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ScienceDirect

Procedia Computer Science 253 (2025) 1103–1112

Procedia Computer Science

www.elsevier.com/locate/procedia

6th International Conference on Industry 4.0 and Smart Manufacturing

Safety-driven Electronic Components disassembly through Human-Robot Collaboration framework

Nima Rahmani Choubeh[a], Mostafa Zarei[a], Walter Quadrini[a,*], Sergio Gusmeroli[a], Luca Fumagalli[a]

[a] *Department of Management, Economics and Industrial Engineering, Politecnico di Milano, p.zza Leonardo da Vinci, 32, 20133 Milan, Italy*

Abstract

Recent trends of industry brought to the attention of the scientific and practitioners' communities the need for providing efficient strategies to manage the End of Life of products. This propensity gained increased importance after the global semiconductor shortage, when the acquired value of Electronic Components (ECs) made their recovery profitable. The most used disassembly techniques, however, dismantle ECs for recycling purposes, usually leaving them unserviceable. To overcome this issue, human intervention appears to be a promising option, but to make this approach productive in an industrial scale, the human operator is supposed to be assisted by robotic equipment. This frames the disassembly operation into a Human-Robot Collaboration (HRC) scenario, which requires additional considerations in terms of safety and interactions. This work, hence, leverages on a framework for HRC in order to design a disassembly operation for effectively retrieving ECs from circuit boards. Additional safety measures leveraging on a computer vision-based computation of the proximity between operator's hands and robot's end effector are also developed and embodied in the scenario. The adoption of this setup resulted in a satisfactory safety assurance reaction time, narrowing the safety-related gap regarding the employing of HRC in semi-automated ECs' disassembly.

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Peer-review under responsibility of the scientific committee of the 6th International Conference on Industry 4.0 and Smart Manufacturing

Keywords: Human-Robot Collaboration; Electronic Components; Circular Economy; Disassembly;

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1. Introduction

Since its early introduction in 2011, the so-called "Industry 4.0" [1] has significantly raised awareness in the manufacturing environment, in particular about the exploitability of data coming from the shopfloor in an office-floor perspective [2]: several researches reported in the last decade have indeed demonstrated the benefits of data-wise operations in terms of assets maintenance [3], scheduling [4], decision-making [5] and transparency of processes.

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* Corresponding author. Tel.: +39 02 2399 9269.
E-mail address: walter.quadrini@polimi.it

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Peer-review under responsibility of the scientific committee of the 6th International Conference on Industry 4.0 and Smart Manufacturing
10.1016/j.procs.2025.01.172

These benefits, furtherly empowered by the diffusion of data-driven algorithms [6] and leveraging on a series of national initiatives [7, 8] , drove manufacturing companies towards the adoption of more "data-centric" shopfloors, through the purchase of new production assets embedding electronic equipment able to pre-process and share data [9] in complex architectures of software [10], or through revamping existing ones to embody these functionalities.

Framing the aforementioned statements in the so-called "Triple Bottom Line" [11] approach to sustainability, the adoption of these technologies was mainly directed from economic reasons, as mainly driven by efficiency drivers. Anyway, in the last decade, the increased sensitivity towards environmental [12] and social [13] factors highly influenced the mass market and, on turn, the manufacturing environment. These trends (in some works referred to as "macro-trends") include the paradigms of Circular Economy [14] and of Human-centric manufacturing [15].

Circular Economy deals with the objective of minimising the consumption of resources in production, consumption and waste management phases of the life of a product [16]. This approach has been inflected and applied in several fields, but recent trends triggered by the COVID-19 crisis and resulting in the so called "Global chip shortage" [17] led manufacturing companies in the supply chain of electronic components to redesign their products' design and production processes, as well as the waste management strategies related to their products arrived at the End of Life (EoL) [18].

If, on one hand, the adoption of design strategies aimed at re-engineering the electronic products minimising the number of embedded components [19] led to important savings in terms of resources consumption, on the other one the possibility to de-manufacture products at their EoL disassembling viable components led to the possibility of re-integrate them in new products, with further savings or even business opportunities [20].

On the human-centricity side, conversely, new technologies like wearable devices and collaborative robots managed to partially address societal issues such as the ageing of workforce [21]. Collaborative robots in particular represent an important topic for the manufacturing community, given their easiness in being configured and programmed by low-skilled personnel, fact which makes them also a suitable option for the customization and flexibility requirements proper of Industry 4.0 [22]. However, the operativity of collaborative robots in manned environments is subject to several grey zones in terms of safety, especially when the robot is supposed to handle end effectors and tools which could expose the operators to sharp edges or hot surfaces [23]. This work, hence, frames itself in a human-robot collaborative scenario and is aimed at embodying new safety measures in a framework where an operator is supposed to disassembly electronic components from decommissioned electronic devices leveraging on the help of a collaborative robot.

To tackle this objective, the paper is structured as it follows: Section 2 describes the state of the art for both the topic of disassembling Waste Printed Circuit Boards (WPCBs) and for the topic of Human-Robot Collaboration; Section 3 introduces the methodology addressed to overcome the research opportunities identified in Section 2; Section 4 explains the implementation of the experimental demonstration; Section 5 concludes the paper with final remarks and opportunities for further investigations.

2. State of the art

The first stage in dismantling is the separation of the ECs from the WPCB surface using physical, chemical, and manual techniques which are mostly operating on the ECs' soldering structures [24, 25, 26], which can be removed using a grinder, chemical reagents, or can be melted through various heating techniques such as infrared heaters, electronic heating tubes, hot air, and hot liquids [27]. From a cost, efficiency, and environmental point of view, the most effective solutions are the hot air heating and the mechanical grinding, even if this last technique has a reduced application in industrial scenarios because of the need to process WPCBs one by one [27]. On the other hand, even if the usage of hot air heating can be exploited for processing entire batches of WPCBs, it still shows some peculiar drawbacks in a Circular Economy perspective, mainly due to the fact that differences in heat capacity and non-homogeneous distribution of ECs can lead to an inconsistent temperature increase in different regions of WPCBs during heating, which can result in the destruction of ECs during desoldering [28, 27]. Furthermore, the components on the WPCBs absorb moisture when they are disposed of outside, which, added to the fact that the heating temperature cause moisture diffusion and expansion inside the chips (resulting in stresses that are greater than the internal interlayer bonding force), produce delamination defects in the chips [29, 27].

Apart from the desoldering operation, the task of the actual disassembly (the separation of ECs from WPCBs) is another critical activity in the dismantling: this activity, indeed, is supposed to detach ECs through mechanical operations (i.e., gripping, vacuum suction, vibrations, and impact), gas jet stripping, or through the usage of gravity, shear, or centrifugal forces[30, 27, 31]. In any case, under the conditions of solder melting, in order to successfully disassemble the components from the board, it is necessary to provide an energy higher than the minimum disassembly one, which takes into account the disassembly force and the separation displacement of the solder [27], but given this constraint, the energy amount should be minimised to lower the economic and environmental impact of the disassembly itself [29]. From an operations point of view, the techniques used for disassembly can be roughly divided into automated and manual processes, depending on their nature [27], even if, in the last years a third technique (namely "semi-automated" or "hybrid") has demonstrated to be the most promising in terms of productivity [32]. This method involves automatic workstations sharing the disassembly assignment, reducing the burden on humans (e.g., a collaborative robot supporting the operator in the manual disassembly [33]). A more modern method of disassembly named "intelligent disassembly" makes use of artificial intelligence to enhance the process' overall accuracy and efficiency. This approach analyzes, identifies, and determines the optimal way to dismantle each component using advanced algorithms and machine learning [32].

The cooperation on the same task of human operators and robots (Human-Robot Collaboration, HRC) refers, however, to a peculiar topic of manufacturing, specifically defined as the "state in which a specially designed robotic system and an operator work on simultaneous tasks within a collaborative workspace" [34]. This cooperation on the same workspace implies the removal of safety measure and barriers which separates the two actors (e.g., safety fences and safeguards), introducing the risk of operator's injuries caused by the collision with the robot. Therefore, safety assurance is essential to allow a robot and its human counterpart to realize their full potential [35]. A fundamental contribution to this objective has been given by the introduction of the cobots, robots specifically designed to directly interact with humans [36]. Anyway, the cobot safety-related functionalities (leveraging on the detection of contact or proximity) are usually limited to the cobot arm itself, introducing the need for additional sensors, like cameras, laser scanners, and IMUs, to assist the cobot with perception and awareness of its surroundings, in order to avoid possible injuries subsequent to a contact between the operator and the end effector or the handles object. This objective is normally tackled through the detection of the human presence and an estimation of his/her position with respect to the cobot [36]. At the time being, the safest implementation of the presence and position feature relies on the detection of skeleton and joints, as able to precisely localise and identify body parts like head, hands, arms, and torso [36]. In addition to safety considerations in HRC applications, the opportunity of efficiently merging human-robot potential while respecting human well-being has recently been arisen by Montini et al., who proposed a framework to assist researchers and practitioners in enhancing HRC systems' effectiveness: beyond the conventional definition of HRC, the framework has been developed to take advantage of the human-aware collaboration between operators and cobots [37, 38]. Human-aware collaboration encourages then safe, concurrent work in a shared workspace where humans and robots share the task equally and have the capability to collaborate without interfering with one another because they are aware of each other's positions and activities [37].

The aforementioned considerations highlight the fact that currently the research and practitioners' community is oriented towards the application of semi-automated ECs' disassembly leveraging on artificial intelligence and that, given the cooperation between human operators and robots, an HRC scenario should include human-aware collaboration techniques. This statement is further enhanced by previous research findings: in particular, it is speculated that cognitive robots will eventually help replace humans during disassembly procedures, but it is not clear when or how much that would cost. In industrial applications, full automation in WEEE disassembly without human intervention is still not feasible [32]. Furthermore, Galparoli et al. motivated that, in a Circular Economy perspective, the human involvement is mandatory, given the operator's contribution (i) in the fast identification of valuable components to be removed and (ii) in the fast decision-making and problem-solving during activities too complex for the cobot. Additionally, the introduction of ML techniques is strongly advised by the research community, given also the fact that vision or other sensors are employed for reasoning and monitoring during the operations, making it better suited for WPCBs treatment due to the complexity of end-of-life products (and, apparently, the lack of scientific applications leveraging on ML tools for disassembly [32]). Finally, at the same time, the skeleton/joints detection seems the most promising technique in terms of enhancing safety aspects in close HRC, given its crucial benefits in determining the operator's position and displacement.

Table 1: *Guidelines supporting the implementation of a human-aware HRC system [37].*

Building block (Pillars)	**Main implementation steps**
Human factors (H)	HF.1 Define the critical human factors in the design and/or operation of the HRC system for the given application. HF.2 Determine how each identified human factor will be addressed in the design and operation of the HRC system. HF.3 Formalise which human factors must be digitised to increase collaboration effectiveness and efficiency. HF.4 Evaluate how the use of a collaborative robot will affect the human workforce (positively or negatively), including their safety, job security, and job satisfaction, assess the potential unintended consequences and determine if and how to mitigate them.
Training (H, A&E)	TR.1 Define the skills required to work with the collaborative robot in the given application. TR.2 Determine the training material needed to let the operator efficiently and effectively operate with the system. TR.3 Evaluate whether the operator must have the skills required to work with the HRC system, including controlling the robot, maintaining it, and troubleshooting common problems and errors.
Leadership & Autonomy (H, A&E)	LA.1 Identify the decisions and behaviours needed to increase the effectiveness and efficiency of the HRC system in which the collaborative robot and human DT are autonomous. LA.2 Determine the procedures and control systems that allow the operator to maintain command and control of the process. LA.3 Determine effective communication and interaction mechanisms between the operator and the collaborative robot. LA.4 Evaluate the workload and responsibilities of the robot and the human operator. LA.5 Evaluate the balance between the autonomy of the collaborative robot and the need for human supervision and control.
Performance (H, A&E)	PE.1 Define the most relevant KPIs for the involved stakeholders (organisation, operator, production manager, etc.). PE.2 Define the expected performance of the system considering not only the process but also the human factors (e.g. well-being). PE.3 Evaluate if the defined KPIs are measurable and able to provide a complete and valuable representation of the system. PE.4 Evaluate if the system achieves the expected performance.
Cobots and related plugins (A&E)	CO.1 Identify the requirements and constraints (e.g., accuracy, communication with other automation devices) of the application that affect the selection of features and characteristics of the robot and its plugins. CO.2 Design the HRC work cell to make the best use of the HRC system and allow re-configurability. CO.3 Define the functions and protocols required to ensure operator and system safety.
Re-configurability (A&E)	RC.1 Determine how HRC system re-configurability may affect performance and human factors. RC.2 Identify the key devices, components, and subsystems that must be re-configurable in the HRC system. RC.3 Determine how the re-configuration needs to be orchestrated.
Human Digital Twin (S)	DT.1 Identify what features need to be included in the DT for the given application to determine the type of data and modelling required for a realistic and accurate representation of the HRC system. DT.2 Collect data from the HRC system using a variety of data collection methods, such as sensors, cobots and devices, or interviews. DT.3 Determine how data must be preprocessed, organised, and structured so that sensors, Functional Models, and Smart Orchestrators can interact to create the human DT. DT.4 Determine the technical requirements and specifications of the human DT to provide the expected functionality. DT.5 Define how the data and information contained in DT are protected from unauthorised access or misuse.
Ethics and Trustworthiness (S, A&E)	ET.1 Map how data is collected and digitised to create the human DT and who needs to access it. ET.2 Inform the people whose data are being used and collect their consent. ET.3 Define all the needed mechanisms to have the system's trustworthiness. ET.4 Evaluate if the implemented human DT could perpetuate or reinforce existing biases or inequalities. ET.5 Evaluate how data are used to make decisions, how decisions are taken, and whether the system is trustworthy.

3. Methodology

This study makes use of a semi-automated combined with intelligent disassembly method to treat the EoL of WPCBs to maximize the benefits of human presence and the installation of visual sensors and artificial intelligence in the workspace to enhance the cobot's awareness of its surroundings. In this scenario, the cobot is equipped with a hot air nozzle and has the responsibility to heat the ECs while the operator still removes the desoldered components from the WPCB using mechanical force by tweezers, guaranteeing his/her safety. The installation of a hot air nozzle on the cobot can be characterized as a hazard caused by the robot system [39],hence, in this study, this risk reduction has been achieved by application of Speed and Separation Monitoring [39] maintaining a sufficient distance between operator's hand and hot air nozzle mounted on cobot (distance supervision, speed supervision, safety-rated camera systems). As far as intelligent disassembly method is concerned, the system consists of three modules [32]: (*i*) the vision system(VS), (*ii*) the cognitive robotics (CR), and (*iii*) the disassembly operation (DO). VS is used to identify important components and their location.VS collects real-time information during disassembly and transmits it to CR for planning and reasoning. A trained model and algorithm efficiently extract important image components and characteristics. During disassembly, DO is carried by CR, which follows the specified trajectory.

Having human operator included in the disassembly procedure of WPCB, the adoption of an efficient HRC framework is invoked to better exploit the potentials of human and cobot while satisfying operator safety and well-being. In order to ensure these features human-aware HRC framework proposed by Montini et al. [37] has been leveraged on. This framework addresses the need for effective collaboration between humans and robots in manufacturing sector.

It focuses on three key pillars: Humanisation (H), Smartification (S), and Automation & Equipment (A&E). Humanisation (H) pillar emphasizes integrating cobots into human work environments to assist or augment human tasks, considering human factors and ensuring effective technology-human integration. Smartification (S) involves the usage of sensors and IIoT systems to collect and manage data, enriching the digital representation of collaborative systems. Smart orchestrators help in decision-making and control, enhancing efficiency and trustworthiness while Automation & Equipment (A&E) highlights the importance of selecting re-configurable automation and equipment to create flexible production systems that optimize human-machine interaction, including cobots. The framework's building blocks include:

- Human factors: Addressing critical human factors in system design and operation.
- Training: Defining needed skills and training materials for operators working with cobots.
- Leadership & Autonomy: Identifying decision-making processes and communication mechanisms between humans and robots.
- Performance: Defining key performance indicators (KPIs) and evaluating system performance.
- Cobots and related plugins: Identifying requirements for robot features and safety protocols.
- Re-configurability: Determining how system re-configurability impacts performance and human factors.
- Human Digital Twin: Creating digital representations of humans to support simulation and decision-making.
- Ethics and Trustworthiness: Ensuring data protection, trustworthiness, and ethical considerations in system development.

Within the mentioned framework, a set of guidelines have been developed to enable the application of each building block and the development of human-aware HRC, as reported in Table 1. The Montini et al. [37] human-aware HRC framework will be hence leveraged to tackle the issues of integrating humans in the development and operation of the disassembly system. The framework includes all the needed components for humans and cobots to effectively work together. However, this study is supposed to associate this framework with WPCB dismantling, focusing on the elements that are most crucial for a safe and effective disassembly assignment.

4. Implementation

4.1. Framework inflection

To adapt to the human-aware HRC framework introduced by Montini et al., [37], the "AS-IS" and "TO-BE" scenarios have been defined, although the technical implementation only of the "TO-BE" scenario has been detailed in this work. The "AS-IS" set-up of the WPCB dismantling consists of following operations:

1. Positioning of the WPCB on the dedicated frame.
2. Identification of the ECs (type, position and technical parameters) to be desoldered and removed .
3. Performing desoldering task using heating nozzle for each EC.
4. Removal of the heated EC from the board.
5. Starting again from the second item till removal of all desired ECs.

This initial scenario is a manual procedure performed by the operator without the application of any cobots or support of artificial intelligence tools. The operator must then have sufficient competence to identify the desired high-value ECs to be removed, as well as knowledge of technical parameters such as hot air temperature, hot air flow, heating duration, and detection of the efficient area of heating. In addition, he/she has to constantly switch on/off the heating nozzle to prevent overheating of the ECs as well as ensuring his/her own safety while removing the heated component from the board, which leads to a waste in terms of time and workload. In order to implement the human-aware HRC framework for the "TO-BE" scenario, Table 1 which represents the guidelines supporting the implementation of a human-aware HRC system [37] has been investigated and its main pillars are reported as follows:

- Human factors (H): maintaining a minimum distance between the cobot equipped with a heating tool and the operator's hands is vital for ensuring safety in HRC (HF.1). This is achieved through a camera tracking positions of the tool and operator's hands (HF.2), as depicted in Fig. 2b. The dismantling workspace has been designed considering the physical characteristics of the human operator to ergonomically satisfy the operator's well-being (HF.2). Using the specific Graphical User Interface, operator can monitor the location of ECs to be heated by robot as well as safety points dedicated to it, increasing the awareness of the operator of possible movements of the robot and its trajectory (HF.3).
- Training (H,S): to help the operator understanding the behaviour of the system, dedicated documentation has been created. The cobot vendor's relevant training materials and courses were discovered (TR.1, TR.2). Several workshops and real-like implementations of the task for interaction with cobot have been designed to monitor the progress of operator (TR.3).
- Leadership & Autonomy (H,A&E): the operator has a crucial role in determining the completion of the heating process of each PCB component and provides feedback through a dedicated Graphical User Interface (GUI) (LA.1, LA.2, LA.3, LA.4).
- Performance (H,A&E): as a primary objective of the experiment, the promptness of safety measurement is considered a key performance indicator, which consists of (i) the required time for the perception of hand presence, (ii) the precision of hand detection, and (iii) the reaction time of the cobot (PE.1, PE.2, PE.3). The expected workload of the operator should be decreased by 40% compared to the initial scenario (PE.2, PE.3).The WPCB component detector algorithm should have Mean Average Precision (MAP) of at least 95% using standard metrics to evaluate (PE.1, PE.2, PE.3).
- Cobots and related plugins (A&E): the selection of a proper camera is crucial since the safety mechanism is activated through images received from the camera. The resolution of the camera and the number of frames per second (fps) are the most relevant specifications. As the resolution increases, the localization of the operator's hands and tool center becomes more precise however, the fps decreases, and image processing requires a longer time (CO.1, CO.2, CO.3). A computer-vision model has been developed to identify the ECs and their location to be heated by the cobot (CO.1, CO.2).
- Re-configurability (S,A&E): the setup is valid for a wide variety of WPCBs with shape and size, as long as the size of a WPCB is within the size of the preheater plate and the range of the cobot's movement (RC.1, RC.2), see Fig. 2.
- Human Digital Twin (S): Asset Administration Shell [40] technology will be exploited as a standard digital twin representation of the WPCB and its related components containing the main data required for performing dismantling task (DT.1, DT2, DT.3).The smart orchestrator assigns to which component the cobot heats, processes the images received from the camera to detect hand presence and corresponding cobot's reaction, and takes into account the feedback from the operator (DT.1, DT.2, DT.3).
- Ethics and Trustworthiness (S,A&E): Collecting personal data and monitoring workers raise privacy and ethical issues, and require the explicit and signed consent of the operators while camera's frame, respects the operator's privacy (ET.2, ET.3).

After defining the various elements that underlie each building block of the exploited human-aware framework, the "TO-BE" scenario has been established, with the fundamental technical details described in the subsequent subsection.

4.2. Software architecture and implementation

The hardware setup consists of a UR5e cobot arm equipped with a heating tool, an Intel RealSense D435i camera [41], a JBL preheater set, an extractor hood intercepting hazardous fumes, and a host PC with an Intel Core i5-8365U Processor and a 8GiB System Memory, where the algorithms are implemented.

The software setup is composed of (*i*) MediaPipe Hands library [42], to detect and localize hand-knuckle within the detected hand regions, (*ii*) OpenCV [43] to localize Aruco marker, (*iii*) YOLOv5 [44], which is based on computer vision and deep learning algorithms, is used to detect and localized WPCB's components [45], (*iv*) MoveIt [46] for the motion planning of the cobot, and (*v*) ROS Noetic [47] as a middleware to establish communications among modules. In addition, at the start of the experiment, the calibration of the camera's coordinate with respect to the robot's origin is performed with the method proposed in IFL-CAMP/easy-handeye repository [48].

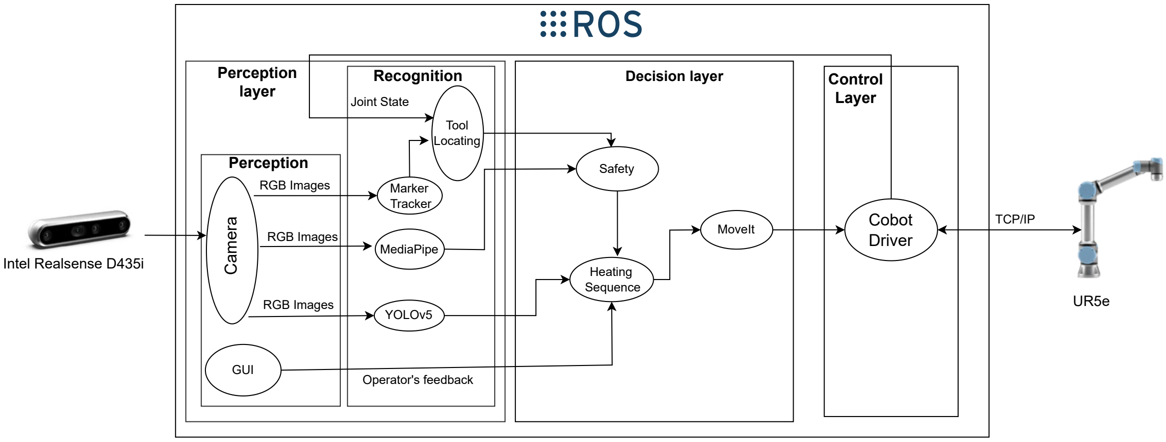

Fig. 1: Experiment's software architecture

As shown in Fig. 1, the software modules are distributed across three logical layers: (*i*) the perception layer, (*ii*) the decision layer, and (*iii*) the control layer. In the perception layer, the camera captures the RGB images and the point clouds, sending them to the sub-layer of recognition, where the positions of the heating tool, hand-knuckles, and WPCB's components are determined respectively through OpenCV, MediaPipe, YOLOv5 modules, while cobot's joint states are received from the cobot's driver. In the decision layer, the Safety module verifies whether the safety criterion is satisfied or not through the known positions of the tool and the operator's hand, then the Heating Sequence module determines whether a component should be heated or if the cobot should switch to the safety configuration, based on the operator's feedback on the success of desoldering, and the components' positions. As a consequence, the MoveIt module receives a trajectory planning request, while in control layer, the trajectories planned via MoveIt are sent to the cobot controllers via TCP/IP communication protocol using Robot Operating System (ROS).

The heating process begins with heating the nearest component to the cobot's origin. The cobot heats the component for a specific duration, then it moves to the next closest component $(i + 1)$ to its origin; simultaneously, the operator removes the component (i) and provides feedback on the success of the desoldering of the corresponding EC via a Graphical User Interface. If desoldering has not been effectively executed, the component is re-included in the queue of unheated components. This iterative procedure proceeds until all desired ECs become desoldered.

Having human and cobot collaborating in close proximity, speed and separation monitoring method [49] has been selected ensuring a safe distance between a human and cobot at all times, controlling and reducing risks in HRC. The ISO 13855 standard defines the minimum protective distance calculation, while the ISO/TS 15066 [39] standard refines it. To track the distance between a robot and a human or between a robot and any other individual entering a collaborative workspace, tracking devices like camera has been employed. According to the ISO 15066, indeed, a minimum distance d_{min} between the operator's hand and the cobot's heating tool must be respected, where d_{min} must be determined considering the cobot's and human's speed, response time and the perception lag. The hand knuckles and the heating tool are localized. As a result, the distance between the j_{th} knuckle and tooltip is calculated from $d_j = \sqrt{(x_j - x_{tip})^2 + (y_j - y_{tip})^2}$ where d_j must be greater than d_{min}, i.e. $d_j > d_{min}$ that the safety requirement is satisfied, see Fig. 2b. When the safety requirement is not respected, i.e., $d_j \leq d_{min}$, the cobot moves to a predefined safety position among the available ones (defined out of the working space of the operator), in particular to the one that has a maximum distance to the operator's hand and remains there for a specified time, then the cobot proceeds with heating starting from the remaining components closest to its origin. To demonstrate the rate at which Speed and Separation Monitoring method minimizes the operator's hand's exposure to heat, the time interval between when a hand knuckle is recognized in the danger zone and when it entirely flees thanks to retraction of the cobot is measured: after several trials, the measured time is indeed $0.52 \pm 0.06s$.

(a) (b)

Fig. 2: (a) Experimental setup, (b) localisation of marker (red dot), heater (blue line), hand knuckles (magenta) and minimum distance between hand and tool (green line).

5. Conclusion and future works

The presented work introduced a disassembly scenario designed to deal the EoL of WPCBs. This application, motivated by the recent paradigm of Circular Economy which is influencing the waste disposal, manages to accomplish the task of disassembly ECs of high value and potentially reusable. The recent trends of disassembly operations are also debated, and the proposed approach falls in the semi-automated and intelligent clusters: this positioning, aligned with the recent trends of research, introduced the human involvement, which required, on turn, a specific framework for its design. Additionally, the introduction of HRC introduced the need of further safety measures, which have been realised through Artificial Intelligence-based algorithms which made the cobot move away from the operator workspace. The implementation of the HRC framework in this paper has been done due to the presence of elements that could perfectly fit within its pillars ensuring inclusion of human factors and its presence in the workspace, however, this framework is meant to address some of the main limitations and difficulties to include humans in HRC applications and industrial exploitability and its benefits in industrial applications should still be investigated [37].

In order to further improve the proposed scenario, future works are supposed to include a higher number of cameras installed, in order to increase the field of view. At the same time, the middleware used for this implementation has been embodied by ROS, where the communication among nodes is managed internally and in a not-always transparent way. This paper has not debated the potential alternatives to it: different solutions (e.g., ROS2) implementing different communication policies, could be employed for a comparative analysis, in order to highlight the most effective one, which would result in an increase of performance with respect to the prompt detection of proximity between the hand of the operator and the hot air nozzle. The development of an orchestrator minimizing the probability of presence of the operator hand in danger zone while cobot is heating or moving within the workspace would be also beneficial to minimize the idle state of the cobot performing its task. Despite these limitations, this work is supposed to have qualitatively demonstrated how a monitoring based on Computer Vision can improve the safety conditions of a human worker collaborating with a cobot, whenever its specific setup introduces safety concerns. This approach is potentially scalable to similar cases in manufacturing companies, where the benefits of HRC are invalidated by safety concerns, leading the manufacturing firm either to continue with pure manual operations, or leveraging on expensive robotic cells. Before installation on industrial scenarios, however, numerical and statistical validations are required. These studies, together with comparative analyses of different implementation technologies, are intended to be reported in further works.

Acknowledgements

This work has been supported by the projects “Regions and (E)DIHs alliance for AI-at-the-Edge adoption by European Industry 5.0 Manufacturing SMEs” (AI REDGIO 5.0), “Agile, human-centric, and Real-tIme enabled open

SourcE technologies advancing industrial HRI in Europe" (ARISE), and "European Lighthouse to Manifest Trustworthy and Green AI" (ENFIELD), which have received funding from the European Union's Horizon Europe research and innovation program under grant agreements No. 101092069, No. 101135784, and No. 101120657. This research is also part of the HumanTech Project, which is financed by the Italian Ministry of University and Research (MUR) for the 2023-2027 period as part of the ministerial initiative "Departments of Excellence" (L. 232/2016). The initiative rewards departments that stand out for the quality of the research produced and funds specific development projects.

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