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Challenges in human-robot collaborative assembly in shipbuilding and ship maintenance, repair and conversion (SMRC) industry

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Abstract

In recent years research in manufacturing has been shifting towards flexible and intuitive Human-Robot Collaborative (HRC) solutions, allowing operators to coexist and interact safely with robots of various payloads. Previous research provided proof that HRC systems can improve the quality and cycle time of processes, including welding, grinding, polishing, assembly and picking. Applying such solutions to shipbuilding and ship maintenance, repair and conversion (SMRC) industry though is not straight forward. Lack of 3D-CAD models, variety of processes that have to be performed, manipulation of dissimilar parts, confined spaces, unpredictable external conditions are some of the challenges that arise. Nevertheless, the shipbuilding and SMRC industry is a dynamic and competitive sector, which could highly benefit from leveraging technology advancements, emerged from Industry 4.0 revolution. These advancements can not only improve the work life of the operators, supporting them in dangerous working environments, but also increase the quality of the final product as well as productivity rate.

In this direction, this paper aims to present the challenges that derive from the shipbuilding and SMRC industry related with assembly operations, as well as a novel user-centric solution that aspires to overcome these challenges. The solution consists of a reconfigurable HRC cell, involving a high payload collaborative manipulator able to perform lifting and positioning of large heavy parts, while the operator performs the welding task. Intuitive interaction solutions allow precise parts handling by workers. Moreover, multi-layer safety systems allow the monitoring of the workplace and ensure the safety of the operators. Finally, hand guiding, and intuitive offline programming techniques enable the manipulation and programming of the high-payload robot by not experts.

Keywords: human robot interaction; human robot collaboration; reconfigurable assembly lines; offline programming; intuitive solutions; assembly; shipbuilding industry;

1. Introduction

Human Robot Collaboration (HRC) has been a widely discussed topic over the last few years, arisen especially during Industry 4.0 revolution, with the focus gradually shifting towards more ergonomic, reconfigurable, versatile solutions [1]. HRC applications can be very beneficial for an industry since they combine the advantages of both robots and human workers. While robots can perform tasks with high precision and repeatability, human operators may handle more delicate tasks that require high dexterity and skills.

One of the most important factors in the easy transition from manual or fully automated production stations to hybrid applications, is the level of trust of the operators [2], since working with a robot may be challenging for non-experts. Efficient and seamless Human Robot Interaction (HRI) interfaces are vital to this purpose, since they allow the proper information of the operator and provide complete control of all devices integrated to the system [3]. One of the latest trends in

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operator support provision technologies is the utilization of wearable technologies that with AI enhancement [4] can support the operators in a non-intrusive way [5].

However, there are still only few industrial applications of high Technology Readiness Level (TRL) in which HRC is applied, with most of them being developed and tested in a controlled environment. This occurs due to the challenges arising in terms of product quality, demanding safety requirements and production rate, since with the inclusion of human operators in an area, the speed of the robot should be limited. However, the main reason for the slow integration of these technologies in this industry is the current methodology for safety analysis of HRC [6], which focuses more on detailed analysis of robots' behavior, without acknowledging the operators as proactive factors [7]. It is common knowledge that in a hybrid environment, the human factor has a significant role in terms of a formal deterministic analysis of the physical world [8]. As analyzed in [9], four basic safety principles for HRC have been defined, as shown in Figure 1.

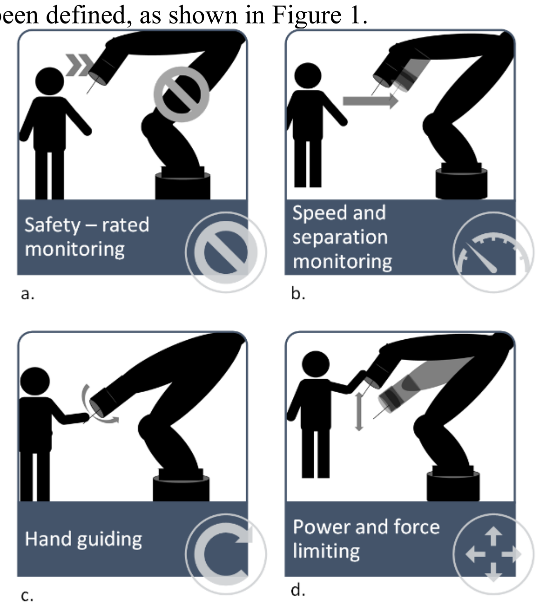

Figure 1. (a) Robot stops when operator enters the collaborative area; (b) Contact is prevented; (c) The operator controls the robot movements actively; (d) Contact forces are limited.

For HRC applications to be applied to more challenging sectors, where human factor cannot and shouldn't be removed, as the Shipbuilding Industry, safety requirements should be analyzed thoroughly and the prementioned basics should be used as guidelines. Generally, in the shipbuilding industry, most ship accidents are caused by human faults, which show that human factor has a major impact on accidents [10]. As a result, it is vital to give emphasis to the safety factor, in order to provide a safer, healthier environment for the workers. The Ship Maintenance, Repair and Conversion (SMRC) industry comprises yards dedicated to maintenance, repair, conversion and retrofitting of ships [11]. Shipbuilding is a traditional mechanical manufacturing process that requires enough building space and resources, due to its large and complex components. These components are highly customizable and mostly not mass produced. Generally, this process involves six stages, as shown in Figure 2, most of which are executed by several workers.

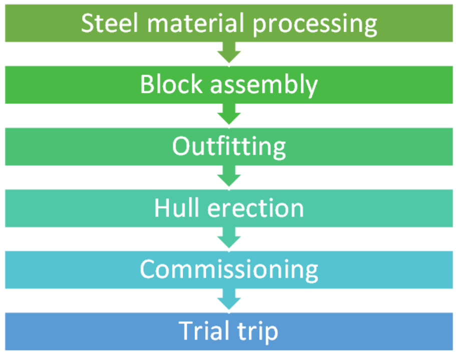

Figure 2. Six main stages of shipbuilding

In the last decade, small and medium-sized shipyards (SME) in Europe seem not to be as competitive in the market in terms of productivity and automation. In order to increase the productivity of SMEs, research should focus on introduction of new technologies to the shipyards. This transition should be handled with caution since mass automation would not be applicable. With semi-automation of the most time-consuming stages of shipbuilding, customization benefits would be preserved [12]. Among the prementioned phases of shipbuilding, block assembly spends the most building time, so with the leverage of upcoming technologies, improvements in block assembly could lead in overall increase of system's efficiency and quality [13].

However, the nature of this industry makes the integration of latest technology advancements complicated. To begin with, the customization needs are very high, since each ship meets very specific requirements defined by each client. Moreover, there is a big variety of parts to be handled in each stage, which differ in terms of shape, weight, and size, thus there is not as much repeatability as in other sectors. Consequently, there is a lack of 3D-CAD models, making the transition to VR/AR solutions [14] more challenging. Except for the customization needs, fully automated mass production cells are not as beneficial due to the building space requirements and external conditions since most of these tasks are performed inside confined spaces, like vessels, where human intervention is necessary. The external environmental conditions may be unpredictable, with unstable connectivity or dangerous points, making the utility of expensive equipment and design of smart systems even more demanding in terms of durability and resistance.

Since fully automated solutions would not be useful, involving the human factor would be promising and even necessary. In this way, the workers wouldn't be replaced, yet supported by systems designed to improve their working conditions. In this direction, the developments should have as a purpose to enhance their work, without interfering or limit their movement and capabilities. Moreover, the fact that more than 125,000 people are currently employed in the European SMRC industry [15], prove that emphasis must be given to the ergonomics and safety requirements. The developments should be easily used by the workers with emphasis on the level of trust of the workers.

More specifically, the annual turnover of the sector is about 3.5 billion Euro [11], making the profit from these advancements, undeniable.

Therefore, SME shipyards need novel cost-effective, modular, human-centric tools capable of improving the operator's performance, while ensuring quality and precision in the execution of the labor-intensive tasks.

The remainder of this paper is organized as follows. Section 2 describes the approach that is proposed in this paper, to address the challenges and requirements of HRC assembly in shipyards. In section 3, the use case in which this proposal is focused on will be presented. In section 4, the main target Key Performance Indications (KPIs) that will allow the evaluation of the effectiveness of the proposed approach will be discussed, while in section 5, the work presented will be concluded and ideas about future work will be explored.

2. Approach

The proposed method aims to address the bottlenecks of shipbuilding process, by improving the working conditions, while introducing automation to the processes. In this direction, a novel solution regarding assembly and welding of parts is proposed. As stated in Section 1, the most effective approach would not be the design of an automated station since this solution would result in limitations regarding customization capabilities. The purpose of this solution is to support the current industry, by enhancing the capabilities of the operators, while interacting safely with robots. In this direction, the developments aim to be considered a portfolio of tools designed for non-expert users (regarding advance programming and robot programming knowledge), to support them by reducing manual labor. The design of these tools is human-centric, allowing their full integration on each task, without burdening them. Moreover, great emphasis has been given to safety measurements, in accordance to safety regulations [9].

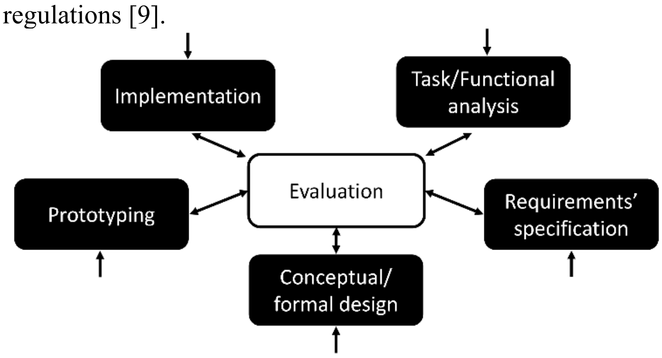

Figure 3. The Star Model (Hartson and Hix, 1989)

In order to facilitate the familiarization of the operators with the developed tools, the key is evaluation, not only internally with dummy testing, but evaluation of the concept by users as well, in order to meet their preferences and define their actual needs. In this direction the Star model proposed by Hartson and Hix in 1989 will be used for guidance. Based on this approach (Figure 3), different concepts will be evaluated and based on the feedback, the designs will be adjusted. The evaluation process is an ongoing activity from the first conceptual design to the final prototype, to fulfill the shipbuilding industry's needs.

Based on this, the structure of the proposed system aims to allow reconfigurability and flexibility, so that the developments can be used by operators with different characteristics and needs, hence the architecture approach shown in Figure 4. Based on this overview, there is not a fixed definition of the architecture per task, rather than a set of modules that may apply in more than one tool. Each module serves a specific role and occupies different aspects of technology. These modules are independent from each other, communicating through I/O data upon request.

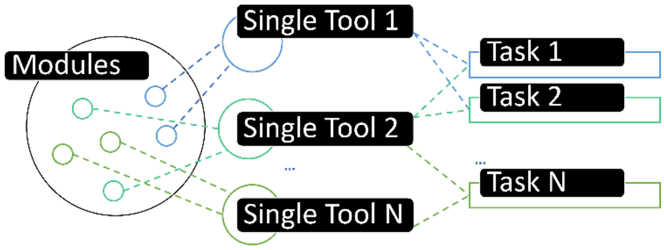

Figure 4. High level approach architecture

In order to define the tools needed for each task needed to be performed (Welding, Assembly, Positioning, Transport etc.), each tool involves a set of modules, so that a higher-level service is provided to the operators, for different levels of assistance. Based on Section 1, several crucial aspects of HRC solutions include: 1. Human Robot Interaction, 2. Multilayer Safety System, 3. Hand Guiding, 4. High Payload Robot, which allow the operators to control and interact safely with the robot and the system. In this way, they may easily accept and trust the HRC systems and adopt new technologies, that will enhance their performance and productivity. Below each of the aforementioned technologies will be further explored in separate subsections.

2.1. Human Robot Interaction

Designing an efficient HRC system, especially a toolset offering freedom and flexibility to the operators is challenging, considering the importance of feedback and trust of the system. In this direction, a module responsible for effective human robot interaction should be defined, hence Human Robot Interaction Module (HRIM). HRIM is responsible for visualization of all shared tasks among the operator and the robot, as well as remote monitoring. Moreover, HRIM should allow online and offline robot programming. Another requirement is the ability to adjust the task execution to the operator's needs. Hand-guiding should be supported, allowing the control of the robot mode of operation and displaying of available visual feedback on the guided process for example, through AR/VR simulations, in compliance to safety guidelines. Safety is an important aspect of HRC application. With the use of HRIM, safety zones, defined based on the collaboration area of the application, will be displayed. Tracking the position of the user and comparing it with the position of the defined zones, will inform the user prior their

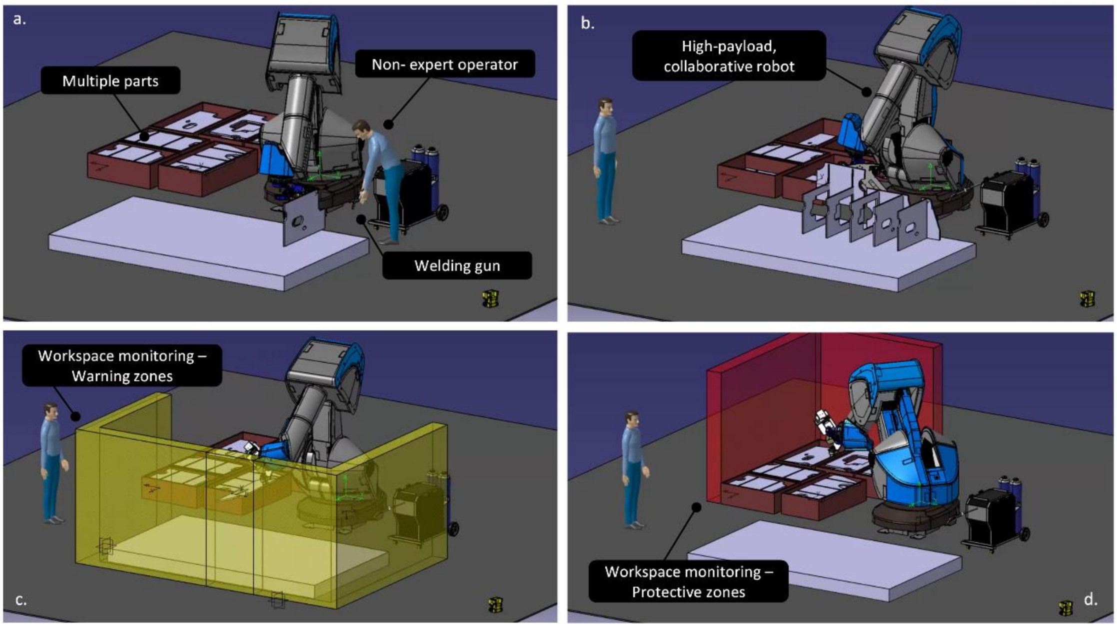

Figure 5. Concept of use case

violation. Finally, future robot trajectory will be displayed, increasing the safety feeling of the operator, being aware of the next robot motion.

2.2. Multilayer Safety System

Safe collaboration of the operator with the robot is the foundation of a successful HRC application. Based on [9], safety functions must be implemented using suitable components in accordance to determined requirements.

In this direction, Workspace Monitoring Solution (WMS) module is defined (Figure 4), allowing the detection of the operator's position and the division of the workspace in safety zones, using certified safety devices, as shown in indicative examples in Figure 5(c, d). Two kinds of zones can be defined: hazardous/detection zone, in which when the operator is detected the robot will stop moving (Safety-rated monitored stop), and the warning zone, in which the speed of the robot will be limited at a safe value (Speed and separation monitoring). For the implementation of such a functionality, WMS should be able to control the robot's operation and alter its speed. The other modules will be informed of the published safety status. The design of this software module will have as basis the gained knowledge from applicable laws and the latest standards, so that the tools can be properly evaluated, using AR/VR technologies. The sensing equipment used should be as less intrusive as possible. Thus, WMS will utilize 3D sensors, laser scanners and other certified industrial safety devices to track operators in comparison to the robot position. The set of devices used will be flexible, in order to serve the purpose of the tasks and the limitations of the shipyard environment.

2.3. Hand Guiding

Hand guiding technology can be very useful in HRC systems, as it enables intuitive finetuning of robot position. In this direction, the Hand Guiding Module (HGM) will be developed, allowing fast teaching through manual guidance, by applying forces in the end effector of the HPR. HGM should communicate with the robot controller and change its mode from auto to programming and vice versa. Force sensors will be utilized as a part of HGM system, which will be responsible to receive and monitor the forces applied.

2.4. High Payload Robot

All technologies and algorithms will be applied to the high payload robot, the integrations and communication of which will be facilitated by a separate module, High Payload Robot (HPR). More specifically, HPR should be able to execute collaborative actions, start/stop/pause/cancel/resume actions upon request, indicate and change its status from collaboration mode to normal operation by alternating speed, force and movement limits. Finally, HPR should support hand guiding, to communicate properly with HGM. These technologies/tools are flexible enough to be integrated with low-payload or mobile robots as well, based on the needs of the use case.

3. Use case

In shipbuilding industry, welding and assembly are common tasks. Currently, these processes are executed manually by several operators, based on the size and weight of the parts. Usually, 2 operators are responsible for positioning the parts to hold them still, while the welding is performed by another operator, using semiautomatic welding machines.

With optimized usage of the resources, the challenges of HRC and shipyard environment may be addressed, resulting in competitive production stations. The solution (Figure 5) includes a high-payload robot and an operator, according to which the robot will perform the lifting, manipulation and positioning of the heavy metal parts, while the operator will weld them in place. The following supportive tools will be available:

1. Autonomous positioning tool
2. Guided positioning tool
3. Autonomous welding tool
4. Guided welding tool

The operator will be able to select the level of assistance needed for executing the task.

A scenario has been defined to demonstrate the application of the aforementioned technologies and modules. In more detail, the script can be divided in these steps:

1. The robot (HPR) moves to the area specified for bin picking of parts to be assembled (autonomous positioning tool).
2. The HPR picks the part with magnetic gripper and moves it near the assembly area either autonomously (autonomous positioning tool).
3. Operator enters the collaborative area monitored by WMS, assisted by AR technology (HRIM) and fine tunes the positioning of the part (HGM) (guided tool).
4. Robot holds the panel still while the operator acquires manual welding gun.
5. Operator tack welds the part with the welding gun.
6. The operator exits the collaborative area (WMS).
7. Robot fully welds the part with guidance from HMI (guided welding tool) or automatically from previously taught action (autonomous welding tool).

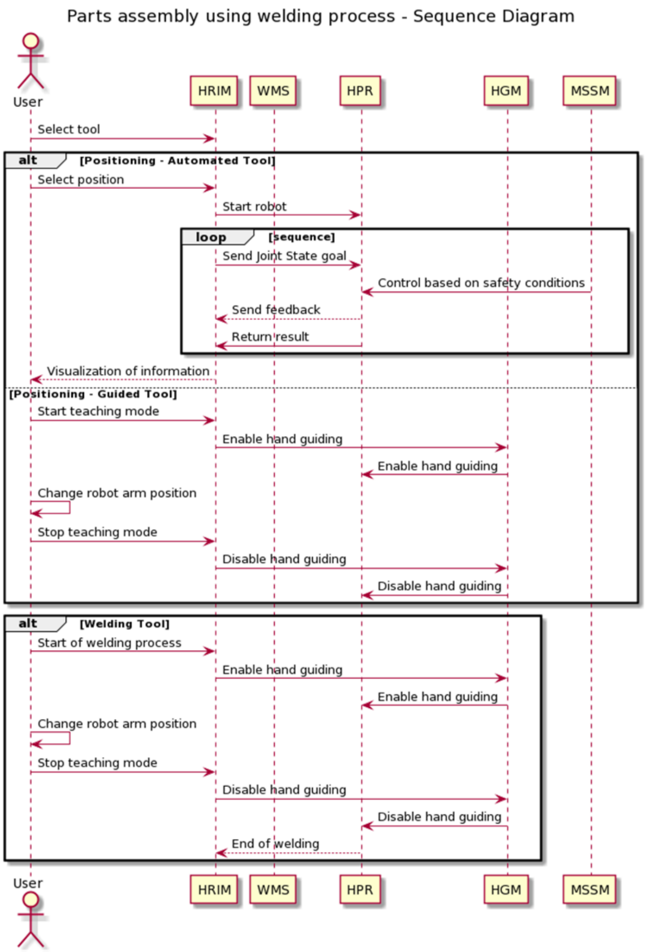

Figure 6. UML diagram demonstrating the communication between the modules applied in this use case

The communication between the modules will be achieved using ROS (structures such as service nodes and action client/server systems, which will receive and publish topics containing useful information on the status of the cell in terms of safety, status, progress etc.). The exchange of information and data flow between the modules as presented in the Section 2 is explained in the UML (Unified Modeling Language) Diagram, shown in Figure 6.

4. Results & discussion

Evaluation of our approach is key, as already highlighted in Figure 3. Key Performance Indicators (KPIs) targets have been set, to allow the quantification of the effectiveness of our approach compared to the current practices in shipyard industry, as shown at Table 1.

Table 1. KPIs summary

no.	KPI
1	Ergonomics improvement in handling of parts
2	Maximum weight to be manipulated by the operator
3	Time required to introduce new variant
4	Cycle time
5	Product quality
6	Number of operators required in the production station

In more detail, these KPIs have been selected to address the effectiveness of the system from different aspects. In Section 1, it was stated that there are limited HRC applications integrated in industrial environment, since with the coexistence of a human and a robot, the process is affected as far as quality (KPI 5), productivity rate (KPI 4), due to the unpredictability of human actions. Moreover, the impact of the proposed approach to ergonomics will be analyzed, using KPI 1. Specifically, Rapid Upper Limb Assessment (RULA) Tool [16] will be used in combination to anthropometric data to conduct fast and accurate ergonomic and health risk assessments. High Payload Robot is utilized, in order to optimize the human resources required (previously 2 operators only for positioning). The usage of high payload robot for lifting and manipulation of heavy parts, will not only improve ergonomics (KPI 1), as less weight will be carried by the operators (KPI 2), but also reduce the number of operators required in the production station (KPI 6). Finally, the SMRC industry is characterized by high level of customization. At many cases, the CAD/3D designs may not be available; thus the solution should be as less dependent to the variant as possible, allowing rapid reconfiguration of the station to comply with the different variants/needs [12] (KPI 3).

5. Conclusion & future work

In this paper, the status and challenges existing in the SMRC industry have been pinpointed. Based on these challenges, requirements have derived for the creation of flexible and safe HRC tools to be used in shipbuilding workplaces allowing seamless interaction and collaboration between operators and other resources in block assembly processes. KPIs have been defined based on the limitations of previous HRC attempts and manual labor as presented. These KPIs (Section 4) will prove the benefits of the proposed solution, since using constant evaluation (Figure 3) the gaps determined will be addressed, with solutions based on the operator and industry's needs. The technologies described in Section 3, are currently being implemented under the Mari4_YARD project, with the first practical results expected during the 2nd quarter of the project. They will gradually be integrated in a pilot coming from the shipyard sector, as presented in Section 3, for evaluation and validation purposes.

Future work will focus on the development of the technologies discussed in this paper, their optimization, and their integration under a common production station, as defined in Mari4_YARD project. After the validation of the concept, a next step is the deployment and testing of the developed production station at shipyard environment. This will allow to accurately measure the performance of the system as a whole and highlight bottlenecks of assembly and welding tasks in SMRC, as well as operator acceptance of such technologies.

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