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Integration of a skill-based collaborative mobile robot in a smart cyber-physical environment

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Abstract

The goal of this paper is to investigate the benefits of integrating collaborative robotic manipulators with autonomous mobile platforms for flexible part feeding processes in an Industry 4.0 production facility. The paper presents Little Helper 6 (LH6), consisting of a MiR100, UR5, a Robotiq 3-Finger Gripper and a task level software framework, called Skill Based System (SBS). The preliminary experiments performed with LH6, demonstrate that the capabilities of skill-based programming, 3D QR based calibration, part feeding, mapping and dynamic collision avoidance are successfully executed and strategies for further expansion of the operational capabilities of the system are discussed.

Peer-review under responsibility of the scientific committee of the 27th International Conference on Flexible Automation and Intelligent Manufacturing

Keywords: Collabrative robots; Smart production; Cyper-physical system; Industry 4.0; Autonomous industrial mobile manipulator, Little Helper

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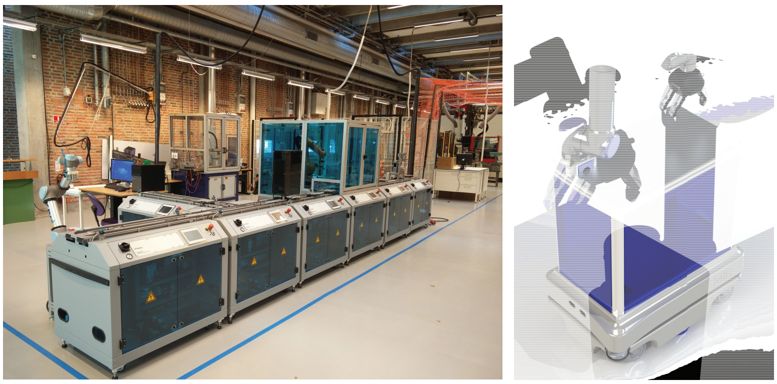
1. Introduction

Nowadays, many manufacturing companies experience unpredictable and dynamic production environment due to increased customization in the production, low product life cycles and increased competition from low labor countries. In order to remain competitive in such globalized market, they have to adapt their production systems accordingly and create flexible automatic solutions. Today, robot-based manufacturing offers the desired automation due to statically fixed industrial robots, often placed in a cell, executing predefined sequence of tasks. However, current robotic solutions lack the anticipated intelligence and flexibility when they are mobile and have to carry out dynamic tasks. Therefore, to achieve a greater flexibility along with an efficient production, it is essential to shift the manufacturing paradigm from traditional industrial robots to flexible and autonomous robotic systems with an intuitive on-the-fly programming, enabling an ideal batch size of 1.

In the pursuit of flexibility within production, a family of five autonomous industrial mobile manipulators (AIMM) called Little Helpers (LH) has been created from Aalborg University. The main scope of LH robots is to deliver a low-cost element in a reconfigurable production environment and achieve flexibility, reconcilability, and efficiency through a high degree of automation [1]. Intuitive on-the-fly programming for non-robot experts is achieved via a programming framework, called Skill Based System (SBS) [2]. By integrating a multitude of sensors and robot actions, SBS is used to program LH robots to solve multiple industrial tasks such as pick and place operations [3,4], peg-in-hole actions [5] and stud welding in ship superstructures [6].

Alongside with the increased need for a flexible and reconfigurable production a new digital industrial trend is emerged, called Industry 4.0, which is a combination of new technologies within internet, robotics and mechanics. The backbone of Industry 4.0 spans nine major technology categories, including autonomous robots, simulation, the industrial internet of things and cloud computing [7]. In Industry 4.0 sensors, robots and IT-systems, are connected by an overall network, that makes it possible to gather and analyze production data across machines, sensors and mechanisms and, thereby, increases the flexibility of the production. In Aalborg University, an Industry 4.0 demonstrator has been implemented using a FESTO Cyber Physical (CP) Factory environment (Fig. 1a) [8]. The FESTO CP Factory is built up by several modules, each consisting of an individual cyber psychical system, which are then connected through a network. Within the FESTO CP Factory environment there are several tasks which could be automated be deploying an AIMM e.g. part feeding, transport and assembly operations.

The focus of this paper is to automate a part feeding challenge in an Industry 4.0 context, by designing and building the sixth version of Aalborg University's family of LH robots (LH6) (Fig. 1b) and integrate it as a modular part of a FESTO CP Factory environment to solve part feeding challenges, and thus adding a new element of flexibility to the factory environment.



(a) (b)

Fig. 1. (a) FESTO CP Factory and (b) Little Helper 6

1.1. Related work

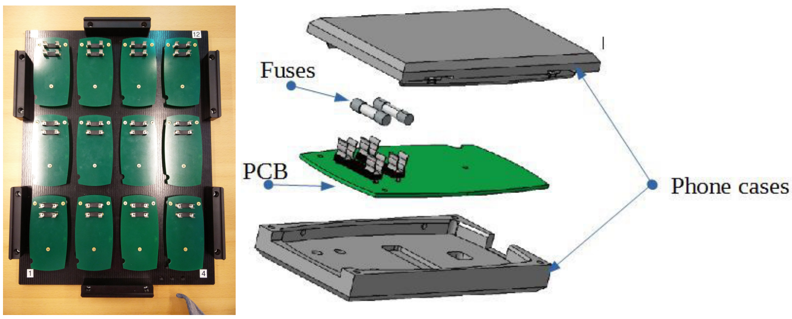
The first concept of a mobile manipulator dates back to 1984, with the introduction of MORO (MObile RO-boter). MORO was able to navigate freely in a shop floor, transporting work pieces and handling tools. However, due to limited processing power, low battery capacity and high cost the robot was never used in the industry [9]. The concept of a mobile manipulator consists of challenges within different research fields, including navigation, path planning, control and human- robot interaction. These fields share the same approach of utilizing a mobile manipulator as a holistic system in order to decrease the dependencies and increase the operational capabilities of the robot. Furthermore, the applications of mobile manipulators span across different domains: e.g. home use [10], health-care [11] and the aerospace industry [12].

To reach a common consensus and secure knowledge exchange within the different fields, official research strategies in Japan, USA and Europe have been established in the recent years. According to the annual roadmap published by the EU supported agent for robotic strategies in Europe SPARC [13], the need for further research within collaborative robots, mobile manipulators and intuitive programming is explicitly identified, which has led to several EU funded research projects, such as VALERI [12], TAPAS [14] and STAMINA [15].

The interest of deploying mobile manipulators within the different domains is also visible in today's market consisting of several emerging solutions: e.g. Mobile Baxter [16], Fetch and Freight [17], YuMi mobile manipulator from ABB [18] and KUKA KMR iiwa [19]. However, despite having the spotlight, both within the research community and commercially, there are only a few examples of successful implementation and integration of AIMMs in a real production environment [1]. Hence, this paper will present the design of a new AIMM consisting of commercially off-the-shelf components and how it is integrated into a production environment. Furthermore, the paper will present the integration details of the mobile platform into a skill based framework and how robot skills bring the desired intuitiveness in robot programming.

2. Task description

The industrial case where LH6 is to be deployed and tested is limited to part-feeding of a single module in a FESTO Cyber-Physical Factory. The part that is to be fed into the module is a tray containing 12 PCB (Fig. 2). According to the task flow, first LH6 will drive to the location where the empty tray is located (Fig. 3a). The next step is to calibrate the position of LH6 so that the manipulator can compensate for the imprecisions of the navigation of the mobile platform (Fig. 3b). The empty tray is removed from the module and placed on LH6 (Fig. 3c). The last step is to insert the full tray (Fig. 3d) and send a signal to the PLC that a new tray is fed (Fig. 3e).



(a) (b)

Fig. 2. (a) Tray containing the 12 PCB. (b) Assembly of the phone.

(a) (b) (c) (d) (e)

Fig. 3. Steps of the part-feeding task.

3. System implementation

3.1. Hardware overview

The LH6 is build-up of four technologies; mobile platform, manipulator, tool, and sensors which can be seen in Tab. 1.

Tab. 1. The four technologies of LH6

Mobile Platform	Robot Manipulator	Gripper	Sensors
MiR100 Payload 100kg Precision ± 10cm	UR5 Payload 5kg Repeatability ±0.01mm	Robotiq 3-Finger Gripper Payload 10kg	MiR100’s Laser scanners ASUS Xtion 3D Camera

These four technologies are combined with a common mechanical structure mounted on top of the mobile platform In Fig. 4. an exploded view of LH6 with its components is illustrated. A 3D camera was also used to calibrate the position of LH6 by obtaining a transformation from a fixed QR-code to the LH6.

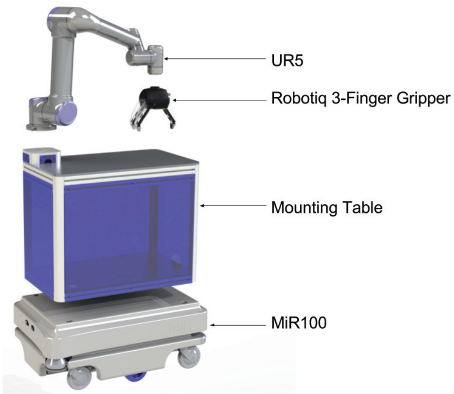


Fig. 4. The main components of LH6.

3.2. Software framework

The Skill based system (SBS) is the backbone software framework where all the components are connected via ROS [20] drivers. SBS is built on the concept of tasks, skills and device primitives where the latter is basic motion commands and skills are basic functionalities the robot has [21]. A model of the concept is displayed in Fig 5a.

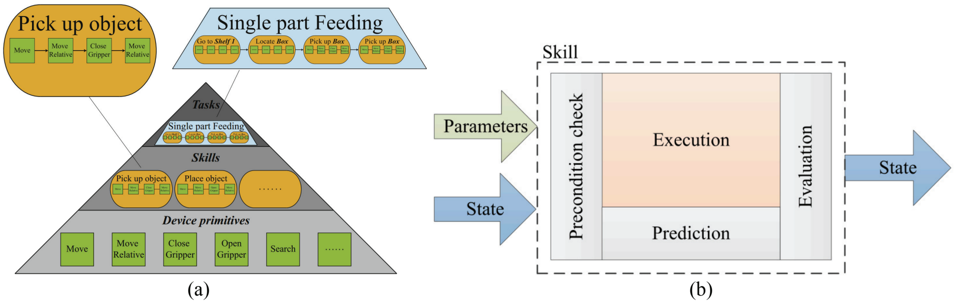


Fig. 5. (a) The building blocks of SBS. (b) Structure of a skill.

Every parameterisable and task related action of the robot is defined as skill and it is characterised by a number of parameters which must be specified prior to execution. A skill can thus be *Pick up object* or *Place object*. The general structure of a skill is shown in Fig.5b. The precondition check is used to check whether the skill is able to be executed, for instance when picking up an object; if the object is in range or if it is already in the gripper. The combination of the prediction and the evaluation generates the post condition check, where the expected results (prediction) are evaluated and compared to the actual results. Both the pre- and post condition checks evaluate to success or fail, i.e. proceed processing or return error.

4. Experimental results

Every aspect of LH6 was designed in small steps called iterations, which were developed on the knowledge gained from prior iterations. The iterations that produced a step change toward the final prototype are illustrated in Fig. 6.

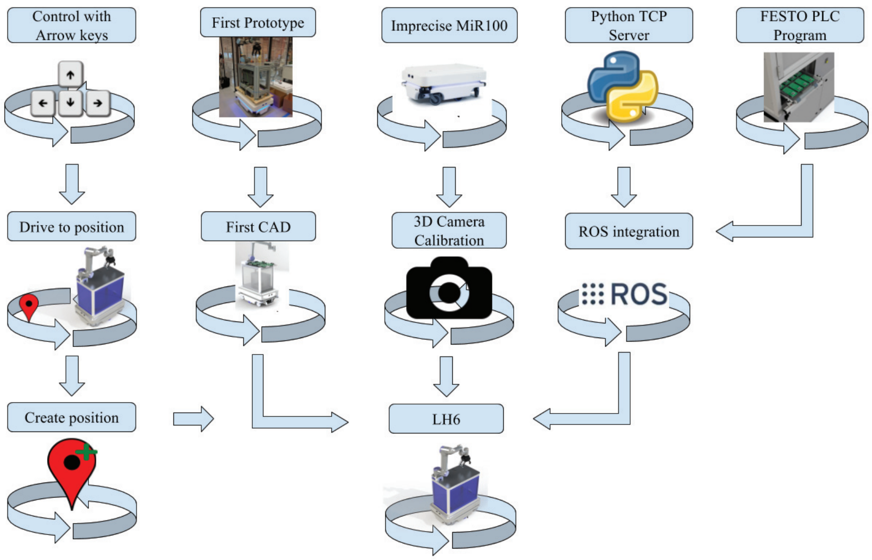


Fig. 6. Main iterations that lead up to the final prototype.

4.1. MiR100 driver

The development of the ROS driver for MiR100 was an iterative process, which was carried out in three main steps. Generally, the work started from the implementation of a simple motion control and concluded with a collection of complex functionalities, such as Drive To capability, programmed in Python. By using REST API, it was possible to create and manipulate missions on the MiR100 platform. This was achieved by adding actions with parameters to a mission queue inside MiR100s internal computer. The REST API also allowed to store multiple positions to which the MiR100 could drive. Furthermore, via a Rosbridge connection with the MiR100 basic motions could be assigned and the current state could be set, checked and verified. After the necessary adjustments, the Drive To capability was also integrated into SBS as a Drive To skill.

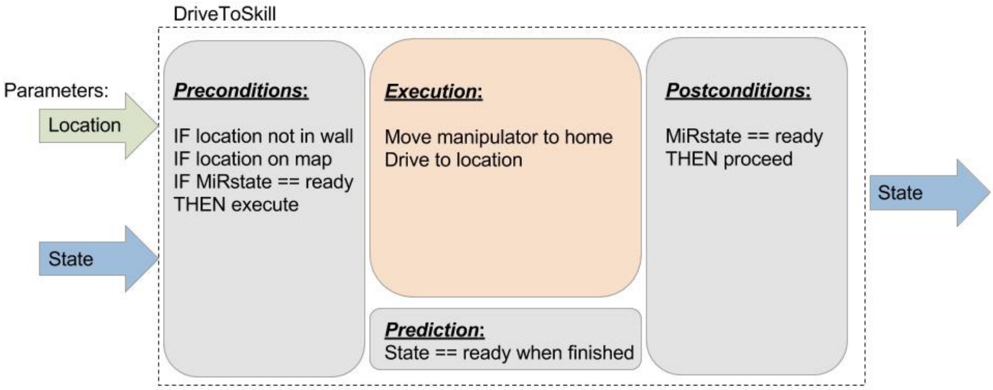
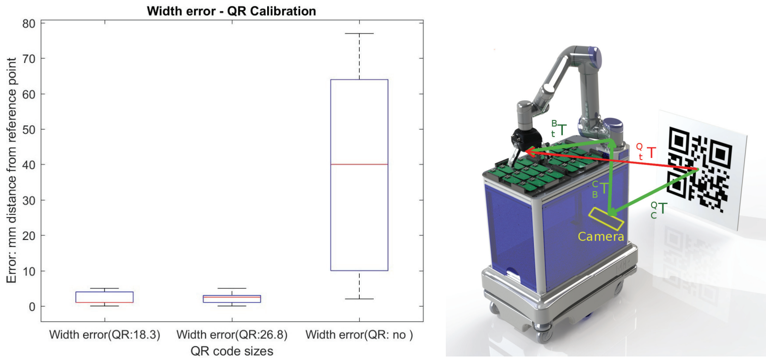


Fig. 7. Structure of the Drive To skill.

The Drive To skill possesses pre- and post conditions to add on to its robustness (Fig. 7). The preconditions to the Drive To skill is that the UR5 arm is in a custom home position, the destination of the MiR100 exists in the map and is reachable (is not in a wall), and that the MiR100 is in ready mode. If these preconditions are evaluated as true, then the skill can be executed. The post conditions are checked after the execution of the skill is completed. The only post condition of the Drive To skill is that the MiR100 should be in a ready state. If this condition is evaluated as true, the execution may proceed to the next skill.

4.2. Calibration

Since the MiR100 has an offset of ±10 cm when arriving to its destination, the precision of the UR5 manipulator is significantly impaired. To compensate for this imprecision, a calibration method used in previous LH projects, utilizing 3D camera reading a QR code, is deployed [22]. This method was tested against the uncalibrated method. The test setup was that the LH6 will set a reference point with the UR5 manipulator and then LH6 will drive away and back again. The UR5 will then try to hit the reference point again and the distance between those two points will be measured. This test was carried out 10 times of with three different scenarios, one without camera calibration, and two with different sized QR codes. The test showed that without a calibrated camera, LH6 will have a radius point impression of up to 75 mm while with a camera calibration the radius point impression will only be up to 5 mm (Fig. 8a). This method with camera calibration allows the UR5 manipulator to save points in space with reference to the QR code, rather than its base (Fig. 8b).



(a) (b)

Fig. 8. (a) Boxplot of radius distance from reference point in mm of the camera calibration test. The QR size is in cm. (b) Transformation from QR code to tool.

4.3. TCP communication

In order to know when a tray exchange is needed, a communication must be established among SBS and the PLC in the module. First iteration was to create a simple TCP server that is able to handle a single request at a time. Simple PLC program was created that sent a message to the server and read its response, when a carrier arrived to a selected sensor in the assembly module. As the TCP server became operational, it was integrated into a ROS node, so it can publish a state of the tray to a topic, and establish a service to inform the PLC that the tray was exchanged. A final PLC program was written that used rewired relays of the assembly module to virtually push the button and to receive readings from the photo-eye sensors. The empty tray was rolled out automatically and according to its position the TCP server acknowledged the state change and published this fact into the dedicated topic. The PLC program was listening for a message from the TCP server that the tray was exchanged, so it can reel the new tray in, using the push-button signal. Fig. 9 highlights the relation between SBS and the ROS drivers.

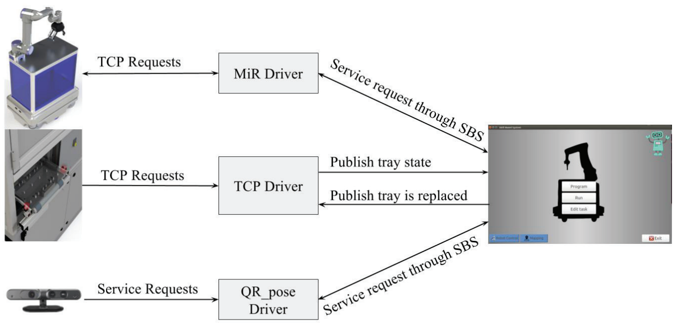


Fig. 9. ROS drivers integrated.

In order to achieve seamless integration with SBS, two new skills were created i.e., Listening skill and Call skill. The Listening skill listens to a topic for messages from the TCP server about tray state and holds execution of the task until the tray rolls out. The Call skill contains in its execution a service call that is handled in the TCP server and instructs the PLC to reel the tray in. Fig. 10 illustrates the relations of the LH6 components.

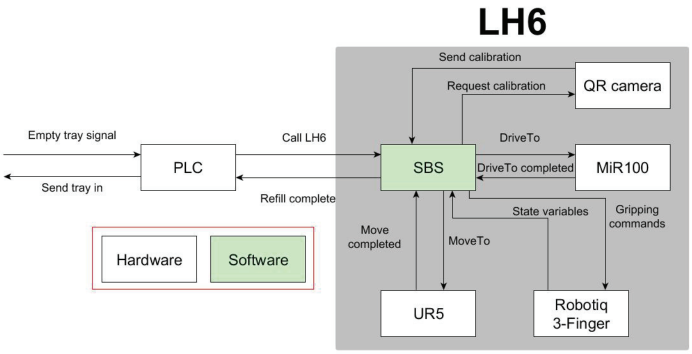


Fig. 10. The components of LH6 and their relations.

4.4 *Evaluation*

In order to evaluate the performance of the LH6, a part-feeding task was created in the FESTO CP Factory. This test was evaluated on five different aspects, each of which had to succeed in order for the test to be considered successful. The steps of the part-feeding procedure were examined in Fig. 3. When the LH6 has arrived at the destination for the part-feeding, the manipulation of the part, consisting of a tray, is done according to Fig. 11.

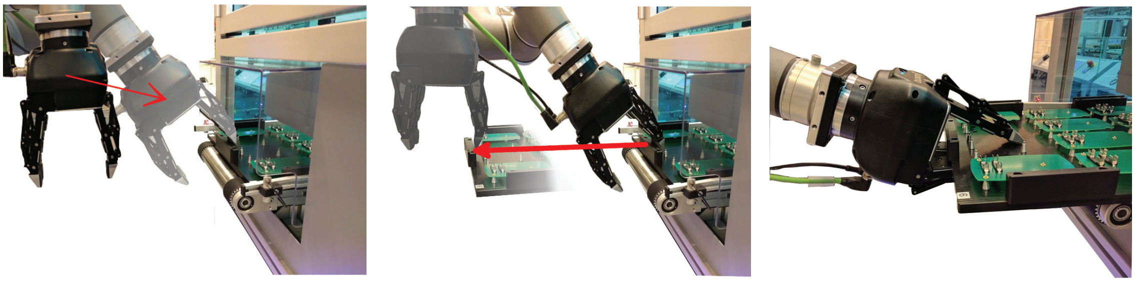


Fig. 11. Part-feeding process.

After 25 test runs with 9 failures, the result showed that the major bottleneck of the execution was the communication between the modules and was accounted for 67% of all failures. It was discovered that the communication error was due to a bug in the PLC program and was later resolved. The rest of the failures were due to the inability of the mobile platform to reach the target locations adequately. It was concluded that the errors of the mobile platform were due to navigation inaccuracies around a corner near the target location. The corners were eliminated by adding two boxes on each side. As a result, the error reduced from 22.22% before adding the boxes to 11.11% afterwards. Finally, with the communication bug resolved and the necessary modifications to the environment to compensate for the mobile platform location error, the rest of the task i.e. replacing the tray in the assembly module and camera calibration, were successful.

5. Future work

In order to expand the operational capabilities of LH6, the concept proposed and developed in this paper can be expanded to include more part-feeding challenges located in multiple modules. This expansion would require a better form of communication with FESTO CP Factory, e.g. LH6 could access directly the database of the Manufacturing Execution System (MES), instead of communicating directly with the individual modules via TCP/IP communication. Furthermore, it requires the introduction of a scheduling capability to LH6 to prioritize the required tasks depending on their importance, and the capability to obtain parts from e.g. a shelf in a warehouse. An interesting aspect for further improvement could be the intuitive programming of LH6, and following the needs identified by SPARC, an adaptive vision system that will allow robust part recognition. Last, the battery of LH6 was not tested nor used in this paper and thus the maximum operating time is not known and should be tested and evaluated.

6. Conclusion

This paper focused on the architecture and integration of an AIMM in an Industry 4.0 environment in order to introduce a flexible and intelligent element in a modern production. A FESTO CP Factory was used to resemble a real production environment and introduce related challenges. An essential part of LH6 was the ability to drive around autonomously using the MiR100 mobile platform by using a custom developed driver in a robot skill based framework. The MiR100 driver was developed to enable LH6 to drive to positions taught via an intuitive user graphical interface. Furthermore, automatic calibration of the position of the mobile manipulator was achieved by utilizing automatic recognition of QR codes using a sophisticated vision system. LH6 proved to be a robust and accurate system as the vast majority of the executed part feeding procedures were successful and it introduced the desired flexibility to the environment of the smart factory.

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