Reconfigurable autonomous industrial mobile manipulator system

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Abstract— **The manufacturing industry is moving from mass production towards more personalized products through mass customization. In order to adapt factories should be highly flexible and rapidly able to adjust their operations.**

The new technologies and concepts in industry 4.0 are important in the transition from mass- to flexible and personalized manufacturing systems. One such specific tool for increased flexibility is the introduction of an Autonomous Industrial Mobile Manipulator (AIMM). The AIMM provides mobility with its mobile part and increased flexibility and functionality with the robot arm. However, a disadvantage with AIMM systems is that when the mobile robot is moving the robot arm cannot work; when the robot arm is working, the mobile robot cannot drive. This creates downtime for both the mobile robot and the robot arm.

In this paper, we will look at how an AIMM can be divided into two parts for increased utilization of the mobile part and robot arm of the AIMM. Our approach is to physically divide the system into two parts, one with the mobile robot and a second with the robot arm on a trolley. In this case, the mobile robot can transport the robot arm, detach from the robot arm and perform other tasks while the robot arm is working at its new location.

I. INTRODUCTION

Industry 4.0 is often referred to as the fourth industrial revolution. It is a manufacturing philosophy that includes a wide area of concepts and new technologies, such as Human-Machine and Machine-Machine communication, Internet of Things (IoT), Enterprise Resource Planning (ERP), Cloud technologies, Big data and mobile systems [1]. The vision of Industry 4.0 is to create a smart factory with intelligent Cyber-Physical Systems (CPS) [2].

Businesses that implement and master technologies, such as advanced automation, virtualization and flexibilization, will gain a competitive advantage [3]. The technologies in Industry 4.0 allow production companies to go from mass production with limited customization towards mass personalized production [4]. Mass personalized customization can be a lucrative strategy that comes with many advantages. However, it does come with some challenges, such as increased complexity in the production system [5]. To achieve mass customized production, the production system in itself has to be adaptive and highly flexible.

Robots are often used to perform simple tasks, which again requires the least amount of sophisticated technology [6]. They are usually mounted to the ground (fixed autonomous), which limits the robot's reach and decreases flexibility. New applications are emerging that require industrial robots (IR) to access environments previously inaccessible [7], and there is an increasing demand for robots performing more complex tasks [6]. Such as assembly tasks that require the robot to make decisions based on a changing environment.

One tool towards increased flexibility and mass customization is the introduction of an Autonomous Industrial Mobile Manipulators (AIMM). AIMM is a flexible autonomous manufacturing assistant that can be used for different manufacturing tasks. The idea behind AIMM is to have a more flexible and varied automation solution. It can work beside people, be fully automatic and be able to perform work at different workstations [8]. It is a combination of different technologies and concepts working together, where the four abbreviations can be explained by the following [9]:

- **Autonomous:** The robot is able to perform tasks independently, with no human intervention.
- **Industrial:** Refers to where the robot is utilized.
- **Mobile:** The robot can map and move around an industrial environment through its localization.
- **Manipulator:** The robot can do mechanical work, such as move objects or change arrangements of parts.

The AIMM benefits from the mobile robot with increased flexibility and mobility, and gets the functionality from having a robot arm [10]. Most of the recent research projects have used a standard mobile robot or ROS-based mobile robot together with an industrial or collaborative robot [11][12]. There have been EU funded projects [13][14] on mobile manipulators, and so companies have started to produce AIMMs, for example: KUKA KMR iiwa [15], Fetch Fright [16], Omron MoMa [17], ER-FLEX [18] and Robotnik mobile manipulators [19].

AIMMs have been tested in real manufacturing system, but there are still challenges and the technology should mature before being implemented in large-scale manufacturing operations [20]. There is a need for further development of control methods for the AIMM system and standardization of its components [9]. It should be noted that industrial robot arms and mobile robots are expensive investments. Typically, a medium sized industrial robot cost 50k€, while a mobile robot cost around 30k€. A substantial investment for most small and medium sized companies.

In order to increase the utilization of both the robot and the carrier we suggest to split the AIMM into two physical parts, the mobile robot and an industrial robot arm mounted on a trolley. This paper look at such division, how to build, connect and control the respective units.

The paper is organized as follows: Section 2 will discuss a new conceptual approach to the AIMM; Section 3 describes an experimental setup, how it works, and how it is connected

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together; Section 4 gives a demonstration of the experimental system; while Section 5 presents a discussion based on the demonstration and a conclusion.

II. An alternative approach to AIMM

One of the disadvantages of AIMM is that the robot arm and mobile robot are fastened together. When the robot arm performs tasks, the mobile robot has to stand still and vice versa. It creates a large amount of downtime for both the mobile robot and the robot arm.

As mentioned, an AIMM can be divided into two parts: a mobile robot and robot arm. A different approach is splitting the AIMM into two physical parts, one with a mobile robot and a second part with a robot arm on a moveable trolley. An illustration of such an AIMM can be seen in figure 1.

Fig. 1. The three figures showcase how an AIMM can be divided into two parts but also work together

The mobile robot can transport the robot arm, then detach itself from it, and do other tasks while the robot arm is working. This allows the mobile robot and robot arm to work as one unit and work separately from each other. This can decrease the mobile robot and robot arm's downtime while maintaining the flexibility of an AIMM system.

The trolley can be equipped with different types of robot arms (SCARA or n-DOF IR) or other machines, depending on what work has to be done. It should be mentioned that most AIMMs today use collaborative robots, since they can work beside humans and are not as dangerous as standard industrial robots.

Depending on the use of the system, it is possible to have multiple trolleys with robot arms and only one mobile robot to transport the robot arm to where it is needed. This again increases the flexibility of the production systems and cuts costs, since only a few mobile robots are required in order to transport the robots.

III. AIMM system structure

A proof of concept has been developed to demonstrate how an AIMM can be divided and how such system can work. In this chapter we will describe each key-component, its setup and connection to an industrial information server.

A. Mobile robot system

The first part of the system is the mobile robot. In this system we used the MiR100, which is a highly flexible autonomous mobile robot. It has a carrying capacity of 100kg and can pull up to 300kg [21].

There are two methods by which the mobile robot can move or transport the robot trolley, either through a hook system where the mobile robot latches onto the trolley and pulls it, or a system where the mobile robot drives under the trolley and then docks into the trolley. It is not recommended to pull the trolley (from outside), since it is harder for the mobile robot to move in a strict predictable way. Attaching the mobile robot under the trolley simplifies the movement of the unit.

The mobile robot is made to be flexible and it is possible to change or add a top-module. A simple top module, which uses a motor to move two L-formed pins outwards, has been developed, as can be seen in figure 2. When the mobile robot drives under the trolley, the two pins move outwards, which hooks the mobile robot to the trolley.

The positioning accuracy of the mobile robot is only ± 50 mm [21] and is too low to dock into a trolley reliably. However, the mobile robot is fitted with two 3D cameras in the front, which can be used for accurate positioning within ± 10 mm. This is done with either a V marker or a VL marker, which can be 3D printed and placed around a production environment for accurate docking positions, as shown in figure 2.

Fig. 2. The figure showcases both robot trolleys, the mobile robot with the pin system, and the marker used for docking with the mobile robot.

It should be noted that in this system the mobile robot can only pick up the robot trolley where there is a marker. Being able to pick up and place the robot in any position in the laboratory would further increase the flexibility of the system. However, that requires a different method to improve the accuracy of the mobile robot.

B. Robot arm system

There are two robot arms in this system, one SCARA Adept 604 (4-DOF) and a Nachi MZ07 (6-DOF). Both robot arms are placed on a movable trolleys, as shown in figure 2. Each trolley is equipped with an Uninterruptible Power Supply (UPS) to power the robots, controllers and grippers. Both robots are fitted with a 3D camera (Intel Realsense D435) used to identify, pick and place objects. The 3D cameras are fitted to the gripper on the robot arm, as shown in figure 3.

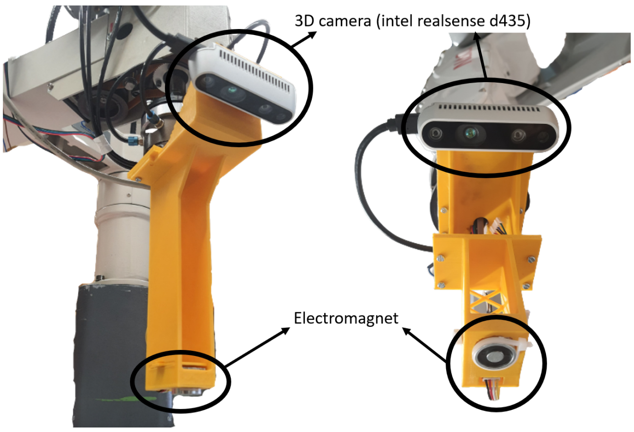

Fig. 3. The robot gripper for the Nachi and Scara robot

An open-source library OpenCV [22] was used for classification of objects. OpenCV is a computer vision and machine learning library that can be used for real-time vision applications [23]. When the robot gets a task to pick a specific item, it drives automatically out with a fixed routine to see if it can find the object using OpenCV. If the object is found the robot will position itself so that the object is in the middle of the camera view. When the robot has positioned itself, the 3D camera is used to read how far away the object is and the robot moves down to pick the object. An electromagnet is used to grip the object, as can be seen in figure 3. The electromagnetic gripper has been made to be flexible and does not require high accuracy where small objects will automatically get pulled towards the gripper.

C. IoT system

AIMMs are usually made to work remotely and wireless, and should be able to communicate with other machines as well as human operators [24]. In our previous project [25], all robot arms and mobile robots were connected to the Open Platform Communications Unified Architecture (OPC UA). The OPC UA Standard [26] is an open-source industrial information server. It's an international IEC 62541 [27] standard and is commonly used today in the manufacturing industry to enable communication between pieces of equipment [28]. It is scale-able and platform-independent, which means it can run on almost all operating systems.

Having all the robots connected to the same server makes it simpler for the machines to communicate. In addition, the robots can be controlled and monitored through the OPC UA server. Since the OPC UA standard is widely supported in the manufacturing industry, it simplifies the integration of new machines into the system.

The IoT system can be structured into five parts, one for each of the robot trolleys, one for the mobile robot, one for controlling the system/generating missions, and the OPC UA server, as illustrated in figure 4.

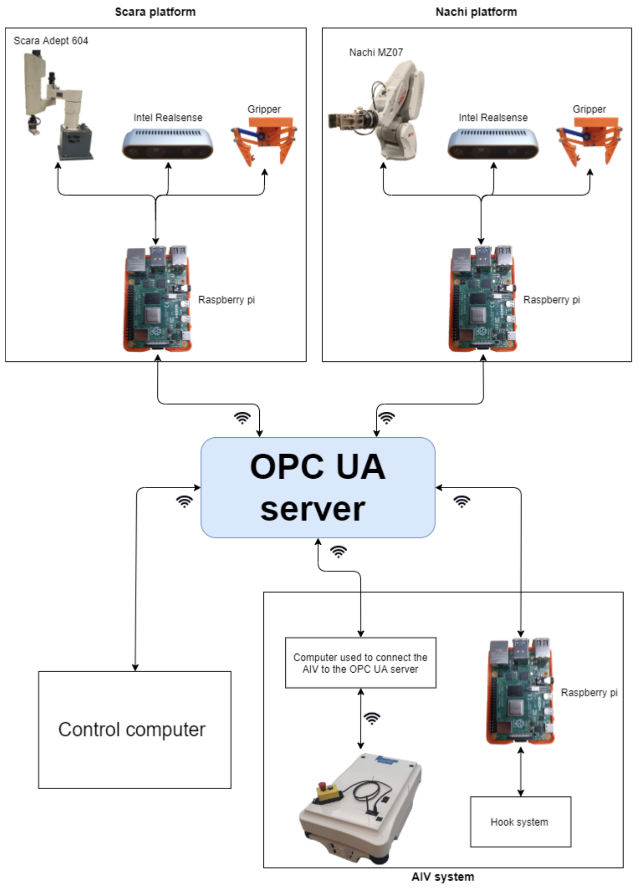

Fig. 4. Illustration on system setup and connections.

As can be seen in figure 4, both robot trolleys is equipped with a single-board computer (Raspberry Pi). It gathers information from the 3D camera and send information to the robot arm and its gripper. There is also a Raspberry Pi on top of the mobile robot, which is used to manage the pins for locking or attaching the mechanism to the trolley. The Raspberry Pis are wireless connected to the OPC UA server.

The mobile robot itself do not support OPC UA, and a computer is used to send and receive information from the OPC UA server.

To start a mission on the Nachi or Adept robot, a computer is used to allocate assignments, which are then started and executed automatically. The Adept and Nachi robots have been made to operate independently from the other parts of the system. Both robot trolleys can control the mobile robot and other machines, for example: call on the mobile robot for transport or get a drawer from the vertical storage lift. The hierarchy of the system can be seen in figure 5.

IV. DEMONSTRATION

To showcase the system, we have created three demonstration videos, as can be seen in table I. There are two versions

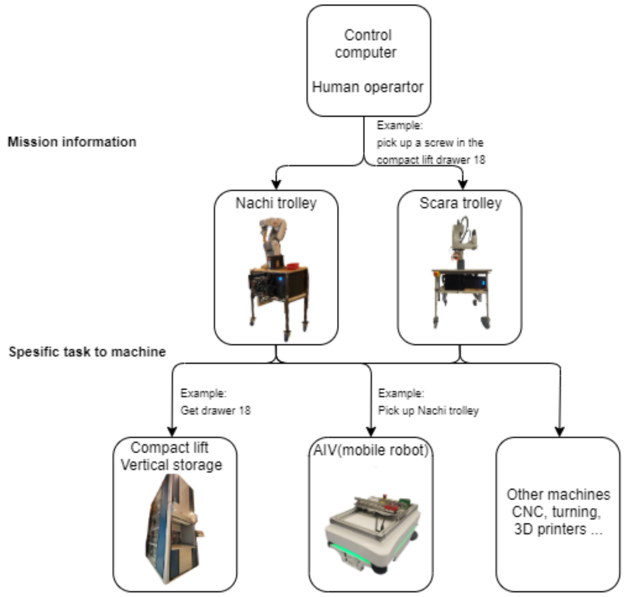

Fig. 5. System control hierarchy.

of each video: one with increased video speed and a second video at normal speed.

TABLE I
THE TABLE LISTS THE FIVE VIDEOS THAT HAVE BEEN CREATED AND INCLUDES A LINK TO THE VIDEOS.

Videos from the demonstration		
Description:	**Speed x5**	**Original speed**
Logistics demonstration	https://youtu.be/8gyoRbaeshk	https://youtu.be/r-DMh_OIFO0
Nachi pick object	https://youtu.be/HgNFWy8n560	https://youtu.be/q9QY52aMSdE
Scara pick object	https://youtu.be/O2DUdpMDWmU	https://youtu.be/C13GEO--DRg

The first video showcases the collaboration between robots in the systems. Four positions/markers have been added to the laboratory. In the demonstration video, the mobile robot transports the Nachi platform, Adept platform and an empty platform around the laboratory to showcase how one mobile robot can be used to transport multiple robots and carry out an logistics operation.

The following happens in the demonstration video:

1) The mobile robot transports the Nachi platform to the Compact lift
2) The Nachi platform calls for a drawer from the Compact lift and starts picking an object(screw)
3) The mobile robot transports the Scara platform to a workstation
4) When the Scara platform has been transported, it starts picking up objects (screw)
5) At the end, the mobile robot transports an empty platform

The other two videos showcase the Nachi and Scara robot picking up a screw using image recognition and the electromagnet.

From the demonstration, we conclude that the mobile robot is able to transport both robot platforms and an empty platform around the laboratory. The mobile robot and the robot arms are also capable of working independently from each other as well as collaborating together.

It should also be noted that using the OPC UA server for communication creates a stable and reliable method for communication between all machines.

The pickup system for the Nachi and Adept robot is relatively simple. A test was conducted on the Scara robot to see how accurate the pick system was. The robot tried to pick up a screw eight times and failed three times which gives room for improvement.

V. CONCLUSION

The AIMM has proven to be a flexible solution that combines different technologies and concepts. It is intended to be used by manufacturing companies that require more flexibility and personalized production. The AIMM often includes an intelligent mobile robot and robot arm with a vision system that increases the robot's flexibility. However, one of the disadvantages of the AIMM is that it is an expensive investment, and it is therefore essential to get as much utilization of the AIMM as possible.

To increase the utilization and the flexibility of the AIMM, we propose to divide the AIMM into two parts. This creates a more flexible system where we better can utilize both the mobile robot and robot arm, as can be seen in the demonstration.

This system relies on IoT functionality for machine-to-machine communication between the robots. Using the OPC UA standard can be a good and flexible solution for IoT connectivity in industry 4.0 systems. It makes it simple to add more robots or other machines to the system without affecting the other parts and creates unified communication between all members.

The experimental system was tested with a SCARA robot and an industrial Nachi robot. The Scara robot is limited to 4-DOF and therefore has somewhat limited movements. In contrast, the Nachi robot has 6-DOF, has a better reach, and is more suited to work on a mobile trolley. It is also important to keep the robot trolley as light as possible. If the trolley is too heavy, the wheels of the mobile robot will start to spin, which reduces the accuracy of the robot. Therefore, the ideal robot trolley should be equipped with a lightweight robot arm and controller, with a long reach/working area.

A general challenge of having the robot on a portable trolley is that robot movement can transfer to an unstable trolley. A docking system of the portable trolley should be considered as a next step in system development.

VI. FURTHER WORK

As part of our future work, the vision system should be made more flexible and able to recognize more objects. More intelligence, such as reinforcement learning and neural networks, should also be added to the robot trolleys to make them more flexible and adaptable to the environment. Adding more intelligence to the system can simplify the integration of more capabilities of the robot trolley.

In this system, the mobile robot can only position the robot arms where a marker has been placed. This again limits the flexibility of the system. The positioning could be improved so that the mobile robot can place and pick up the trolley in any given position. Finally a trolley docking system should be developed in order to secure stable IR robot movements.

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