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Evaluation of the Design of a Tool for the Automated Assembly of Preconfigured Wires*

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Abstract— **The assembly of control cabinets is highly affected by manual processes. For reasons such as the shortage of skilled workers, there is a considerable need to automate the production steps. The automated wiring of prefabricated wires, which is a mayor process step in the manufacturing, is not automated yet. Besides different sensor technologies, a reliable tool for assembly must be developed. This article discusses the challenges and criteria for the development of such a tool. The most important functions of the tool include the handling of wires with different lengths, cross-sections, and colors as well as the consideration of close mounting positions. Based on a morphological box, a tool concept is derived and validated via tests on a demonstrator.**

I. Introduction

Control cabinets are essential in many areas of industry. Accordingly, their production is of great economic importance. However, due to the high customization of the control cabinets, production is still carried out manually at high cost. In terms of the required process steps, the wiring takes up a considerable amount of production time. Thus, an automated solution has a positive effect on both production costs and production time [1]. A successful solution for automated wiring must fulfill various criteria, and there is currently no solution available on the market that meets all. Among others, the following criteria must be considered:

- The wires mounted in a control cabinet differ in length, cross-section, and color. The fewer variants of wire that can be handled, the lower the cost-effectiveness of automation.
- The installation positions of the wires are often very close to each other, so that installed wires can hinder further mounting. In addition, installation positions can be difficult to reach because other components or wire ducts prevent direct access.
- Many companies that produce control cabinets are small and medium-sized enterprises. As a result, the acquisition and operating costs for automation should be as low as possible and the amortization period as short as possible.
- The manufacture of unique control cabinets is a common business. The resulting high variance must not lead to increased set-up time, as otherwise it is not economically viable.

There are many aspects to be solved, such as control, vision, and mechanical design. In [2], for instance, a distributed control approach for a robot based wiring system is presented. This paper focuses on the development of mechanical design of the tool and is structured as follows. In the next section, the assembly process is described in detail, especially the certain process steps that are required. Section III gives a short overview on related work. Section IV presents the tool design that is derived by using on a morphological box. With this tool, the performance at all process steps is evaluated. The paper ends with a discussion of the tool and its evaluation.

II. Problem Description

Figure 1. depicts a typical situation in the assembly of control cabinets. There are several components mounted on the mounting plate, such as terminal blocks, PLC components, or frequency converters. The components are connected by wires to implement the certain function. In the figure an exemplary mounted wire is shown. Although the shown components are very close to each other, they can be placed elsewhere inside the cabinet. Each component has several input/output or power supply connectors, and to achieve a certain function, the components' connectors must be linked via wires.

Figure 1. Picture of a typical wiring task, where two terminal blocks are connected by a wire. The middle piece of the wire is routed through a wire duct.

To assemble a wire, there are five process steps required, while the order of the steps may vary. The end of the wire must be fixed to the component. From the component the wire must

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be routed to the next wire duct and fed through a slot into the wire duct. These two steps must also be done with the other end of the wire (step three and four). The fifth step is the routing of the wire within the wire ducts. Furthermore, the wire must be cut to length and crimped before assembly. Alternatively, the wire can be prefabricated and then taken, for instance, from an external magazine.

Based on these process steps, different key performance indicators can be defined which must be provided by a tool for automatic wiring. Among others, these are as follows:

- Gripping wires with different cross-sections.
- Handling wires with significantly different lengths.
- Insertion of a wire end into the connection of a component. Thereby, only push-in technologies are considered in this paper.
- Routing a wire into a wire duct through its slots.
- Routing a wire within the wire ducts.

III. Related Work

There are several skills required to design a proper solution for the automated wiring. Due to the non-rigid shape of the wires, many works deal with image processing. In the context of vision, there are two main areas of work described below: detection of the wire as well as the wire tails, and detection of mounted parts.

The detection of wires – or deformable linear objects in general – is a non-trivial problem due to occlusions of other components, other wires, or itself. However, reliable detection is important for grasping wires and handling them without collisions. For example, de Gregorio presents an algorithm that simultaneously implements semantic segmentation and b-spline modeling to detect multiple deformable linear objects at the same time [3]. Caporali et al. used a similar approach to estimate the shape of a wire and determines suitable grasping positions [4]. This is done by generating images from different views with a low-cost 2D vision sensor and determining key points for the wire calculation [5]. A general method for determining grasping points is presented in [6]. The model-free algorithm provides automatic selection of contact points and enables a stable object handling. Palli and Pirozzi developed a calibrated image processing system that can determine the physical parameters of a wire using a trial-and-error approach with continuous optimization [7].

The detection of component positions is a further crucial function for the reliable automation of wiring. While the nominal positions result from the system planning, the real positions deviate from these due to component and assembly tolerances. Hence, it is necessary to compensate for these tolerances. Hefner et al. described an algorithm for recognizing components [8]. The real structure is recorded using a 3D sensor. The data is then compared with a 3D model and deviations are determined. The method is used for both the components and the detection of the wire tails. Bründl et al. presented an approach that analyzes CAD models of components and automatically extracts their characteristic features [9]. In real environments, these features can be identified, and their position determined using AI-based object recognition. The position of the component is then derived from the recognized features.

Next to the vision, simulation is used as an option for learning and testing the necessary skills. Alvarez and Yamazaki, for example, implemented a real-time simulation that enables the calculation of actions to move a wire from one configuration to another [10]. The planning algorithm can react to changes and will be used in real environments in future. Jaensch et al. used the simulation of a virtual commissioning to learn cable handling strategies [11]. The behavior of wires can be learned using standard reinforcement learning methods. A combination of simulation and vision is used in [12] to implement vision feedback. This allows the wire deformation to be controlled in such a way that the wire does not come into contact with surrounding obstacles. Another approach for determining the robot movement is presented in [13]. A robotic simulation is used to analyze the planned path of a manipulator and derive optimizations regarding the programming code. However, a fundamental problem with simulations is a limited transferability to the real environment. To compensate for the resulting deviations, a feedback method is proposed by [14]. Deviations from the simulation to the real environment are determined and used to iteratively improve the parameters of the simulation models.

In addition to the detection of wires and components, the mechanical design of a tool is of crucial importance. It is important to ensure that the interference contour is sufficiently small to guarantee collision-free handling. Gao et al. developed a tool concept that is capable of gripping and sorting the individual wires of a cable so that a correct connection to a circuit board or connector can subsequently be made [15]. However, the mechanical concept is only transferable to a limited extent, as the focus is on sorting the individual stranded wires. Another tool concept is presented in [16]. The tool developed there is equipped with a camera, a screwdriver, and a gripper with a tactile sensor. This tool can be used to grip wires and install them in screw terminals. Tolerances can be compensated, and a high level of process reliability is achieved. However, it is not possible to fully assemble the wire with the tool.

IV. Tool Design

The type and number of manipulators for automated wiring has a significant influence on the design of the tool. Regardless of the required mounting direction, five degrees of freedom are sufficient due to the rotational symmetry of the wires. When handling a wire, both ends must be assembled. Moreover, it must be ensured that the wires do not get stuck during assembly. Three variants are therefore feasible regarding the number of manipulators. In the first variant, three manipulators are used. One robot grabs one end of the wire at a time and the third manipulator ensures that the wires are guided correctly. In the second variant, the third robot is omitted, and the wire is guided by one of the other two manipulators individually or in turn. The third variant uses only one manipulator to perform the necessary tasks. As more functions must be integrated into the tool, the smaller the number of manipulators, the more complex the tool becomes. Nevertheless, due to the expected lower overall costs, the last variant is preferred, so that only one robotic manipulator is to be used for automated wiring. A standard articulated robot arm is used as the manipulator. The

Table 1. Morphological Box

Feature	Option 1	Option 2	Option 3
Joint	Parallel	Rotational	
Finger	Flat	Form	Prismatic
Number of gasping units	1	2	
Pivoting	Finger	Gripper	
Active feeding	Wheel	Belt	Incremental
Clamping force for feeder	Passive	Active	
Wire storage	Reel	Tube	

size is chosen so that all positions of a typical mounting plate can be easily reached.

Another general decision is the use of prefabricated wires. While the provision of such wires is significantly more complex than a direct wire feed, this variant is preferred for two reasons. The first reason is the wide variety of different wire cross-sections and wire types. For efficient operation, these must be fed to the tool in a suitable manner, which requires frequent change of wires. This creates a certain complexity in the feeding process. It is also questionable whether the feed can be designed in such a way that a sufficient range of different wires can be installed. The second reason is that prefabricated wires are often already in use in companies. Accordingly, their production is already established, and the wires produced can be used for both automatic and manual wiring.

A. Morphological Box

The central task of the tool is to hold the wire reliably during handling and assembly. Since only a single robot is used, there are additional aspects that need to be considered when designing the tool. A total of seven features were specified, which are roughly divided into assembly features and features for guiding the wire. Different variants were identified for each feature. Table 1 gives an overview on the functions and the associated variants.

The assembly features contain four parts. As basic kinematics, a distinction can be made between a parallel gripper or a rotational gripper. With both variants, it is possible to grab the wire in different directions. The jaws of the fingers must allow reliable contact with the wire but must not damage it. Flat jaws, form-fitting jaws or prismatic jaws are options. When selecting, it should be noted that the wires must not only be gripped and released, but it must also be possible to guide the wires. In addition, an implementation with one or two grasping modules can be realized. One feature that is not mandatory is the ability to pivot the fingers or the entire gripper. Particularly if only one grasping module is used, pivoting can make collision-free assembly easier or even possible in some cases.

The wire storage is essential for the wire guidance features, as controlled routing is not possible without storage. The wires have a length up to two meters, meaning that there are loose pieces of wire apart from the grasping modules. This loose wire can either be rolled up or pulled/pushed into a tube or similar. To further support the routing process, active feeding of the wire can be provided. This can be implemented with a wheel or a combination of wheels, a belt or incrementally. In the incremental version, the grabbed wire is moved in the desired direction, released, and grabbed again, resulting in a step-by-step feed. In the first two variants, a certain force must be applied between the actuator and the wire. This can be generated passively, usually by a spring, or actively, for example by an electric or pneumatic cylinder.

B. Tool Design

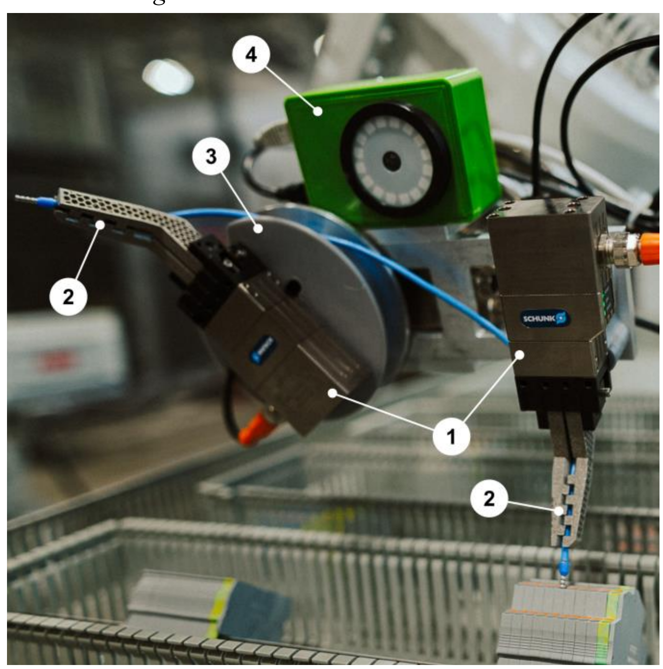

Figure 2. Picture of the tool design that includes two grasping modules (1), fingers with custom-made prismatic jaws (2) and a rotational unit (3) to roll up the wire. Furthermore, a 3D camera (4) is mounted to detect the assembly positions.

For the tool design, a variant with two parallel grippers is selected. This allows both wire ends to be gripped simultaneously and eliminates the need for a pivoting unit. A prismatic design is used for the jaws of the gripper fingers. This shape is self-centering and does not lose the wire even if the jaws are opened slightly. As a result, the wire can be easily guided. The loose wire is rolled up via a rotation unit. For cost

Table 2. Key Performance Indicators (KPI)

KPI	Target	Status
Gripping wires with different cross-sections.	0.75 mm² to 6.0 mm²	Possible with the designated tool.
Handling wires with significantly different lengths.	0.10 m to 2.00 m	Due to the mechanical setup, a minimal length of 0.30 m is required. The maximum length of 2.00 m can be taken up.
Assembly of a wire end into the connection of a component.	Both ends of the wire can be mounted reliably. The assembly is checked by a pulling test. The test must be documented.	The first end of the wire can be mounted reliably. In general, the assembly of the second end is similar. However, this step is not implemented yet due to preceding errors in the assembly process.
Routing a wire into a wire duct through its slots.	The wire is routed reliably into the duct. This step must be visually checked. Any error must be reported.	Possible with the same limitations as the mounting process described above.
Routing a wire within the wire ducts.	The wire must be routed completely inside wire ducts. Any surplus wire must be laid in such a way that no parts of the wire are outside the wire duct. Manual reworking might be allowed.	The routing of the wires within the wire ducts does not work properly.

reasons, an active wire feed has been avoided for now. Additionally, the wire is unwound actively, and thus, the rotation unit partially takes over the function of the active wire feed. Figure 2. shows the developed tool. The second gripper module is practically connected to the rotation unit. The fingers of both grasping modules are modeled at a 45° angle, which makes it easier to reach the assembly positions. Industrial-grade components are used for both the grippers and the rotation unit.

V. Evaluation

To evaluate the tool design, several experiments are performed. Especially the pick-up and assemble procedure are executed. Table 2 summarizes the specified key performance indicators. The given targets are the result of an analysis of typical control cabinets. The next sub-sections discuss the results in more detail.

A. *Picking up Wires*

The procedure to pick up a wire starts by approaching the wire magazine as shown in Figure 3a. The rotation unit must be placed in such a way that the orientation of both grasping modules is the same. Furthermore, both modules must be opened. The stroke per jaw and a prismatic finger design allow wires with cross-section of 0.75 mm² to 6.0 mm² to be gripped. After the tool is positioned over the magazine, the wire is gripped. Subsequently, the tool is moving away from the magazine (Figure 3b) to prevent collisions when rolling up the wire (Figure 3c and d). The number of revolutions to roll up the wire depends on the length of the wire. However, a minimal length of about 0.30 m is required to allow the wire to be gripped with both grasping modules. Figure 3 sketches the pick-up sequence.

The pick-up process has been sufficiently tested and works well. However, if the wire is not positioned accurately in the magazine, the self-centering feature of the jaws is not sufficient, and the wire is grabbed incorrectly. Nevertheless, within the subsequent detection of the wire tail this will be detected. Furthermore, the orientation of the tool when rolling up the wire is important. The tool should be oriented with the rotational axis of the wire storage looking upwards. Otherwise, a reliable roll-up cannot be established.

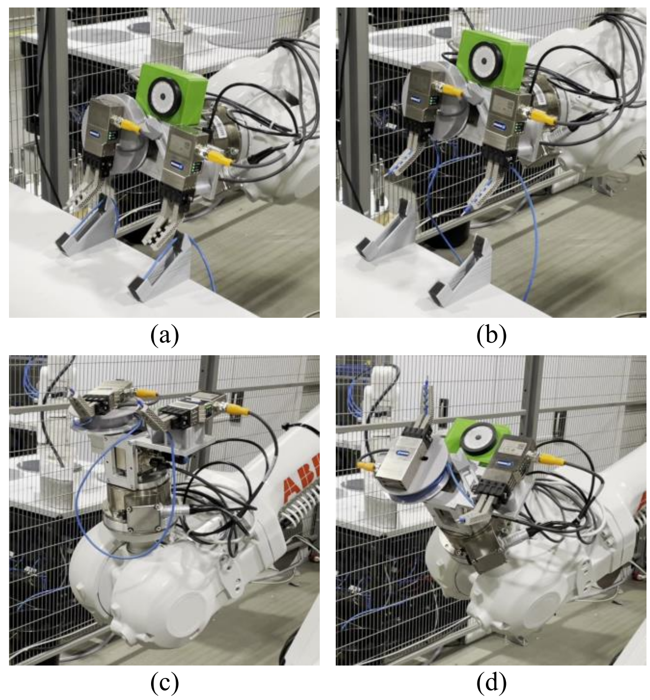

Figure 3. Pick-up sequence of the wire. Firstly, the tool is approaching the magazine (a). Then the wire is grabbed and the tool moves up (b). To roll up the wire, the orientation is changed (c) to prevent errors. Finally, the pick-up of the wire is done (d).

B. *Wire Assembly*

The wire assembly procedure is straightforward. With the fixed grasping module, the first end of the wire is mounted, as depicted in Figure 4a. The design of the fingers allows wires to be inserted at a distance of 3 mm, provided that one of the adjacent terminals is free. After the wire is mounted, it is routed into the wire duct (Figure 4b and 4c) and inside the ducts to the next component (Figure 4d). The assembly of the second end of the wire also starts by mounting the wire and the routing of the wire into the duct.

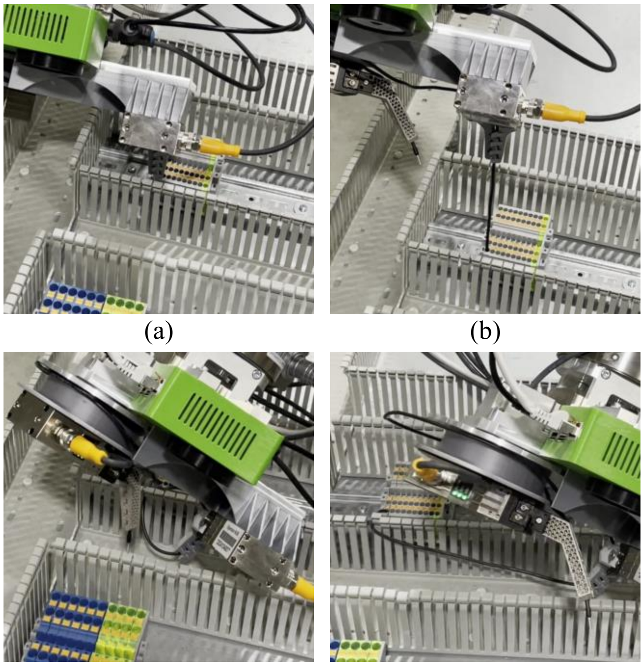
(a) (b) (c) (d)

Figure 4. Assembly sequence of the wire. Firstly, the wire is mounted to the terminal block (a). Afterwards, the wire is routed into the wire duct (b) and (c). Inside the duct, the wire is routed to the next component (d).

While the mounting and the routing into the duct is quite reliable, there are challenges routing the wire through the wire ducts. Firstly, due to the open design of the wire storage, the wire may fall out of the storage system if the unwinding speed is not sufficiently synchronized with the robot movement. Moreover, the passive wire feed is not sufficient, and the wire is subjected to a high level of stress, particularly at the transition from one wire duct to the next. This can lead to undesirable damage to the wire. This occurs due to insufficient synchronization between the robot movement and the unwinding movement, or the gripper jaws might be too rough.

C. Design Improvements

The main issue with the presented design arises during the unwinding of the wire. The wire is not guided correctly from the wire storage through the gripper jaws, resulting in the errors shown. An active wire feed is to be integrated as a solution. Additionally, the overall path in the tool will be reduced. This is achieved by replacing the two grasping modules with a combination of grasping module and pivoting device. As a result, the parallel kinematics must be replaced by a rotary gripper. Moreover, this leads to a considerable reduction in size and thus accessibility can be further improved. Figure 5 illustrates the new design. The pivoting device can move the grasping module from the presented position to a straight position as well as to an opposite position. When the grasping module is moved to the straight position it can pick up the wire near to the wire end. Afterwards, the gripper with the wire is moved to the feeder and the wire is transferred into it. The wire is completely pushed into the tube and is then ready for assembly. After assembly and routing through the wire ducts, the grasping module is moved to the opposite position to be able to mount the second end of the wire. If required, the pivoting device can also support the process of routing the wire through the wire ducts. The wire storage is not shown, as it is simply implemented as a tube that is mounted at the end of the wire feeder.

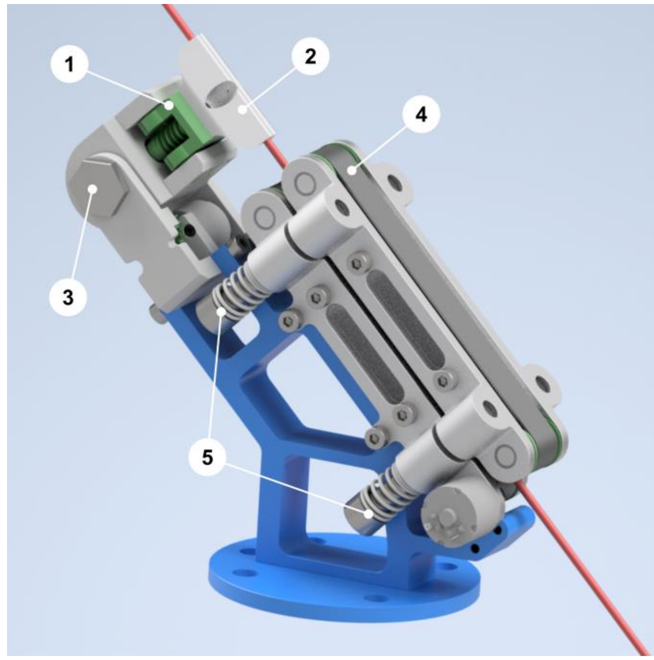

Figure 5. Rendering of the new tool concept with the grasping unit (1), the finger (2), a new pivoting unit (3), and a new active wire feeder.

VI. Conclusion

An important element for automated wiring is the development of a reliable tool for assembly. To develop an appropriate tool, a morphological box was developed firstly. The box is used to identify different variants and to derive a complete tool design. The selected variants are discussed, and a suitable model was created under the boundary conditions that the automation solution only uses one robot and pre-assembled wires are to be installed. The design implements the necessary functions such as gripping and assembling wires and laying wires in wire ducts. However, assembly tests in a real environment have shown that the routing of wires within wire ducts in particular leads to errors. An analysis of the errors led to a proposal for further development of the tool.

In future work we will build the new concept. Further experiments will show whether the problems identified have been eliminated. A subsequent analysis will identify improvements and shortcomings. The findings will be used to further enhance the tool. A reliable tool is the first step to automate of the complete manufacturing of control cabinets. The magazine also needs to be examined more closely. The magazine is currently filled manually, which is not feasible in a productive environment. Therefore, the magazine must either be filled automatically or the wires must be picked from a box in which the they are stored unsorted. While there are still some hurdles to overcome, the approach presented is a good step towards the vision of automatically wiring individualized control cabinets.

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