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Automatic Fingertip Exchange System for Robotic Grasping in Flexible Production Processes

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***Abstract*— Object handling in automated manufacturing processes lacks the flexibility to adapt to rapid production changes on the workshop floor typical for small and medium enterprises. Introduction of new grasping solutions represents a time-consuming process. Therefore in this paper, we present a flexible and cost-efficient grasping solution for adaptation to rapid changes in the production processes. The solution consists of a mechanical fingertip exchange system, which can be installed on various grippers and a fingertip design procedure, for rapid development and testing of tailored fingertips for handling multiple parts. The versatility of the approach was benchmarked during the World Robot Summit 2018 where the proposed solution was applied on several use cases in an automated assembly where precision is of the essence to the manufacturing process.**

I. Introduction

Shifting to high mix/low volume production, central efforts in *Agile Production* push for robotizing all sorts of production operations – with a special focus on assembly, where any complexities resulting from part and product varieties today are still mostly countered by commissioning manual operations. Attempts to transfer these manual assembly operations to fully automated robotic assembly stations thus need to systematically address rapidly evolving varieties with lean and reconfigurable approaches that eventually allow for implementing similar levels of agility as manual operations. Therefore, in the work of Gašpar et al. [1], a reconfigurable assembly workcell technology is presented that can efficiently utilize and transfer human knowledge for various assembly processes, reducing the downtime when a new task arises.

In order to facilitate, showcase and benchmark such agile robotic assembly stations, the Japanese Ministry of Economy, Trade, and Industry sponsored the ”World Robot Challenge” (WRC) as part of the ”World Robot Summit” taking place in Tokyo, Japan, 17-21 October 2018 [2]. Out of 250 applicants, eight Japanese and eight international teams from industry and academia were selected to compete in the major event of the WRC, the ”Assembly Challenge” in the ”Industrial Robotics Category”. The challenge was organized in four tasks, each reflecting some of today’s most demanding topics in robotic assembly.

Task 1 required to pick up and handle a range of different parts including screws, nuts, pegs, and a flexible belt. The exact pick location of the part was randomized (though limited to a given area), and several handling operations encompassed screwing, precise peg insertions and tautening a flexible belt onto two pulleys.

Task 2 resembled a kitting situation, where parts had to be picked from part bins (with varying fill levels) and positioned on trays according to given orders. This particular bin picking problem featured a wide variety of parts, ranging from screws to washers, motors, and flexible belts.

Task 3 started with the kitting trays prepared in Task 2, from which the parts had to be picked in order to be assembled into a a belt drive unit consisting of roughly 30 parts. Major challenges in the assembly procedure consisted of screw insertions, screwing operations under narrow access conditions, parts assembly under high tolerances and tautening of the flexible belt.

Task 4 finally introduced variations of the nominal product in Task 3, where the new assembly part model numbers were provided less than 24 hours before the competition and the physical parts were handed over 2 hours before the start of the competition trials.

When designing a robotic assembly system for the WRC, it became evident that all four tasks require:

- means for safely and precisely grasping and transporting the wide variety of parts used in the competition,
- means of easily and flexibly extending the set of graspable parts to meet the requirements of Task 4.

Tackling the challenges mentioned above requires new dedicated grasping technologies. In this domain several guidelines for designing customized grasping solution based on the proven industrial solutions are given by Monkman et al. [3], although the solutions are precise and reliable they lack the flexibility to adapt to rapid changes in the production process. On the other hand, several flexible grasping solutions [4]–[7] exist that can deal with various object geometries. Brown et al. [8] presented a highly flexible grasping system, based on jamming of granular material, that can be utilized for manipulation tasks of soft and rigid objects. Although the gripper can efficiently pick and place the objects, it lacks the precision and repeatability which is essential for robotic assembly. To overcome these limitations grasping solutions with specialized gripper finger designs [9], [10] are used in the production process. Integrating some

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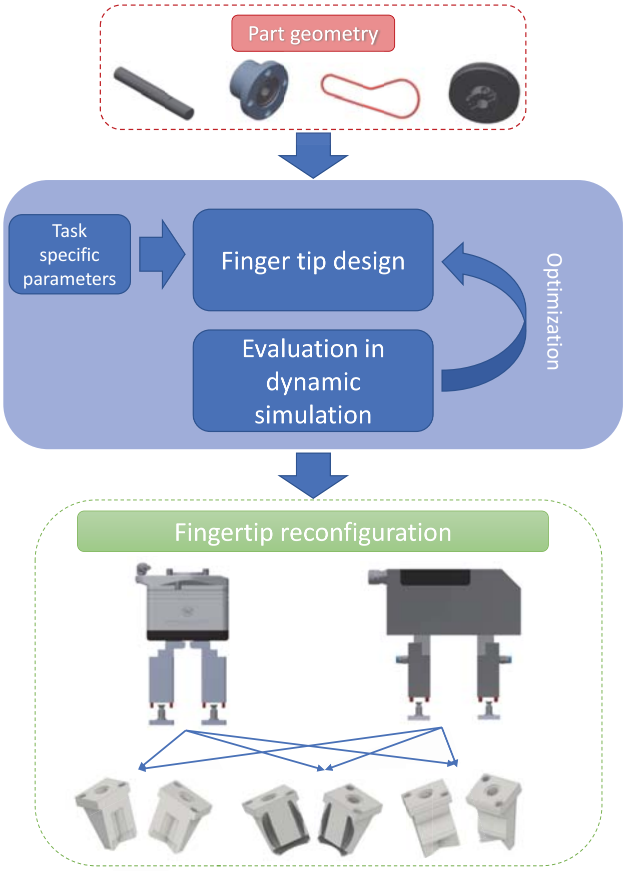

Fig. 1: Overview of the proposed fingertip exchange and design approach.

flexibility in the custom grasping process for handling multiple objects, involves the use of tool exchangers [11]. This solution is highly applicable in today's robotized industrial processes [12].

Instead of adopting a conventional tool exchange system that allows exchanging of the entire mechanical toolchain (including the actuator), our proposed solution focuses on only exchanging the fingertip, thus enabling the use of only a single preferable actuator as it reduces changeover times and utilization costs.

The paper is organized as follows. In the following section, we provide an overview of the presented approach. The fingertip exchange and fingertip design procedure are explained in Sec. III. Experimental evaluation of the fingertip performance in simulation and the integration of the system are presented in Sec. IV, with conclusions given in Sec. V.

II. Method overview

The part handling approach presented in this paper consists of two separate methods, which in combination offer a fast and reconfigurable solution for handling production parts in automated workcells.

The first method deals with the design of the fingertips. The required input parameters for the design method are the geometry of the parts and the part specific parameters, e.g., material, weight, surface treatment, etc. upon which the required fingertip shape is designed. After the initial design, the fingertips are tested in dynamic simulation. If the simulation outcome complies with the task requirements, for example, the design must compensate vision pose estimation uncertainty, geometrical restrictions to avoid collisions, etc. the fingertips can be used in real production setups. On the other hand, the fingertip shape is optimized until it complies with the specified requirements.

The second method utilizes the fingertip exchange system for part manipulation. Several fingertips dedicated to a specific task are placed in a holder, from which the robot can automatically attach and detach the acquired fingertip when the need arises in the production cell. Compared to standard industrial solutions where several grippers with dedicated fingers are used to accommodate the handling of various parts, our solution is simpler and more cost-efficient. With this approach the benefits of servo-electric grippers can efficiently be exploited in the workcell, thus providing a solution for precise part manipulation especially in robot assembly.

III. Grasping solution for automatic reconfiguration

For optimal grasping of differently shaped parts with a single robotic gripper, universal fingers are not the best solution. The performance of the fingers must comply with the task requirements which in manufacturing terms mean, grasp repeatability, positioning accuracy and the ability to compensate for the parts misplacement, if it occurs, at the picking position. Therefore, dedicated fingers that comply with the characteristics of the part must be used in the production process.

To meet these requirements, several comprehensive solutions based on exchanging the entire tool assembly (Fig. 2-left) of the robot are available on the market, for example, the tool exchange system from SCHUNK GmbH [11]. This method ensures a rigid, accurate and repeatable automatic coupling of the tool and the manipulator. The disadvantage

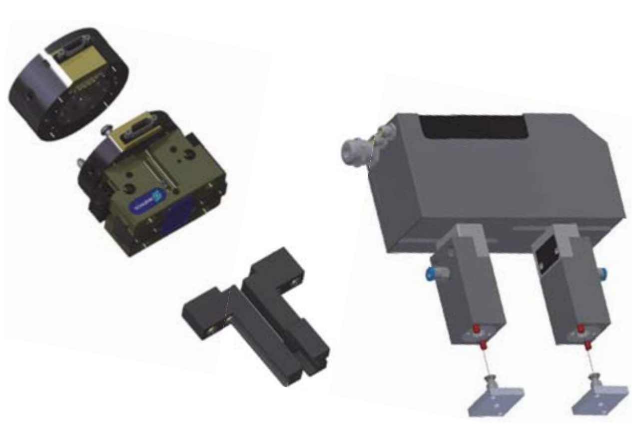

Fig. 2: Graphical representation of the tool exchange system (left) and the fingertip exchange system (right).

of the method is the complexity of the exchangeable system since it is necessary to exchange the entire tool, which also includes the electric, pneumatic or mechanical actuator. In practice, this means that for every manipulated object, we need an exchange plate, actuator and dedicated fingers, which in turn leads to an increase of the complexity and higher cost of the entire robot cell.

In this paper, we took the idea further and developed a fingertip exchange system (Fig. 2-right) reducing the complexity and cost of the overall system. The concept was already introduced in the past [13], due to its mechanical complexity it was never fully adopted in the industry. The need to efficiently handle a variety of small parts and test their manufacturing accuracy emerged in the GOSTOP project. With the proposed method we lowered the complexity of the exchange procedure, reduced the cost of the overall system and could efficiently handle small production parts.

The fingertip exchange system consists of a fixed part permanently attached to the robot's tool and a detachable fingertip, which is specially designed to cope with the geometric features of the manipulated part. With the introduction of additive manufacturing technologies, complex fingertip features can be manufactured, for optimal grasping performance. The fingertip exchange system is suitable for robotic applications in the collaborative domain, for example, part manipulation or assembly where servo grippers are applied and lower overall loads are expected. When dealing with more significant loads, e.g., > 30 kg, the above mentioned tool exchange system is more appropriate due to its structural robustness. Please note, the presented solution was integrated on a parallel gripper, other options are possible. By integrating the fingertip exchange system into the robot work cell, we provide a cost-efficient and reliable solution for various grasping tasks.

A. Fingertip exchange system

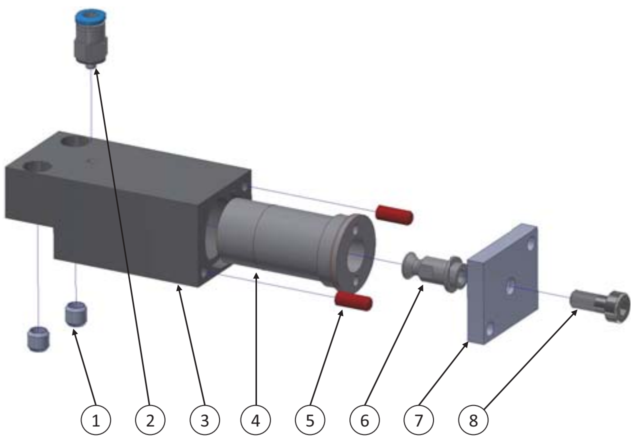

Fig. 3: Exploded view of the fingertip exchange system.

The proposed fingertip exchange system consists of components presented in Fig. 3 and Tab. I. The first component (No. 1) is a standard machine element bushing for precise mounting of the fingertip exchange housing with the gripper finger mounting element. Please note, tight tolerances are required to ensure parallel installation and operation of the fingers. Pneumatic actuation of the locking mechanism (No. 4) is enabled with a standard 4xM3 pneumatic industrial house fitting installed on the fingertip exchange housing (No. 3). The housing is manufactured out of aluminum and designed in such a way, that it can be fitted to a servo controlled gripper (in our case Weiss WSG50 and SCHUNK PG70). The proposed system can be used with other actuators, e.g., pneumatic; therefore the housing mounting points must be adapted according to the actuators requirements. The connection plane, which connects the fingertip to the housing, must be machined perpendicular to the side planes of the housing to ensure an even distribution of the fingertip load when grasping is executed. In the coupling phase, the

No.	***Component***	***No. units per exchange system***
1	Bushing	2
2	Festo 4xM3 fitting	1
3	Aluminum housing	1
4	Pneumatic locking mechanism	1
5	Centering pin $\phi 3$	2
6	Locking pin	1
7	Exchangeable tip	1
8	M5x10 screw	1

TABLE I: Fingertip exchange components.

fingertip (No. 7) must be uniformly positioned with respect to the housing, to ensure a successful interlocking. Therefore, two centering pins (No. 5) for guiding the fingertip to its position are installed in the housing. The second feature of the centering pins is to prevent axial movement of the fingertip when locked and under load. The mechanical locking of the two parts is accomplished with a pneumatically actuated locking mechanism (No. 4) and the associated locking pin (No. 6). The corresponding machine elements are often used for uniform clamping of workpieces in CNC production centers because they ensure a high precision positioning repeatability and holding force when locked. The locking mechanism is normally locked, therefore in the event of power loss, the mechanical coupling will not decouple. In other words, the mechanical coupling decouples only when a standard industrial pressure of 6 bar is applied. The geometry of the locking pin allows for a positioning displacement of approx 1 mm during the coupling process and still ensuring a successful and tight connection. This feature is vital for a successful fingertip exchange if the calibration between the actual and recorded fingertip resting pose changes. The fingertip consists of a base plate (No. 7) on top of which the fingertip features are designed. In the base plate design, two guide holes with high tolerance and a bigger hole for attaching the locking pin with an M5 screw (No. 8) are embedded. The design procedure of the specialized fingertips for different use cases is explanted in the next section.

B. Fingertip design

Efficient grasping of variously shaped parts requires an optimal design of the fingertips, based on the shape of the

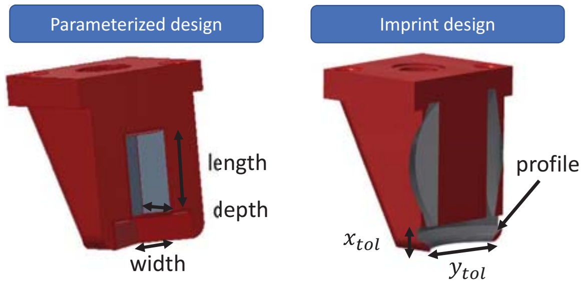

Fig. 4: Fingertip design: a) parameterized fingertip (for grasping the shafts and nuts) b) imprint fingertip (for grasping pulleys).

part. Universal fingertips capable of grasping multiple objects are suitable primarily for manipulation tasks, e.g., pick and place where precise positioning is not required. In specific tasks, such as automated part assembly, the gripper fingers must provide uniform grasping without pose uncertainties. Position uncertainties resulting from unreliable grasping affect the performance of the system and should, therefore, be avoided. With this in mind, specialized fingertips must be designed to accommodate the parts geometry and ensure repeatable, reliable and accurate grasping.

We developed our fingertip base geometry on top of the connecting plate (Fig. 3 No. 7) that attaches to the stationary finger exchange part. To design the fingertip features, we adapt our previously developed approach for design and simulation of gripper fingers [9], [14] and extend it to facilitate the design and evaluation of fingertips. The framework consists of two design methods:

Parameterized method is utilized for designing fingertips for grasping parts with simple features, e.g., cylinders and squares. An example fingertip designs for the shaft part can be seen in Fig. 4 b). In this particular case of the parameterized design, the design parameters related to the diameter of the shaft. The fingertip cutout is defined using three parameters: cutout *length*, cutout *width* and the cutout *depth*. A more detailed description of the parameterized method is given in the work of Wolniakowski et al. [9].

Imprint method uses three general design parameters: *profile*, *tolerance_x* and the *tolerance_y*. The *profile* parameter defines the rate at which the recess in the finger due to the molded object's shape recedes from the object's mesh. The tolerances roughly indicate the distance at which the object's geometry influences the shape and the overall size of the cutout. An example design can be seen in Fig. 4 a). For a more detailed explanation of the imprint method, we refer the reader to the work of Schwartz et al. [14].

The initial fingertip design is tested in dynamic simulation. The output of the simulation indicates, how good the fingertips perform under pose uncertainties. If the performance is not sufficient, the designed shapes are enhanced with an optimization procedure. The benefit of the proposed approach is that it eliminates time and resource consuming trial and error design procedures commonly applied when designing specialized gripper fingers or fingertips.

IV. Evaluation and implementation

A. *Evaluation of the fingertip design in simulation*

To simply and efficiently design the fingertip shape for the presented tasks, we have utilized our previously developed gripper simulation framework [9]. The simulation framework utilizes the Open Dynamics Engine [15] for dynamic simulation and a simulation 3D interface provided by RobWork [16]. This framework enables efficient workflow when designing gripper fingers or fingertips for a variety of grasping tasks.

All fingertips designed for the WRC18 competition are based on fingertip blanks with embedded features for attaching them to the locking mechanism of the exchange system. In the blank fingertip, cutouts and imprints were designed to accommodate the geometry of the manipulated part. To illustrate the design process, we will describe the design procedure for the fingertip used for grasping the shaft part. We chose the parameterized method to design the cutouts for the part. The design parameters relate to the shape of the part in our case; it is a simple cylindrical part. Therefore only the diameter is relevant. Based on this parameter a triangular cutout was constructed in the base fingertip.

The initial design of the cutout works sufficiently if the part's pose in the workspace of the robot is defined at all times. In our case, the task requirements state: the part is freely served to the robot, and therefore the pose of the part must be defined by vision. For this reason, we ran an optimization process coupled with verification in simulation, to optimize the cutout, so that it could compensate for pose uncertainties of roughly 1.5 mm. In total 100 grasps were simulated and evaluated. The quality of the fingertip design was quantified based on the ratio of the successfully aligned grasps to the number of grasps performed in simulation. The output of the joint optimization and simulation process indicates how much the maximal misalignment of the part can be; thus a successful grasp can be performed. The results for each principal axis of the fingertip design are shown in Fig. 5 and the 3D fingertip used in the workcell in Fig. 4(b).

Similarly to the explanted design process, fingertips for other parts were design and evaluated.

B. *Setup implementation*

The proposed method was implemented in the WRC18 robotic assembly challenge. The challenge was to assemble a variety of different parts for which a single pair of gripper fingers was not suitable for. In this section, we give an explanation of how the fingertip exchange system was implemented and used in the workcell during the competition.

1) WRC18 workcell description: For the needs of the WRC18 competition we designed a workcell (Fig. 6 - right) that is easily reconfigurable to accommodate a variety of different robotic tasks. The primary components of the cell are:

- *Worktable*: The table provides multiple possibilities for fixating the parts according to the needs of the task.

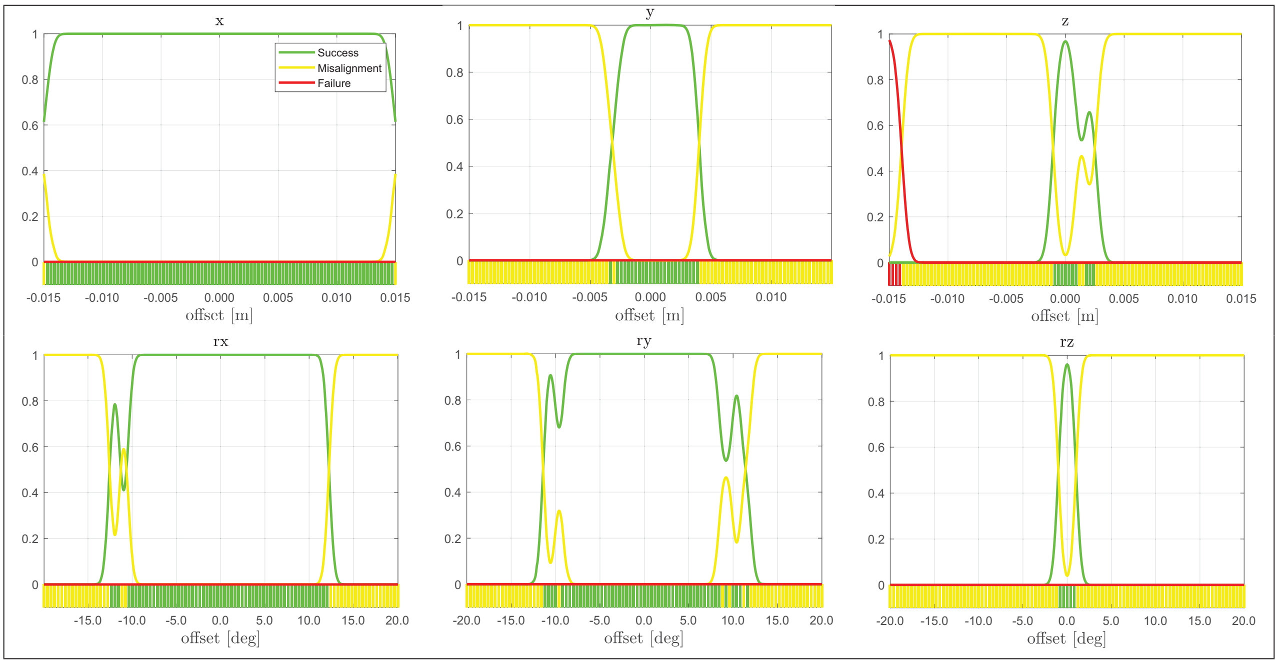

Fig. 5: The figure shows the alignment capabilities of the designed fingertips. The green line represents the probability of a successful grasp, the yellow one of the misaligned grasp and the read one the failed grasp.

It also provides an integrated automation environment with different options to exploit, for example, PLC, pneumatics, safety sensors, etc., all of the components can be controlled with the OPCUA communication standard.

- *Robot manipulators*: For manipulation and assembly tasks, two Universal Robot UR10e arms were utilized. The robot arms have an embedded force/torque sensor at the TCP, enabling force measurement and tracking and can also be utilized in bimanual robot operations.
- *Tools*: A variety of reconfigurable robotic tools and attachments, were developed and used throughout the competition. Some of the examples are:
  - Grippers: Robotiq 2F-85 adaptive gripper, fitted with specialized multipurpose fingertips, for manipulation and assembly tasks were a high grasping force is acquired. Weiss WSG-50 parallel gripper, equipped with the fingertip exchanger, mainly used for precise object handling and assembly.
  - Screwdriver: Desoutter ECSF torque and position controlled screwdriver fitted with an automatic bit exchange system.
  - Clamping device: a pneumatically actuated clamping table, to ensure a firm positioning of the part.
- *Sensor frame*: The worktable was fitted with an aluminum frame to which different sensors (e.g., cameras for pose estimation) and various other devices can be mounted.

A video presentation of the setup is available at: `https://youtu.be/qo08SCGUFnw`.

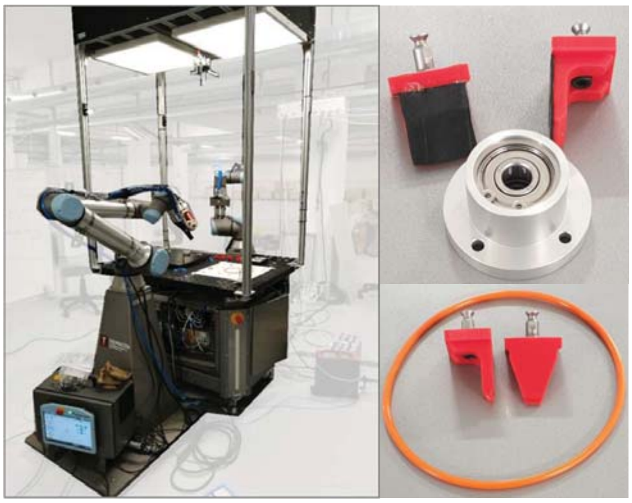

Fig. 6: Representation of the workcell (left) and two example fingertips (right).

2) Fingertip implementation: Secure, precise and efficient grasping of the given parts, presented a big challenge. Therefore, we designed and tested in simulation several fingertips, which were due to their geometrical complexity, manufactured with 3D printing. This technique provides additional flexibility for quick development and customization of the fingertip geometry to comply with the task. A new fingertip can be produced in a few hours and implemented in the workcell, adding another reconfiguration possibility to the process. Fingertips manufactured in such a way can be implemented in production cells for a limited number of cycles. For long-term use, the fingertips must be manufactured out of

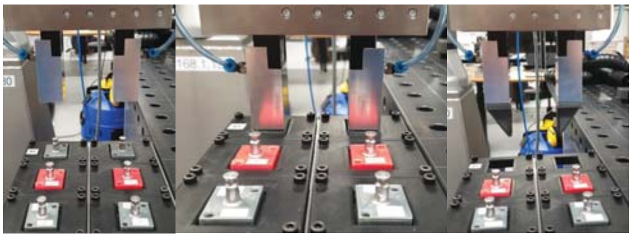

Fig. 7: Fingertip exchange procedure. First the robot approaches the fingertip holder (left Fig.) second, moves to the desired fingertip location and couples with the fingertip (middle Fig.) and lastly, lifts the fingertip out of the holder (right Fig.).

a wear resistant material, e.g. steel or aluminum. An example of two different designs is presented in Fig. 6 - left .

3) Fingertip exchange implementation: The fingertip exchange system was implemented on a parallel servo gripper. The pneumatic activation of the locking mechanism is performed with a solenoid valve, which can be controlled with digital outputs on the robot controller or an external PLC. To store the fingertips at a defined location, a specialized holder, mounted on the edge of the table, was designed and manufactured out of sheet metal. The holder was fitted with specialized 3D printed fingertip fixtures. The fingertip fixtures match the outer geometry of the base fingertip's shape. Therefore when the tip is detached (approx. 3 mm above the fixture), it slides into a uniquely defined pose. The exchange procedure is presented in Fig. 7.

To test the reliability of the exchange system, we executed 1000 coupling and decoupling actions with 100 % success. In addition to this experiment, the method was successfully applied in different grasping and part feeding scenarios during the entire competition. The reliable performance of the fingertip exchange system proves to be a great asset to the overall successful performance of the workcell in the competition.

V. Conclusion

In this paper, we presented a method for efficient and precise grasping of multiple different objects in a changing production environment. The method consists of two parts. In the first part, we presented a mechanical solution for exchanging fingertips, ensuring optimal grasping of objects based on its features. The method represents a flexible and cost-efficient solution for advance customizable industrial processes. In the second part, we described the automated design process for fingertip development. Both methods were applied in the context of the World Robot Summit 2018 and gave excellent and reliable results.

In future work, we will focus on four main enhancements of the presented system. The first enhancement introduces sensors for fingertip detection and force sensors for precision handling of delicate and flexible objects. Hence, the system will give more grasping information to the user. Secondly, we will embed pneumatic connections, which can be used at the exchangeable fingertip for vacuum grasping. Thirdly, we will redesign the coupling mechanism, so that it will be more compact and electrically actuated. The last enhancement focuses on the fingertip design. We will mainly focus on reducing the number of setup parameters, making the design procedure more streamline and simple to use.

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