Rapid Hardware and Software Reconfiguration in a Robotic Workcell

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***Abstract*— In an increasingly competitive manufacturing industry it is becoming ever more important to rapidly react to changes in market demands. In order to satisfy these requirements, it is crucial that automated manufacturing processes are flexible and can be adapted to the new production requirements quickly. In this paper we present a novel automatically reconfigurable robot workcell that addresses the issues of flexible manufacturing. The proposed workcell is reconfigurable in terms of hardware and software. The hardware elements of the workcell, both those selected off-the-shelf and those developed specifically for the system, allow for fast cell setup and reconfiguration, while the software aims to provide a modular, robot-independent, ROS-based programming environment. While the proposed workcell is being developed in such a way as to address the needs of production-oriented SMEs where batch sizes are relatively small, it will also be of interest to enterprises with larger production lines since it additionally targets high performance in terms of speed, interoperability of robotic elements, and ease of use.**

***Index Terms*— Reconfigurable, Robotics, ROS**

I. Introduction

In industry, particularly in the realm of *small and medium-sized enterprises (SMEs)*, rapid changes in market demands lead to decreasing product lifetimes and also to more frequent product launches. SMEs must react quickly, efficiently, and in an economically viable way to such market changes. Although robots have been highly successful in many industrial production processes when applied to complex repetitive tasks with long production runs and high unit volume, the frequent shifts in the required product type or in the number of required products, as dictated by the market forces to which SMEs are exposed, often preclude them from exploiting any potential benefits such robots might provide.

These so-called *few-of-a-kind* assembly production scenarios [1] are typical of SMEs and given that SMEs are the “backbone of the manufacturing industry”, e. g. in Europe providing some $\sim$45% of the value added by manufacturing [2], it would be highly beneficial if rapidly reconfigurable robotic workcells could be developed specifically to ease the burden of such use-cases.

The main hindrances to further uptake of SME robot production are the complexities involved in setting up existing solutions, since they usually require expert knowledge as well as significant time for testing and fine-tuning. Since SMEs usually do not have such expertise available, they avoid introducing such solutions, even when they are economically justifiable. Looking at such robotic systems in more detail, we can recognize that these problems are due to the time costs involved in re-configuring and re-programming the robot workcell for new assembly tasks, which are often too prohibitive to make the application of robots profitable.

A. *A reconfigurable workcell for automated assembly*

In this paper, we present the design of a new kind of autonomous robot workcell that is attractive not only for large production lines, but also for few-of-a-kind production [3]. We propose reducing set-up times by exploiting a number of hardware and software technologies, some of which were partially developed in prior work, and some of which are novel contributions in this paper particular to the proposed workcell design. The main novelty of the workcell lies in the automatic reconfiguration of passive fixtures and other passive elements in the cell, which can be performed by the robots installed therein. This reconfiguration process allows the robots to autonomously configure their workspace and prepare the workcell for the execution of new assembly tasks. This way set-up times and costs of preparing a new production line can be greatly reduced.

We describe the application of various reconfigurable elements in the workcell, including the use of a reconfigurable steel frame structure with modular beam connectors for both high flexibility and stiffness, robot arms with quick pneumatic tool changers, *plug and produce (P&P)* connectors for simplified coupling of system infrastructure, reconfigurable passive fixtures, and a passive linear rail unit for rapid robot-driven automatic relocation of the robots. The unique combination of these technologies is, to the best of our knowledge, a novel contribution to the field.

The rest of the paper is organized as follows.We firs discuss related work and compare our design choices to the state-of-the-art. Next, in Section II we describe the reconfigurable hardware of the workcell and in Section III the reconfigurable software system architecture. In Section IV, we describe the application of these new reconfigurable technologies in a focused industrial use-case for automotive light production, demonstrating how the system can be used to reduce production costs by increasing both efficiency and flexibility. Finally, in Section V we conclude and discuss our plans for future work.

B. Related Work

A number of surveys have been released in recent years documenting the development of reconfigurable robotic systems, both in research and in industry [4]–[7]. A prominent example among research on modular reconfigurable robotic systems is the work of Chen [8], [9], who put a specific emphasis on finding optimal module assembly configurations from a given set of module components for a specific task. His subsequent work on the design of a reconfigurable robotic workcell for rapid response manufacturing [10] is of particular relevance with respect to the workcell proposed in this paper. However, while that work involved the development of a workcell containing hardware elements that can be rapidly reconfigured *manually*, our proposed workcell focuses on introducing hardware elements that can be rapidly reconfigured *automatically* by the system itself with respect to a family of parts within a given product line and its respective assembly task.

In our system this is made possible due to the application of reconfigurable fixtures known as *hexapods* (*c.f*. Section II-C), the use of which in a robot-guided reconfigurable assembly system was first proposed in the work of Gödl *et al*. [11]. A similar reconfigurable fixture concept was later described in the work of Jonnsson & Ossbahr [12] and Salminen *et al*. [13] in the context of the production of bogies in the railway industry. In this paper, we describe a refined version of this concept, involving smaller units, to bear on the particular use-case of the production of headlamps for the automative light industry (*c.f*. Section IV), with a view towards expanding their application to further industrial use-cases in the area of automated robot assembly. We also propose enhancements to the original concepts proposed in [11] via a number of separate hardware augmentations within the workcell as described in Section II.

In the work of Krüger *et al*. [1], [14], a set of methods was developed to facilitate the set-up of a complex automated assembly processes, such as they arise in the standard assembly benchmark, the Cranfield benchmark [15]. The proposed set of methods included pose estimation and tracking of parts using a 3-D vision system, fast and robust robot trajectory adaptation using *dynamic movement primitives (DMP)* [16], and ROS-based software control and state machine programming [17]. In this work we build on these approaches and supplement them with the ability to automatically reconfigure the workcell, as well as with the integration of CAD-based product design for assembly that takes into account the requirements of robotic manipulation. Moreover, the proposed system advances beyond synthetic benchmarks such as Cranfield benchmark and demonstrate the viability of the system on actual industrial use-cases.

II. Reconfigurable Hardware

The proposed robotic workcell is in large part constructed of modular hardware that allows for fast and easy reconfiguration; from the structural frame to the fixtures, end-effectors, tool exchange system, P&P connectors, and other peripheral devices. With this approach we make it possible to use the proposed workcell in a wide range of industrial applications and environments. Furthermore, we also make it relatively easy to change its shape and purpose within those environments. In the following subsections we will give an overview of the technologies and solutions that were used to achieve said hardware reconfigurability.

A. Reconfigurable frame

The frame structure of the workcell is made of rectangular steel beams that are connected via the BoxJoint patented modular frame coupling technology [18]. The advantage of this technology is that a workcell frame can be easily configured into a large variety of shapes. Typically in industry purposely made frames are either welded into the desired shape or an aluminum modular system is used to construct the desired frame. The issue with specially designed welded frames is that they are not reconfigurable, while the issue with aluminum frames is the fact that aluminum is less thermally stable. By using steel beams as the core element of the modular frame for the cell, we make the cell more stiff, robust, and less susceptible to deformations due to changes in temperature. The latter feature also makes the cell a viable solution for robot welding tasks.

B. Tool Exchange System

Different workpieces demand access to a variety of different robot tools depending on the tasks that are required to be performed on them. In order to ensure that such tasks can be efficiently and precisely executed in the workcell given the limited number of robots therein, we developed a stand where different end-effector tools can be placed. The robots can then pick the appropriate tool for the different stages of the task. So if the task to be performed is the assembly of different pieces, the robots can equip different grippers for each piece that needs to be assembled into the given workpiece. If reconfiguration of the cell is needed to assemble a different workpiece, new end-effectors can be placed on the already prepared robot tool stands. The stands that hold the end-effectors were custom designed and developed and are mounted directly on the steel beam frame with the same BoxJoint technology that was used to assemble the frame.

C. *Reconfigurable Fixtures*

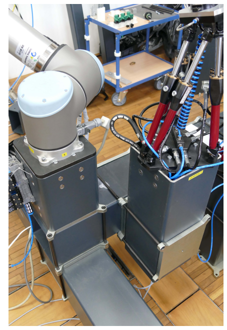
In small production lines where shifts in demand occur frequently, it is difficult to maintain a robotic workcell due to the time it takes to re-adjust all of the fixtures within it. In order to help mitigate against this specific problem, we added passive reconfigurable flexible fixtures (Fig. 1b) to the workcell. The fixtures are made in a Stewart-platform like shape with 6 legs, hence the name "hexapod". These fixtures can be dynamically reconfigured by the robot arm on demand. By designing the fixtures to be passive and sensor-less it is possible to manufacture them for relatively low cost. With this technology, not only can the workspace be easily adapted to cope with the change in the workpiece, but the workspace can be adapted by the robotic workcell itself.

D. *Passive Linear Unit*

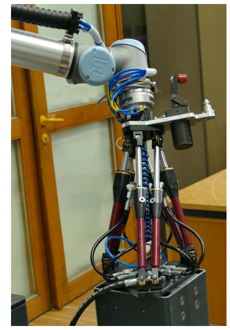
To make it possible to enlarge the work area of the cell the robot was mounted on a custom passive linear rail unit. This way the robot base can be moved up and down along the linear axis. The purpose of the passive linear unit is to expand the work area of the robot within the work cell with minimum additional cost. Conventional actuated solutions are extremely expensive and thus inappropriate for SMEs. A way to reduce the cost without significantly reducing the functionality is to omit the actuation and position sensing from the linear unit. The robot itself is used to propel itself along the linear rail. This is achieved by connecting the tip of the robot to the frame with the use of the previously discussed tool exchange system and then by using the robot actuators and position control to move the base of the robot. This approach is appropriate for applications where the need to move the robot is not too frequent.

III. Reconfigurable Software System

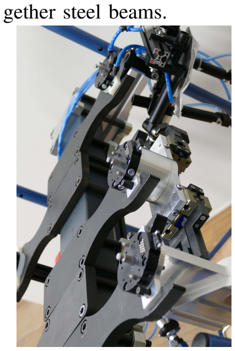
The introduction of a robotic system into a production line represents a big investment and change for small or medium sized companies. The high costs usually come from price of the necessary hardware and the time spent for the integration of the robotic system into the production line. One of the time consuming aspects of the integration involves the programming of tasks sequences for the robot that make up the production process. The programming process is usually done either via on-line programming using a robot teach pendant directly connected to the robot controller, or via off-line programming in a simulation environment, both of which require knowledge of the specific robot system. With this in mind, we developed a software system that would facilitate the programming of robot tasks regardless of the robot system. The software system is designed to be distributed, modular and offers seamless adaptation of the robot cell. The package also provides the necessary tools to enable simple, intuitive programming of robot tasks.



(a) The BoxJoint coupling system holding holding together steel beams.



(b) The passive reconfigurable fixture being reconfigured by a UR10 robot.



(c) Tool exchange stands holding various end-effectors for the robot.

(d) Passive linear axis rail with the robot mounted on it.

Fig. 1: Reconfigurable hardware in the ReconCell robot cell.

Our system was build within *Robot Operation System (ROS)* framework [17], where the *Matlab Simulink Real-Time (SLRT)* platform [19] was used to develop the hard real-time components of the cell. We chose ROS because it provides a reliable open source framework, the capacity for cross-platform and multi-language flexibility, and a vast number of useful libraries and tools. However, ROS in its current form does not provide any form of hard real-time implementation, which is a crucial requirement for reliable and accurate robot control. The second iteration of ROS called ROS 2 is planning to patch this culprit [20], but it is currently still in the alpha stage under heavy development. That is why we used SLRT to build a robot control server (SLRT server), which is responsible for high frequency real-time trajectory generation and force control.

A. *System Architecture Overview*

The SLRT server connects directly to the robot controller via Ethernet and is responsible for communicating to the robot. It works as a proxy offering advanced trajectory generation methods and feedback control strategies. Robot controllers usually offer only basic control methods, on the other hand our approach gives the system great flexibility, since we can easily and quickly implement any control method. It also makes our system independent of the robot.

For a new robot to be integrated in the cell, its controller must offer the ability to receive joint configurations over Ethernet and then only the kinematic model must be adapted on the SLRT server.

The SLRT server also connects to some other measurement units (e.g. force/torque sensors) that can be used for closed loop control policies (e.g. force control). A ROS package has been developed that acts as a driver for the SLRT server and provides tools and functionalities for running, reconfiguring and calibrating the robot cell. The ROS architecture provides the versatility needed for connecting different modules to the workcell and our tools facilitate programming of the desired workcell task using data from the connected modules. The nodes from our package run on the ROS Master Computer, where ROS core is running as well. Modules can also have their own individual nodes running on their respective computers. In the following subsections we will briefly explain the main functionalities of our package.

Figure 2 shows elements of the software architecture of a typical workcell design. In the schematics there are two "Robot Modules" representing a robot with its robot control server, one additional measurement unit and all its tools and gripers. The "ROS Master Computer" refers to the computer in the system that runs the ROS core and our ROS package. In order to provide connections to different a "Digital Interface Unit", a "Vision Module" and other. Depending on the needs the workcell design can be adapted by adding or removing various modules.

B. Simulink Real-Time Server

A core part of the robot module is the previously mentioned SLRT server, which has been developed to ensure that the robot can be reliably controlled with the maximum frequency of the provided robot controller (125 Hz in case of UR-10 robots). The SLRT server sends the robot controller the desired joint configuration. The inner loop of the SLRT server can run on a higher frequency than the robot controller, if we have a measurement unit connected to it with a higher frequency readout. In our case, where a 1000Hz force/torque sensor has been connected to the SLRT for force control, the SLRT server runs at 1000 Hz as well. In case of a UR-10 robot, the SLRT server can process 8 samples per robot controller loop for a better estimation of the force/torque derivative. This provides a better filtered force/torque signal for high quality force control, improving the stability, accuracy and speed of robot trajectories in contact with the environment.

As mentioned before, a real-time robot control server was developed as a proxy between the ROS system and the robot controller. The main motivation behind this approach is that trajectory generation and control is handled by a hard real-time system that is robot independent. This way, the trajectory generation and control algorithms can be developed independently of the used robot. Various trajectory generation algorithms were implemented up to this point to cover the most common robot motion needs in the context of automated assembly. These are:

- trapezoidal speed profile in joint space,
- minimum jerk for position and minimum jerk SLERP for orientation trajectories in Cartesian space.
- admittance force control [21],
- joint space dynamic movement primitives for free-form movements [22],
- Cartesian space dynamic movement primitives free-form movements in Cartesian space [16].

C. ROS Software Package

To allow the robot workcell to be accessed, controlled and calibrated within the ROS environment, various ROS nodes were developed to offer an interface to the before discussed SLRT server and other modules in the workcell. In this section we will focus on the core software capabilities of the robot workcell that come standard in every "ReconCell".

1) SLRT State Publisher: the purpose of this ROS node is to read the data stream from the SLRT server and publish it within the ROS network via ROS topics using conventional ROS messages. The published data covers all the relevant information about the robot, such as joint positions, velocities, payload, tool information, forces from the force/torque sensor and several control flags for different control strategies. One of the vital packages in ROS is *tf2*, which is used for keeping track of multiple coordinate frames in the system. We use the ROS *robot_state_publisher* package, which latches onto the joint position topic and, using the robot kinematic description from the URDF file, tracks coordinate frames in all joints of the robot system.

2) Action Servers: are nodes built with the ROS *actionlib* stack that handle communication to the SLRT server and are used to trigger robot motion and monitor the progress of the trajectory. The *actionlib* provides a reliable client - server interface where the lower level communication and logic is handled by the action server node, whilst the client simply triggers the motion by sending a goal request. After the action server node detects the robot motion is finished it sends a result message to the client. The unique advantage of using the actionlib stack instead of ROS services to trigger robot motion is that it offers a preemption requests and feedback messages during execution. This means a client can preempt motion that is already being executed and also gets various information back from the action server during.

Each trajectory generation algorithm that is implemented on the SLRT server is offered as a separate action server with its own goal, feedback and result messages. The low level logic of all the action servers assures that only one motion can be executed at a time.

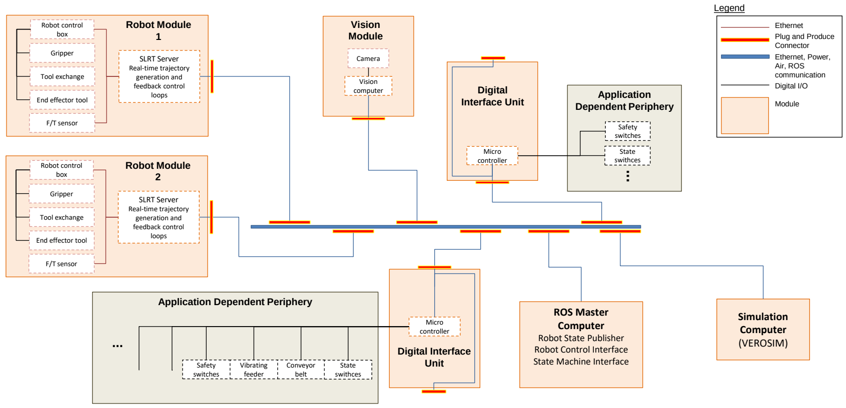


Fig. 2: Schematics of the workcell software and hardware architecture.

3) ROS Services: provide an interface for handling short duration tasks such as changing the state off a digital output. Our ROS package includes services that

- change the robot mode from position control to gravity compensation mode,
- trigger direct joint control on the SLRT server,
- set digital outputs on the robot controller.

As with Action servers, ROS services are very practical for programming the top level robot task program.

4) Database: A robot workcell needs to keep track of its state at all times, be it during operation or downtime. Some sort of persistent storage is required, however none of the basic ROS functionalities, such as the ROS parameter server, offer that. We decided to follow a common approach with wide support in the community and implemented a MongoDB database. There are different ROS packages offering simple interfaces in C++ and Python for all clients in the ROS network to read from and write to the database using ROS type messages.

The information stored in the database consists of poses of different elements in the workcell, saved robot configurations in Cartesian or joint space, calibration parameters and other parameters. We have developed a node that reads transforms from the database and publishes them on *tf2*. These transforms can then be used for robot assembly tasks.

5) Robot capture: is a versatile tool for storing various robot related configurations to the database. It is commonly used in conjunction with the kinesthetic guiding of the robot, where the programmer of the robot workcell can freely move the robot in its workspace and then save the points of interest. The tool offers saving the robot tool center point in Cartesian space, the robot joint state (position and velocity) and also a robot to robot calibration mode. The first functionality is commonly used for calibrating the workcell state (reconfigurable fixture positions, tool pick up slots) and for saving pick and place poses of the robot assembly task. The saved joint configurations are generally used for path planning and the robot to robot calibration is used to define the relative transformation from one robot base to another, when more robot modules are present in the workcell.

D. Additional Functionalities

1) Programming by Demonstration: Robot programming by kinesthetic guiding received a notably increase in demand in recent years. More and more robot manufacturers are starting to implement this functionality on their robots. It provides an intuitive method to teach the robot either points in Cartesian or joint space or whole trajectories. The robot used for our work allows kinesthetic guidance via the so called *Gravity compensation mode*. In this mode, the robot controller estimates the input torques to the robot motors to compensate the effect of the gravity on the robot links. The gravity compensation mode should also always take into consideration the payload on the robot’s end-effector, otherwise the calculated torques would not be correct which means the robot would not be still but drifting.

2) Adaptation of Learned Trajectories: When programming a robot task via kinesthetic guidance in physical contact with the workpiece, it is very often the case that the learned trajectory is not ideal or optimal. By learning the executed forces on the end-effector of the robot and by using admittance control, we can then use the displacement due to the force error as a correcting offset to our DMP encoded trajectory. By adapting the trajectory to follow a desired force profile we can achieve better and faster executions of our first demonstrated trajectory [21].

IV. Use Case Evaluation

As noted above, manufacturing industry aims towards lower production costs and high efficiency assembly lines with high repetition, flexibility, and easy to use interface.

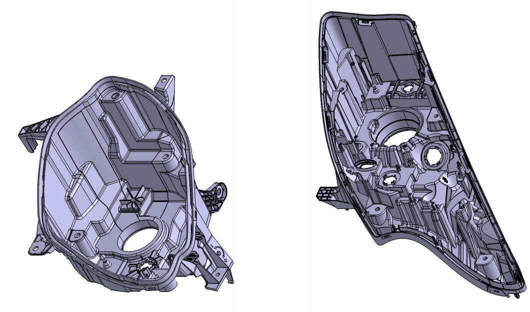
Manual work and quality is highly dependent on workers’ qualifications, skills and their knowledge of the assembly process. Costumers expect that the supplier company is very flexible in coping with the changes in demand. This is why SMEs crave to time every task carefully and look for optimizations.

The number of parts produced in a single company can vary per project in a year. In the industry of automotive lights, it is typically between 100,000 -??- 300,000 per item. However, these lights are not assembled in one batch. With new orders it is often necessary to switch from one automotive light type to another. For the assembly of each light type it is necessary to reconfigure the workcell. This is where the technologioes described in this paper become useful.

A. Description of the challenge

In automotive light industry, each light requires its own unique assembly device, which is typically very large and cumbersome. When the subcontractor company stops producing the parts to match the regular demand, assembly devices must not be discarded because they are required so that the subcontractor company is able to produce spare parts for at least the next five years. This means that the assembly devices are stored in a company for the next five years after the production has stopped. This means that companies needs a lot of storage space just to store these assembly devices. Since subcontractor companies do not produce only one specific part, this means the assembly devices are accumulating. Production of spare parts is a low quantity piece production and is made only few times per year. It is therefore very useful to have one robot cell which is able to assemble many different types of lights.

Automotive lights (headlamps) are made up of typical structural elements such as housing, actuators, bulb holders, adjustable screws, heat shields, wires, etc. In our experiments we demonstrated that the developed reconfigurable robot workcell provides the much needed flexibility and fast set-up characteristics for automated assembly processes in the context of automotive lights. By working together with the Elvez company, we were able to show that the proposed workcell can be automatically reconfigured for the succesful assembly of different car headlamps, two of them shown in Fig. 3.



(a) Light housing model X07.

(b) Light housing model X82.

Fig. 3: Two different automotive headlamp housings that Elvez produces.

V. Conclusion and Future Work

In this paper we presented a new reconfigurable robot workcell that aims to help manufacturing industry with small production batches where change in demand happens relatively often. The developed workcell is built of both, reconfigurable hardware elements and modular software components. In respect to the hardware reconfigurability, we presented a unique combination of various technologies that allow for fast setup and reconfiguration. Affordable passive flexible fixtures are automatically reconfigured via robot manipulation. The software system architecture was built to be robot-independent. We developed a real-time robot control server that is responsible of the low level real-time trajectory generation. On top of the real-time server, we developed ROS drivers to provide an interface of the cell within ROS. To show the benefit of using such a workcell, a case study was developed in collaboration with a partner from the automotive industry. By applying the developed workcell to a real industry use case, we demonstrated the applicability of the developed technologies.

AIn the future we will focus on the ease of programming tasks so that it will become possible for non-experts to program the workcell by themselves. A special visual programming interface is being developed that will remove the need of a robotic expert for assembly task programming. This will facilitate the companies to use their existing experts for production to program assembly tasks. In this way the universality of the developed workcell will be shown.

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