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Review of Current Status and Future Directions for Collaborative and Semi-Automated Automotive Wire Harnesses Assembly

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Abstract

Wire harnesses are vital for any modern automotive vehicle. They control the basic functions in a vehicle, for example, windshield wipers and critical functions such as sensors, cameras, and autopilot functions. Thus, the quality of wire harness assembly is highly important. Today, wire harnesses are usually assembled manually, which creates unergonomic and tedious working conditions for operators. Traditional and collaborative industrial robots have been identified as possible solutions to overcome challenges faced by operators in this type of assembly. The international research community has proposed many solutions for automating the assembly of wire harnesses in automotive vehicles but despite these solutions, the industry has not been able to adopt a method to automate this assembly process fully or partially. This paper presents a review of findings on robot-assisted wire harness assembly processes based on a systematic literature review. Specifically, the assembly of wire harnesses in Electric Vehicles (EVs). The state-of-the-art review focuses on solutions to improve unergonomic work situations and ensure the quality of assembly operations. Best practices and reasons for the lack of extensive implementation in automotive final assembly systems are described. Further, the paper presents suggestions based on success stories where the automation of the wire harness assembly in automotive vehicles has been realised by leveraging human-centred automation solutions. Based on the findings, this paper identifies the research for future study. The findings also indicate that there is already technology that can support the automation of wire harness assembly processes in EVs but it is crucial to identify the human aspects and the role of humans in the assembly of wire harness assembly process.

Keywords: Automotive Wire Harnesses; Assembly Operator; Semi-Automation; Collaborative Robots; Electric Vehicles.

1. Introduction

Wire harnesses are vital in any modern automotive vehicle, particularly for Electric Vehicles (EVs). Wire harnesses are used to carry power and signals to control critical functions such as autopilot, sensors and cameras used to manage the vehicle manoeuvring. With the rise of EVs and the addition of intelligent functions to hybrid and combustion-engine cars, the number of wire harnesses in their bodies and floors will continue to grow exponentially (to represent a global market size of USD 74.46 billion by 2030 [1]). High-capacity wire harnesses are now delivering the current in EVs. Thus, assuring high-quality wire harness assembly is of utmost importance for vehicles' functioning and safety.

The assembly of these wire harnesses is manual today, and this process is very strenuous and unergonomic for operators. This process frequently leads to musculoskeletal disorders (MSDs) in the workforce. Researchers have tried to solve these occupational health and safety (OHS) issues in many ways.

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One prominent approach is the use of automation, where a robot or any other automated solution helps in the assembly of these wire harnesses on the vehicle. Automation, especially robots with their capabilities for heavy-duty, repetitive, and accurate work, has been seen as an ideal solution for overcoming not just unergonomic processes but also credited with increased quality and productivity results. The operation of assembling wire harnesses into vehicles is one of the most difficult tasks to automate [2].

Based on a systematic literature review, this paper presents a summary of wire harness assembly processes in the automotive industry. In doing so, this paper also identifies the obstacles to the lack of full implementation in final assembly and presents possible solutions to the challenges. While the authors of [3] previously published a state-of-the-art review of wire harness manufacturing, this paper deals with assembly inside vehicle bodies and floors. This paper looks into existing and emerging technologies and methods to enable efficient and human-centred wire harness assembly.

This paper is organized as follows: Section 2 explains the research methodology (i.e., PRISMA) used for conducting this state-of-the-art review and the results of it, Section 4 discusses the findings in the scientific literature, and Section 5 provides conclusions and further research outlook.

2. State-of-the-Art Review

2.1 Research Methodology

This research work aims to build a state-of-the-art review of the current trends and methodologies that manufacturers adopt when dealing with the assembly of wire harnesses into their products (i.e., vehicle bodies). A systematic search of the existing scientific literature has been performed to construct a solid body of knowledge about this topic. The search has been performed on the Scopus database, as a de-facto reference standard for the engineering community [4]. The Scopus database has been preferred over the Web of Science database because of its higher inclusiveness in terms of contributions and over Google Scholar due to the higher reliability of collected sources (mostly peer-reviewed papers and articles) [5].

In the Scopus database, on date 08/08/2022, the search engine was queried with the formatted string "(wir* OR cabl*) AND (harness* OR bundl*) AND assembl*" limiting the research to titles, abstracts and keywords fields, where the * char was used to make the search insensitive with respect grammar number and the words "cable" and "bundle" have been included as synonyms of "wire" and "harness". The search engine returned a set of 959 items. To exclude works referring to completely different subjects, a filter on the subject area has been added, and the search has been consequently limited to the topics of Engineering, Computer Science, Multidisciplinary, Business, and Decision Sciences. The new query produced a set of 695 items, whose metadata have been extracted for a second phase based on their title and abstract analysis. No filters have been applied in regards to the year of publication of any item to not exclude past research works, which could have been dropped because of technological gaps that have been recently filled (e.g., usage of collaborative robots in assembly processes).

The title and abstract screening have been driven by exclusion criteria, namely, papers: not about manufacturing; about wire harnesses manufacturing; about wires' physical properties; and conference proceedings that have been excluded. This filtering process ended with a set of 77 papers eligible for full-text screening.

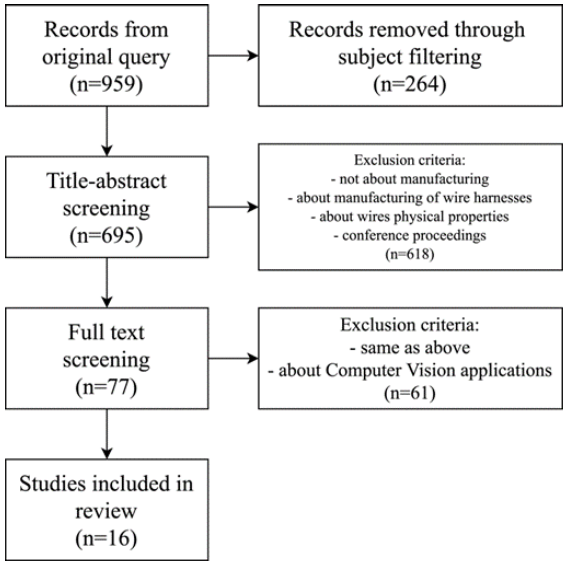

Fig. 1. PRISMA Diagram

The entire papers have been analysed and filtered in this third phase according to the same criteria. In addition, given the high number of papers debating the usage of computer vision (CV) in quality control and considering their importance, papers dealing with CV were excluded too. This last phase resulted in 16 papers that are reported in the following section. Fig. 1 represents a PRISMA diagram summarising the search process, while Table 1 summarises the content of the selected works. In this perspective, and to cluster the analysis, the research has been divided into two sets or domains, according to the fact that the selected work tended to deal with "automation principles" (e.g., modelling and control of a certain system) or was more devoted into "robotics systems" (e.g., handling the wire harness through a robotic arm and with a particular focus on its trajectory planning). Table 1 catalogues the selected papers and highlights the discipline mostly addressed and the specific topics debated in these works. It also presents a (short) summary of their content, which forecasts the key considerations listed in the following sections.

2.2 Results

Several of the analysed research works deal specifically with modelling semi-deformable linear objects (SDLOs) and implementing methodologies and programs to handle these components. It is the case of [6], who modelled wire harnesses as SDLOs to leverage their rigid part(s) to improve the performance of a robotic manipulation system composed of a machine vision system (based on 3D pose estimation) and a dual-arm robotic manipulator. A plug-in operation is performed by a robot in both single- and dual-arm configurations.

Table 1. Selected works (Criteria: A – Automation, R – Robotics)

Article	Criteria	Topics of Interest	Contribution
[7]	A	Deformable Linear Objects, Manipulation	This paper deals with the dynamic modelling and control of deformable linear objects by single- and dual-arm robots, which contributes to improving the performance of robotic manipulation systems for wire harnesses. The modelling and control approach relies on horizontal and flat surfaces to work, which are more common to find in the aerospace industry than in the automotive industry.
[8]	A	Accessory services/machines	This paper reports on developing and validating a material application tool for the covering process of a wire harness. A nozzle was developed to move along routed cables and cover them with silicone rubber. The nozzle can be infinitely adjusted to different cable strands using an iris diaphragm mechanism. The main contribution of this new material application tool is the ease of installing wire harnesses into their assembly boards.
[6]	A	Deformable Linear Objects, Manipulation	This paper reports on the progress of wire harness modelling as semi-deformable linear objects and proposes a solution consisting of a machine vision system (based on 3D pose estimation) and a dual-arm robotic manipulator that leverages the rigid part(s) of wire harnesses to successfully handle them. The solution was tested in a case study on cable harness connection. Single and dual-arm configurations of a collaborative robot were used to test the solution that contributes to developing robotic manipulation systems for wire harnesses.
[9]	A	Mating	This paper reports on the development of a background noise mitigation technique for a dual-microphone system aimed at detecting the “clicking” sound that corresponds to a successful connection of mating electrical connectors. The main contribution of this work can be seen as a feedback system for an automated process for mating cable connectors.
[10]	A	Mating	This paper presents an assembly method for the electric connectors of a wire harness using a tilt strategy with impedance control and a cable connector-feeding system. The main contribution of this work is towards the automation of the electric connector-mating process in a wiring harness assembly system by supporting the alignment of cable connectors so that can be grasped straight and held firm by a robot during their mating.
[11]	A	Trajectory planning, Manipulation	This paper presents an algorithm and a method for automatically planning and finding a smooth and collision-free mounting path of connectors in a wire harness installation on a car body. The paper offers pseudocode and the method proposed was tested based on simulation and in an industrial case. The main contribution of this work is towards the development of virtual manufacturing tools supporting deformable components so automatic path planning for collision-free robotized installations of wire harnesses in vehicles can be possible.
[12]	R	Mating, Error Management	This paper exemplifies the “peg-in-hole” of a wire harness connector assembly. A fault-tolerant assembly strategy for mating electric connectors is presented in this paper based on error recovery approaches. Experimentation is executed in a controlled environment, not on a vehicle or assembly line. The main contribution of this paper is towards a robotic fault-tolerant electric connector-mating process.
[13]	R	Manipulation	This paper presents an accurate method to detect wire harnesses profiles using a computer vision system based on deep-learning techniques. An example of manipulation over a series of clamps is provided. The work is limited to a flat vertical application surface. The main contribution of this work is towards the automatic detection of wire harnesses profiles so guided robot arms can be implemented for their assembly.
[14]	R	Accessory services/machines, Manipulation	This paper presents a new end-effector for a robot specifically designed to handle wires and perform different manipulations (e.g., twisting, dragging, sliding, etc.) over them. The main contribution of this work is the proposal of a multifunctional gripper design that integrates many functions for the in-hand manipulation of cables to reduce robot tool change.
[15]	R	Manipulation	This paper reports on the development of control strategies for a mobile robot manipulator for the assembling of wire harnesses onto a moving vehicle. The approach uses visual tracking for identifying and locating plugs and holes in a vehicle’s body. The proposed system is capable of detecting and assembling wire harness inserts. The main contribution of this work is towards achieving robotic wire harness assembly automation on moving assembly lines such as in the automotive industry.
[16]	R	Mating	This paper presents a new approach for robotized mating of wire harnesses capable of sensing initial contacts while mating the connectors and reacting to the perceived force when the connector is mated so any damage to the connectors is avoided due to excessive mating force. The main contribution of this work can be seen as a feedback system for a successful robotized mating of wire harnesses.
[17]	R	Accessory services/machines	This paper presents a new human-robot collaboration assembly system for cellular manufacturing capable of significantly reducing lead time and dramatically reducing assembly errors thanks to hard (i.e., parts delivered by robots) and soft (i.e., an instruction given by screens and speakers) safety designs for the assembly worker. It was tested in a use case for the electronics industry. The contribution of this work towards robotic wire harness assembly automation in the automotive industry could be limited due to the inexistence of fixed workstations in the final assembly line of a vehicle.
[2]	R	Mating	This paper reports on the development of a robot system that exemplifies the automation of the assembly process of a wire harness into the body of a car under a condition similar to a real plant. Location codes are used to find the pick points by the robot using bar code readable cameras for later assembling the wire harness. The main contribution of this work is all the problems that it highlights in handling the deformable properties of a wire harness by a robot.

[18]	R	Deformable Linear Objects, Manipulation	This paper reports on the simultaneous usage of robotic manipulators to handle a wire harness and fix some points on specific clamps in an automotive assembly line. The solution whose effectiveness has been tested in simulation for a 3D complex scenario is also provided. The main contribution of this work is towards the development of a robot motion planner characterized by multiple manipulators to support robotic wire harness assembly automation.
[19]	R	Deformable Linear Objects, Manipulation	This paper addresses the same research as the aforementioned paper but it is deployed in a real experiment on a simple 2D surface. The experiment of automatically completing the assembly of a wire harness into the instrument panel frame of a car is decomposed into smaller tasks, namely detection/grasping and handling/ mounting of the wire harness. The main contribution of this work is its detailed analysis of the requirements for the development of a robot car wiring system.
[20]	R	Mating, Error Management	This paper reports on a new procedure to manage electric connector-mating errors in a robotic wire harness assembly system. The implemented procedure can autonomously detect and fix two of the most common mating errors by leveraging the physical constraints of a robot (without relying on computer vision). Hence, the main contribution of this work is towards a robotic fault-tolerant electric connector-mating process.

Moreover, [7] et al. discuss wire harness modelling, which in this case is adapted to an elastic rod. Leveraging on the inclusion of friction, collisions, and contacts, the authors implemented single- and dual-arm placement of a wire harness on a surface. Given the fact that gravity plays a crucial role and that the target surface is 2D and horizontal, the application is suitable for the aerospace domain (e.g., wire harness mounting on plane wings) but its deployment in car manufacturing is limited based on the current state of the art.

On the other hand, [11] et al. focus their contribution not on the modelling but on the manipulation of wire harnesses. In their work, they present a method for planning a collision-free robotized installation of a wire harness in complex surfaces such as car bodies, demonstrating it in a simulation environment.

More isolated contributions see improvements in specific wire harness assembly operations, such as the paper published by [9] et al., which considers the "click" sound as feedback for a control loop governing an automated process of mating cable connectors and tests it for its affordability of mating detection in a controlled-noise chamber. [8] et al. propose a 3D printing process to wrap wires into their harnesses, which is potentially beneficial in vehicle manufacturing if done online since thanks to the adhesive properties of the 3D-printed harnesses, wires are sunken in, and the installation on the car body could result easier.

In a different industrial sector, the assembly of electronic products, [10] et al. propose an automated system composed of a feeding ramp, a manipulator, and a computer vision subsystem that enables an automation increase. It still needs to be specified that, referring to the electronics mass-production market, the system suffers less from some of the "burdens" of vehicle manufacturing, such as dimensions, production flexibility, and collisions.

In the earliest reference, Design for Assembly (DFA) is used for increasing cost-effectiveness and efficiency in the wire harness assembly process. An advantage of following the DFA principles is reducing part count, so applying these principles to wire harness assembly will help to also reduce the part number. Based on this, in the context of the robotic assembly of wire harnesses, [21] et al. propose using rigid connections, avoiding intermediate parts, and utilizing ribbon cables since these can help eliminate the need for cable ties.

[12] et al. proposed a robotic wire harness assembly process based on the "peg-in-hole" approach based on a piecewise linear model. This proposed method uses a multi-camera vision system to align the wire harness connectors; the mating process is measured and verified using the force-torque sensors. In a similar approach proposed by [20] et al., the authors argue that vision systems, although powerful, are not entirely reliable due to the small-size of connectors in cars and highlight that the blind-search strategies of using the "peg-in-hole" approach may not be directly applicable to the assembly of wire harness connectors as the recovery approaches for the robots to retry the mating is not studied in detail. Hence, a fault-tolerant robotics assembly strategy for mating electric connectors based on error recovery approaches is proposed. Another example of the "peg-in-hole" approach is presented in [15], where a mobile robot manipulator can utilize a visual servo with force constraints to react to the force conditions encountered during the manipulator motion. However, the paper highlights the significant challenges for improving a mobile robot assembly system performance, such as higher assembly speed and using features on the vehicle body instead of artificial visual fiducials. This problem can be overcome by using a computer vision system for wire harness recognition and force sensing for initial contact detection to improve the assembly speed and performance [16]; barcoded clamps bound with the wire harness are used for location and assembly in this approach. A similar process is studied in [6]. Still, the location identification is based on determining the pose of rigid parts such as connectors and clamps in the so-called "Semi-Deformable Linear Objects (SDLO)" in 3D space using a specially developed algorithm. Such an approach of using computer vision systems to identify deformable and semi-deformable objects is further studied in [13], simulated in [18], and emulated in [19], where a computer vision system is used to detect different wire harnesses profiles, including clamps that are then tested for assembly on a flat surface. The variation of shapes and sizes and its implication on robot grippers are addressed in [14], where a multifunctional end-effector (gripper) design is proposed capable of twisting a cable at a specified angle, sliding the cable within the gripper, griping and dropping the cable. The multifunctional gripper can also identify the cable's pose at the grasp point using a specially designed tactile sensor GelSight. The implications of an ageing workforce and the necessity for human-robot collaboration is also significant motivation for using traditional or collaborative robots in process of wire harness assembly. In [17], a multi-modal assembly-support system (MASS) is proposed, it uses

robots to support assembly operators, and several information devices to monitor and guide them during the wire harness assembly process. This reduces lead time and assembly errors but its implication in vehicle assembly is challenging since the assembly line is constantly in motion. Furthermore, with a focus on transforming deformable objects such as wire harnesses and cables, [2] et al. focus on using robots to handle and clamp wire harnesses simultaneously, as exemplified by experimentation on a 2D surface.

3. Discussion

In addition to improving operations efficiency and accuracy, using robots in the wire harness assembly process for automotive vehicles can also improve human aspects and ergonomics in the assembly process [3]. Robots can automate repetitive and physically demanding tasks, which can help to reduce the risk of injuries and improve working conditions for assembly line workers. However, it is also essential to consider the interaction between humans and robots. Of utmost importance are the safety and collaboration between humans and robots. In these cases, it is crucial to design the workspace and use robots to minimise the risk of accidents and maximise the efficiency of human-robot collaboration. Moreover, ergonomics also plays a pivotal role in developing assembly processes and the workstations where the workers operate. This includes considering factors such as reach, posture, and force required to perform tasks and providing proper equipment and tools to reduce the risk of injury and improve overall comfort and productivity.

Though this paper focuses on wire harnesses assembled on automotive vehicles, automated assembly of wire harnesses is also vital in other manufacturing industries such as aerospace, assembly of home appliances, and various other products that use electrical and electronic components. The aerospace use cases present several similarities with the automotive ones and can be considered as a wider set with relaxed constraints in terms of room for maneuver and target surface (which, in the case of wings, can be considered flat). Humans today assemble the majority of these products. The assembly station of wire harnesses in an automotive vehicle is nowadays completely manual. Any solution for the automated assembly of wire harnesses needs to fundamentally incorporate human aspects in the production design. Collaborative robots (cobots) are ideal for human-robot collaboration as exemplified in [22] and due to their unique characteristics have the potential to be an ideal solution for automating the assembly of wire harnesses.

There are some aspects of a wire harness assembly process that need to be considered while designing a human-robot collaborative wire harness assembly station. The findings from this state-of-the-art review have highlighted many examples that can and should be incorporated into an assembly station with collaborative robot applications. The work done on DLOs offers vital information on picking and placing wire harnesses. For example, the modulization of cables and the advantages it brings, as explained in [7] which only works effectively on flat surfaces, can be combined with a human-robot collaborative application for assembling wire harnesses on the vehicle's floors. The findings from similar studies on DLOs can be used as long as they meet the takt time requirements.

Error detection and error recovery are important parts of any automated process. It is vital to fix the errors related to wire harness assemblies in vehicle assemblies as close to the source as possible as it is expensive to solve the errors down the line and one might even need to disassemble the vehicle to find errors in wire harnesses as they are often under other components such as seats, dashboards, and floor mats. It is also crucial to meet the takt time demands, so the need to quickly identify and solve the errors in assembly systems is even higher. [12,17,20] have presented error detection and recovery methods in various contexts. For example, using "peg-in-hole", by using human-robot collaboration, and force analysis and recovery methods for identifying and fixing errors in wire harness assembly and connector mating processes. These are excellent examples, but they need to be tested in the time limitation scenarios as the authors have not clearly stated the time required in identifying and fixing the errors.

Much work has been done on the identification and location mapping of wire harnesses. Though this topic is explained in detail in another paper, the need for combining computer vision systems with robots is paramount in a wire harness assembly operation using collaborative robots. The vision system is the primary source for identifying wire harnesses and clamps and locating and guiding the robot to the final location. Various computer vision systems have been proposed previously for better perception of clamps and connectors of wire harnesses [6,12,16], monitoring mating of connectors [23,24], fault detection in assembly [12], and wire recognition [13] to guide the robot to approach, grasp, and assemble to the final location. However, most previous research on vision-guided robotized assembly discussed the identification task using 2D images and basic image processing methods. Recent advanced imaging technology and computer vision research also enable more possibilities for better vision systems. Computer vision systems are also critical in the mating process of wire harness connectors, as exemplified by [13] and [16]. These examples need to be studied further in the context of an industrial application.

Grippers, also known as "end-effectors", are crucial in human-robot collaboration. They allow a robot to interact with and manipulate different objects in its environment and play a vital role in humans' safety during collaborative assembly. The ability to grasp and manipulate the wire harness and connectors is crucial to human-robot collaboration tasks in wire harness assembly. The design and functionality of the gripper can significantly impact the overall performance and effectiveness of the wire harness assembly process based on human-robot collaboration. Therefore, it is essential to carefully consider the task's requirements and select an appropriate gripper that can effectively and safely interact with the wire harness. A new multifunctional gripper has been proposed in [14] to assemble wire harnesses.

Lastly, the allocation of tasks and functions between humans and robots is another crucial aspect that needs to be thoroughly studied in the context of human-robot collaborative wire harness assembly. The allocation of tasks between humans and robots needs to be based on the abilities and capabilities of each and not based on intuition.

4. Conclusions & Further Research

This paper provides an overview of the current status of the use of robots and other automation solutions for the wire harness assembly process. All solutions that are applicable in the scientific literature to wire harness assembly in automotive vehicles are identified and presented in this state-of-the-art review.

This paper also discusses automation solutions in terms of their applicability and challenges in the context of the wire harness assembly process. Various solutions identified in this state-of-the-art review have huge potential for use in the assembly of wire harnesses, but these solutions are isolated from each other as discussed in this paper.

Proposals for future research include testing the identified methods, tools, and technologies collectively, focusing on enabling efficient human-centred wire harness assembly operations, primarily through human-robot collaboration. The human behavior around a robot in an enclosed space such as a vehicle body also needs to be studied for developing efficient assembly solutions.

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