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Augmented Reality (AR) based framework for supporting human workers in flexible manufacturing

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Abstract

This paper presents an Augmented Reality (AR) application that aims to facilitate the operator's work in an industrial, human-robot collaboration environment with mobile robots. In such a flexible environment, with robots and humans working and moving in the same area, the ease of communication between the two sides is critical and prerequisite. The developed application provides the user with handy tools to interact with the mobile platform, give direct instructions to it and receive information about the robot's and the broader system's state, through an AR headset. The communication between the headset and the robot is achieved through a ROS based system, that interconnects the resources. The discussed tool has been deployed and tested in a use case inspired from the automotive industry, assisting the operators during the collaborative assembly tasks.

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

1. Introduction

In recent years, the concepts of flexibility and reconfigurability are becoming more and more relevant in the fields of manufacturing and automation [1]. The idea of Industry 4.0 is also emerging as a standard for the new and contemporary manufacturing systems [2]. The transition and compliance with these new standards can become, most of the times, a really difficult task for the more traditionally structured systems. At the same time, the achievement of flexibility and adaptability can be the distinguishing feature between a successful and an unsuccessful production system [3].

Human-robot interaction and collaboration (HRI - HRC) can play a key role in these new concepts [4]. The combination of human and robot abilities is inevitable for the achievement of dynamically adjustable and highly versatile manufacturing environments. Thus, the hybrid production model has been receiving a lot of attention recently, both in the research and industrial fora. There have been several research projects [5-8] that aim to combine the high strength, speed, repeatability, and low error rates of the robots with the intelligence, advanced decision making, and dexterous manipulation of small or sensitive parts that human operators can easily undertake.

However, the realization of such flexible and adaptable hybrid production systems, introduces high levels of complexity [9]. There should be tools, able to conceal this complexity from the operators and help them communicate with the rest of the system, interact with the hardware, and make immediate and educated decisions. These tools must offer easy to use interfaces, with intuitive interaction mechanisms, that should not distract the workers (physically or mentally) from their other tasks.

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Different approaches towards the achievement of this seamless communication and interaction have been proposed. Devises such as tablets [10] and smartwatches [11] have been used as interaction media. The user can exploit their portability, getting notifications and sending commands through on-screen graphical interfaces. However, these approaches lack in the immediacy and intuition aspect. In other suggestions, Virtual Reality (VR) headsets are used as a more immersive way of interaction [12], but in this case, the user is cut off from their environment.

The Augmented Reality (AR) technology can offer the immersive and intuitive nature of a VR approach, while allowing the user to be fully aware of their surroundings when interacting with the virtual information and objects. AR tools, realized in the form of tablet applications, or with the use of head-mounted displays (HMDs) are in the scope of research in the last years [13-15], since the advancements in the field give space for complex, real-time interaction and visualization.

In the context of this study, an AR tool has been developed, with the intention to assist the operator's work in a flexible manufacturing environment. In this environment, human and "smart" mobile robot operators are working in parallel, sharing space and tasks. The AR application is running in Microsoft's HoloLens AR headset and is responsible for informing the user about his/her tasks, any exceptions or emergencies of the system, and the way these can be overcome. In addition, the operator can give direct instructions to the Mobile Robot Platforms (MRPs) and visualize safety data. The whole system is based on a ROS platform, which allows end-to-end integration, from the human operator's side, to the level of the robot's controllers, through a hierarchical structure of handlers, instructors, task planning modules and a real-time Digital Twin of the whole system [16].

2. Approach

Following the previous analysis, the main goals of the augmented reality framework, that this study proposes, are the seamless collaboration of human and robot operators, as well as the support of human operators inside a complex and sometimes unpredictable system, because of its flexible nature. The application focuses on the ease-of-use and intuition aspects, so it can be used by the operators without any specific knowledge or training. One of the main goals of the proposed software is to provide an interface that will be self-explainable, and the users will be able to figure out on their own the provided functions, without any external guidance.

More specifically, the software suit can assist the operator's work and increase the overall efficiency of the system through the following functionalities:

- Supply of information about the operator's current task.
- Feedback acquisition from the user to the system, about the outcome of their tasks.
- Provision of real-time information regarding safety.

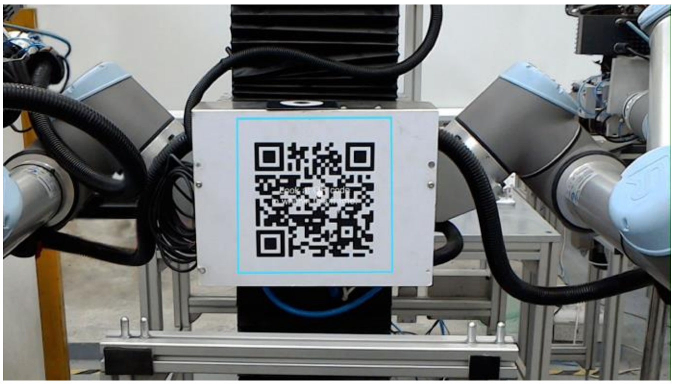

Fig. 1. Initialization - QR Code scanning

- Support of direct instructions to the robot platform. The user can immediately move the robot by pointing the desired location.
- Provision of specific instructions, coming automatically from the system, on how to overcome certain failures or exceptions that may occur during the execution.

With the above functionalities the operators can get full support on their tasks during both the programming and execution phase of a production scenario. Additionally, the fact that the provided features and information come directly and automatically from the controlling system, contributes to the main goal of the study, which is the achievement of high flexibility and reconfigurability.

The following subsections deliver a more detailed description of the developed features and the way that they can be used to support the operator's work.

2.1. Software Initialization

At the initialization of the application, there needs to be a connection between the real and the augmented world. A QR code, which is placed on the Mobile Robot Platform (MRP), is used as reference for the definition of the user's position. The user only has to look at the code and perform an AirTap gesture to perform this calibration process (Fig. 1). After that, they can verify the successful calibration and optionally refine it by looking and dragging a hologram that appears over the actual robot. With this procedure, the AR application is able to visualize space-dependent data in the correct place and start tracking the movement of the moving parts of the system, like the MRP.

2.2. Current Task Information

As mentioned before, the application provides notifications to the user about their current task. These notifications appear in the place (workstation) where the task has to be performed along with a short textual description, as shown in Fig. 2. In addition, the user can inform the system about the completion of their task with the press of the "Task Completed" button, which is also depicted in Fig. 2.

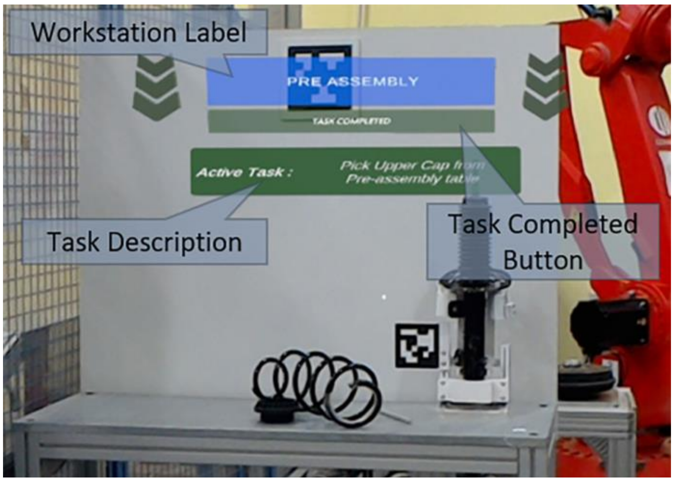

Fig. 2. Current task information / Task completed button

Fig. 3. Safety fields' visualization

2.3. Safety Data Visualization

The application also supplies the operator with data that can enhance the system's safety. The user receives notifications when the robot platform is moving, in order to be aware of the potential danger. In addition, in case of any violation, the application visualizes the safety fields around the robot, as they are produced by the robot's laser scanners (Fig. 3). Also, the user can turn on or off this feature on demand. In this way, the operator can understand clearly which space around the robot is safe to be in. This feature is also helpful in the process of the violation identification, as the operator can see immediately which zones are infringed and easily remove the object that caused the violation.

2.4. Robot Navigation Instructions

One of the most important features of this framework is the easy programming interface that it provides. The operator can utilize the robot's planners and controllers within the application in an easy and intuitive way. Two different modes of this functionality are available:

1. The operator can command the robot to navigate to a certain workstation, by tapping on a button that is displayed over the workstation.
2. The operator can click to any point inside the shopfloor to instruct the robot to navigate to this location.

In both cases, a hologram appears in the user's field of view, that designates the final position of the robot, as well as a line that indicates the path to be followed by the platform. Hence, the operator is informed in advance about the robot's actions in order any unexpected behavior to be avoided. A cancel button is also available that can be used from the operator to stop the platform's movement.

2.5. Failure/Exception Handling Information

In cases of emergencies, failures, or exceptions the operator gets informed with popup notifications that describe the type of emergency and give specific information about the way it can be overcome. When the required steps get performed, the operator can resume the execution by clicking on the OK button.

In the investigated execution scenario two types of such events are identified by the system, namely the Safety Field Violation event and the Emergency Stop event. In the first, if the safety fields of the robot get violated, the operator is informed with a Zone Violation notification.

This notification includes a description of the failure and the proposed recovery steps. In the second, if for any reason the emergency stop of the robot gets triggered, an Emergency Stop message pops-up to the user's field of view, informing him/her about the state of the robot and the recovery steps. This message is shown in Fig. 5.

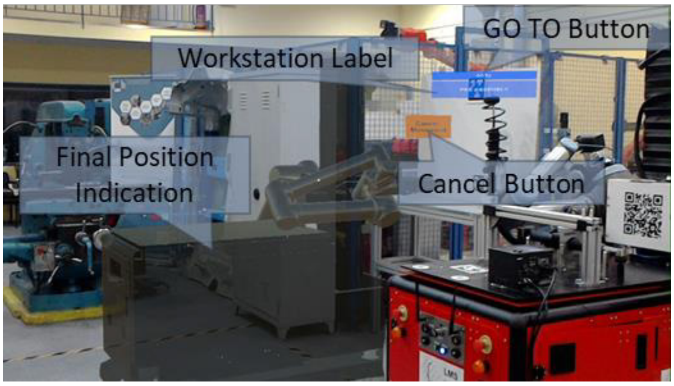

Fig. 4. Direct robot programming - Navigation to workstation

Fig. 5. Emergency handling notification

3. System Implementation

The proposed augmented reality framework is built over a ROS-based platform. The Robot Operating System, which is running on different Linux machines inside the system, provides two main advantages for the achievement of an end-to-end integration. The first one is the unified communication between all the individual components and modules of the system. The robot, as well as all the other resources, sensors and controllers are interconnected through a unified ROS infrastructure, that handles the communication and data exchange. The second is the hardware abstraction, meaning that the same controlling interfaces can be used for different robots or other automated machines, contributing to the reduction of complexity, and easier scaling.

In a structural perspective, the AR application is the module that connects the human resources (operators) with the rest of the system. A broad schema of the system's architecture is shown in Fig. 6. In this schema there are depicted the entities of the Digital Twin and Station Controller, which play a dominant role in the operation of the overall system.

- The Digital Twin is providing all the environment information based on CAD models of the layout and the different components of the system. It is also responsible for the gathering and structure of all the real-time data from the various sensors of the system, which are used from the planning and controlling modules and for visualization purposes.
- The Station Controller acts like the orchestrator of the different, modules and resources. It is responsible for breaking down the scheduled tasks into specific actions and assign them to the available resources. It is also responsible for the monitoring of the execution and the provision of recovery strategies and instructions in case of failures.

The way that the Digital Twin and the Station Controller interact with the AR interface should comply with the unified communication protocol of ROS, that was mentioned above. Namely with the use of ROS Topics, Services and Actions that are passing Messages between the Nodes of the system. The way that our AR application complies with this convention is with the use of RosBridge server [17] (in the side of ROS) and the ROS# library [18] (in the side of HoloLens).

With the RosBridge server, a TCP-like WebSocket is created in ROS. This socket sends and receives messages that are formed as JSON objects, according to the ROSBRIDGE 2.0 protocol, over a local network. At the other side, the ROS# library is providing the same WebSocket infrastructure for programming inside the Unity engine environment and .NET protocol. ROS# also provides other useful components, like Publishers, Subscribers and Action Servers/Clients that can handle the information included in the incoming and outcoming messages.

Via this connection the AR tool sends:

- The feedback of the operator's tasks
- The goal positions for the robot platform

And receives:

- Information about the operator's current task
- Positional information of the different workstations and other static elements
- Robot status information like the current position of the robot, moving or operational status.
- Unified Robot Description Format (URDF) files and other 3D of 2D object representation files that are used for visualization.

For the correct visualization of the objects in the augmented space, as well as for the accurate provision of navigation goals to the robot platform the calibration process, that was described in 2.1, is necessary. The detection mechanism of the QR code is based on a .NET (C#) port of the open source library ZXing (Zebra Crossing) [19]. With this marker detection the calculation of the marker's position with respect to the headset's world frame is achieved. By using this value in combination with the MRP's current position, we can determine the operator's position in the ROS environment's coordinate system and have the two "worlds" connected.

The AR functionalities, regarding the visual representation and interaction mechanisms, were programmed in Unity with the tools provided by Microsoft's Mixed Reality Toolkit (MRTK).

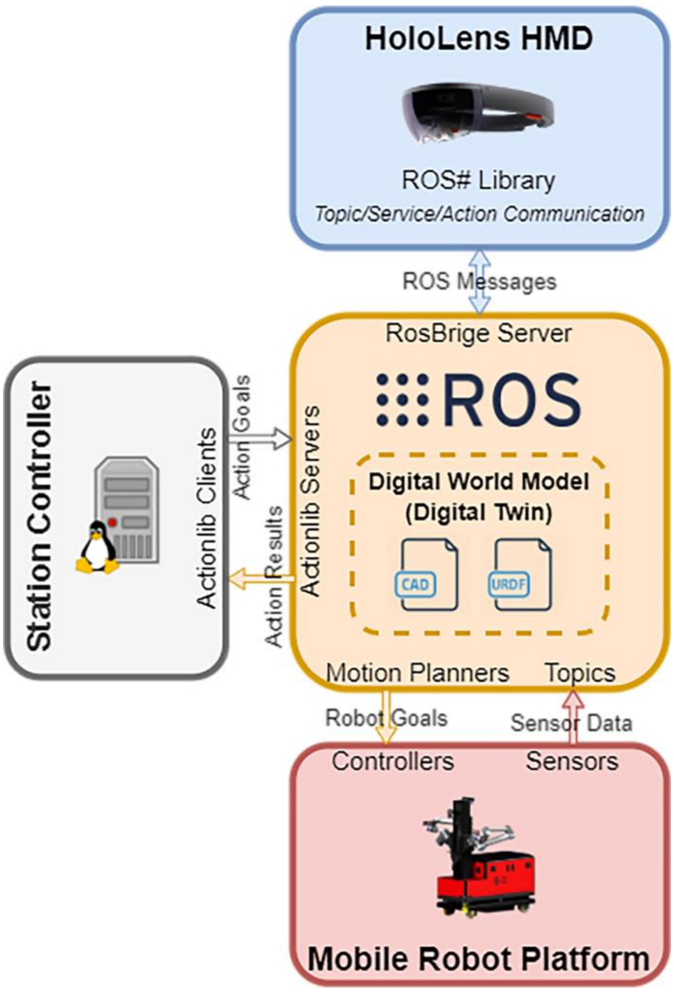

Fig. 6. Overall system architecture

The digital work instructions, both for the operator's tasks and the recovery steps, are stored in the system's database. The textual descriptions are preprogramed, and the Station Controller can retrieve them on runtime and send them to the user based on the assembly schedule and certain events that may occur in the shop-floor.

4. Case study

The proposed AR framework has been tested and validated in a case study, deriving from the automotive industry, in which the assembly of the front suspensions of a passenger vehicle is taking place. Currently, the necessary tasks are performed manually from three human workers in four workstations. In these workstations, the suspensions (dampers) get assembled by putting together all the needed parts, compressing the spring, attaching the compressed damper to the disk and inserting some cables. As it has been proposed, this production system can profit form the incorporation of dual arm robot operators with autonomous movement and abilities that improve the H-R collaboration [20].

With this hybrid approach the system can become more versatile and flexible. Additionally, it can exempt the human operators of the most ergonomically inefficient tasks, like the repetitive lifting and carrying of parts, which can weigh up to 7 Kg. In particular, with the proposed assembly system, the operator has to perform three separate tasks:

- Place some parts on the pre-assembled damper at the Pre-Assembly workstation.
- Prepare the damper before the compression action, at the Compression Machine workstation.
- Insert some cables and screws to the MPP workstation.

Additionally, the operator may need to take over some of the robot's tasks, if this is necessary, or to recover the system in cases of errors or exceptions.

In this specific use case, the robot has to navigate through different workstations and manipulate or carry multiple parts, using spatial and object localization techniques. At the same time, the tasks assigned to each resource (human or robot) are not strictly determined, but they can be reassigned during the execution based on several events. The fluid nature of the working environment and the execution schedule can lead to unique situations in every cycle.

Moreover, the reliance on multiple sensor data, for the performance of each action, results in a non-deterministic approach of the processes. This uncertainty can cause exceptions or errors. The proposed framework handles these situations by guiding the worker through the solution of such events, as described in Section 2.

The AR application offers to the operator an immediate and intelligible way of interaction with the system, being the medium through which he or she can get informed about the currently assigned tasks and about the state of the robot.

As mentioned before, the developed framework can assist the operator or the engineer at the programming of the robot, by teaching new waypoints for the platform to move towards. This part is important since this system aims to be highly reconfigurable, so the need for teaching new robot positions in an easy and quick way is frequent.

Fig. 7 Operator's view of the hybrid workcell

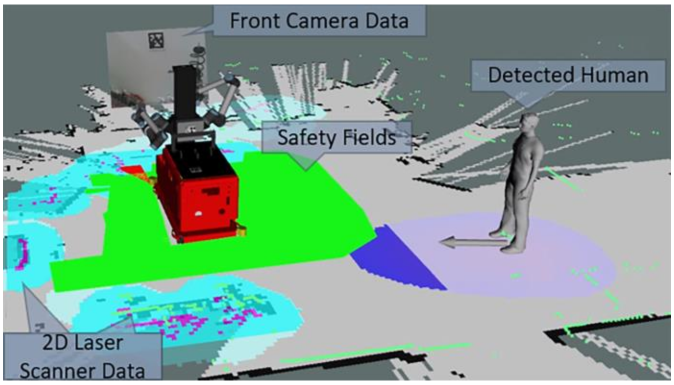

Fig. 8. The digital representation of the shopfloor

Fig. 7 and Fig. 8 depict the same snapshot of the shop-floor, once from the user's perspective, and once through the view of the Digital Twin of the system. Fig. 7 is showing the operator's view of the overall workcell, through the augmented reality application. In this figure, many of the features of the application are present, namely: a) the workstation labels, b) the active task information, c) the robot state notifications, and d) the safety fields visualization. In Fig. 8 the "system's view" is depicted through the real-time 3D digital reconstruction in the of the working environment in RViz [21], which is based on the data of multiple sensors placed on the robot.

5. Conclusions & Future work

The contemporary tendencies towards the Mass Customization and Industry 4.0 concepts are pushing the manufacturing systems to new standards regarding their structure and function. The achievement of flexibility and reconfigurability is becoming a necessity for the factories that aim to be efficient and competitive. The approach of Human – Robot Collaboration in hybrid production lines, with simultaneous operations performed by both counterparts in a common environment, is been considered as a key solution for the realization of the above characteristics.

This study focuses on the development of a framework that can facilitate the introduction of flexible production techniques and HRC in a manufacturing system, by assisting the operator's interaction with the robots and the overall system. The augmented reality approach, around which the proposed framework is built, supplies the workers with powerful yet easy to use tools. The AR interfaces can blend in the working environment and enrich it, making the interaction with them natural and intuitive.

The developed system is also easy to be extended or adjusted in different working cells, because of the hardware independent character of ROS, and the schedule management abilities of the implemented Station Controller module. This is very important, because it can make easier any reconfiguration attempts.

Through the testing of this AR tool, inside the automotive industry use case, and the conduct of a user evaluation with students of the University of Patras, the following were observed. a) The time needed for programming navigation goals was reduced. b) The errors in the programming were also reduced, because of the visualization of the final position in the real space. c) The idle time of the system in cases of errors has been reduced. d) The people who participated in the evaluation where more confident in the execution of their tasks when they were using the application.

All the evaluation participants, regardless their familiarity with AR, rated their overall experience positively. Only one out of the eight users found the robot programming easier with the PC interface and none of them had problems in recovering the robot after the two failure scenarios (Zone Violation and Emergency Stop). Half of the users answered that they preferred the AR instructions for the execution of the assembly tasks. The other half answered that the AR instructions were equally helpful with the ones written on paper.

The main drawback of this implementation was detected in the ergonomics of the HoloLens headset, since all the evaluation participants suggested this as the weak point of the system. Despite its advanced technological features and its overall functionality, it is a bulky device with excessive and poorly distributed weight. Hence, long periods of usage can cause discomfort and pain to the user, making it ineligible for full scale usage in a working environment.

Further research could be concentrated on the deployment of this framework to other systems. The amount of time and effort needed for the deployment of the tool is having a big impact on its efficiency. Ways to increase its adaptability may need to be examined. Another aspect that can be further investigated is the safety, with work that will focus on the standardization of the protective measures.

Acknowledgements

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