Design of a Modular Robotic Workcell Platform Enabled by Plug & Produce Connectors

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***Abstract*— To respond to the increasing global demand for highly customisable production systems, we developed a new standardised component for modular robotic platforms. It supports a modular framework for building robotic workcells of the next generation. The main building blocks for the framework are the archetypical module, on which the equipment that provides the functionality of the module is mounted, and the newly developed "Plug & Produce" connector. The latter is the key enabling technology of the system as it allows us to mechanically couple and decouple different modules while also providing all the necessary signals and energy sources to the module. To demonstrate the potential of the proposed framework, we have built a fully functional robotic workcell and applied it in the context of automated recycling of electronic devices. To prove the feasibility of such a system for real-world settings, we evaluated the repeatability of the module coupling and deflections of the modules as a result of floor unevenness.**

***Index Terms*— Modular robotic workcells, plug & produce connectors, flexible manufacturing systems**

I. Introduction

The tides in the global market are shifting [1]. Standardized mass production is slowly giving way to personalised production of many highly customised small batches. Conventional automated assembly lines and manufacturing line-ups, however, are not built to support this kind of production. To ensure quick and reliable production of millions or even billions of pieces of the same product, they are build very rigidly, with no easy way to implement changes into the process, let alone doing it quickly. With the increasing demand for personalised products, this is not sufficient anymore. In order to be able to supply highly personalised products and remain competitive in the global market, companies need to be able to quickly adjust their production capabilities [2].

This in turn requires a different approach to the design of robotic workcells and automated production systems. They need to support near-immediate implementation of new manufacturing capabilities or work changeovers, without the need for special tools or highly skilled engineers to execute such modifications. All this must be accomplished while maintaining high resource and energy efficiency.

In response to this global demand for highly customisable production systems [3], we developed a new standardized modular robotic platform. In our platform, a robotic workcell is built out of several interconnected standardized modules, each of them augmented with its own specialised equipment to achieve full workcell functionality. Based on the proposed design, a pilot robotic workcell was built and used to evaluate the repeatability of module coupling as well as the deflection of modules due to a combination of manufacturing tolerances and floor unevenness.

In the rest of this paper we first review the related work in Section II, followed by a detailed overview of the proposed design in Section III. The evaluation of the implemented system is described in Section IV and finally concluding remarks at the end.

II. Related work

The basic idea of reconfiguration and modularity in robot-supported manufacturing is not new. In fact, it goes back to 1999 when Koren et al. [4] described a Reconfigurable Manufacturing System (RMS) that is made out of reconfigurable elements at both hardware and the control level. It took some time for the idea to gain traction, but slowly others followed suit with Bi et al. [5] outlining the requirements for manufacturing systems of the next generation and Wiendahl et al. [6] describing changeable manufacturing, as they called it, at different levels of the production system. Modular manufacturing machines, developed by Xing et al. [7] is an example of implementing the previously outlined principles into a working production system. To reduce setup and reconfiguration times, a hardware-agnostic Plug & Produce system is required [8]. Profanter et al. thus developed a generic software architecture based on OPC UA protocol [9]. Alternatively, ROS-based architectures can be used to achieve Plug & Produce functionality [10].

A robot-guided reconfigurable assembly system presented by Gödl et al. [11] was at the time a state of the art system. Following the trend, Azab et al. [12] implemented a framework that helps assess the need for reconfiguration and its feasibility. Gašpar et al. built upon all this work with not only reconfigurable hardware elements [13], [14] but also software that enables automatic reconfiguration of robotic workcells [15]. Besides in research sector, the reconfigurability and modularity paradigm has also been gaining traction in industry, with Bosch [16] introducing its production line for Industry 4.0 which promises great flexibility due to its modular design.

Tool changers have been designed to provide the robots with the flexibility to automatically change the tools mounted at the end-effector [17]. Companies like ATI Industrial Automation, DESTACO, and SCHUNK offer commercial solutions [18], but open source solutions also exist [19]. Research efforts to develop better tool changers are on-going [20]–[22], but they are mainly directed at the development of

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tool changers mounted at the end-effector, which are usually not suitable for quickly connecting and disconnecting large workcell modules as proposed in this paper. We presented the first version of Plug & Produce connectors suitable for quickly connecting and disconnecting large workcell modules in [10], where the strength of such a system was demonstrated. It also helped identify the drawbacks of the implemented design, which we have used to develop the new, improved version of Plug & Produce connector.

In this paper we propose a novel standard module for robotic workcells (presented in Section III-A) and a novel Plug & Produce connector (presented in Section III-B) that can be used to quickly build robotic workcells with different layouts and functionalities as required to accomplish different production tasks. Our proposed system is not only reconfigurable at both hardware and software level, but completely modular in its design. This modular design is what enhances the flexibility of the system and makes it easy to build upon.

III. Modular robotic platform

A modular robotic platform is a framework for building completely modular robotic workcells. A functional robotic workcell consists of several interconnected modules, each of them augmented with its own specialized equipment to achieve full functionality. While each modules brings its own functionality, they all share the same base, which is described in detail in Section III-A. Built into this base are also the so called "Plug & Produce" (PnP) connectors (Section III-B), which ensure not only stiff and repeatable mechanical coupling of the modules, but also provide pass-through for all the energy and data lines required by the modules and their equipment, respectively.

This approach enables fast development and implementation of new robotic workcells, fast development and integration of specialized tools by third parties, and extremely fast and reliable work changeovers. All these are essential properties of a robotic system for small batch production of highly variable products.

In Figure 1 an example of a robotic workcell, that was built using the proposed modular robotic workcell is presented. The workcell is used for recycling of hazardous waste electronics and is composed of two robot modules, a vise module, a cutter module, a material input module and a tool storage module.

A. The archetypical module

We have already established that all modules of the reconfigurable workcell should share the same base, or an archetypical design. In the next few paragraphs we will take a look at how they are made and what exactly makes them work.

The first concern when designing any base for robotics or automation is rigidity, which in turn ensures the repeatability of the process. Hence the frame of our archetypical module is made out of thick-walled welded steel tubing. Special care has been taken in the design and fabrication process to ensure the squareness and paralellity of the frame.

Fig. 1: An example of a robotic workcell used for recycling of waste electronics, built using our modular robotic workcell platform.

Fig. 2: 3D render of the archetypical module, with a quick calibration feature circled in red.

At the top, a 20 mm aluminium work surface plate serves not only as a mounting point for all the additional equipment, but also doubles as the upper structural part of the frame. Aluminium was used because of its corrosion resistance as the work surface is prone to abrasion damage. Corrosion and abrasion resistance are further improved by anodizing [23]. The last feature of the aluminium plate is ease of mounting of peripheral equipment, which is easily done by drilling additional tapped holes and bolting the equipment directly to the plate. It is worth noting that this can easily be done on site by technicians using common tools, and does not require a specialized workshop or disassembly of the plate.

For modularity to work, it must be possible to move the archetypical modules to different locations. Thus, industrial grade castors with levelling capabilities are mounted at the bottom. This makes moving the modules around and re-configuring the workcell an easy task. This ability, however, introduces another challenge into the whole concept. Traditional robotic workcells are built to be stiff and rigid for a good reason, namely to ensure that robots, peripheral equipment and workpieces do not move about during the task execution. This is important because the location of all items must be constant to ensure that robot programs can run smoothly. If modules can be disconnected and reconnected as in our proposed platform, the relations between the robots, peripheral devices, and workpieces could change for a number of reasons. The first and most obvious one is that we can re-connect the module at a different location. The second, more subtle one is the fact that PnP connectors have their own coupling and decoupling repeatability. This means that every time we disconnect a module and reconnect it back, its location is not exactly the same. This is especially problematic, when the PnP connectors are equiped with the mechanical gland, that can off-set the height of the module surface and consequently the equipment in the order of several milimeters (up to ± 15 mm).

To deal with these challenges, a quick calibration feature is built into our platform (Figure 2 circled in red). To perform the calibration, we take advantage of the gravity compensation mode available on modern collaborative robots such as Kuka LBR iiwa, all Universal robots and Franka Emika Panda to guide the robot to a calibration location on the archetypical module where one end of a tool exchange system is mounted. The other end of the tool exchange system, which is mounted on the robot's end-effector, is attached to this calibration location. This way we obtain the relative position and orientation of the archetypical module in the robot's base coordinate frame. Provided that all positions and orientations are given in the local coordinate frame of the archetypical module, they can be transformed to the robot base coordinate frame automatically using the calibrated transformation matrix.

For the module to be able to do some work, it needs to be augmented with additional equipment. This equipment usually comes with a set of power, data and control requirements. Every module has built into it a basic set of 230V AC electric wiring, 24V DC electric wiring, network wiring with a network switch, and pneumatic wiring with pneumatic control valves. While 24V DC electric wiring runs of a switching power supply contained within the module, the 230V AC and pneumatic wiring are fed from outside of the module via the PnP connector, which also exposes the module's network to the rest of the cell. A Raspberry Pi 4 micro-computer is built into every module, to which we deploy our modular control software [10]. A standardized high-level interface for controlling the equipment inside the module is deployed on this micro-computer. All these equipment is mounted onto two pull out panels via standardized DIN rails as seen in Figure 3. The pull out panels and any additional controllers or computers that are needed to ensure the module's full functionality can be securely inserted into the module utilizing standardized 19" server racks that are built into the frame.

Fig. 3: Electronics of an archetypical module mounted on pull out panels.

(a) (b)

Fig. 4: Robot and vise modules, based on the same archetypical module.

Based on the archetypical module, several specialized modules have been developed. An example shown in Figure 4a is the robot module. In this case, the archetypical module serves as a base for the Franka Emika Panda robot with seven degrees of freedom. In addition to basic wiring and control electronics described in the previous paragraph, there are robot controller and control computer mounted onto the integral server rack. This makes this module a completely self contained unit that can easily be disconnected from one location in the workcell and reconnected somewhere else, or even moved to a completely different workcell.

Fig. 5: Various reconfiguration possibilities

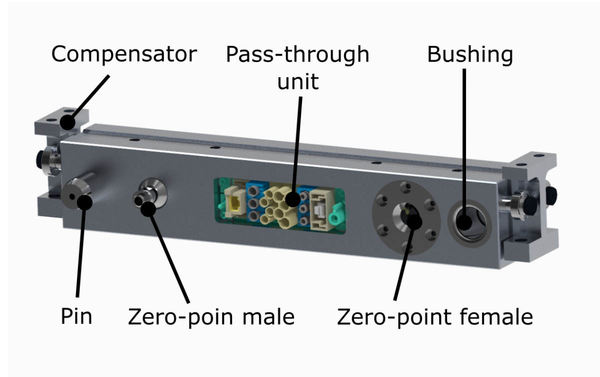

Fig. 6: 3D render of a ”Plug & Produce” connector.

Another example is the vise module shown in Figure 4b. This module houses a pneumatic vise mounted on a pneumatic rotary unit, which is used for work holding during the production process. This module only utilises the basic wiring and control electronics provided in every module, which demonstrates the broad capabilities of the basic archetypical module.

The proposed system is completely modular, and can be very easily reconfigured into a completely new workcell layout in a matter of minutes. This is due to the plug-and-produce connectors built into the archetypical modules and the mobility of each modules. Some possible configurations of the workcell using 4 modules are displayed in Figure 5.

B. *"Plug & Produce" (PnP) connector*

The term "Plug-and-Play" carries an expectation of ease of use and reliable, foolproof operation. A Plug-and-Play product, as its name suggests, can simply be connected and turned on – and it works. The practical extension of Plug-and-Play concept when applied to industrial automation has given name to a new term: "Plug & Produce". The Plug & Produce approach is the foundation of our standardized reconfigurable modular platform. It enables fast deployment of robotic cells, development of compatible specialized tools by third parties, and extremely fast, cheap and reliable work changeover. These properties are essential for a small batch production of highly variable products.

The enabling technology of the Modular robotic platform is a "Plug & Produce" (PnP) connector, which standardizes how a group of specialised individual modules are connected into a functional production system. Any module that is using the PnP connector is compatible with the modular platform. The new PnP connector described in this paper is the result of knowledge and experience gained through the use of several other PnP connectors and tool exchange systems in several successfully completed projects.

The main characteristics of the new PnP connector are:

- Cost of a connector pair is around 1600 €.
- Repeatability is better than 0,05 mm.
- Resistance to forces: up to 1500 N in all directions.
- Torques: up to 1000 Nm in all directions.
- Transmission of electrical power: 5 x 3.5 kW connections.
- Transmission of compressed air: 3 x 8 mm connections @ 6 Bar.
- Transmission of ICT signals: 1 x 8 pin Ethernet connections.
- Coupling: achieved by pushing together two sides of the connectors. No unlocking needed.
- Decoupling: automatically by pneumatic actuators, optionally can be aided with a decoupling force of 600N (@ 6 bar).
- Mechanical gland: compensation of inaccuracies up to ±15 mm in height and $\pm5°$ in rotation around the axis parallel to the long edge of the connector.
- The connector is "unisex", meaning that it has no male and female side.
- Integrated small industrial computer, which makes the connector IoT device.

The developed PnP connector is thus of a universal shape which means it does not features a male and a female variant as many competitors. Although this feature brings along a higher price tag, it adds greatly to the ease of use and flexibility of the system. The backbone of the connector is a single piece CNC machined aluminium body that ensures rigidity and stiffness as well as provides housing for all other features. First of these features is a set of centring pins and bushings that facilitate the proper alignment of a pair of connectors that are coupled together. A precise mechanical coupling is achieved using custom zero-point clamping units that provide a secure and repeatable connection of the connector pair. A big advantage of our zero-point system over most commercially available systems is that it does not require any unlocking action before the coupling. This eases the coupling process as the two connectors simply need to be pushed together with some force and the mechanism locks into place without the need for any control or actuation. The central piece of a PnP connector is its power and data pass-through unit, which enables all modules in the workcell to use power and share data amongst themselves. In our design, it is realised by using a commercially available modular connector unit, which can be assembled according to individual needs and can provide pass-through of electrical power and data lines as well as pneumatic lines. The biggest addition to the proposed design is a mechanical gland for compensation of inaccuracies, that can even out height alignment errors of up to ± 15 mm and angular alignment errors of up to $\pm 5°$. This is also one of the reasons the modules are equipped with a calibration feature described in previous Section III-A. As the connectors take up the alignment errors, the positions of the equipment within the workcell need to be calibrated to account for the alignment errors. Depending on the needs, the connector can of course be used with or without the mechanical gland. In case of the latter, the calibration is only necessary the first time around, when the system is programmed, since the coupling process is repeatale enough as described in section IV. Although similar systems are commercially available, none of them come close to our solution when price/performance is taken into account.

IV. Evaluation

We measured the system's repeatably to evaluate if the designed system is appropriate for use in robotic workcells. For the evaluation of the system a pair of PnP connectors without the mechanical gland for compensation of alignment errors was used, since otherwise, the only thing that would be measured is the unevenness of the floor. Figure 7 displays the experimental setup where two measurement locations can be observed. In this experiment, only variations in the z-direction were measured. This is because the repeatability in this dimension is expected to be an order of magnitude worse than in other dimensions. The reason behind this is in construction of the archetypical module and the PnP connector, which only allow rotational deformations around the y axis.

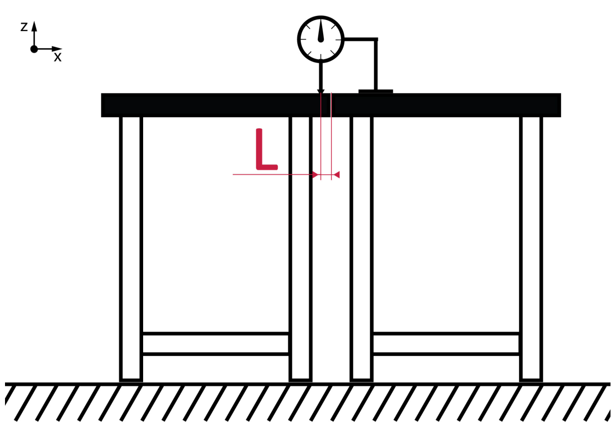

Fig. 7: Schematic of the experimental setup for measuring of system repeatability. L denotes the distance from the Pnp connector's face to the point of measurement on the work surface

Two measurement locations displayed in Figure 7 were selected with specific measurement goal. The first measurement location is close to the connector's mating face offset only 12.5 mm, with intention to measure only influence of the PnP connector's repeatability. The second measurement location is offset by 150 mm from the connector's mating face in order to measure the repeatability of the modular system as a whole. The experiment was conducted in two phases, with 30 measurements of absolute difference in Z direction between the two surfaces taken, after the modules are mechanicaly coupled, at every location of each phase respectively.

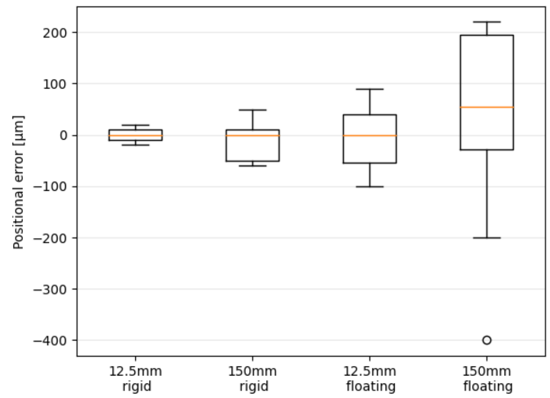

Fig. 8: Boxplot of repeatability measurement

In the first phase, the measurements were taken with one module rigidly fixed while the second module was repeatedly connected and disconnected. This was done with the intention to show the repeatability of the system in ideal conditions where the floor is perfectly straight. The measurement was taken at the previously described locations on the module's top plate. In the second phase, the same measurements were taken, only this time the two modules were moved around. Before every measurement the two coupled modules were moved to a new location in the laboratory, decoupled, coupled together again, and then the measurement was taken. This was done to show the effect of unevenness of the floor on the system's repeatability, which is the ultimate indicator if the system is appropriate for use in robotic applications.

The measurement results are displayed in Figure 8. The leftmost boxplot is the repeatability measurement of the fixed module 12.5 mm away from the PnP connector's face, where the main contributor to the error is the PnP connector. It can be observed that the repeatability is better than 40 μm. The second boxplot is the repeatability measurement of the fixed module 150 mm away from the PnP connector's face, where the main contributor to the error is the deformation of the archetypical module. Here the repeatability is better than 100 μm. The repeatability of the archetypical module is best near the PnP connector and drops with the distance from the connector. This should be considered when designing the robotic workcell.

The third boxplot in Figure 8 displays the repeatability measurements of the module, which was moved around prior to taking the measurement, 12.5 mm from the connector's face. In this case, the biggest contributor to the repeatability error are the deformation of the archetypical module due to the unevenness of the floor and the repeatably of the PnP connector. The repeatability in this case is 190 $\mu\mathrm{m}$. The rightmost boxplot displayed in Figure 8 shows the repeatability measurement of the module, which was moved around prior to taking the measurement, 150 mm away from the connector's face. In this case, the biggest contributor to the repeatability error is the deformation of the archetypical module due to the unevenness of the floor. Repeatability in this case is 420 $\mu\mathrm{m}$. It can be observed that repeatability of the archetypical module is best near the PnP connector, about 190 $\mu\mathrm{m}$, and again drops as we get further away from the PnP connector.

V. Conclusion

In this paper we presented the design of a standardised modular robotic workcell platform, which can be used to quickly build and re-build advanced robotic workcells. The proposed design takes advantage of the newly developed Plug & Produce connector, which provides for its flexibility and reconfigurability. The platform is not only completely modular, but also scaleable and can be used to design a wide variety of automated solutions. To demonstrate its potential for industrial applications, we analyzed the coupling repeatability of the Plug & Produce connector and the module's deformation due to the unevenness of the floor. Our results show that the connector's repeatability and module deformation are well bellow the repeatability of the robot. However, if the production process calls for high tolerances, it is advantageous to perform operations closer to the mating connector. The repeatability could be improved by using multiple connectors for the same mating face, at the cost of an increased price.

To fully exploit the capabilities of the proposed modular hardware and Plug & Produce connectivity, a suitable software is also needed. We have designed an appropriate modular software architecture for this purpose, which is described in another paper [24].

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