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Enabling Human Robot Interaction in flexible robotic assembly lines: an Augmented Reality based software suite

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Abstract

This paper presents an Augmented Reality (AR) based software suite for supporting operators in production systems that employ mobile robots These robot workers may increase assembly system's flexibility while supporting humans in assembly given their ability to navigate to different workstations and change tools for performing various assembly tasks. Driven by the need to immerse the human in the execution loop, the discussed AR based framework aims to enable their direct communication and interaction of human operations with a) the robot coworkers providing them online task instructions and b) the central execution system through natural means of communication such as virtual buttons. The developed tool has been tested in a case study inspired from the automotive industry showing that it may facilitate the communication between the humans and mobile robots increasing human operators' job quality while supporting them during collaborative assembly.

Keywords: human robot interaction; augmented reality; mobile robots; remote guidance;

1. Introduction

In the existing assembly systems, the capability of offering more variants per model, and introducing new models faster, is constrained by the current technologies and the equipment of mass production operations, which are incapable of supporting product variability [1], [2]. Achieving flexibility and adaptability that can be defined as the production system's sensitivity to internal and external changes is regarded as one of the most promising solutions over the last years [3]. To manage these dynamics several paradigms such as holonic, flexible [4], lean [4], reconfigurable [5], evolvable [6], self-organizing and autonomous assembly systems have been partly realized in the last decades.

Currently, hybrid production systems enabling Human Robot Interaction (HRI) have been receiving a lot of attention by the research community as well as by the industrial world [7]. These systems aim to exploit in their full extent the capabilities of human operators such as intelligence and cognitive skills supporting them through robot's repeatability, dexterity and strength [8]. Such co-existence of humans and robots is considered as a promising solution that allows sharing both workplaces and tasks. New projects [9], [10], [11], and products [12], [13], have been introduced for the exploitation of the flexibility and productivity [14] potential of these hybrid systems. Beyond these, the latest trends in European research suggest the introduction of mobile dual arm workers acting as assistants to human operators achieving higher reconfigurability of the production system [14].

Despite the wide range of challenges in the field of HRI such as task planning and coordination, safety, learning by demonstration and easy robot programming etc. this study is focused in the required bilateral communication between the human worker and the robot assistants.

As described above, human operators are a valuable actor for the hybrid production systems [15] given their intelligence and flexibility especially in the case of small-scale production [16] where re-configurability and costs need to be sustainable for SMEs [8]. However, in order to exploit their capabilities,

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human operators should be equipped with the required means of communication, interaction and support.

Augmented Reality (AR) technology has been used during the last decades in several applications related to manufacturing. Collaborative product and assembly [17] design allowing easier product personalization can be achieved through specifically developed AR tools [18], [19]. Furthermore, remote assistance and instructions provision for assembly process execution [20], as well as remote maintenance [21] can be facilitated through AR developed applications. Extending these approaches, the usage of AR technology has been identified as of added value towards increasing human safety feeling in human robot collaborative environments [22]. AR applications providing text based [23] as well as 3D CAD model based [24] assembly instructions has been design and developed for supporting human operators under HRI production scheme. The latter enhances the information sent to the human by adding robot behavior real time data such as visual / audio alerts, upcoming robot trajectories and robot working volumes visualization [25]. These tools are deployed on wireless connected wearable devices such as AR glasses, smartwatches etc. [26].

Nevertheless, apart from some small-scale experimental installations where humans have a more active role, most of the above applications have not reached the production site. In addition, the existing approaches have been focusing and successfully achieved on providing information to the human. To achieve a more user – friendly and intuitive HRI there is the need of establishing a bilateral communication channel between the human and the robot allowing the human to directly interact with the robot.

To this direction, this study aims to extend this concept and close the communication loop between the human and the robot. In particular, this paper focus on enabling the interaction of human operators with mobile dual arm robots, namely Mobile Robot Platforms (MRPs) through an AR based software suite. The novelty of the proposed systems relays in the end – to – end integration of the AR based framework from the human side interface to the mobile robot controllers exploiting the capabilities provided by the Digital Twin of the production entities [27].

The following sections of the paper are organized as follows: Section 2 provides a description of the proposed approach and implemented functionalities. The integration architecture in terms of software and hardware components is detailed in Section 3. In Section 4 an automotive case study is presented. The last section is dedicated on summarizing the conclusions from the study as well as suggesting the aspired by the authors future work.

2. Approach

This study considers human robot collaboration combined with robot's mobility as the major enablers for flexibility in current assembly systems. Mobile Robot Platforms (MRPs) that can navigate in different workstations for performing various assembly operations such as handling, screwing etc. may highly contribute in the reconfigurability of the production system both in structural as well as process level.

A key requirement for enabling the efficiency of these hybrid systems in the effective interaction between the different kind of resources. Following the above analysis, this paper presents an AR based software suite aiming to address the industrial requirements for a closer and more intuitive HRI in hybrid production systems. This software suite exploits the latest advancements in AR technology for implementing novel interfaces for human robot interaction while closing the communication loop between human operators and robot resources. In this context the suggested framework, enhances human robot interaction by allowing human workers:

- To directly instruct the robots: a) during execution in cases of unexpected / unplanned events, b) for short term MRPs re-programming requirements when changes occur in the production environment,
- To receive real time information: a) on robot active tasks, b) his / her assigned tasks.
- To provide feedback on the real time execution status in the central execution control system.

The novelty of the proposed system relies on the deployment of the end – to - end integration and data flow from the human side AR interface to the robot controllers.

The following sub-sections provide a deep insight in the developed functionalities and their added value towards supporting human operators during the assembly process. In the conducted experiments, the Microsoft HoloLens AR glasses have been used implementing a markerless based object visualization approach that may increase the application's stability and user experience [28]. For the navigation in the AR environment, the AirTap gesture has been defined as user input for all the virtual buttons included in the application.

2.1. User initialization phase

Given that in the industrial environments usually each operator may work in several workstations, the discussed framework has been designed so as not to relate to the particularities of a specific workstation. In addition, variations in the different operators' characteristics needed to be considered in order to make sure that all the digital objects are superimposed in the field of view of the operator in the correct scale and position with respect to the physical world. After several experiments, the height of the operator who wears the AR glasses has been identified as a variable that needs to be initialized for each different user. For every new user, an initialization phase is required as visualized in Fig. 1. The user is instructed to spot a marker placed in a specific location in the assembly area and based on its distance of the camera the required height is calculated.

Fig. 1. Human operators' field of view - User initialization phase

2.2. Robot Instructing phase – Direct robot control

One important limitation in existing robotic applications is that the robots need to be offline programmed by robot experts with high accuracy based on the specific layout and the parts involved in the assembly. If changes occur either in the assembly are layout or the product variants the production needs to stop until a robot expert may manually re-program the robot. This creates losses in terms of cost and time that have a great impact in productivity especially in the cases of SMEs. The discussed flexible production paradigm aims to overcome the limitation providing the human operator the mechanisms that will allow him / her to directly instruct the robot in an easy and fast way when needed, without having any expertise in robotics. Two different functionalities have been implemented comprising this robot instructing phase.

2.2.1. Direct robot navigation instructions

The first functionality allows the user to give new navigation goals to the mobile robots which they were not initially programmed for. In that way, the mobile robots may be online allocated to new workstations when this is needed based on the production requirements. As visualized in Fig. 2 the user may simple AirTap in the desired location for the MRP. This user input is transferred in real time in the MRP path planner which generate the optimized path for achieving this new navigation goal. The planner then sends this path to MRP controller for the final execution.

2.2.2. Robot position corrections - Teleoperation

The second functionality aims to allow the user to make small adjustments and real time corrections in the mobile robot's location. This may be useful considering the dynamically changing environment and the non-static positioning of the resources. This teleoperation is implemented by visualizing to the user a cross pad composed of four virtual buttons. When the user AirTaps on one of these buttons the MRP moves in the respective direction based on a pre-defined offset. As the mobile robots moves and possible rotates, the pad is rotated as well to have always the correct orientation with respect to robot's platform orientation. Through the available buttons the user may request robot position correction by: a) moving forward, b) moving back, c) rotating to the left, d) rotating to the right. For instance, the user in Fig. 3 instructs the robot to rotate in the left so to ensure better reachability of the robot arms in the workbench in front of the platform.

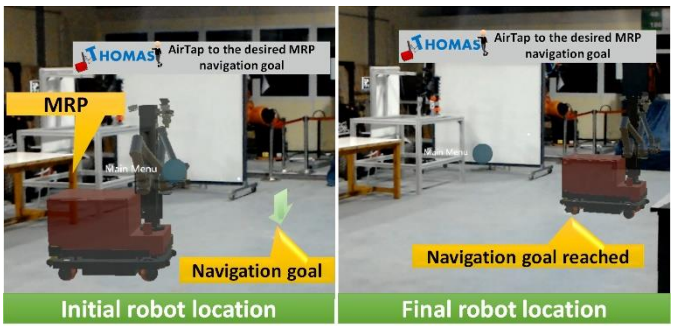

Fig. 2. Human operators' field of view - MRP direct navigation instructions

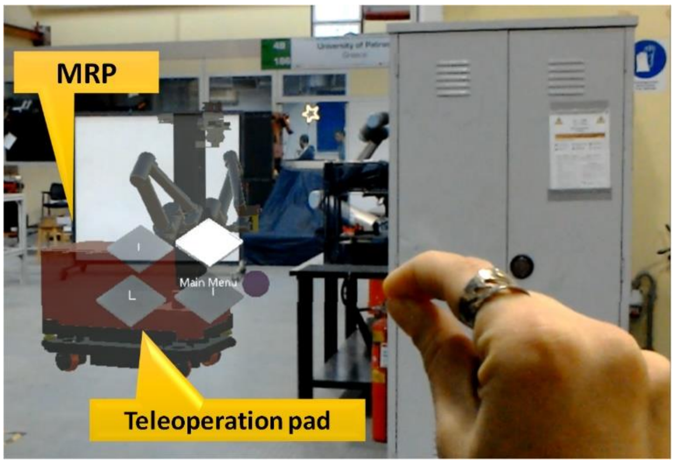

Fig. 3. Human operators' field of view - MRP position corrections

2.3. Execution phase – Assembly status information exchange

In conventional fully automated robot-based assembly systems the process execution control and coordination may be realized through various approaches such as Programmable Logic Controller (PLC) based or service oriented based control architectures [29]. Nevertheless, when human workers are also part of the assembly, two important requirements occur:

- Provide them information on their assigned task as well as provide them interfaces for reporting back in the execution system the execution status,
- Inform them on the robot active task in order to be alert with respect to robot real time behavior and thus increasing their safety awareness.

This information exchange is achieved through the integration of the AR based framework with the central execution system, namely the Station Controller.

2.3.1. Robot active task execution information

Once the assembly tasks have been dispatched to the resources and the execution has been started, the human operator may request to receive information on active tasks in each workstation. Fig. 4 presents the field of view of the operator enhanced with information on the current active task, the assigned resource as well as the task execution status.

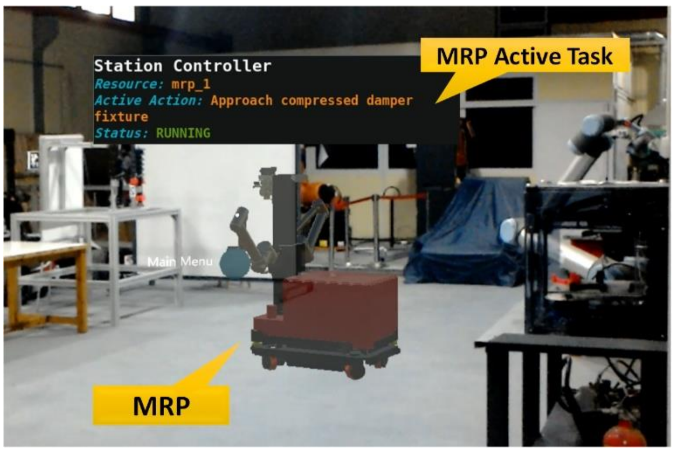

Fig. 4. Human operators' field of view - MRP active task information

Fig. 5. Human operators' field of view - Human operator's active task information

2.3.2. Human operator's assigned tasks information

Respectively, when a task is dispatched to the specific human operator, he / she receives a notification along with a textual description on how to perform the task that he/she needs to performed as shown in Fig. 5. In complementarity, a virtual button, namely the "Task Completed" button, is superimposed in his field of view allowing him to notify the Station Controller when he / she has completed the assigned task. In that way, the Station Controller may efficiently coordinate the entire assembly processing execution respecting the precedence relation among the different tasks to be performed by the different humans and robot resources.

3. System Implementation

Although the focus of this study is the development of the discussed AR based HRI framework, to realize the integration and testing of the AR tools to a realistic robot environment two additional components have been used:

- A Digital Twin of the production environment involving [27]: a) the scene reconstruction based on the CAD models of the layouts and the involved components as well as the real time data of the sensors placed on the mobile robots, b) the interfaces to MRP's path planner for requesting optimized paths giving as input the real time sensor data,
- The Station Controller responsible for dispatching the scheduled tasks and monitoring the execution status through the robot side and human side interfaces [25].

Considering the above, with respect to the end-to-end system integration the main challenge that had to be met was the diversity of these systems in terms of software programming and communication channels compatibility. For encountering this complexity, the discussed solution deployed a networking architecture based on Robot Operating System (ROS) [30]. The ROS framework, running in Linux environment provides a standard communication infrastructure based on topic publisher / subscribed paradigm customized for robotic systems. The Digital Twin and Station control are developed in C++ directly compatible with ROS system and may be deployer in any Linux PC. The AR based functionalities were created in Unity 3D game engine using Microsoft Mixed Reality Toolkit for UWP applications running in Windows Operating System.

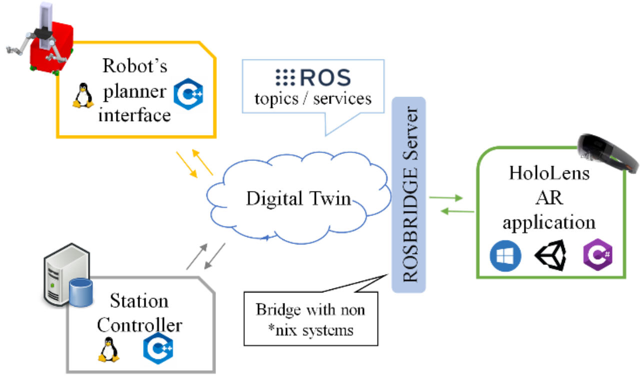

Fig. 6. Overall system architecture.

All the data that are exchanged between the a) AR application, the b) Digital Twin, c) Robot's planner interface and d) Station controller are in form of ROS messages enabling the use of topics and services. For this communication to be realized, ROS# library was used establishing a ROSBridge server. This server allows the communication of non *in system such as the AR tools with a ROS based environment. In that way, the AR tools have direct access to the following information:

- robot's Universal Robot Description File (URDF) file that enables the robot's visualization as well as manipulation based on the robot kinematics,
- robot's base position in the global map for the accurate superimpose in the physical world,
- robot's status information for robot behavior awareness,
- execution status and status feedback provision.

The AR based tools were deployed in Microsoft HoloLens glasses used as the human side hardware interface. The Digital Twin, the Station Controller and the robot side software interfaces were deployed in a Linux PC running Ubuntu 16.04 and ROS Kinetic version. The connection between the hardware components involved was established through a local Wi-Fi network.

Fig. 7 visualizes the exchange of information for the realization of the Direct navigation instructing functionality.

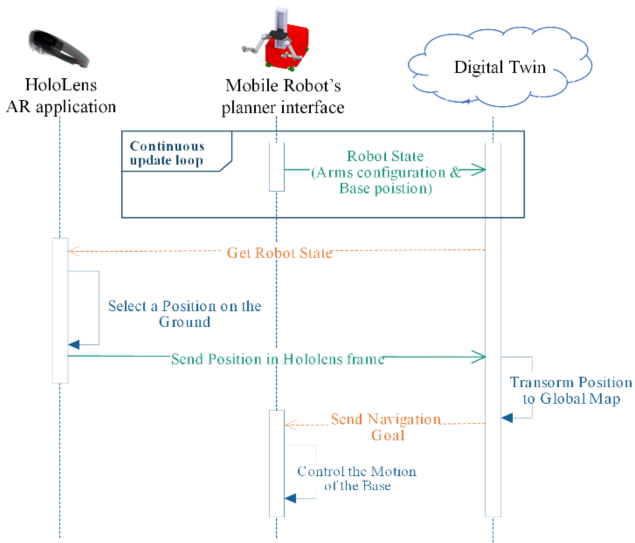

Fig. 7. Sequence diagram for robot direct navigation instructing

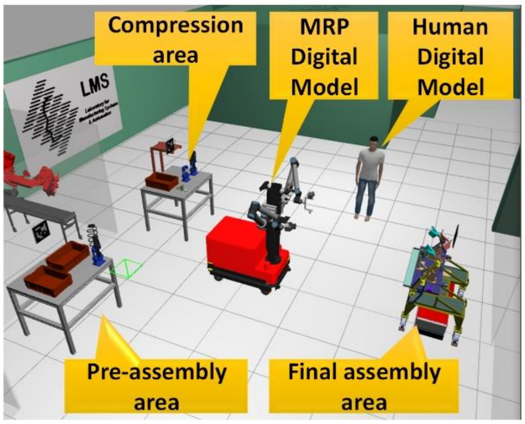

Fig. 8. GAZEBO Simulation environment

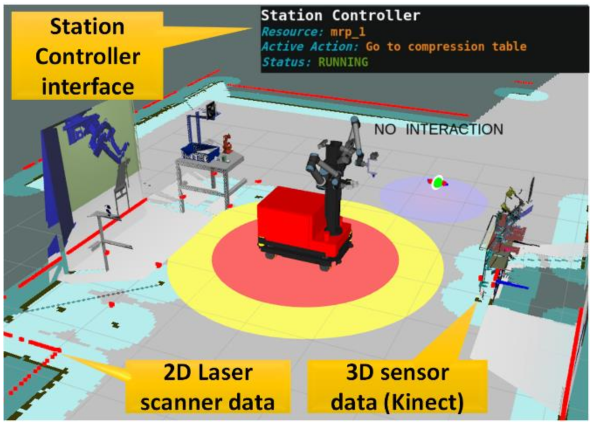

Fig. 9. Digital Twin scene re-construction

4. Case study

The discussed AR based framework has been tested and validated through a case study inspired from the automotive industry and the assembly process of the front suspension for a passenger vehicle. In current industrial practice the assembly required is being performed manually having at least one human operator in each work station. As suggested by Kousi et al. [15], the introduction of mobile dual arm workers may be beneficial for this assembly system in terms of increasing flexibility as well as ergonomics issues. Thus, this study considers the introduction of one mobile dual arm worker (MRP), supporting one human worker on the assembly operations in three workstations: a) the damper pre-assembly area, b) the damper compression area and c) the final assembly of the damper to the disk area. The MRP undertakes the more strenuous operations (heaviest load 7-9 Kg) while the human performs delicate tasks such as cable assembly, pad insertion etc. lifting parts weighting up to 5 Kg.

To be able test the application in a realistic set up, a GAZEBO simulation [31] was set up replicating the real environment (Fig. 8). The digital models of the MRP (URDF) and human where added in the simulation integrating the human side interface and robot controller in the backend.

Fig. 9 visualizes the re-construction of the environment based on the sensor data: a) two laser scanners placed in the mobile platform and b) one Kinect located on its torso. In this way, any instruction send to the robot from the human through the AR tools, is transferred to the robots through the Digital Twin ensuring collision free paths for the new actions.

The developed AR tools, which run on the HoloLens AR glasses allow the operator to visualize the MRP digital model in the physical world and directly interact with it by: a) teaching it how to reach unknown workstations and b) be notified on robot and human operators assigned and active tasks. The user can perform programming of new goals for the robot without having any background and expertise to robotics. The augmentation of new goals into the real world allows the definition of more accurate goals from the user. Fig. 10 presents the visualization of the a) Physical world – field of view of the operator, b) Digital Twin and c) Simulation environment during the different stages occurred in the environment while the human instructs the mobile robot on how to reach the final assembly area.

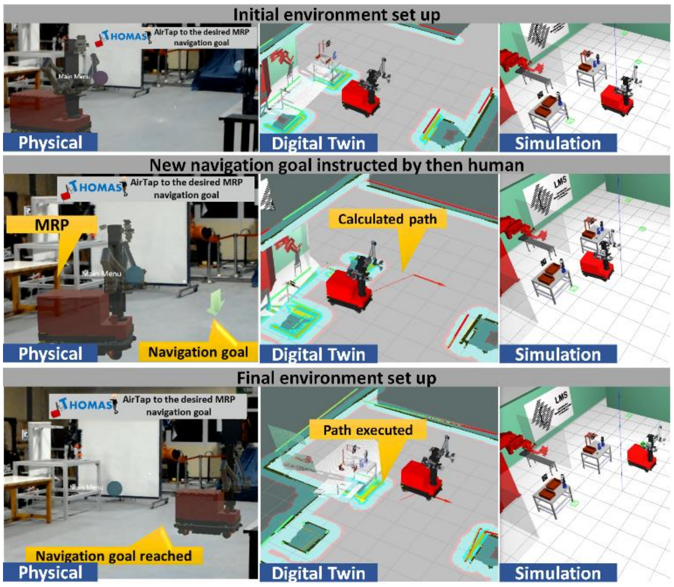

Fig. 10. Direct navigation instructions functionality workflow

5. Conclusions & Future work

Currently there is constant need of increasing EU manufacturing systems flexibility towards meeting the turbulent marker demand. To this direction, flexible resources such as mobile dual arm workers combined with human intelligence will play a vital role in the factories of the future. The key aspect that needs to be addressed in this aspired production paradigm and that is in the forefront of EU research activities is the effectiveness and efficiency of HRI.

Driven by this need, and investigating lessons learned during the last decade from past HRI applications, this study aims to enable human robot interaction exploiting the latest trends in AR technology. The main goal that this application tries to achieve is to provide human operators with novel, easy to use and even more intuitive interfaces allowing them to understand, feel comfortable and interact with the robots without needing any expertise in robotics. Multiple functionalities have been implemented in this direction involving the visualization of robot behavior, the possibility on teaching the robot how to reach unknow workstations and correct its position when changes in the environment occur as well as the possibility to be informed on the real time active tasks and report back in the execution system the manual tasks execution status. Considering that the human operator is able to easily fast on-site re-program the mobile robot and perform correction to its position, it is resulted the minimization of set up time required when geometrical changes need to be made in the assembly areas. The end-to-end system connecting the AR tools with the robot controller is generic enough to meet the requirements of various assembly processes varying the layout and the robot model.

The first experiments have been technically validated for the ease of deployment using HoloLens AR glasses. Having experience on marker-based AR object visualization applications deployed in other AR glasses types, the authors verify that the markerless approach provides a significantly higher stability increasing user experience and feeling. However, existing on the market AR glasses allow lot of room of improvement in terms of human ergonomy before being used in a real manufacturing environment.

Further research should focus on integrating and validating further "smart" wearable devices targeting on reducing the impact related to human operators experience and comfort. The validation of user acceptance and ease of use of the hardware should be investigated. The testing of the application in a physical assembly layout including the physical robot is already an ongoing activity. Nevertheless, the safety aspects raised in these HR collaborative environments are of critical importance. Risk Assessment along with safety measures definition activities towards complying to the safety related EU legislations and standards (ISO / TS 15066, ISO 12018 1,2) are in progress. The authors will extend the AR tools capabilities so as for the human operator to be able to interact with the mobile robot arms as well. Finally, target is to extend the application in other industrial environments where HRC may be beneficial.

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