardware and software of the system. Therefore, it is necessary to review the technology and research of CMIM overall in recent years.

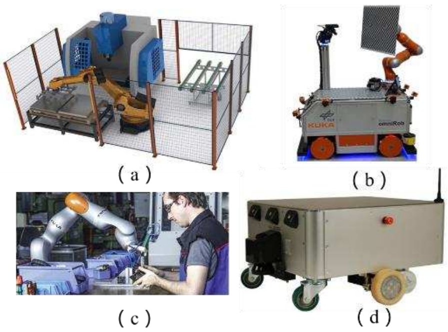

Figure 1. Industrial robots (a) Robot with fence (b) Mobile manipulator (c) Stationary robot (d) Mobile platform

This paper will be organized as follows. Section II describes the architecture and related works of CMIM, which contain the hardware, software, interface and middleware of system and so on. Section III presents the application scenes of CMIM. Research challenges and future directions are presented in section IV while conclusions are presented in section V.

II. SYSTEM OVERVIEW & RELATED WORKS

It is still a challenge for mobile manipulator systems to cope with the relationship of modularity and integration. On the one hand, modularity decomposes the whole complex into several subsystems, which would be easier to build up. On the other hand, the synergies of the integrating systems should be considered to ensure that the incorporation of the components would make the whole system work more effectively [4]. In this paper, the components of the system will be introduced and that will be divided into two subsystems: hardware and software. The layout and their relationship are displayed in Figure 2.

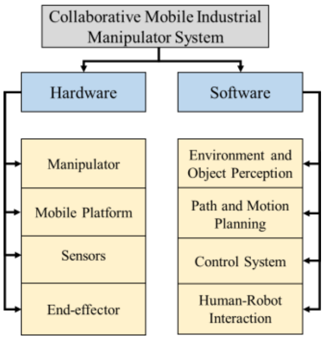

Figure 2. The framework of CMIM system

A. Hardware

The hardware of a typical CMIM contains three sections, which are mobile platform, manipulator and sensor. Simply put, a mobile platform would be used for movement. A manipulator is used for manipulation and completing some tasks, such as 'pick and place'. Sensors are used for perceiving the environment or objects. The components could be modular, which could be combined together arbitrarily and flexibly in order to build up the system.

1) Mobile platform

For a mobile manipulator, a mobile platform is always used for navigation and localization because of its mobility. Omni-directional wheels could make the platform move into any direction directly without turning on the ground, and the system is holonomic in this case. The platform always works in the plane and its Degrees of Freedom (DOF) is 3, which are the position of center and rotation angle. Based on Omni-directional wheels, different modes of autonomous control systems could be designed [5]. Nowadays, there are some companies focusing on mobile platform, such as Neobotix [6], some of the products have been applied into factories.

2) Manipulator

In industry, there are two main kinds of manipulator, one kind of manipulator is large but has to be fenced because its working velocity is relatively high, which is dangerous for humans. It has extensive applications in industry, such as metal cutting and forging. However, some of them are pre-programmed to repeat the same job. The size of another kind of manipulator is comparatively small but is compatible with human interaction. In general, its work velocity and payload is quite low, such as Universal Robots, but it could be mounted into a mobile platform to do more complex and flexible tasks.

Usually, manipulators are often equipped with an end-effector to achieve the complex task. There are many commercial manipulators that could be selected, such as Universal Robot. Manipulators with different DOF are adapted into different tasks. Manipulators with 3 or 6 DOF are introduced because the former is similar to human's arm and typically used in humanoid robot. The later has been employed extensively in industry because it combines the advantage of simplicity and flexibility. Some manipulators have two or more arms. For example, both of the flexible arm and rigid arm are designed in a mobile platform for different manipulations [7]. Obviously, it could perform more complicated or flexible works than a single arm and it collaborates with humans very well, and has been commercialized. In addition, the singularity issue of manipulator should be concerned and some methods have been proposed, such as rejecting the control references [8].

3) Sensors

Different kinds of sensor should be used in system for obtaining the desired information. Some sensors are used for localization, such as encoders, GPS, Laser scanner; others are used for identification e.g. camera. In general, a head sensor is analogous to the human eye and mounted on a pan-tilt because it needs a wide view to perceive the environment. Force/torque sensors are mounted on the end-effector and the system would stop if the force detected exceeds the threshold. Meanwhile, sensor fusion is used to obtain more accurate odometer by combining the data from different sensors. A workspace monitoring system, which contains three stereo cameras and one time-of-flight camera, is used in the VALERY project for protecting the tool of mobile manipulator and has proven effective [9].

In order to make the measurement more precise, further work needs to be done with the data. For example, coordinates transformation between sensors located in different frames. Moreover, calibration is necessary before or during the work and Quick Response(QR) marker could be used for 3D vision calibration [10]. Besides, sensor data may contain some noise, which need to be eliminated by methods such as Kalman filter and particle filter [11]. High resolution sensors could also make the whole system more flexible and accurate. Overall, the sensor system is vital for system and planner or controller to get the accurate information for navigation or collision avoidance.

4) End-effectors

End-effectors are the equivalent of human hands and are used for gripping or performing assignment. The shape of end-effectors change according to the task. For example, the novel end-effector, a cable-driven gripper with internal sensors is designed for picking strawberries [12]. Nowadays, some bionics end-effectors are designed like the shape of an eagle's claw. As is mentioned above, some sensors are employed in the end-effector for safety or fulfilling the task. For instance, sensitive force feedback sensors are built-up with end-effectors, which means that the system would stop if the force detected exceeds the threshold [13]. Some vision-based sensors, such as camera, or controllers, such as PID, are set-up to precisely and reliably grab objectives [14].

B. Software

For CMIM systems, the software involves multiple modules, such as programming, control, interaction, manipulation. In general, different tasks need to adopt suitable software strategies. And, the task needs to be divided into several steps because of the complexity of software architecture.

1) Environment and Object Perception

Perceiving the surrounding environment is the first step in software architecture, which connects to sensors. Some vision-based systems are employed for detecting objects and humans to avoid collision, such as camera. For example, thermal vision systems, which is based on thermal cameras and combined with a neural network for detection by acquiring the temperature image. The system is robust, reliable and would not be affected by light or skin colour [15]. Considering collision avoidance, a method is developed that could detect external forces and react quickly. That is, placing a torque sensor in the drivetrain, which could estimate the direction, position, magnitude of forces of mobile robots, then using admittance controller to react to the collision forces [16]. Another strategy for rapid detection is combining Extreme Learning Machine (ELM) face recognition with Microsoft Kinect sensors, which has been implemented on a four-wheeled mobile robot and has achieved a good performance in terms of speed and accuracy [17].

Additionally, further research is required concerning image processing after obtaining the surrounding information, such as using semi-supervised methods or visual saliency modelling for object recognition [18]. Some other technologies, such as deep learning and image segmentation have been applied into perception to make the system more intelligent. Deep learning used in image processing could make the system detect the target accurately [19]. Bonn team used detect architecture based on deep neural network to find tools and complete the challenge well in MBZIRC 2017 [20]. Image segmentation could improve the system in terms of understanding the environmental scene [21].

2) Path and Motion Planning

CMIM planner usually contains two parts: motion planning for manipulator and path planning for mobile platform. The common planning algorithms could be divided into pre-programmed and real-time programmed, which depends on that if the environment map is known or unknown. In previous works, there are plenty of research based on structured environments. Nowadays, the trend is for more flexible mechanisms where the system can update the map simultaneously thereby increasing the system's effectiveness. Simultaneous localization and mapping (SLAM) is one common solution that structures the environment simultaneously. Some other methods for localization have be used in industry, such as sensor-based, odometry-based, ape-based system, bar code or laser triangulation [22]. Moreover, collision avoidance is one important factor when designing the planning method because the environment is dynamic and obstacles are not static [23]. Sampling-based and rapidly exploring random trees algorithm [24] are also used for planning. The former has been successfully adopted in a high DOF manipulator system.

3) Control System

The control system aims to make the whole system perform better in tracking, disturbance rejection, robustness and it contains several aspects, including control type, method and controller. In general, there are three kinds of types to control CMIM, which are manual, semiautonomous and fully autonomous control. To date, much research has examined manual control, which is a safe but complicated way to control the system. Semi-autonomous control strategy combines the advantages of both manual and autonomous control. In order to allow the system to learn and act independently, autonomous control is the best way to achieve fully intelligent industry. The difference among three control types is displayed in TABLE I.

TABLE I. CONTROL TYPES COMPARISON

Type	Features		
	Description	***Advantage***	***Disadvantage***
Manual	Human control the system entirely	Safe; Robust	Complicated; Inefficient
Semi-autonomous	Human control the system partly	Robust	Inefficient
Fully autonomous	Without human's control	Efficient	Unstable

Control method of CMIM is a complex problem because the operator has to consider both manipulator and mobile platform. In past, some research have been conducted on the whole body control [25], which means that both platform and manipulator move at the same time. Krasinskaja developed a whole body control method [26] and constructed a mathematical model to make the system more stable. A discretization method can also be used for controlling, which means that the mobile platform and manipulator adopt different control methods [27]. For a system combined non-holonomic mobile platform and holonomic manipulator, a robust adaptive controller considering the coupling is proposed by designing Lyapunov functions of subsystems relatively. The disturbance rejection ability has been proven by simulation but lacks experimental results [28].

Nowadays, some researchers consider the damping controller to improve the interaction between human and CMIM. The mobile platform would move unless they reach a set of constraints such as the singularity, minimum of manipulability, distance to objects and angular deviations. In a real environment, the situation is more complicated and these four constraints cannot ensure fully intuitive collaboration so that more constraints need to be researched in future [29].

4) Human-Robot Interaction

Safety and interaction methods are two key factors in the way of realizing human-robot collaboration. The safety problem haven't solved completely because the real situation is complex. The changing environment and work configuration require robots to re-plan the path and feedback the contact force continually. The interaction type could be divided into two ways, contact or contactless operation. Contact operation has traditionally been the standard approach for human-robot interaction. This allows direct control of the machine (e.g. via joystick), though this may require extensive training in order to achieve competence. To date, many contactless methods have been introduced, such as pose, speech, brain waves and so on. The contactless methods above are simple for workers to use but have not been applied widely. Another tendency of interaction is intuition, which means that the robot could forecast human's next movement based on a movement library and training. An MIT (Massachusetts Institute of Technology) team presented a data-driven approach and built a human motion library, which could reach to 70% or higher correct classification on predicting trajectory[30]. Therefore, we could conclude that contactless and intuitive operation and would be the tendency in human-robot interaction. Besides, the system needs to consider both mental and physical factors, which means that the system should be very safe and comfortable for humans. In future, with the development of force feedback and predicting methods, the operators would interact with the system easily and naturally without professional knowledge.

III. INDUSTRIAL APPLICATION SCENE

Mobile manipulator subsystems are introduced individually above and they need to be integrated to implement some functions. A significant application for mobile manipulators is industry. In fact, the sales have increased rapidly in recent years, especially in industry areas. Until now, some mobile manipulators have been used in logistics successfully. Other industrial applications have also been researched, such as painting, which could be used for large equipment and assistant for homo-kinetic joint assembly [31]. It is predicted that mobile industrial manipulator sales would still have a considerable increase and some key technology would get breakthrough in industry 4.0. Michael concluded that manufacturing mobile robots need to be focused on and mobile robots could be applied into more areas with the progress of sensors and hardware [32]. At present, collaborative mobile industrial manipulator is mainly applied into three industrial areas, which are logistics, manufacturing and assembly, since CMIM is very suitable to transport objects or perform 'pick and place' task.

1) Logistics

Logistics is the area that calls for CMIMs because there is a high volume of transferring tasks. The operation environments are stable such as a factory or warehouse and extensive research regarding CMIM with object transferring capabilities has already been conducted. For example, the collaborative autonomous kitting logistics in a car manufacturing warehouse [33].

However, very little of CMIM research to date could be used into the real industry environment directly. TAPAS (2007-2013), a project aims to realize a robot not only used in intelligent automatic logistic system, but also in some assistant service, such as preparing or assembly [34]. As one of the participant of TAPAS, Ole Madsen team applied two mobile manipulators (Little Helper) into real industry environment for pump production. One of them mainly worked as a logistics robot for transporting the rotor from one workstation to another. Another one was used as an assistant for assembly and quality control. The two Little Helper cooperate well, however the experimental results indicate that there are some problems, such as the speed and safety, which need to be solved before CMIMs could be used in the real environment. Besides, hardware setup is quite time-consuming and navigation errors often occurred [35].

2) Manufacturing

Manufacturing is another area in which CMIM has been shown to have high utility. In 2017, Andreas combined a CMIM (Omni Rob) with another CMIM (Little helper) to transfer the parts for water pump manufacturing [36]. Furthermore, the system could be used in processing/reprocessing line as material transferring tool. For some manufacturing which require high precision, where CMIM is rarely applied, it is not difficult for a stationary manipulator to guarantee the accuracy and performance. Nevertheless, Shuai Guo applied CMIM in aerospace manufacturing, the drilling work, which needs both accuracy and flexibility simultaneously. Plenty of experiments have been conducted to test the feasibility [37]. While Paul applied CMIM into screwing task. The experimental results showed that the system and human work together well and it could be applied into other industrial areas in future [38].

3) Assembly

Stationary manipulators are quite popular in assembly lines. However, in some cases the assembly line needs to be changed. Compared to stationary manipulators, mobile manipulators are more flexible and effective, which means that they could make more production and reduce cost in industry. Furthermore, assembly is an essential process in automotive industry and some specific mobile manipulators are designed for that. Which currently require human labour to transfer large or heavy components. For example, the placement of aero panels, a small anthropomorphic collaborative robot has been introduced as a lifting tool [39]. Moreover, the application of lightweight assembly has also been considered.

IV. RESEARCH CHALLENGES & FUTURE DIRECTIONS

Robotic systems promote the development of industry majorly in recent years. Due to extensive research and increasing knowledge in this area, various robotic systems are now being applied in a variety of settings. Among the various kinds of robots, mobile platforms with manipulator are quite practical since they could move flexibly and pick objects easily, which is well suited to work in a factory for pick-and-place tasks. Through the review of CMIM's research, architecture and applications in recent years, some avenues for future research can now be outlined. The issues and directions highlighted in this paper can be a reference for further research.

Firstly, some CMIMs are semi-autonomous control systems and partly pre-programmed. However, industrial environments may be variable and require that the system could be applied into different scenes. Until now, the system has not reached a sophisticated level of intelligence as of yet. In some cases, the system may meet some problems or ambiguous information that it cannot handle independently. Based on the survey above, fully autonomous systems would be the future direction, which means the system could complete the entire task independently. Only in this way could the industry achieve a revolution. At the same time, the intelligent system should be robust and safe and could figure out the errors or solve the problems by itself in structured or unstructured environments.

Secondly, some research has been conducted according to competition, simulation or the experiments conducted in the lab. However, the real industrial environments are more complex, and more human and objectives would be involved here. As is known, the real industrial environment is quite difficult to simulate and use. In coming years, several advanced technologies involving CMIM should be performed in real environments because lab environment or simulation are quite different from the real situations. It would be more convenient for researchers to test the system and get the real feedback, then solve the problems, which forms a loop.

Thirdly, some other technology, which used in other areas would be adopted into CMIM. Experimental results showed that the mobile manipulator using deep learning could detect and pick up garbage by itself and the recognition is quite effective and accurate, which revealed the potential in cleaning lawn [40]. In future, more and more research used in other areas should be combined with CMIM in order to develop more application possibilities.

Fourthly, CMIM system contains a range of components, such as sensor and manipulator, which means that the performance metrics of the system are various and difficult to define or unify. So far, there are no unified standards for CMIM and that hamper CMIM's popularity into factory. According to that, the research could improve the performance directionally. In future, the performance measurement methods and standards especially for mobile manipulator need to be researched [41]. Standardized system is more straightforward to understand the design and could improve the efficiency. Workers or researchers could also set up the system quickly and the experimental results would be more instructional.

Moreover, due to that collaborative robots may work with human closely, the interaction between human and CMIM is another issue that is quite crucial. The development of a more intuitive interaction system would allow the robot to predict human intentions more accurately, which would be advantageous for path planning. Meanwhile, the system must ensure security for human operators, or it cannot be realized into the real environment. In future, it would be easier for the human to interact with the robot. More and more ergonomic and intuitive methods would be discussed, especially in contactless interaction. Furthermore, the robustness, operability and accuracy of interaction methods should also be reinforced.

Additionally, on one hand, CMIM integrates the merits of mobile platform and manipulator, on the other hand, the manipulation and control become more complicated since CMIM is a redundant system and has a dynamics coupling problem. Current control strategies have not solved the coupling problem and made use of the system redundancy very well [42]. Thus, the coordination between manipulator and mobile platform requires to be studied, especially when human intervening the scene. Many solutions have also been proposed to make sure that human could manipulate or control the robots safely. What's more, extensive research is being applied to different methodology or controllers and various of theories are proposed. The main control methods are decentralized and whole body control, which means that manipulator and mobile platform would move separately or synchronously. There are currently few generalized methods or controllers, which could be applied into many tasks or mobile manipulators. The universally applicable coordination method or algorithm should be researched in the future.

So far, most of the literature is about single kind of robotic system performing a task. However, in the real industrial environment, the situation is quite complicated. Despite the fact that there is currently a large number of fenced stationary manipulators, there is a lack of research addressing the issue of how to supply the materials. Mobile industrial manipulator could be the intermediates because it could co-exist with both human and stationary manipulators. Human-Robot(CMIM)-Robot (Stationary manipulator) system could not only ensure human's safety but also perform the task, hence, the system requires further research.

V. CONCLUSIONS

Given that CMIM developed very fast in last few years, many aspects of CMIM research have been conducted. This paper introduces the hardware and software of a classical CMIM and overviews the applications in industry. In view of above literature survey, some research challenges and future directions are outlined. As the research further develops, there is no doubt that CMIM would become more intelligent and could assist human to do more complicated tasks.

ACKNOWLEDGMENT

This research is funded by the International Strategic Partners (ISPs), University of Strathclyde.

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