Augmented Reality for Digital Manufacturing

Conference Paper · June 2018

DOI: 10.1109/MED.2018.8443028

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Augmented Reality for Digital Manufacturing

Andreea Blaga Levente Tamas

Abstract—**The focus of this paper is on enhancing the possibilities of manufacturing operations by taking advantage of augmented reality (AR) technology and highlighting its benefits by implementing a product manufacturing case. The latter appearance of augmented headsets, such as the Microsoft HoloLens allows more opportunities for creating innovative solutions. After introducing concepts about smart manufacturing, improvements regarding human-robot collaboration in assembly tasks are presented. The developed scenario is based on the integration of AR, a cobot, a see-through device, a digital twin and an algorithm for assembly visualization. This approach pledges a compelling interaction of the 3D real and virtual unit, so that the operator can work in a more intuitive environment. This methodology has been implemented on a assembly case to investigate users' enhanced perception using the virtual world while cooperating with the robot.**

Index Terms—**Augmented reality, manufacturing, human-robot collaboration, assembly**

I. INTRODUCTION

In manufacturing processes, there is an ongoing need of improving quality of products, as well as workers' productivity. Such an approach is using digital manufacturing, where data management systems and simulation technologies are commonly used for improving manufacturing before commencing production. Over the past years, this concept has been considered as a rising set of technologies for lessening product development cost and time, taking into consideration the need for customization, increased quality, and faster reaction to the market [1]. Smart manufacturing manages data through a product's life cycle, while aiming to create flexible manufacturing processes that have a rapid response rate to changes. Furthermore, the process information is accessible on demand and is used across the entire network. Some of the key technologies in this trend include human-machine interfaces and advanced robotics.

Augmented Reality (AR) is in continuous development in virtual reality research. Such a system combines the real world seen by the user with a generated virtual scenario, adding extra information. This boosts a person's cognition, constructing a unitary structure in which, ultimately, individual real and virtual elements cannot be differentiated. Some researchers define AR having the requirement of using head-mounted displays (HMDs). In order to avoid the restriction to definitive technologies, AR can be described as a system with the following characteristics: combines real and virtual; interactive in real time; 3D registered view. This definition allows other technologies, such as projection and mobile devices, to be categorized, while retaining the essential elements [2]. The interaction with 3D models is executed more smoothly than through a simulation or computer screen, making them more accessible when computer access is difficult or limited time is available for receiving support. Thus, this technology can be used in industrial settings, helping the manufacturers to reach faster their targets. Furthermore, AR has proven to be an innovative and effective solution in helping and solving critical problems by simulating and improving manufacturing processes before being carried out in the production line [3].

In various industrial applications, the primary executor of the assembly process is a human operator. This is because certain operations require human intuition. Different material variations used often show unpredictable but compliant behavior. Moreover, multiple operators are doing coordinated activities in each station [4]. However, the existence of humans and robots working under a collaborative scenario brings potential benefits. The combination of a robot's reliability, precision and strength with a worker's perception, intuition and flexibility is invaluable, especially in scaled-down production, where reshaping and the ability to adjust to changes are of considerable importance, see Figure 1.

Smart manufacturing using AR technology, along with human-robot collaboration, is a profitable scenario that includes key characteristics of these technologies. Blending perception enhancement using virtual elements with robot robustness and accuracy, the manufacturing process becomes a well-defined environment which manages product life cycle efficiently, greatly reducing cost and boosting teamwork.

A. Motivation

Our target application was a augmented reality system for human-robot collaboration in daily manufacturing pro-

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Connected!

init: x: -0.0463 , y: 0.0001 , z:
1.5:
0.2458489, 0.2753726,
0.6578321
0.2458489, 0.2753726,
0.6578321
```

Fig. 1: Augmented preview of final product

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cedures. The main objectives are linked to the development of 3D vision potential of the industrial worker using head-mounted display (HMD) devices, as being an eye-level equipment that facilitates immediate perception of the mixed AR scene.

By using an augmented reality approach, the final product can be simulated by visualizing virtual assembly sequence elements even before the actual production begins, as visualized in Figure 1. In the design stage, the product model to be assembled can be decomposed in key sections, having certain assembly sequences. In production, the operator will acquire the appropriate visual data using these conditional sequences, which can be automatically adapted to the current assembly phase. Product development can greatly benefit from this scenario, leading to shorter lead time (latency between the initiation and execution), reduced cost and improved quality [5].

B. Problem description

The first step in 3D assembly visualization is achieving real-time synchronization between real and virtual in the shortest feasible time. The subject of constant space calibration needs to be considered, in order to keep the real and virtual scenes spatially aligned in the final structure of one steady working space [6]. For this purpose, the marker method can be used in order to detect the position of crucial elements, as well as calibration of the HMD can be achieved. Moreover, the human-robot working environment needs to be adjusted, by computing spatial links between the robot's workspace and operating device, in order to attain an exact connection between the positions and orientations of all equipments in the scene.

A crucial step in developing an AR application which collaborates with a robot is taking into consideration the discrepancy between the physical reference points of each technology, which define their individual location. In this situation the robot can receive inaccurate information about the worker's whereabouts, while the worker can get deceptive input data regarding the robot's workspace. To rectify this, the appropriate alternating transformations need to be made, as well as properly computing the position of the virtual elements in the robotic workspace. Issues regarding human-robot cooperation safety are worth mentioning, where human awareness and vigilance is not sufficient.

AR applications demand more advanced hardware and software. Special equipment such as HMDs, and accurate trackers are required [3]. From the hardware point of view, the optimal wearable equipment needs to be chosen, so that is beneficial to all concerned parties. A small, light and portable device should be taken into consideration when discussing about manufacturing activities, which must support the operator the whole working day, along with convenient field of view, to prevent critically limiting the information that can be displayed at a time [7].

C. Related work

When discussing about smart manufacturing, AR is one of the innovative technologies that has the potential to reduce process execution, in consequence lowering the cost of production and labor. However, this category of operations present a number critical issues that may decrease productivity. The main concern is human error, where intricate procedures are prone to negative spikes in recalling accurate directions to fulfill, deficient training presenting a considerable part also [8]. With AR, inaccuracies are greatly cut down as a result of visualizing individual stages of production, so that any inconsistencies may be intercepted and eliminated. Additionally, simulating distinctive fabrication scenarios is a strong benefit when considering the cost of real equipment. Damage to components is ceased, entire events occurring virtually.

Developing adequate manufacturing processes using AR technology has the advantage of enhancing human perception through a compilation of interface elements used for common tasks in industrial settings. In such an environment, a crucial aspect is providing specific information for a particular scenario, at an appropriate time and place, in order to obtain the desired outcomes.

The above mentioned advantages may be integrated into production applications, defining and validating operation sequences to carried out, with respect to a customized model. Using AR means graphical assembly instructions are designed and displayed on demand, while virtually superimposing the associated sequence on the actual product [9]. Thus, recurrent calibration must be achieved in order to keep the real and virtual elements spatially aligned in one, steady form.

Concerning real-time detection of relevant objects, an image-based approach may be applied. Markers are placed in space, used as an anchor between real and virtual items, which can be recognized by a camera. Predecided patterns are used for identification, matching the position and orientation of the camera with an offset to the determined transform belonging to the virtual element, which is rendered over the real world, conveying the impression of an homogeneous view [10]. Consequently, accurate camera parameters may be decisive terms in increased accuracy and diminished lens distortion in see-through devices.

In this context, a realistic model of the product to be operated on should be created, based on a 3D CAD object. A consistent organization of the model properties into a specific ranking can generate proper assembly sequences [9].

D. Contributions

This paper focuses on presenting feasible scenarios in improving human-robot collaboration regarding assembly tasks in manufacturing execution systems (MES). Integration of AR technology with the robot is done by implementing an application able to communicate with the robot workspace, while transmitting and receiving data regarding the worker's position, as well as robot's points of interest.

In assembly, the physical object has a digital twin, a CAD model that accurately resembles real features. This virtual model is organized into multiple elements, having determined a specific ranking in order to have a convenient assembly sequence.

The implementation of AR applications in industrial settings is exposed to difficulties regarding objects with reduced textures, having shiny surfaces - these properties can cause inaccuracies in 3D pose. Additionally, the lighting conditions in a particular environment strictly restrict the representation definition and accuracy. This can reduced by using leading devices, such as Microsoft HoloLens, which can better manage abrupt changes in lighting [11].

II. COBOT USE CASE WITH AR

A. Overview

The scope of possible use cases is certainly vast and involves a variety of manufacturing operations, from production to maintenance and training. Here, the focus is on operations that require step by step procedures, managing risk and safety of operators and equipments, as well as improving design and visualization in the appropriate phases. AR improves tasks completion time, in addition to smaller errors.

The leading concern is the constant communication and data transmission between AR using HoloLens, and the robot workspace with Robot Operating System (ROS). Information regarding the device's current pose, along with the marker's pose found by using marker detection, is sent to ROS. This data is converted into ROS messages, and used as frames in the overall transform (tf) tree. In turn, ROS sends back right end-effector pose, used for the assembly task in this case. This is used for accurate augmentation of the next piece which needs to be assembled into the final product, as it can be seen in Figure 1.

B. Application details

Firstly, the HoloLens camera needs to be calibrated in order to get best tracking accuracy, especially when looking directly into a flat marker. For this device, it also helps removing lens distortion in the displayed video image. To achieve this, the tool ARToolKit was used [12], combined with OpenCV camera calibration. The input is a chessboard pattern, standard for these tools. Using specific calibration functions, camera parameters can be found.

For distortion, OpenCV considers the radial and tangential factors. Consequently, the five distortion coefficients are presented, where (k_1, k_2, k_3) are the radial factor parameters, while (p_1, p_2) are the tangential ones, and are constants:

$$Distortion_{coefficients} = \begin{bmatrix} k_1 & k_2 & p_1 & p_2 & k_3 \end{bmatrix}$$

The following formulas can be used for the radial factor, where in this case (x_{radial}, y_{radial}) is the corrected position of a pixel:

$$x_{radial} = x \cdot (1 + k_1 \cdot r^2 + k_2 \cdot r^4 + k_3 \cdot r^6)$$

$$y_{radial} = y \cdot (1 + k_1 \cdot r^2 + k_2 \cdot r^4 + k_3 \cdot r^6)$$

In the input image, for a pixel at position (x, y), on the output image it will be changed to (x_{radial}, y_{radial}). The existence of the radial distortion is visualized as the fisheye effect. Since the lenses capturing the image are not flawlessly parallel to the imaging plane, the tangential distortion appears. This can be adjusted using the formulas, where $(x_{tangential}, y_{tangential})$ is the corrected position of a pixel in terms of the tangential factor:

$$x_{tangential} = x + [2 \cdot p_1 \cdot x \cdot y + p_2 \cdot (r^2 + 2 \cdot x^2)]$$

$$y_{tangential} = y + [p_1 \cdot (r^2 + 2 \cdot y^2) + 2 \cdot p_2 \cdot x \cdot y)]$$

For homography mapping, having (X, Y, Z) parameters in 3D space, the following formula can be used [13]:

$$\begin{bmatrix} x \\ y \\ w \end{bmatrix} = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

The existence of w is explained by using the homography coordinate system, where $w = Z$. The parameters to be determined are the camera focal lengths represented by f_x and f_y, along with pixel coordinates of the optical centers (c_x, c_y). The matrix consisting of these four parameters is known as the camera matrix. Using the calibrated resolution, the matrix is scaled with respect to the current resolution.

The calibration process implies the computation of these two matrices, using basic geometrical equations and chosen calibrating objects. In this case, a classic black-white chessboard was used. Multiple snapshots from different positions and angles of the input pattern should be done, in order to obtain accurate parameters with an error as close to zero as possible.

Using ARToolKit, virtual elements can be superimposed into the real scenario using a see-through display, HoloLens in this case. Square markers are recognized and tracked using this tool, used for calculating position of a certain virtual object in 3D space. The camera captures video of the camera view and sends it to the software which, in turn, searches through each video frame for any fiducial markers. If any is found, and the pattern is matched and identified, the software computes both the position of the square, and the pattern orientation, relative to the camera. Once these are known, a virtual model is drawn, with relative calibration as seen in Figure 2.

In order to integrate ARToolKit with HoloLens, a Universal Windows Platform (UWP) wrapper was used, which contains the marker training (recognition and tracking) as well. Using the determined camera parameters and the selected marker pattern, one can verify the accuracy of the parameters and visualize a custom virtual object, its position being determined by the marker recognition and tracking algorithm embedded in the kit.

The connection between the HoloLens application and robot workspace is done by using a common communication protocol, through Rosbridge package. This is useful in providing an interface between JSON and ROS, especially for non-ROS application, as it can be seen in Figure 3. To be able to send HoloLens data to ROS properly, custom C# classes were used in a way to simulate the equivalent message type received by the ROS service. In this case, current position and orientation of the HoloLens is being sent, along with the initial marker transform of the tracked pattern. In the receiving end, the callback from the service will take the data and, using a custom ROS publisher, will publish the data on the /tf topic. Then, the transform between the right end-effector of the robot and the initial position of the HoloLens is searched, so that the transform of the robot element will be in the latter's coordinate system. This will be the response sent back to the HoloLens application by the service. The transformations can be visualized in Figure 4.

Unity3D, the software means to develop on HoloLens, uses a left-handed coordinate system, while ROS operates with a right-handed coordinate system, a conversion from left-handed to right-handed and back needs to be done. In order to do this, for the left-handed system, an axis should be reversed, along with the w component of the rotation quaternion. In a matrix-vector form, the conversion from a left-handed point P_l to a right-handed point P_r can be written as:

$$P_l = \begin{bmatrix}-X\\ Y\\ Z\end{bmatrix} = \begin{bmatrix}-1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{bmatrix} \cdot \begin{bmatrix}X\\ Y\\ Z\end{bmatrix} = Diag(-1,1,1) \cdot \begin{bmatrix}X\\ Y\\ Z\end{bmatrix}$$

Even if now HoloLens' system is expressed as a right-handed one, some computations need to be done in order to fully express it in robot's coordinate system. In this case, a rotation on X, followed with a rotation on Z is enough to achieve this. In a matrix-vector form, to express a transform T_G of a point $P_G = \begin{bmatrix}X\\ Y\\ Z\end{bmatrix}$ in ROS' coordinate system, the conversion can be computed as the composition of the transforms T_H^X and T_X^G, expressed as:

$$T_H^X = \begin{bmatrix}Rot_X(-90^\circ) & P_G\\ 0 \quad 0 \quad 0 & 1\end{bmatrix}$$

and

$$T_X^G = \begin{bmatrix}Rot_Z(90^\circ) & P_G\\ 0 \quad 0 \quad 0 & 1\end{bmatrix}$$

Finally, the transform composition can be simply defined as:

$$T_H^G = T_H^X \cdot T_X^G$$

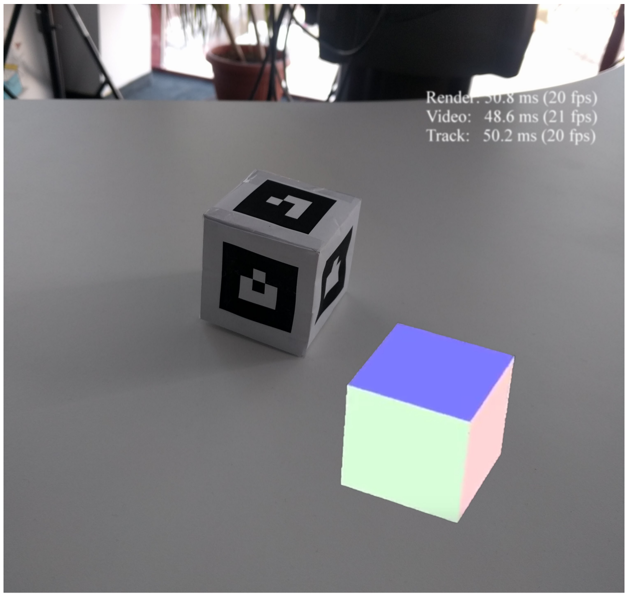

Fig. 2: Verification of marker training during calibration

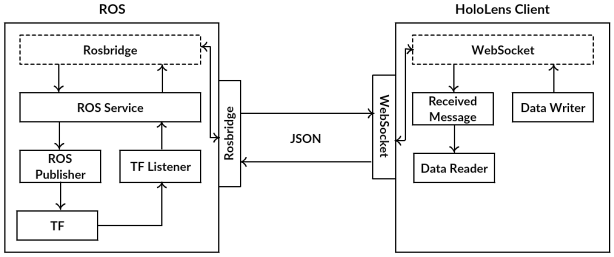

Fig. 3: Rosbridge communication between cobot and AR device

To find the transformations from ROS' to HoloLens' coordinate system, the inverse need to be done, meaning that, for a point P_G, a rotation on Z, then one on X is necessary. This transform is the multiplication between transforms T_Z^G and T_Z^H, defined by:

$$T_Z^G = \begin{bmatrix}Rot_Z(-90^\circ) & P_G\\ 0 \quad 0 \quad 0 & 1\end{bmatrix}$$

and

$$T_Z^H = \begin{bmatrix}Rot_X(90^\circ) & P_G\\ 0 \quad 0 \quad 0 & 1\end{bmatrix}$$

This can be simply written as:

$$T_G^H = T_Z^G \cdot T_Z^H$$

Furthermore, the conversion from the right-handed HoloLens to the classic left-handed, the same inversion as above needs to be done.

C. Relative pose estimation

In order to perform an extrinsic calibration of the HoloLens camera with respect to the robot base, computing the transformation between the two, a custom camera-robot calibration package was used. Given a set of pose measurements of the robot end-effector and HoloLens attached to it, the pose of the static coordinate system of the device is computed, along with the device position, relative to the end-effector [14]. This algorithm implies that the position of the HoloLens with respect to its start position is known (motion tracking), this start position does not change against robot base, while the pose of the end-effector in relation to the base is already determined. Furthermore, multiple samples

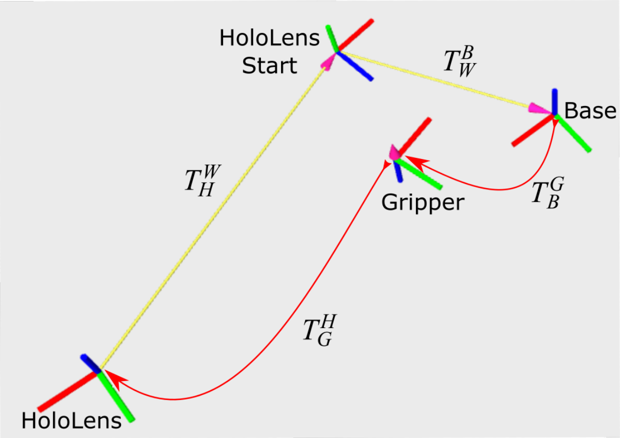

Fig. 4: Frames used in the application

are used to find the unknown elements. These are collected by moving the end-effector in different positions and angles, covering a rather large range of movements.

With more measurement samples, the relative calibration can be improved, so that the virtual object can be accurately aligned with the real elements.

D. *View augmentation*

The physical object to be assembled has a digital twin, in the matter of a CAD model, which accurately imitates the real characteristics. This virtual model was split into multiple pieces, in such a way that a specific ranking can be determined in order to organize a convenient assembly sequence, as seen in Figure 5. In order to have a real product to operate on, 3D printing can be considered also as an appropriate solution.

Fig. 5: CAD model with augmented part (blue)

Then, the real assembly elements can be used in synchronization with the application. At a certain moment, the operator will visualize the corresponding element to be assembled and get information about assembly instructions and fitting pose. In this case, the right end-effector of the robot has attached a part of the assembly, while the next part will be visualized through HoloLens. Using the response data from ROS, which is the right end-effector pose in the device's coordinate system, is used to define the pose of the virtual element, with respect to the current position of the real object.

III. EXPERIMENTAL RESULT

For the extrinsic calibration of the HoloLens, different approaches were attempted in order to obtain a minimal calibration error. At first, using the camera-robot calibration package provided, at the start of the application, the worker needed to change the position of the HoloLens while detecting the marker on the robot's right end-effector, in addition to moving its arm to a wide range of poses. This proved to be inefficient and a strain on the user due to the task not being optimal for a single person. Moreover, just a single iteration of the marker not being detected would give a poor result. Attaching the device to the end-effector greatly reduces the first potential daily task, making the calibration more accessible, as seen in Figure 6.

Fig. 6: Calibration procedure with Baxter and HoloLens

As final application involves the CAD model of a light bulb, where its' socket is attached to the right end-effector of the robot, with its corresponding marker fixed on its arm. After starting HoloLens, the extrinsic calibration needs to be carried out. A good calibration will give an accurate synchronization between real and virtual, the pose of the two being spatially aligned properly. Several iterations could be needed. Then, the operator will be able to visualize the virtual elements in the proper place of HoloLens' coordinate system.

Additionally, experiments were done in order to test the calibration between the Baxter robot and HoloLens. For repeatability, the tests were realized in three phases. Firstly, the device was attached to the right end-effector, the ordinary calibration was completed and the position with respect to the gripper was recorded. Then, the HoloLens was attached to the other end-effector, registering once again its' position. In the end, the transform of the virtual model of the end-effector was compared with its' corresponding real element, measuring the degree where the virtual unit is overlapping the real one.

After repeating the mentioned above process 11 times, the obtained empirical data was handled using two measures: mean and standard deviation. First off, the Euclidean distance between each sample and the mean attained for each component of the position of the HoloLens related to the end-effectors was computed. For each end-effector, the resulting errors were used in concluding the mean and standard deviation of this data. As can be seen in Table I, the measures are much lower for the right end-effector than the other since the calibration was done using the first one. Then, the superimposition of the virtual model on the real element was computed in relation to the number of pixels of the virtual part that overlap the real one, measured in percentage. In Table II the final data is shown, concluding a $\approx 58.83\%$ mean, correlated to the percentage of the overlapping, having a defined standard deviation of $\approx 11.84\%$.

TABLE I: Experimental data obtained using calibration

End-Effector	**Error Mean (m)**	**Error Standard Deviation (m)**
Right	0.0047	0.0019
Left	0.0095	0.0045

TABLE II: Virtual model overlapping on the real element

	Mean (m)	**Standard Deviation (m)**
Overlap [%]	58.83	11.84

IV. CONCLUSIONS AND FUTURE WORK

In this paper we summarized our lessons learned from the state-of-the-art of current AR applications, as well as human-robot collaboration. Even more, we have succeeded integrating these two concepts into an unitary system, meant to ease a worker's daily tasks regarding the visualization of next possible assembly step, while synchronizing with a cobot in executing specific assembly scenarios. This way, a proper organization of the assembly sequences is crucial, especially when the CAD model has unusual shapes or complex elements. In the future, using object recognition combined with 3D printing, along with the latest HMD devices, could improve the manufacturing processes.

ACKNOWLEDGMENT

The authors would like to thank to their project colleagues (Laszlo Tofalvi, Levente Bagoly, Peter Mago) and colleagues from TUCN (Cristian Militaru, Mezei Ady Daniel, Mircea Murar) their support and involvement in realizing this work. This work was supported supported by the Romanian National Authority for Scientific Research and Innovation under Grant number PN-III-P2-2.1-BG-2016-0140, PN3-CI125 Grant and Hungarian Research Fund Grant K 120367 and MTA Bolyai Scholarship.

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