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Review

Wire Harness Assembly Process Supported by Collaborative Robots: Literature Review and Call for R&D

Gabriel E. Navas-Reascos [1], David Romero [1,*], Johan Stahre [2] and Alberto Caballero-Ruiz [3,4]

[1] School of Engineering and Science, Tecnológico de Monterrey, Mexico City 14380, Mexico; gabriel.navas.reascos@gmail.com
[2] Division of Production Systems, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden; johan.stahre@chalmers.se
[3] Instituto de Ciencias Aplicadas y Tecnología, Universidad Nacional Autónoma de México, Ciudad Universitaria, Mexico City 04510, Mexico; alberto.caballero@icat.unam.mx
[4] National Laboratory of Additive and Digital Manufacturing (MADiT), Ciudad Universitaria, Mexico City 04510, Mexico
* Correspondence: david.romero.diaz@gmail.com

Abstract: The wire harness assembly process is a complicated manufacturing activity, which is becoming more complex because of the evolving nature of mechatronic and electronic products that require more connectors, sensors, controllers, communication networking, etc. Furthermore, the demand for wire harnesses continues to grow in all industries worldwide as the majority of equipment, appliances, machinery, vehicles, etc., are becoming "smart" (i.e., more mechatronic or electronic). Moreover, most of the wire harness assembly process tasks are done manually, and most of these are considered non-ergonomic for human assembly workers. Hence, the wire harness manufacturing industry is faced with the challenge of increasing productivity while improving the occupational health of its human assembly workers. The purpose of this paper is to conduct a literature review exploring the state of the use of collaborative robots in the wire harness assembly process due to their potential to reduce current occupational health problems for human assembly workers and increase the throughput of wire harness assembly lines, and to provide main findings, discussion, and further research directions for collaborative robotics in this application domain. Eleven papers were found in the scientific literature. All papers demonstrated the potential of collaborative robots to improve the productivity of wire harness assembly lines, and two of these in particular on the ergonomics of the wire harness assembly process. None of the papers reviewed presented a cost–benefit or a cycle time analysis to qualitatively and/or quantitatively measure the impact of the incorporation of collaborative robots in the wire harness assembly process. This represents an important area of opportunity for research with relevance to industry. Three papers remark on the importance of the integration of computer vision systems into a collaborative wire harness assembly process to make this more versatile as many types of wire harnesses exist. The literature review findings call for further research and technological developments in support of the wire harness manufacturing industry and its workers in four main categories: (i) Collaborative Robotics and Grippers, (ii) Ergonomics, (iii) Computer Vision Systems, and (iv) Implementation Methodologies.

Keywords: wire harness; assembly; collaborative robots; ergonomics; computer vision systems

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1. Introduction

Wire harnesses join cables from different electrical equipment. Their assembly has not changed over time, even with the progress of manufacturing technology [1,2]. The wire harness assembly process is a complicated manufacturing activity, which is becoming more complex because of the evolving nature of mechatronic and electronic products that require more connectors, sensors, controllers, communication networking, etc. Moreover, most of their assembly tasks are done manually [2,3]. Heisler et al. [4] indicated that 90% of the wire harness assembly process tasks are done manually. The steps needed to manufacture a generic wire harness are presented in Figure 1. For the scope of this work, the process only focuses on manufacturing a wire harness, including tasks such as strapping its different wires to a supporting structure and adding plugs to its wires.

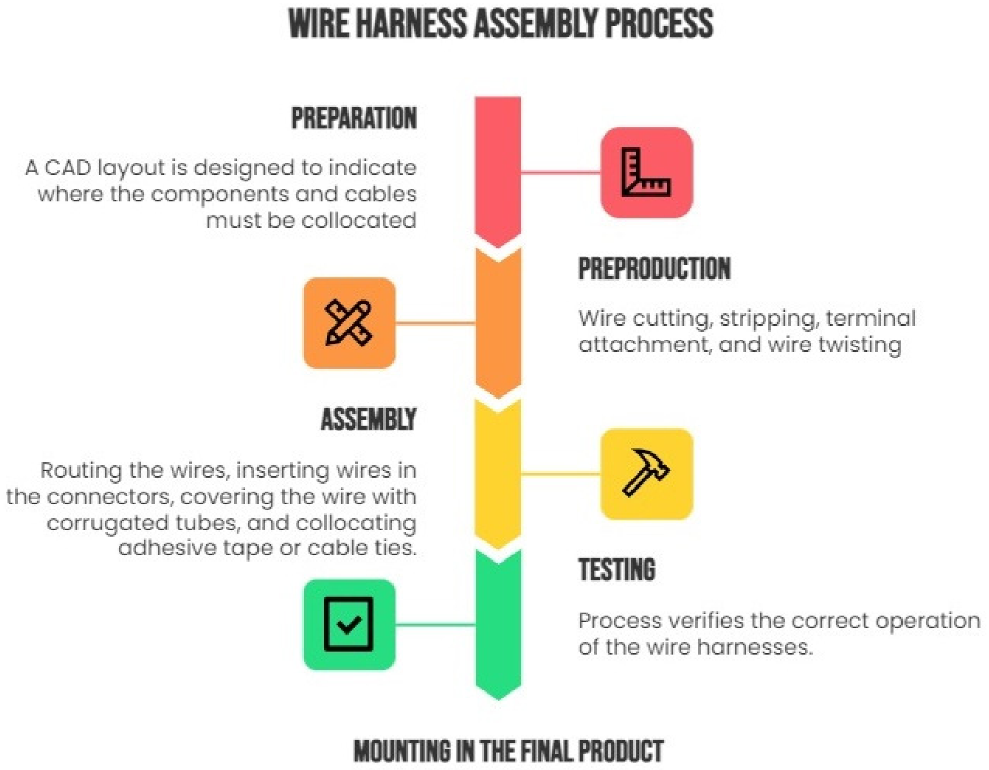

Figure 1. Steps in a Generic Wire Harnesses Assembly Process.

A *collaborative robot* (*cobot*) can perform multiple tasks to assist humans. *Cobots* work hand-to-hand with employees to achieve a job; for this reason, they are dependent on them in an industrial process [5,6]. Using a *cobot* could decrease the number of tasks that an employee will perform and improve the quality of the process at hand [7]. *Cobots* can reduce the physical and mental strains in human work. Moreover, a *human–robot assembly process* is a cost-effective solution between a manual and a completely automated assembly operation [8].

Assembly is a manufacturing process. It is a procedure for obtaining a final product through sequential tasks and sub-assemblies. An *assembly process* needs to be flexible, and humans are considered the optimal production resource for this kind of manufacturing process. However, with the new advances in (collaborative) robotics technology, the combination of humans and robots is now possible in assembly processes [9].

The advantages of a *collaborative assembly process* are mixing the flexibility, creativity, and skill of quickly making decisions of humans with cobots' accuracy, repeatability, and payload [10–12]. Another advantage is the reduction in repetitive tasks that generate fatigue in humans producing a reduction in quality and increasing the cost of production [13].

When a *collaborative assembly process* is carried out, the essential objectives are obtaining operational efficiency, reducing production costs, and increasing the production rate. A critical element in this *human–robot integration* is selecting and allocating the tasks between humans and cobot(s) [9].

The main barrier to implementing *automation solutions* in the wire harness assembly process is that cobots have problems working with flexible materials, such as 'cables', because of the high variety of alternatives in their types, shapes, sizes, and lengths [7,14]. Moreover, the complexity, the high number of parts, and the absence of technological solutions are barriers to implementing *automation solutions* in the wire harness assembly process [2,15]. The disadvantages of *manual work* can mainly be related to low productivity, especially in large productions. In some cases, the effort required to teach a robot/cobot to perform a very complex task may not be worth it [4].

Currently, equipment, appliances, machinery, vehicles, etc., are becoming "smart" (i.e., more mechatronic or electronic). They must provide additional services to users because of the improvement in technology; this causes large, medium, and small-sized enterprises to handle more than one wire harness assembly process in the manufacturing of their products [16]. Moreover, wire harnesses are one of the most expensive electrical individual components [4]. Some examples where wire harnesses are used and their usage will contribute to growth are in vehicles, aircraft, home appliances, machinery, etc.

Furthermore, due to their manual assembly nature, which includes repetitive and non-ergonomic tasks, the wire harness assembly process is considered a relevant area of opportunity for improving the occupational health of human assembly works.

Some occupational health problems, such as carpal tunnel, tendinitis, tenosynovitis, etc., can be caused when industrial workers do repetitive movements and excessive effort. The wire harness assembly workers are not an exception [16].

According to the European Agency for Safety and Health at Work (EU-OSHA), musculoskeletal disorders cause 61% of cases of permanent incapacity. These are the problems presented in industrial workers' bodies' skeleton, muscles, and joints.

For the above reasons, the ultimate purpose of this study is to explore pathways to reduce current occupational health problems for wire harness assembly workers and increase the throughput of wire harness assembly lines using the support of collaborative robots. To do so, this paper conducts a literature review on the state of the use of collaborative robots in the wire harness assembly process and provides the main findings, discussion, and further research directions for collaborative robotics in this application domain.

This paper is organised as follows: Section 1 introduces some general terms and topics around the wire harness assembly process; Section 2 describes the method used for conducting this literature review; Section 3 presents the latest advances in the wire harness assembly process supported by collaborative robots, including computer vision systems; Section 4 discusses the main findings that originated from the scientific literature; Section 5 proposes further research; and finally, Section 6 provides conclusions.

2. Research Method

The literature review was conducted using the following scientific databases: Science Direct, Springer, Scopus, IEEExplore, Web of Science, and ProQuest. The papers found were filtered from the year 2017 to 2021 to focus on the state-of-the-art (last 5 years) of the "wire harness assembly process supported by collaborative robots". The inclusion criteria were academic journals and conference materials, and the exclusion criteria were magazines, non-scientific journals, books, and news. Then the repeated papers between databases were eliminated, and the remaining ones were analysed in full detail (reading).

When performing this first investigation, it was realised that for a complete analysis of the state-of-the-art, it was necessary to conduct two additional (related) investigations on the topics of (a) recent advances in the wire harness assembly process without the support of collaborative robots, and (b) newest advances in collaborative robots in industry.

The first investigation was on the latest advances related to the "wire harness assembly process supported by collaborative robots". The keywords used were: ("wire harness" OR "cable harness") AND ("automation" OR "cobot" OR "collaborative robot") getting eleven papers as a result.

Next, the second investigation was on recent advances in the "wire harness assembly process without the support of collaborative robots". The keywords used were: (("wire harness" OR "cable harness") AND "assembly") NOT ("cobot" OR "collaborative robot"); this provided three papers as result.

Finally, the third investigation was on the newest advances in "collaborative robots in industry". The keywords used were: (("cobot" OR "collaborative robot") AND "industry") NOT ("wire harness" OR "cable harness"); this provided ten papers as result.

3. State-of-the-Art of the Wire Harness Assembly Process

3.1. Latest Advances in the Wire Harness Assembly Process Supported by Collaborative Robots

Heisler et al. [4] in their paper: "*Optimization of Wire Harnesses using Human-Robot Collaboration*", did not find any automation solution covering the entireness of the wire harness assembly process for mass production, and they concluded that further research and technological developments are required in this manufacturing process. The only wire harness assembly tasks currently being supported by an automation solution are cable-routing and mating electric connectors.

The mating tolerance is the distance required for successful mating between the female and male connectors. In the paper: "*Tolerance Dataset: Mating Process of Plug-in Cable Connectors for Wire Harness Assembly Tasks*", Yumbla et al. [17] presented a study of the mating tolerance for seventy different types of terminals for wire harnesses. Their objective was to determine the tolerance for different types of connectors. It is essential to know the number of pins, thicknesses, lengths, and shapes of the connectors for this purpose. They also determined that it is crucial to consider the corner shape. They developed a dataset that can be used to design and select the right robotic manipulator control for a robot. They concluded that their dataset, obtained using a CAD system, has a good tolerance [17]. A related study, titled: "*Robotic Wire Pinning for Wire Harness Assembly Automation*", was developed by Tunstel et al. [13] using a cobot to establish a possible automation solution to insert a wire in an electrical terminal.

Another study by Yumbla et al. [18], titled: "*Reposition and Alignment of Cable Connectors Using a Vibration Plate Manipulator for Wire Harness Assembly Tasks*", proposed using a vibrating plate to align the cable and the connector for the wire harness assembly process. Furthermore, they demonstrated that the proposed vibrating plate could move the connector to the desired position. The accurate pose is critical for a successful docking process in the wire harness assembly process.

Nguyen and Yoon [19], in "*A Novel Vision-based Method for 3D Profile Extraction of Wire Harness in Robotized Assembly Process*", developed a method to determine a wire harness profile using a computer vision system to pick and collocate a wire harness in the correct position. Similar research was conducted by Kicki et al. [20] in "*Tell Me, What Do You See?—Interpretable Classification of Wiring Harness Branches with Deep Neural Networks*" to identify different types of wire harnesses with a computer vision system and neural networks to guide a cobot in the wire harness assembly process. They designed algorithms to classify the type of wire harness. Moreover, they obtain a colour map where the most illuminated regions are the critical parts where a wire harness is located in an assembly board, which could be used to guide a cobot. The third paper by Yumbla et al. [21], "*Preliminary Connector Recognition System based on Image Processing for Wire Harness Assembly Tasks*", presents a computer vision system that identifies the final connectors of a wire harness, but they did not do any other task related to the wire harness assembly process.

Trommnau et al. [2], in their investigation: "*Overview of the State of the Art in the Production Process of Automotive Wire Harnesses: Current Research and Future Trends*", concluded that the tasks with higher automation potential in the wire harness assembly process are wire routing, wire insertion, cable tie colocation, and adhesive taping. Nevertheless, these tasks need further research and technological developments to realise a viable and feasible automation solution for the industry.

Meanwhile, Heisler et al. [22], in "*Automatization of the Cable-Routing-Process within the Automated Production of Wiring Systems*", made an automation solution where a cobot routed a cable in a wire harness assembly board. The wires were cut and crimped previously. Their process was the following: (a) to pick the first cable end; (b) to pick the second cable end; (c) to plug in the first contact; (d) to route the cable; and (e) to plug in the second contact.

They concluded that integrating a collaborative robot in a cable-routing process is possible and that the process could be optimised.

When Román Ibáñez et al. [7] did their literature review on "*Collaborative Robotics in Wire Harnesses Spot Taping Process*", they found no collaborative solution to incorporate a cobot in the wire harness assembly process. They proposed a solution where the employee can work on two-wire harness assembly boards simultaneously. His/her task is to collocate the wire harnesses on the board, and a cobot will collocate the spot taping. They proposed that a cobot makes the taping because it will not require moving the wire harness in this task. After all, it is challenging for a cobot to work with flexible materials. In this case, a cobot performed the repetitive task to find ergonomic improvements and reduce workers' movements. They finally presented a simulation where an operator could work with a cobot doing the repetitive task of collocating the spot taping.

In addition, the paper from Gualtieri et al. [15] on "Design of Human-centered Collaborative Assembly Workstations for the Improvement of Operators' Physical Ergonomics and Production Efficiency: A Case Study" presents a conversion from a manual wire harness assembly workstation to a collaborative one they consider safer, more ergonomic, and more efficient. They conducted this development for a specific type of wire harness where they taped together three-wire groups using a taping pistol. They had the objective to reduce the awkward postures of the assembly workers. They placed a cobot at the back of a workstation while an operator worked in the front, reducing the possibilities of collision. The cobot worked in two stations, placed in the middle of these. They used the RULA (Rapid Upper Limb Assessment) method to evaluate ergonomics, getting a reduction from six (left arm) and seven (right arm) in the manual task to a value of three using a cobot in both arms. They concluded that using collaborative robotics can improve ergonomics because a cobot will do the most stressful task, that is, in their case, the taping colocation, reducing awkward postures, and the number of movements done by an operator.

3.2. Recent Advances in the Wire Harness Assembly Process without the Support of Collaborative Robots

In the study by Naijing et al. [23] on "*Assembly Simulation of Multi-Branch Cables*", a simulation for the assembly of multiple wire harnesses was conducted. Specifically, it was attempted to model the junctions of a wire harness, considering its topological and anatomical characteristics. Therefore, their model can provide realistic simulations of wire harnesses deformation.

In contrast, Ruppert and Abonyi [24], in their work "*Software Sensor for Activity-Time Monitoring and Fault Detection in Production Lines*", aimed to develop a sensor system that continuously estimates the time consumption of the different activities/tasks in the wire harness assembly process. Activity time was determined, and then compared to estimated activity times and generated alerts when the worker productivity decreased.

Sugiono et al. [25], in "Reducing Musculoskeletal Disorder (MSD) Risk of Wiring Harness Workstation using Workplace Ergonomic Risk Assessment (WERA) Method", were looking for the best work posture for wire harness assembly employees using the WERA method. This method is used to evaluate ergonomics, and it considers the neck, the shoulders, the back, the wrists, and the legs. Initial results showed that all three analysed jobs were at the medium activity level, which means that these three jobs needed more research and changes or improvements. Risk factors values were elevated in the analysis of WERA for the shoulders and neck because the operator's arm was raised but still below the chest limit, and the operator's neck would have to bend to perform the activity.

3.3. Newest Advances in Collaborative Robots in Industry

In the paper of Sánchez Restrepo et al. [26] on "*Toward an Intuitive and Iterative 6D Virtual Guide Programming Framework for Assisted Human-Robot Comanipulation*", they developed a virtual guideline, which is a software tool for offline programming of cobots. It is used to delimitate a cobot movement to avoid collisions between workers or objects in the environment. Moreover, it could improve the accuracy of the task at hand. The virtual guideline is a specific zone where a cobot could move. This zone could be delimited manually, moving the cobot to specific points.

Meanwhile, in the paper from Karaulova et al. [27] about "*Lean Automation for Low-Volume Manufacturing Environment*", they analysed the advantages of integrating a cobot into the manufacturing operations of a small-sized enterprise. The result showed that using a collaborative robot could reduce manual work, improve ergonomics, and financial efficiency as well as increases competitiveness in the market.

Capitanelli et al. [14] in their work "*On the Manipulation of Articulated Objects in Human-Robot Cooperation Scenarios*", explained the difficulties cobots have with working with flexible materials, such as cables.

The methodology presented in Mateus et al. [8], in their work on "*A Structured Methodology for the Design of a Human-Robot Collaborative Assembly Workplace*", offers some guidelines on how integrating collaborative robots into an assembly workplace focused on safety, ergonomics, and time performance.

The paper of Malik and Bilberg [9] on "*Collaborative Robots in Assembly: A Practical Approach for Tasks Distribution*" presents a method for integrating cobots in an assembly process, which provides specific characteristics necessary to carrying out collaborative assembly tasks (i.e., cycle times, adaptability, and safety) between humans and cobots, working as a team according to their different abilities.

Gualtieri et al. [11], in their work "*An Evaluation Methodology for the Conversion of Manual Assembly Systems into Human-Robot Collaborative Workcells*", presented a methodology to evaluate the conversion of a manual assembly workstation to a collaborative one.

The paper from Girbes-Juan et al. [28] on "*Haptic and Visual Feedback Assistance for Dual-Arm Robot Teleoperation in Surface Conditioning Tasks*" presents an architecture of teleoperation with tactile and visual feedback for tasks of surface treatment, such as wiping, polishing, sanding, etc. Teleoperation is useful when the worker and the robot cannot work in the same space because of the dangers this could represent, such as inaccessible locations or ergonomic problems. They significantly improve the surface treatment tasks, especially in the subtask that requires applying force in motion.

In contrast, the paper from Schmitt et al. [29] on "*Assisted Human-Robot-Interaction for Industrial Assembly: Application of Spatial Augmented Reality (SAR) for Collaborative Assembly Tasks*" shows an installation of a collaborative robot and a space augmented reality (SAR) system applied to the assembly of a toy truck with 17 pieces. They demonstrated how to divide the work sequence according to competencies between the human and the robot.

The second paper by Malik and Bilderberg [30] on "*Complexity-based Task Allocation in Human-Robot Collaborative Assembly*" develops a methodology to define the possibility of transforming a task from manual to collaborative.

Finally, Castro et al.'s [31] work on "*Virtual Simulation of Human-Robot Collaboration Workstations*" illustrates the development and use of an integrated digital human modelling and robot simulation tool, both intended to be a tool for engineers to create and adapt successful collaborative workstations.

3.4. Tabular Summary of the State-of-the-Art

Table 1 provides a tabular summary of the papers reviewed as part of this literature review to describe the state-of-the-art of the wire harness assembly process.

Table 1. Summary of the State-of-the-Art of the Wire Harness Assembly Process.

Author(s)	Categories		Contribution
	State-of-the-Art	Topics of Interest	
Heisler et al. [4]	SCR	CR	This paper presents an automation process that could be adapted for the assembly of wire harnesses.
Yumbla et al. [17]	SCR	CR	This paper offers a database of different tolerances of connectors used in wire harnesses.
Tunstel et al. [13]	SCR	CR	This paper presents a solution for the attachment of cables in the wire harnesses assembling process.
Yumbla et al. [18]	SCR	CR	This paper provides a solution for the alignment and manipulation of wire harnesses through vibrating plates.
Nguyen and Yoon [19]	SCR	CR and CV	This paper offers a solution for identifying the profile of a wire using a computer vision system for its later use in conjunction with a cobot in wire harnesses assembly procedures.
Kicki et al. [20]	SCR	CV	This paper presents a computer vision system and a neural network for identifying different types of wire harnesses for its later use as a navigation guide for a cobot.
Yumbla et al. [21]	SCR	CV	This paper proposes a computer vision system for the recognition of wire harness terminals.
Trommnau et al. [2]	SCR	CR	This paper reviews the state-of-the-art in wire harness assembly processes.
Heisler et al. [22]	SCR	CR	This paper presents an automation solution using a cobot for the routing task in a wire harness assembly process.
Román Ibáñez et al. [7]	SCR	CR	This paper proposes an automation solution using a cobot for the spot tapping task in a wire harness assembly process.
Gualtieri et al. [15]	SCR	CR and ER	This paper addresses the conversion of a manual workstation to a collaborative one for the wire harness assembly process's spot tapping task.
Naijing et al. [23]	WCR	CR	This paper proposes a simulation model of a wire harness based on its physical properties by considering its topologies and anatomical characteristics.
Ruppert and Abonyi [24]	WCR	IM	This paper presents an alerting system using fixture sensors to notify when the productivity in a wire harness assembly process has been reduced.
Sugiono et al. [25]	WCR	ER	This paper evaluates the ergonomic conditions of workers in a wire harness assembly process using the WERA methodology.
Sánchez Restrepo et al. [26]	CRI	IM	This paper proposes an intuitively virtual guide for the easy programming of a robot without the need for an expert/expertise.
Karaulova et al. [27]	CRI	CR	This paper analyses the advantages that the integration of a cobot into an assembly process can offer in terms of flexibility and variability handling.
Capitanelli et al. [14]	CRI	CR	This paper details the difficulties that cobots can have when working with flexible materials and what solutions can be developed to handle these materials.
Mateus et al. [8]	CRI	IM	This paper presents a methodology to integrate a cobot in a sequential assembly process.
Malik and Bilberg [9]	CRI	CR	This paper develops a methodology that allows assigning the tasks that must be carried out by both a cobot and a human in a collaborative assembly process by optimizing for the best possible assembly sequence.
Gualtieri et al. [11]	CRI	IM	This paper provides a methodology for evaluating the transformation of a workstation from a manual to a collaborative semi-automated one.
Girbes-Juan et al. [28]	CRI	IM	This paper develops a teleoperation architecture for a cobot, which is responsible for conducting surface conditioning tasks.

Table 1. *Cont.*

Author(s)	Categories State-of-the-Art	Categories Topics of Interest	Contribution
Schmitt et al. [29]	CRI	IM	This paper offers a methodology for the design of a collaborative workstation focusing on its user acceptance.
Malik and Bilderberg [30]	CRI	IM	This paper develops a methodology for modifying a generic manual assembly task to a collaborative one.
Castro et al. [31]	CRI	IM	This paper offers a simulation model to design collaborative workstations optimizing for efficiency.

Legend: SCR—Wire Harness Assembly Process supported by Collaborative Robots. WCR—Wire Harness Assembly Process without the Support of Collaborative Robots. CRI—Newest Advances in Collaborative Robots in Industry. CR—Collaborative Robots. ER—Ergonomics. CV—Computer Vision System. IM—Implementation Methodologies.

4. Main Findings and Discussion

This section presents the main findings of the literature review conducted on the state of the use of collaborative robots in the wire harness assembly process and discusses how this technology can contribute to (a) reducing current occupational health problems for human assembly workers, and (b) increasing the throughput of wire harness assembly lines. The studied papers were classified into four R&D categories based on their main scientific contribution(s) to the achievement of the two objectives stated before: (1) Collaborative Robots and their Grippers, (2) Ergonomics, (3) Computer Vision Systems, and (4) Implementation Methodologies.

4.1. Collaborative Robots and Their Grippers

There is limited research on the use of cobots in the wire harness assembly process. Only eleven papers were found in the scientific literature review conducted, giving an excellent opportunity to further investigate this topic. Moreover, all of the papers found about this topic are recent, so the research topic is currently relevant and in development.

Román Ibáñez et al. [7] and Gualtieri et al. [15] worked on the task of spot-taping since they determine that it can generate productivity and ergonomic improvements in the wire harness assembly process. In this case, the cobot performs the repetitive task to improve ergonomics and reduce worker movements [7,15]. It is also a process that a cobot can carry out. In the papers by Tunstel et al. [13] and Yumbla et al. [17], they carry out their research on the tasks of connecting the male–female connectors. Nguyen and Yoon [19] and Heisler et al. [22] work on the cobot's task to place a wire harness on an assembly board. These tasks can be considered for cobot integration into the wire harness assembly process.

No evaluation of the complete wire harness assembly process was found in any paper studied in this literature review. It seems to be an arbitrary decision, the selection of the assembly task the authors decided to work on. However, the paper from Gualtieri et al. [15] is the only one that evaluates the different steps to perform a specific assembly task, the spot-taping, and finally decides that the cobot can work with the task of placing the spot-taping while the human puts on and takes off the wire harness from its board.

On the other hand, the Román Ibáñez et al. [7] and Gualtieri et al. [15] investigations were made for only one specific type of wire harness. This could be a problem because in the industry the type of wire harness produced is changing continuously. Gualtieri et al. [15] placed a cobot in the back of a workstation while an operator worked in the front, and in the case of Román Ibáñez et al. [7], they put both the cobot and the worker in the front of the workstation. It would be interesting to analyse the best position where the cobot should be placed in a collaborative assembly workstation.

Roman Ibáñez et al. [7] and Gualtieri et al. [15] worked on two-wire harness assembly boards simultaneously. This would be recommended since a cobot could be underutilised if it only works on one assembly board. Therefore, working on two or more assembly boards is recommended to improve production throughput in a wire harness assembly line.

Performing the assembly of the wire harnesses is complicated because these are products with flexible materials, making it difficult for a cobot to handle these, according to Román Ibáñez et al. [7], Capitaneli et al. [14], and Gualtieri et al. [15]. It is why tasks, where the wire harness does not move from its position, could be considered suitable to be assigned to cobots.

In addition, in the paper of Yumbla et al. [17], they presented the mating tolerance needed to reduce the error when a cobot connects a female connector to a male one since many variables can cause the connection not to be effective, such as thicknesses, shapes, etc. In another paper by Yumbla et al. [18], they complemented their previous work. In this work, they aligned a wire harness using a vibration plate to connect the male and female connectors and then mount the system to the cobot.

In contrast, Trommnau et al. [2] and Heisler et al. [4] conducted a state-of-the-art review. Both found limited research on the wire harness assembly process using collaborative robots. Due to this, it is essential to carry out further research and technological developments, mainly in wire routing, wire insertion, cable tie colocation, and adhesive taping tasks of the wire harness assembly process according to these authors.

The paper of Naijing et al. [23] presents a simulation that can enable working with wire harnesses and their deformations. This simulation could be applied in other projects, providing great versatility to work with different types of wire harnesses, which is very common in the industry.

The paper by Gualtieri et al. [15] designs a clamping system to prevent the movement of a wire harness when the cobot collocates the spot-taping. This clamping system must be considered to prevent the wire harnesses from moving.

After reviewing all the papers in this literature review related to this R&D category, it was realised that three approaches for specialised grippers development were used in these investigations. The first approach is based on the adaptation of a hand tool to a cobot for working as a robot gripper. In the paper from Gualtieri et al. [15], they used an adapted spot-taping pistol as their gripper. The second approach is based on adapting an existing robot gripper for a specific task as in the papers of Tunstel et al. [13], Yumbla et al. [17], Nguyen and Yoon [19], and Heisler et al. [22] where they used an adapted robot gripper that has two articulated fingers for the tasks of cable routing and wire insertion. A third and last approach is based on the development of a new specialised robot gripper for the task at hand, starting the design from scratch (i.e., conceptualisation stage).

4.2. Ergonomics

Gualtieri et al. [15] and Sugiono et al. [25] evaluated workers' ergonomics in the wire harness assembly process. Gualtieri et al. [15] used the RULA method, and Sugiono et al. [25] the WERA method. Both found ergonomic problems in the wire harness assembly process, and this could be harmful to the workers' occupational health. Sugiono et al. [25] found it is essential to make changes in the wire harness assembly process, and the principal issues were presented in the shoulders and neck of the workers. Gualtieri et al. [15] determined an improvement in the workers' ergonomics using a cobot in the wire harness assembly process in the spot-taping task. It should be essential to consider these methods for evaluating workers' ergonomics in the wire harness assembly process.

4.3. Computer Vision Systems

The use of computer vision systems in the wire harness assembly process can be an excellent opportunity to integrate a cobot into a collaborative assembly process. Nguyen and Yoon [19], Kicki et al. [20], and Yumbla et al. [21] used computer vision systems in their research works. Nguyen and Yoon [19] and Kicki et al. [20] used computer vision to recognise the shape of a wire harness. However, Nguyen and Yoon [19] used the recognition so a cobot could work on placing a wire harness on its assembly board. This task is very complicated because wire harnesses are a flexible material, and this investigation presents a new solution of how to move a wire harness with a cobot. At the same time, Yumbla et al. [21] used computer vision to identify the terminals of a wire harness, but they did not implement their investigation.

4.4. Implementation Methodologies

Petruck et al. [12], Schmitt et al. [29], Malik and Bilberg [30], and Castro et al. [31] provided methods to integrate a collaborative robot into different assembly processes. These methods can give us a guide on how to adapt cobots for the specific case of a collaborative wire harness assembly process.

On the other hand, Ruppert and Abonyi [24] presented an excellent method to manage and report if (human) production speed decreases. However, they do not consider that the applications could use a cobot to improve (human) production time and avoid fatigue in repetitive tasks.

Girbes-Juan et al. [28] considered the safety of the workers. For this purpose, they decided to use teleoperation since sometimes the worker could not be close to the robot to control it. Teleoperation can be very useful when the robot makes rapid movements and is very close to operators. Other methods include specific work areas where the cobot must move, such as in the work of Sánchez Restrepo et al. [26], where the workers are near a cobot. Other methods, such as reducing forces or speed, can also be used.

Finally, Mateus et al. [8], Gualtieri et al. [11], and Malik and Bilberg [30] presented methods that allow the integration of collaborative robots into assembly processes. Mateus et al. [8] raised fundamental aspects of collaborative work, especially safety, ergonomics, and time performance. These could help in making a better task distribution and determining certain work restrictions between humans and cobots. Malik and Bilberg [30] presented a method for the distribution of tasks between humans and cobots to work as a team in the picking and assembly of parts. Gualtieri et al.'s [11] method allows analysing and evaluating if it is possible and necessary to change a collaborative workstation. These three methods presented could be considered when integrating a collaborative robot into a wire harness assembly process.

5. Further Research

This section is divided into the same four R&D categories as in the Main Findings and Discussion section. It provides Further Research directions in support of the wire harness manufacturing industry and its workers aiming for increased productivity and job ergonomics in the assembly lines.

5.1. Collaborative Robots and Their Grippers

More research and technological developments are needed for achieving a suitable *collaborative wire harness assembly process solution* because, in all the papers studied in this literature review, limited solutions were found. Most of the wire harness assembly tasks are nowadays manually done in the industry. Many ergonomic problems can be solved with the use of a cobot. This investigation could be carried out, mainly focusing on wire routing, wire insertion, cable tie colocation, and adhesive taping tasks [2,4].

In one of the papers studied in this literature review, an analysis of the production time of the whole wire harness assembly process was found. Only it is carried out for a specific task: spot-taping [7,15]. It would be interesting to carry out and analyse the whole process (all tasks–see Figure 1) to verify the improvement of the production time of the wire harness assembly process using a cobot.

Moreover, Román Ibáñez et al. [7] and Gualtieri et al. [15] only investigated the production time for the task of spot-taping. Other tasks in the process could be explored to know the best tasks for integrating a cobot for production time improvements in the assembly line. For example, the papers of Tunstel et al. [13] and Yumbla et al. [17] are focused on the task of connecting the male–female connectors, and it could be interesting to measure these to determine their potential for productivity improvements by the use of cobots. Heisler et al. [22] worked on the cobot's task to place a wire harness on its assembly board. Román Ibáñez et al. [7] and Gualtieri et al. [15] can complement this previous work with their work on collocating the spot-taping in the wire harness for further productivity improvements in the assembly line.

None of the authors in the reviewed papers carried out an evaluation comparing the different wire harness assembly tasks to assess their potential for support by a collaborative robot. This type of evaluation would be beneficial for the wire harness manufacturing industry to better plan where a cobot can be used for productivity and ergonomics improvements. A complete cost–benefit analysis of integrating a cobot in a wire harness assembly process was not found in any of the papers reviewed. It could be relevant to conduct such an analysis because it would be useful for motivating the adoption of cobots in the wire harness manufacturing industry.

Meanwhile, in the papers from Román Ibáñez et al. [7] and Gualtieri et al. [15] their investigations focus on a specific type of wire harness, but this does not provide versatility to their automation solution. This presents issues with regards to the flexibility of programming and re-programming the automation systems involved in their solutions. Most industries that make wire harnesses frequently change the type and form of the wire harness they are working with. For this reason, computer vision systems could be implemented to work with different types and forms of wire harnesses without changing the robot/cobot programming. Otherwise, the operator should change the robot/cobot program every time the type of wire harness changes [22]. Moreover, it is recommended to analyse the best position of the cobot in its collaborative assembly workstation considering its specific application and its pros and cons, comparing both places at the front and the back of the workstation [7,15].

On the other hand, Gualtieri et al. [15] and Sugiono et al. [25] worked on two-wire harness assembly boards simultaneously. These two works do not provide a comparative analysis of the differences between using one or two (or more) assembly boards. It could be relevant to know the potential production time improvements and whether it is beneficial to work with one or more assembly boards simultaneously when using a robot.

It could also be interesting to integrate the two papers of Yumbla et al. [17,18] to get an integrated wire harness assembly solution. Furthermore, these could be applied to industry to prove the efficiency gains in production time and ergonomics. These only consider the female and male connections and do not consider other tasks in the wire harness assembly process. These could develop new technologies in different areas of the wire harness assembly process.

In the paper of Naijing et al. [23], they simulate the physical properties of wire harnesses. The work presents a clear gap between knowing whether the simulated physical properties are realistic compared to the real ones of wire harnesses.

Lastly, there is a wide field of studies on gripper types because of the different tasks involved in the wire harnesses assembly process (see Figure 1); therefore, it is recommended to use an automatic tool changer for assembly operations efficiency. Moreover, some new robot grippers may be designed for different tasks; one option is based on soft actuators [32].

5.2. Ergonomics

Román Ibáñez et al. [7] and Gualtieri et al. [15] demonstrated that a collaborative robot could be used for the wire harnesses assembly process, improving the ergonomics of the workers. Their research could be a starting point for developing a methodology that could integrate cobots in the wire harnesses assembly process to improve the workers' ergonomics.

In the paper by Sugiono et al. [25], further analysis could be done with a more significant number of workers in the assembly line to verify that the ergonomics results are constant and not influenced by other factors since they did their investigation with only three workers. Moreover, different ergonomic assessment methods could be used, such as the RULA or JSI (Job Strain Index) methods, to check if the results are similar [25].

An ergonomic analysis is suggested to be carried out when integration of a cobot in the wire harnesses assembly process is proposed.

5.3. Computer Vision Systems

The papers from Nguyen and Yoon [19], Kicki et al. [20], Yumbla et al. [21], and Karaulova et al. [27] could be used to implement computer vision systems into different tasks from the wire harnesses assembly process, such as the cable tie collocation or spot-taping.

In the context of the wire harness assembly processes, computer vision systems is a young research field that is beginning to be explored in the collaborative robots domain. Therefore, this research field and application domain could be further studied. For example, computer vision systems could provide a cobot with more versatility for conducting different assembly tasks. Moreover, a computer vision system could help to obtain information about the real world to offer flexible automation solutions to a wire harness assembly process more efficiently because this process has constant changes. Additionally, such vision systems could help to improve the "human-robot collaboration" in the collaborative wire harness assembly processes.

Furthermore, computer vision systems can help reduce the errors that a cobot could make in performing its tasks, and it could additionally be used to verify the correct performance of a task. For example, if the tape is correctly positioned in the spot tapping task. Moreover, vision systems can allow an operator to work efficiently, avoiding reprogramming a cobot when the wire harness is changed. It could also be interesting to integrate "artificial intelligence" into computer vision systems to give autonomy to a cobot since there are many changing variables in a wire harness assembly process.

5.4. Implementation Methodologies

The paper from Sánchez Restrepo et al. [26] offers a methodological solution that could be used in cable tie collocation or spot-taping tasks to avoid collisions with objects in the working environment or with the operator because the areas in which the cobot can move are limited, improving the employees' safety. Another method to enhance the safety of the workers could be including presence sensors to stop or reduce the movement of the cobot. The Ruppert and Abonyi [24] solution could be implemented by considering integrating a collaborative robot to compare it to their analysis of production time.

Most of the methods proposed for improving the wire harness assembly process could be incorporated into a single integrated method. For example, using the methods proposed by Petruck et al. [12], Schmitt et al. [29], Malik and Bilberg [30], and Castro et al. [31] to successfully integrate a collaborative robot into an assembly process. For example, the method proposed by Petruck et al. [12] could be utilized to design an ergonomic collaborative workstation. The Schmitt et al. [29] method could be adapted for analysing the workers' acceptance of collaborative robots as assembly partners. The Malik and Bilberg [30] method could be used for human–robot task allocation considering human safety first. In addition, the Castro et al. [31] method could be used to detect dead times in human–robot interaction that may affect the collaborative assembly process productivity. For instance, two-wire harness assembly boards can be used simultaneously in cable tie colocation or spot-taping tasks to avoid these dead times, allowing a cobot to work on one board, meanwhile, an operator works on the other board, reducing the dead time in this way.

Furthermore, the method of Mateus et al. [8] could be used to determine at which task, in particular, a cobot could be placed considering its capabilities, complementing the work of Malik and Bilberg [30], and the Gualtieri et al. [11] method could tell if this integration of a cobot is possible and necessary from safety, ergonomics, and time performance perspectives. For safety, the method proposed by Sánchez Restrepo et al. [26] and Girbes-Juan et al. [28] should be considered.

6. Conclusions

Eleven papers were found in this literature review on the "wire harness assembly process supported by collaborative robots". It is essential to mention that the papers found in the literature corpus are relatively new. Therefore, further research and technological developments as detailed in the previous section of this paper are necessary for this manufacturing process in support of the wire harness manufacturing industry and its workers, which are under extreme productivity pressure due to the increasing demand for wire harnesses by multiple industry sectors as their products become "smart".

The wire harness assembly tasks considered with higher automation potential in the investigations referred to in this literature review are spot-taping, connecting the male–female connectors, and placing wire harnesses on their assembly boards. For this reason, these tasks could be taken into account for immediate further investigations, but also other tasks could be studied to improve the quality, cycle time, ergonomics, etc.

Two methods were found to make an ergonomic analysis in the wire harness assembly process: WERA and RULA. Both show that there are ergonomic problems in the current wire harness assembly process. It is why it is essential to redesign the process.

The previous works analysed in this literature review focused on specific tasks of the wire harness assembly process for potential automation. There is no fully integrated automation solution using a collaborative robot in the wire harness assembly process as of today in the scientific literature. A complete analysis of the tasks involved in the wire harness assembly process is needed because it was not found in any of the reviewed papers in this literature review to determine at what tasks a cobot will be more beneficial for the productivity of the process and the ergonomics of the assembly worker.

The collaborative assembly workstation designs of Román Ibáñez et al. [7] and Gualtieri et al. [15] demonstrate that the integration of a collaborative robot in the wire harnesses assembly process can be useful. In their research works, the cobot only works with one type of wire harness, making this not as versatile as required by industry. In an actual industrial application, it is essential to have the flexibility of managing multiple types of wire harnesses.

The main contribution of this work is to showcase and discuss the state-of-the-art of the wire harness assembly process in terms of automation solutions, focusing on existing R&D gaps to improve its efficiency, quality, and ergonomics with the support of collaborative robots, and providing—based on the identified research gaps—future research directions for this application domain for collaborative robotics.

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