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Methodology for Reconfigurable Cobot-Based Quality Control System for SME Production

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Abstract—**More than a decade ago, we were introduced to the concept of Industry 4.0 (I4.0), and today a lot has been applied in the manufacturing industry. Moreover, the concept of Industry 5.0 (I5.0) is spreading its branches, focusing on collaboration between humans and machines. The continuous development of collaborative robots (cobots) has led to a situation where Small and Medium-sized Enterprises (SMEs) have the financial resources, but lack of knowledge how to integrate these robot systems into their production by the principles of I4.0. The functions of the cobots meet the requirements of SMEs as these are easy to program, lightweight, and universal machines. In this article, we propose a methodology for reconstructing an existing cobot cell into an autonomous quality control system for SME production. This implies the use of Machine Vision (MV) technology with the development of various product databases, and in the future, adapting Machine Learning (ML) functionality. First, the variables are examined and classified by their features, determining their importance in the redesign process. Then, a digital twin model of the robotic system is developed to evaluate the effectiveness and simplify the preliminary programming of the system. This includes technology process-based design for elements such as gripper and multi-position fixture. Finally, we present the assembly and testing of the reconfigurable cobot-based quality control system with test results which imply that the quality control system can perform by the established goals.**

Keywords—**collaborative robot, machine vision, machine learning, quality control, Small and Medium-sized Enterprise (SMEs) production**

I. INTRODUCTION

Industrial companies are using robot solutions in every part of the world to increase throughput, quality and reduce the cost and lack of human labor. According to a Eurofound survey, 39% of European manufacturing companies stated limitations in production due to labor shortages. According to the prediction, made by the United Nations (UN) analysis, we will witness a decrease of 95 million workers from 2015 to 2050 [1]. The demographic effect will accelerate and force even more rapid usage of smart robotic systems. Robot solutions are different in nature: industrial robots, cooperation robots, and specialized autonomous product-based robots adapted to production. Industrial Robots (IRs) are directed at high-volume production and are aimed mainly at large enterprises. Product-based specialized robot systems are also for high-volume production, but on the other hand, lack the flexibility for retuning the Robot Cell (RC), which is important for Small and Medium-sized Enterprises (SMEs). SMEs need to compensate for the lack of labor but still increase the throughput and quality of products. SMEs represent 98% of European manufacturing and mainly produce high-mix low-volume products [2], where the speed of retune and flexibility between different positions in production is essential. Therefore, it is reasonable to implement parts of I4.0 [3] concepts such as Additive manufacturing, Cloud computing, the Internet of Things (IoT), System Simulation, and Integrated Manufacturing [4] etc. to SME manufacturing. Lots of companies are already using these technologies, but it is common to use RC for one application, etc. pick and place. A typical cobot system is equipped with a gripper to move or index products as required. These types of RCs are easy to program, and no high level of knowledge and competence is necessary [5]. The objective of this research is to find methodological ways to develop existing RCs into multi-purpose robotic systems, allowing to maintain the flexibility to react and retune the RC to another position in the production.

For developing a cobot-based quality control system, vision capability must be given to a cobot system to sense and detect objects in an environment. Machine Vision (MV) enables this possibility for a RC. According to the Automated Imaging Association (AIA), machine vision encompasses all industrial and non-industrial applications in which a combination of hardware and software provide operational guidance to devices in the execution of their functions based on the capture and processing of images [6]. The information gathered from MV serves great importance in terms of digitalization and takes robot cells to the next level. In terms of functionality and flexibility, the solution is capable of changing products in SME production quickly. Also, we point out the flexibility and reconfigurability functions of the cobot-based quality control system.

The rest of this paper is organized as follows. Section II presents the proposed framework of cobot unit in SME production. Section III describes the principles of reconfiguration methodology for quality control. Section IV describes the design of cobot-based quality control and its elements. Section V presents the integration of the cobot-based quality control system and reveals the onsite testing. Section VI concentrates on discussion and conclusions, following future work and acknowledgment.

II. LITERATURE REVIEW

A. *Collaborative Robot Systems*

Collaborative robots are a relatively recent and very active

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field of research. Since its advent, the main aim of collaborative robot manufacturers and researchers has been to improve the aspect of human safety during human-robot interaction while increasing the payload capacity of the robot and at the same time maintaining and enhancing the mobility and flexibility in collaborative robots [7]. Collaborative robotics aims to be complementary to such a modern way of doing conventional robotics, increasing the degree of human participation, in terms of shared time and space, and featuring new types of applications or domains [8].

The EU parliament study states that collaborative robotics is the main driver of I4.0 and Europe is the global leader in the supply and implementation of I4.0. The objective of collaborative robotics is to combine the current capabilities provided by robotics, such as effort and precision capacity, with the inherent human skills to make decisions and solve complex problems in inaccurate tasks [9].

Safety is also a topic in any project or research connected with IR-s or collaborative robots. Since 2016, a standard of ISO/TS 15066:2016 was introduced that specifies safety requirements for collaborative and IR systems and work environments [10]. In terms of terminology, Vicentini [11] has presented an overview and developments in this field. According to the EU study, the market for collaborative robots had grown in 2021 by nearly 50% and the forecast for next years shows the range between 20–30% [9]. It is a rapidly developing field in the industry, especially in SMEs. However, currently the cobot market represents only 7.5% of the total robotic market [12].

B. Machine Vision and Learning

Different Machine Vision (MV) systems exist, and these are used for a broad range of applications. The variety of applications use line scan, area scan, and 3D scan cameras and mainly perform presence inspection, measurement, identification, positioning, and defect detection. The vast advantage of MV-based inspection is increased throughput in the detection process. Huang *et al.* [13] improved inspection of glass bottle breakage and contamination. The system developed uses a radial scanning method followed by contour fitting to identify breakage on bottle mouths. The system accomplished an inspection rate of 72,000 bottles per hour while detecting 100% of defective bottles and mislabeling 0.297% of bottles [14]. Kinell *et al.* [15] presented the 3D vision mounted to IR in their research "Autonomous metrology for robot mounted 3D vision systems". A viewpoint selection algorithm was developed to locate objects using cloud data. Useful viewpoints are ranked by algorithm, providing necessary positions where to position the camera. Alonso *et al.* [16] presents an overview of two methods to inspect welding seams. First, they use a 3D vision sensor to acquire a cloud point dataset, and second, a laser-based method, measuring weld bead dimensions and acquisition data using depth.

Machine Learning (ML) concerns the construction and study of systems that can automatically learn patterns from data. Models built with ML can be used for prediction, performance optimization, defect detection, classification, regression, or forecasting [17]. Razvi *et al.* [18] presents a detailed overview of ML applications throughout the AM design-to-product transformation cycle. Different ML methods are discussed to find well-suited solutions to problems.

C. Reconfiguration Methodology

As the nomenclature in manufacturing is rapidly changing and technical solutions are developing continuously, companies are required to upgrade their production systems. The system must have a feature for simple reconfiguration or even a redesign option for quality control cell improvements. Yim *et al.* [19] introduced three subtypes of modularity in product design: slot architecture, bus architecture and sectional architecture. In slot architecture, each of the interfaces between components is a different type, the various components in the product cannot be interchanged. For example, the robot arm which has rigid links, motors, transmission, and sensors. In bus architecture, a common feature is that the other physical components connect via the same type of interface. A laptop with USB ports, for example, modular elements can be added or reconfigured. In sectional architecture, all interfaces are of the same type, and there is no single element to which all the other components attach, there is no base component [20]. In our research, we are using the principles of slot and bus architecture for the reconfiguration of existing robot cell for quality control system.

The advantage of a reconfigurable system is evident from its evolvability, multifunction, and survivability. The changing environment, in terms of product and production, forces us to keep an open mind for additional development of existing systems. Kalimuthu *et al.* [21] introduced research on a reconfigurable robot which is capable of expanding and collapsing its dimensions to adapt environment. Paramasivam *et al.* [22] have discussed an overview of general reconfiguration methodology, using classification for subtopics such as manufacturing, environment, assembly, safety, and reliability. On the other hand, Gualtieri et al. have developed a multicriteria methodology for evaluating the conversion of manual assembly workstations into collaborative human-robot work cells. The research mentioned above supports the background for our study and using its elements, we have adapted the reconfiguration principles for developing a cobot-based quality control system.

III. THE FRAMEWORK OF COBOT UNIT IN SME PRODUCTION

The cooperative company's main products are in the field of IoT and focus on zero-emission small vehicles like e-bikes and e-scooters and their components. This SME has a high product variation of similar products. Also, the procedures of manufacturing a single product are complex and consist of highly automated manufacturing lines for producing assembled circuit boards and on the other hand, manual labor for soldering soft and delicate cables for enabling functionality between different parts of the product. Quality control is carried out throughout production and multiple positions between different processes. We are focusing on the cobot quality control unit in our research which is illustrated in Fig. 1 and the RC will be added into production. Currently, the quality test position is manual. No data is preserved about the number and reasons for defects. In terms of reconfiguration of existing RC to a cobot-based quality system, it is important to evaluate the environment, manual workplace, and processes and workflow. A subparagraph Human-robot collaboration and environment is dedicated to different methods of evaluation.

As a manufacturing SME, the enterprise uses a multidimensional production system, where they have full control, starting with the product and manufacturing design, and quality and ending the chain with support, as shown in Fig. 2. That enables the freedom of making changes in production but also sets the constraints.

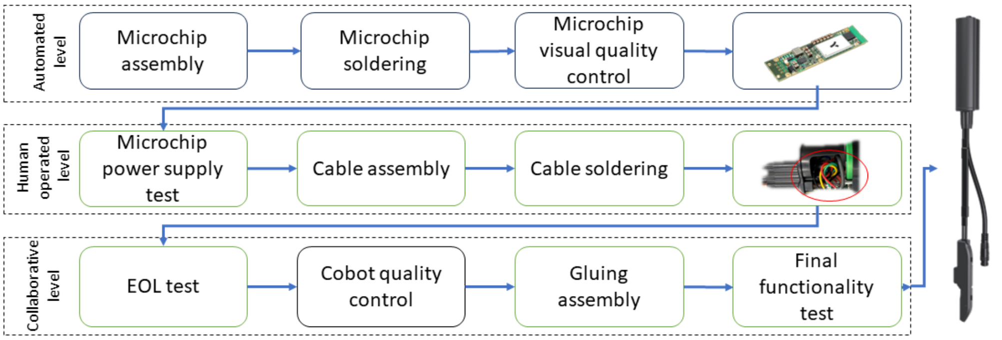

Fig. 1. Typical SME production levels.

Fig. 2. Multidimensional production of SME.

A. *Human-Robot Collaboration and Environment*

According to Rauch *et al.* [23], part of manufacturing SMEs do not have knowledge and skills about the implementation of collaborative robots even if experts in the field believe that it will be an important technology for the growth of their business. A similar approach extends to the enterprise we are doing our research. There is knowledge of product and manufacturing design, but a lack of competence in integration of collaborative robots. The Human-Robot Activity Allocation procedure is a fundamental part of the conversion process. Starting from an existing manual assembly workstation, this procedure allows for the separation of tasks and activities between the operators and robots by considering the influence of different production indexes concerning technical feasibility, safety and ergonomics, process quality and economic aspects [24]. Here is a list of related research presented which is applied to the topic. Kangru [25] has developed an optimization of the decision-making process in industrial robot selection based on Key Performance Indicators (KPIs) and a Decision Support System (DSS). Haydaryan [26], on the other hand, has developed a hierarchy decision-making method for the human-robot task analysis based on productivity, human fatigue, safety, and quality evaluation criteria. Cencen [27] have proposed a human-robot coproduction design methodology to overcome the challenges faced in the SME context [24]. All these approaches support SMEs in focusing on important topics while being in the starting position of implementing a cobot system into production or reconfiguring an existing cell.

The quality control process involves three areas: input area, process area and output area shown in Fig. 3. The input area is for stacking various products by human operators to be ready for control. The process area is the most complicated in the RC. It involves picking up the product, which is an IoT module, one at a time, taking the product into a robot-controlled fixture, opening the product, detecting the product model, multi-position vision processes, closing the product, and taking it to the output area. The output area is divided into two: finished products and defective products. The defects are divided into categories according to the defect type for repair or utilization.

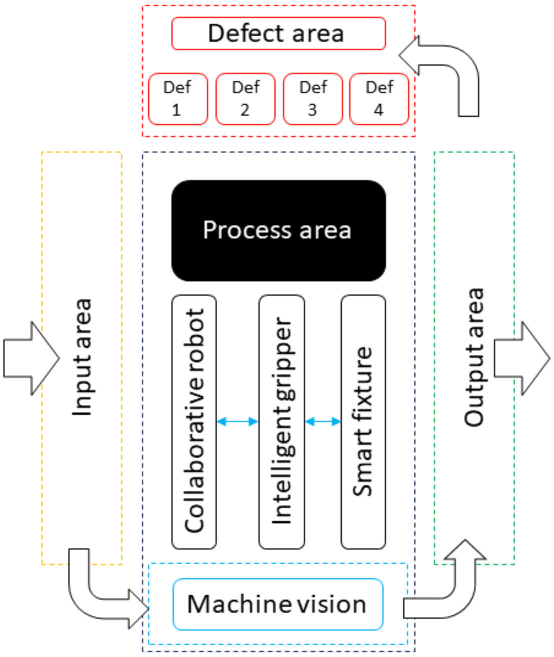

Fig. 3. The concept of redesigend RC for quality control.

The environment in SME production sets limitations and constraints to the layout. The biggest factors are floor space, production workflow and Human-Robot Collaboration

(HRC). The floor space sets definite boundaries for cobot system size and offers irregular shaped space for the floor plan. A rectangular shape of 2.1 m by 2.6 m, where a triangle of size 1.0 m by 1.5 m is cut away. In terms of any development project involving industrial or collaborative robots, this is one of the essential constraints to be focused on.

Flow production is a manufacturing process that is defined by the continuous 'flow' of goods along an assembly line. The goods are put through different stages on the assembly line before being packaged for delivery to the end customer [28]. Production workflow sets the location of the developed cobot system between different processes inside SME production. This feature is directly connected to the floor space and usually influences each other. In our research, the quality control cobot system is planned between the End-of-Line (EOL) testing and glueing process. The importance of the quality of information in this point is essential. Validated products are sealed waterproof in the next process flow of glueing, making it impossible to reopen the product to repair any defects.

The third important topic to consider is HRC and interaction in the developed system which we create a third, collaborative level, in SME production. HRC is expected to increase the quality rate and performance efficiency [29], which is divided into a variety of aspects, safety, regulations, technical potential, and ergonomics, as stated above. A changed environment needs preventive training and a test period. Afterwards, analysis can be carried out to make changes in HRC, if necessary. The following model in Fig. 4, presented by Oberc [30] can be observed and followed by management of SME to execute the training period, followed by analysis.

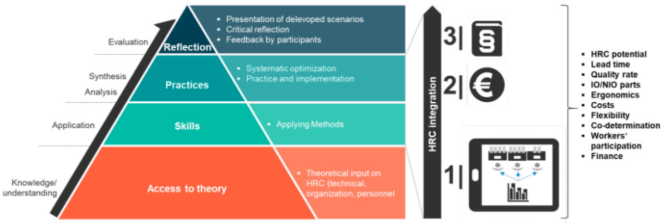

Fig 4 HRC training cycles [30].

B. *The product*

The following subchapter presents the importance of the product and why it is necessary to analyze it. The product can be characterized by many features such as size, shape, color, weight, material, part or assembly, soft and rigid elements, quantity etc. In terms of redesigning a system, it is essential to evaluate the features that affect the system the most. Paramasivam [22] has presented a combination and methods in his research for design which can be used in the redesigning process of a system. One of the steps in general methodology, in the paper, stated above, is adapting the Product design Evaluation Matrix (PEM) which will be a M × M matrix. In this paper, we suggest a simplified scheme of using features in columns and effects in a row for quick evaluation for use in SMEs. The product-based features and effects are presented in the table below Table 1.

Table 1. Simplified evaluation of product features

Feature/Affect	No affect	Small	Moderate	Vast
Size				x
Shape				x
Color	x			
Weight			x	
Material		x		
Part/assembly			x	
Quantity		x		
Soft/rigid elements				x

The product for this research, as stated above in A, is an IoT module. Using the information from Table 1, the most important features are size, shape and soft/rigid elements which are followed by weight and part or assembly features. In terms of size, the product has an irregular shape and length-to-diameter ratio which makes it challenging to handle with a cobot system. The product is a complex assembly, consisting of shell-type elements, cables, connectors, circuit board assembly, and battery. This type of assembly is not commonly presented in pick-and-place assignments for cobot systems. Fig. 5 presents the shape and size of the IoT module assembly. The limitations set by the product features are essential for reconfiguring any industrial or cooperative robot cell.

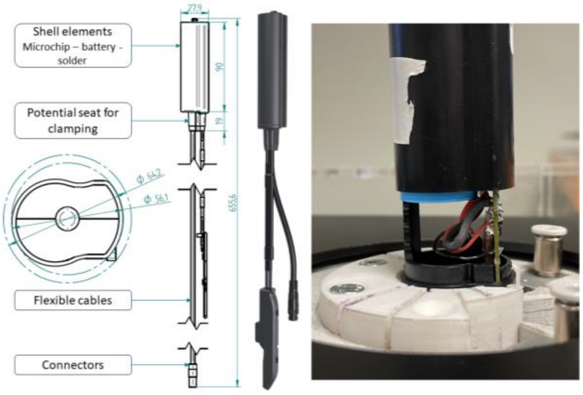

Fig. 5. The product's size and shape.

IV. Reconfiguration Methodology and Design of Cobot Based Quality Control Cell

The information gathered in previous paragraphs is the key feature of reconfiguring the collaborative robot cell into a robot-based quality control system. In this phase of our research, we focus on the necessary reconfigurations and redesign steps needed to be executed. Also, the aspect of constraints is being considered.

A. *Existing Robot Cell*

Considering the constraints and features of the product and floor space, they must fit the requirements, but also fulfill all the functions. The collaborative robot reach area starts from 500 mm and ends around 1800 mm. The suitable collaborative robot must, at minimum, stay in the mid-range of stated values. Most collaborative robots can be mounted to the wall, table, and ceiling. In terms of height, concentrating on the product length Fig. 5, the robot must be mounted to the height of 1000 mm at least for clearance to the cables. From the point of view of ergonomics, input and output area is defined with average operator height, for loading and unloading of the products. In this paper, we have used a collaborative robot Omron TM5-900 with a reach of 900 mm. The controller allows the usage of 16 digital inputs and outputs, 2 analogue inputs and 1 output for I/O ports. Communication can be established using RS232, Ethernet or Modbus Transmission Control Protocol (TCP)/Remote Terminal Unit (RTU) which is important for equipment added to the system [31]. As a common solution, this existing robot cell uses a modular aluminum profile frame with the possibility to add modular features with low time consumption, but high precision and rigidness.

B. The Principle of Smart Fixture

The product always sets several limitations for the fixture. In this research, the crucial feature of the product is the sequence of cables which are in two rows shown in Fig 5. These cables ensure the functionality of the product. Due to the variety of similar products in SMEs, the detection by MV of the present product model is also one of the key features. Therefore, the smart fixture must ensure two positions for MV detection, from both sides of the product.

The principle of smart fixture is divided into three positions, shown in Fig. 6: Clamping Process (CP), Quality Control Process (QCP) and Unclamping Process (UNP). The clamping process is described as follows: the cobot places the product in the fixture, the fixture clamps the product for a stable and accurate position, and then the cobot opens the product to reveal the important area inside the product. All the communication is executed through the cobot system controller. Secondly, the quality control unit actions can be described as detection of the model, checking the first-row cables of the product, fixture rotation to position 2, checking the second-row cable sequence by color and finally fixture rotation back to position 1.

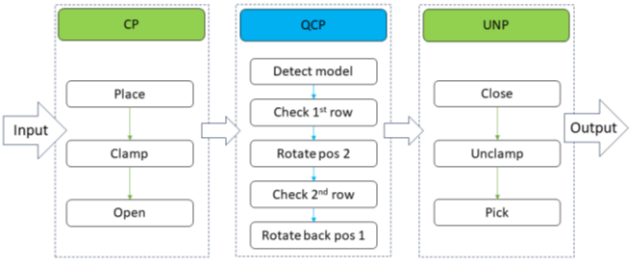

Fig. 6. The principle of smart fixture.

C. The Design of Fixture and Additive Manufacturing Techniques

As the principle of smart fixture is presented above in Section IV.B, the technical design and additive manufacturing techniques are discussed in the following subparagraph. Several versions of the design were discussed, here we present the final version of the smart fixture. The same approach has been used for the frame, as used in the frame of the existing robot cell, the modular aluminum profile. The frame supports the base plate which has a V-shaped opening for inserting the long product with flexible cables.

The limitations foresee the use of two positions of the product for quality control. Only the start and end position of the rotational axis is determined. With the start position of 0° and the end position of 180°, no other position is relevant in this case. The motion of the product could be achieved using a step motor, servo motor or rotary cylinder. With no need to determine specific degrees in the rotational axis, we have used a pneumatical rotational cylinder with electric control through cobot control. One of the benefits of the cylinder is adjustable acceleration and deceleration speed which ensures the smooth positioning of the product inside the fixture. The usage of spur gears allows to relocation of the rotational position. One of the gears has a similar V-shaped opening, as the base plate, creating access for the product. That gear has a groove on the bottom, allowing bearings to guide the rotation. A guide plate supports the gear from below of bearings. On top of the gear, there are pockets for pneumatic cylinders. These cylinders apply the force of 10 N to clamp the product inside the modular insert. The modular insert is designed according to the shape limitations of the product and bolted to the gear. In terms of manufacturing, the design of insert and spur gears, additive manufacturing [17, 32] principles are followed. This gives the freedom of creating sharp corners, pockets inside closed solid bodies and complex geometry, such as narrow slots inside insert for making it a flexible body on one side. The moving parts of the fixture are protected with the side and top plate for safety, as shown on the right side of Fig. 7.

On the left side of Fig. 7 is located the machine vision unit for quality control. For image quality and focus adjustment, it is assembled on a guide assembly and bolted together with a camera mount. It allows manual adjustment for focus. In this research, we use a 2D-vision system, In-Sight 7905C from Cognex.

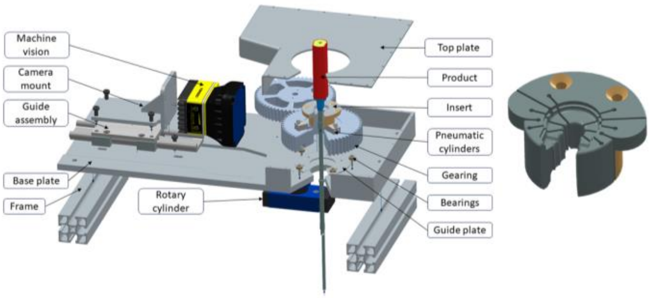

Fig. 7. The modular assembly of smart fixture and product insert.

V. INTEGRATION AND ONSITE TEST

This paragraph presents the overview of the integration and testing of the reconfigured cobot-based quality control system. Our research presents the preliminary results of this application. Furthermore, continuous development and testing in the SME of the system will be done according to the preliminary results.

The quality control module, shown in Fig. 8, is assembled to the process area, shown in Fig. 3, using an aluminum profile solution. Then, the stacking shelves are added to create an input and output area for the products. The programming of the system consists of multiple layers where the main program controls the subprograms, MV unit and smart fixture. For creating the multi-layer programming, following the structure of the system concept, shown in Fig. 3, and smart figure processes shown in Fig. 6, allow efficient architecture for programming. For example, inside the input area, the positions of the products are described as variables and the detection is done by a force feedback gripper. This allows RC to cope with the changing environment in production, where all the product slots must not be sequentially fulfilled with products. A similar approach is used in the output area, where the cobot divides the products into different areas, using a preliminary programmed ratio between OK and NOK products.

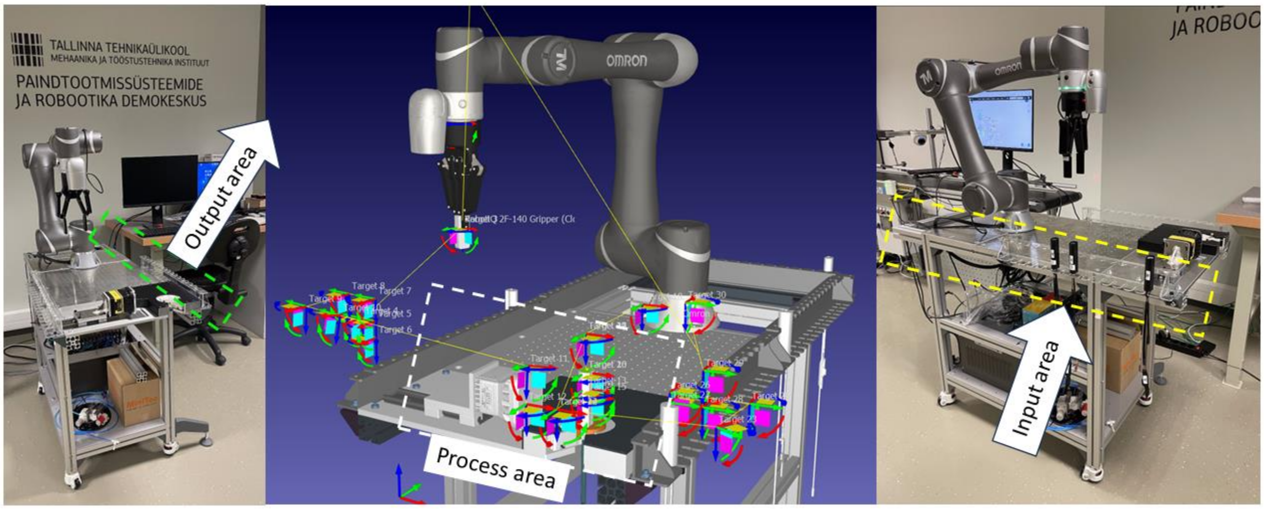

Fig. 8. Virtual and real cobot based quality control system.

The importance of smart fixture positioning precision is essential in the quality inspection process. The MV camera detection is based on the location, size and color of the specific area of the product, where the cables are connected to. The lighting, focus area and size, and background are important properties for successful detection. As shown in Fig. 9, the image presents the areas for specific products and important areas inside the product. On the left side of Fig. 9, green boxes represent the successful detection of cables by their color and sequence. This means the functions of the product are correct and the product can move to the next process in the production. While the right side of the figure represents the failed detection of the cables, this means that the product is defective and is moved to the defect area. In the example, the product has failed all the detection areas out of three. In terms of any failed feature, the product is classified as a defective product. The following steps are required to repair the product and test it again in the quality control unit.

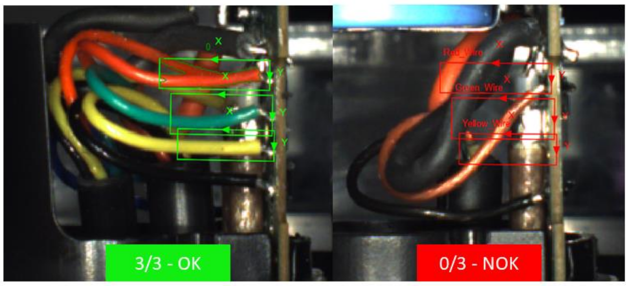

Fig. 9. Machine vision testing OK-NOK.

Conclusively, the preliminary testing has been successful using different products from SME production. The cobot-based quality control system is capable of detecting correct and defective products and separating them. In terms of cycle time, we tested the cobot-based system at various speed rates. Using a 10% application speed for the robot, the cycle time was 90 s. While, using 90% of the movement speed, the cycle time was 50 s. We suggest that the motion speed should stay in the range of 250 to 500 mm/s. This constraint is connected to the dynamics of the product. In terms of MV, the detection process varies from the number of objects being tested. For example, the detection of four objects took a time of 200 ms for one side of the product. In terms of the smart fixture, the clamping and rotation of the product took two seconds to rotate the product 180°. It is easily possible to adjust the rotation speed, but the sustainability of the quality control process is far more important. Finally, the results of the presented cobot-based quality control system show that the application is capable of detecting defective products effectively. Further testing will be carried out to check the sustainability of the system.

VI. Discussion and Conclusion

In this study, the importance of reconfiguration methodology for quality control systems has been discussed. The implementation of the cobot-based system in SME production is a productive way to increase precision and preserve data for future analysis and predictions inside the production. Reconfiguring methodology discusses the essential features such as environment, product, and existing robot cell for executing the redesign process in low time consumption.

In the practical use case, using the presented methodology, an existing cobot cell was reconfigured into a quality control system to check the cable sequence of a product and differentiate defective products by their fault. The quality module can be easily detached from the current cobot and used otherwise. Moreover, in the future, we will carry out testing the system in real production for reliability, precision, and data transfer. Developments such as the implementation of Electronic Shelf Labels (ESL) allow output to adapt according to defect type and sequence and make predictions about error sequences in previous processes.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

MM and MS conducted the research and the development project of this cobot based quality control system; TO and JR analyzed the data that was generated using virtual environment tools; MM, and JMV wrote the paper. All authors had approved the final version of this article.

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