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An integrated environment based on augmented reality and sensing device for manual assembly workstations

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Abstract

One of the main problems encountered in manual assembly workstations is human error in performing the operations. Several approaches are currently used to face this problem, such as intensive training of personnel, poka-yoke devices or invasive sensing systems (e.g. sensing gloves) used for monitoring the process and detect wrong procedures or errors in joining the parts. This paper proposes an innovative system based on the interaction between a force sensor and an augmented reality (AR) equipment used to give to the worker the necessary information about the correct assembly sequence and to alert him in case of errors. The force sensor is placed under the workbench and it is used to monitor the assembly process by collecting force and torque data with respect to an XYZ reference system; a pattern recognition technique allows the error identification and the selection of the appropriate recovery procedure. Two AR devices have been tested in this application: a video-mixing spatial display and an optical see-through apparatus, comparing the pro and cons of these two solutions. The first device includes a CCD camera positioned over the workstation and an LCD display used by the worker as a support for the correct execution of assembly operations and receiving instructions about recovery procedures. The latter consists of a head mounted display (HMD) having the capability of reflecting projected images in front of the worker's eyes, allowing a real-world view with the superimposition of virtual objects. The CCD camera is also used for identifying errors that are not detectable by the force sensor. At the end, a case study concerning a typical assembly procedure is presented and discussed.

Keywords: Augmented Reality; Assembly; Error Detection

1. Introduction

A manual assembly line is a production line consisting of a sequence of workstations, where the assembly operations are performed by operators with the aid of specific tools and equipment. The largest percentage of the employed workforce in the manufacturing industry is currently involved in the assembly process. As a matter of fact, the human factor proves to be essential in production systems, thanks to its cognitive abilities, versatility and flexibility demonstrated in facing unexpected events. However, several factors, called Performance Shaping Factors (PSFs) [1], can influence and cause errors in the operator performance, such as [2]:

- Assembly system factors. Workplaces with high repetitiveness of tasks, high noise and poor ergonomics can cause both mental and physical stress and reduce the attention of the operator.
- Product factors. Over time products with many or similar components can cause an increase in the number of errors; the increasing variety of products was also identified as the main cause of the complexity perceived by an operator in carrying out his tasks [3].
- Operator factors. The worker's memory, mental and physical abilities, skills, training level and experience are some of the factors that determine the probability of mistakes during the assembly phase.

Assembly errors can increase production time and cost, production waste and a deterioration in the quality level of the product, resulting in serious damage to the entire production system. To minimize the number of manufacturing defects in

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the assembly process, these factors must be analyzed in order to identify a tool that reduces the probability of human errors.

2. Assembly errors

The word "error" will be taken as a generic term to encompass all those occasions in which a planned sequence of physical or mental activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency [4]. The best known classification of possible errors is the one proposed by the combination of Reason and Rasmussen's studies [5]:

- Real error: involuntary action that compromises the execution of a task. These errors can be divided in skill-based errors (failure in the execution of a planned action) and mistakes (failure in the planning of an activity).
- Violation: voluntary transgression of a rule, a procedure, a norm, divided in routine violations (becoming a part of a person routine), situational violations (caused by the conditions in which the operator performs his work) and exceptional violations (unusual and generally extreme violations, associated with non-negligible consequences).

In manual assembly workstations, the operator faces an error when the result obtained for a certain action is different from what expected. Most frequently, the errors occurring within manual assembly can be identified by the following specific terms [6]:

- "Wrong object": action taken on an object which is different from what required.
- "Omission": one of the requested actions is not performed or only partially performed.
- "Too low / too high": the applied force is lower / higher from what required.
- "Wrong action": action performed in a way which is different from what planned.

3. State of the art and motivations of the work

Several methods have been implemented in industry to face these kinds of problems. Some of the them are well tested and others are still in an experimental stage:

- Training of personnel, using different approaches such as on-the-job training (OJT), face-to-face training (FFT) and computer-based training (CBT).
- Poka-Yoke, implemented by devices that prevent the occurrence of an error in the performance of a particular activity, or by designing the parts in order to suggest to the operator how to assemble the product (Design for Poka-Yoke Assembly).
- Sensors: wearable sensors, mounted on the wrist or arm, and remote sensors, placed inside the work environment are employed to detect possible errors in the sequence and execution of tasks.
- 3D CAD models, used as an alternative to assembly instructions, in order to allow the user a detailed graphical view of the product.
- Augmented Reality (AR), increasing the human sensory capacity by integrating virtual contents in a real environment. The ability to provide informational supports directly in the field makes it a useful tool for education and training of personnel.

A comparison of these methods is shown in Tab.1.

Table 1: Comparison of the methods used to reduce the probability of human errors in assembly operations.

	PROS	CONS
Training of personnel	No special devices needed on the line. Higher responsibleness of workers.	Involvement of other skilled operators. Distraction errors partially influenced by training level.
Poka-yoke	Easy to use. Physical prevention of errors.	Not all of the assembly errors can be detected.
Sensors	In-process detection of errors. Measured values usable as process monitoring.	Not all of the assembly errors can be detected. It requires a database for a comparison with the measured values.
3D CAD Models	Availability of detailed technical information about the object	Presence of a display in the workspace that detracts attention from the process
AR	Easy interpretation of information and messages. Immersive system: information integrated with the real environment.	Less comfortable wearable devices. Presence of a display in the workspace that detracts attention from the process.

In recent years, the scientific literature has been mainly focused on the development of the last three methods.

Sensors can be positioned on the arm (or hand) of the operator or, alternatively, on the tool. The analysis of the movement is realized by devices that are capable of transforming kinematic and dynamic quantities into electrical nature quantities, that can be captured, digitalized and then processed by a computer [7] [8] [9]. A solution developed in the automotive sector [10] uses a device consisting of a magnetometer, an accelerometer and a gyroscope, to monitor the movements made by the operator's hand.

Several studies [3] [11] have shown that providing spatial information to the operator is a good starting point for the development of a valid support to the assembly activities. Specifically, three methods for the presentation of the assembly instructions were experimented, each of which differs in location and content [3] [11]: by lighting the container from which the operator must take the parts to be assembled; by projection of process schemes or CAD models on the workspace; by representation of the assembly process on the monitor.

Other scientific contributions have dealt with the applications of AR in assembly processes. For instance, this promising technique has been used to simulate [12] and verify the feasibility of a given assembly process [13] or as a training tool and guidance for manual assembly [14], displaying assembly instructions on the screen and recording the exact procedure in a 3D environment.

In the light of the above-mentioned considerations, it is evident that several technological solutions of a different nature are currently available to reduce the probability of human errors during the assembly process. AR must fit into this extremely dynamic framework, the use of which in industry is still in an experimental phase. The field is therefore still open to the investigation of new applications and the development of the methodology. In particular, AR can guide the operator to perform the correct action, also providing a support to recover any committed errors. An issue to further development relates to the integration of AR with other systems such as sensors, above analyzed, to create a synergistic system in which the limits of one may be filled by the other. The aim of this work is therefore to propose a new configuration of manual assembly workstation based on the use of a sensing device and augmented reality equipment, able to guide the actions carried out by the worker.

4. Description of the assembly workstation

The proposed assembly workstation is shown in Fig.1 and the following main components can be observed:

- Workbench, including the assembly area, the containers of the parts to be assembled and the tools.
- Force sensor, located centrally under the workbench.

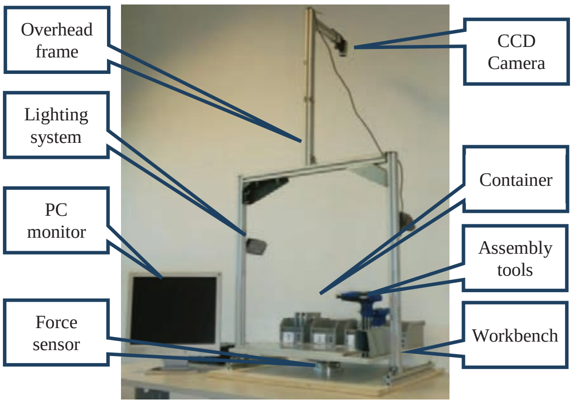


Fig. 1. Proposed assembly workstation.

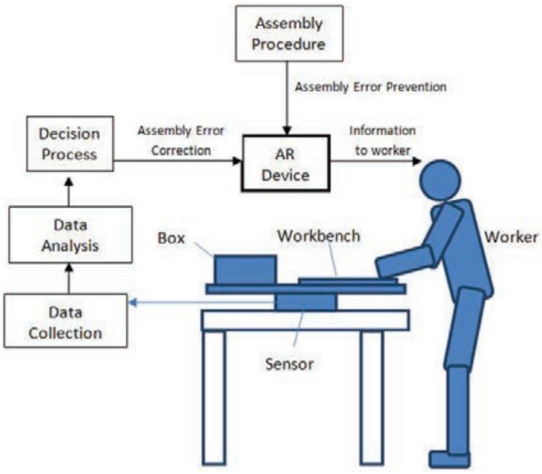


Fig. 2. Data flow to the worker during assembly operations.

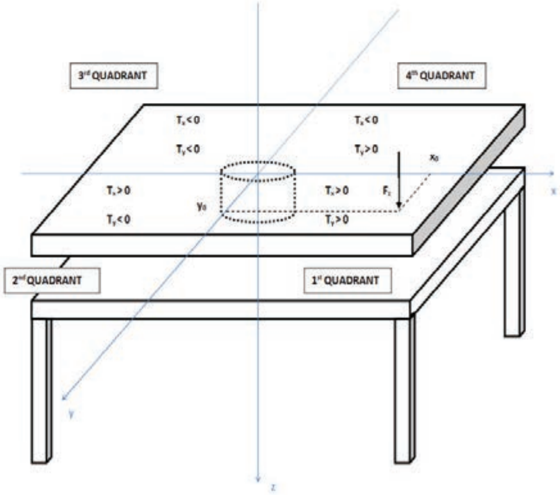


Fig. 3. Position of force sensor and orientation of XYZ reference system.

- Overhead frame, supporting the CCD camera and the lighting system.
- PC monitor, used for exchanging information with the worker.

Fig.2 schematically shows the general data flow of the system, where an AR device is used to collect and give to the worker the information concerning:

- Assembly error prevention: through the visualization of the correct actions for performing the assembly sequence.
- Assembly error correction: through the visualization of the assembly error and the procedure to recover it. This situation is detected by the force sensor and it is performed by the following steps: i) data collection from the sensor accomplished during the execution of an assembly operation made by the worker; ii) data analysis and feature extraction from the force and torque signal; iii) decisional process, performed comparing the extracted features with reference values in order to detect the event occurred (i.e.: correct action or assembly errors); iv) presentation of the visual aids by means of the AR device.

4.1. Sensing device

The sensor positioned under the workbench is an ATI 330 6-axis force sensor able to measure the 3 force components (F_x, F_y and F_z, with a resolution of 0.25 N and an accuracy of) and the 3 torque components (T_x, T_y and T_z, with a resolution of 0.015 Nm and an accuracy of). As depicted in Fig.3, the components F_z, T_x and T_y are used to evaluate the force exerted by the worker and the position (x_0, y_0) where he is acting, given by:

$$x_0 = T_y / F_z$$
$$y_0 = T_x / F_z$$

The sensor is therefore able to detect and monitor the following assembly operations which could be included in a more complex assembly sequence:

- Picking of an object from one of the 4 quadrants of the workbench (detected by measuring the variation of F_z, T_x and T_y).
- Positioning of an object in one of the 4 quadrants (detected by measuring the variation of F_z, T_x and T_y).
- Peg-in-hole insertions in one of the 4 quadrants (detected by monitoring F_z, T_x and T_y).
- Press fitting operations (detected by monitoring F_z)
- Screwing and tightening operations (detected by monitoring T_z).

It is obvious that the capability of monitoring operations concerning small objects strongly depends on the resolution of the sensor output: the smaller the mass of the object, the higher should be the resolution of the sensor.

In the following expressions, the measured force and torque components F_z, T_x, T_y and T_z are respectively indicated by F_i, with i=1,..,4.

In order to correctly monitor the entire assembly sequence performed at the workstation, each assembly operation has been associated with n "events" which can occur during the process: correct way of performing an operation (event no.1); set of probable errors a worker can make (events no.2, 3,…n).

The sensing system detects a generic event j by the following steps:

- An assembly operation is monitored by measuring force components vs time, as reported in the example of Fig.4.
- The force sensor output is analyzed by subdividing the signal in three parts (pre- worker's action, transitory phase, post- worker's action).
- The quantity ΔF_i is extracted for the i-th force component and compared with minimum limit $m_{i,j}$ and maximum limit $M_{i,j}$ allowed for each event j. These limits are experimentally evaluated by preliminary tests.
- The event j is detected if the following logical condition is satisfied:

$$\begin{array}{ll} \text{IF} & m_{i,j} \le \Delta F_i \le M_{i,j} \\ & \forall\, i = 1,..,4 \qquad\qquad (1) \\ \text{AND NOT} & m_{i,k} \le \Delta F_i \le M_{i,k} \\ & \forall\, i = 1,..,4 \text{ and } \forall\, k = 1,..,N \text{ except } j \\ \text{THEN} & \text{event j occurs} \end{array}$$

This procedure is able to distinguish most cases which can occur during the assembly sequence performed at the workstation and the system consequently selects the appropriate visual aids to be shown to the user by the AR device. However, in few cases the following situations may take place:

- Condition (1) is not satisfied by any j.
- Condition (1) is simultaneously satisfied by different values of j.

This last case for example is given by two events j and k for which it results:

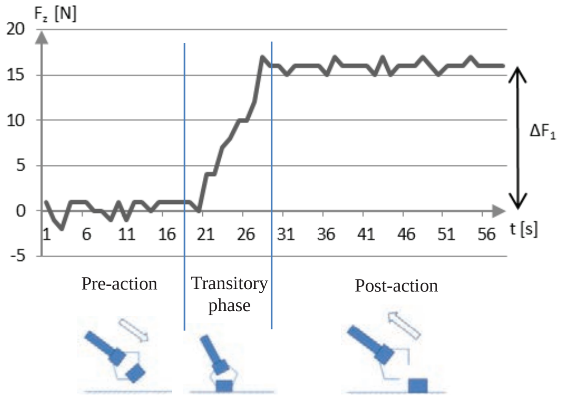


Fig. 4. Example of sensor output: F_z component vs time during the assembly operation "positioning of an object".

$$m_{i,j} = m_{i,k} \text{ OR } M_{i,j} = M_{i,k} \quad \forall\, i = 1,..,4$$

A typical undistinguishable situation may occur in performing the operation "positioning of an object" and considering the following two events: correct position of the object on the workbench (event no.1); upside down position of the object in the same x_0 and y_0 coordinates (event no.2). It is obvious that the force components F_i do not change at all. For this reason, the CCD camera of the AR equipment is used as another sensing device able to recognize and solve this kind of situations, as described in the following section.

4.2. Augmented reality

The AR software has been developed using the Unifeye SDK Metaio platform with the aim of visually supporting the worker in all the phases of the assembly process. Basically, it gives all the information needed to accomplish each assembly task but, as soon as the sensing device perceives a wrong action, the software generates and displays to the user the error and the recovery action. In this regard, three kinds of visual aids have been created:

- Textual instructions, explaining the operation to be accomplished or the recovery action to perform.
- Virtual elements, such arrows or other symbols to be easily and quickly interpreted by the worker.
- CAD models of the objects, which can be superimposed to the real ones and animated in order to explain the correct way of performing the task.

The connection of the previous visual elements to the real environment has been obtained using a marker-based tracking system. Three markers have been placed directly on the workbench (Fig.5) and the "multiple marker" algorithm has been implemented in order to have an uninterrupted tracking, even if one or two markers are hidden by the arms or the body of the user.

As far as the hardware is concerned, two different solutions has been experimented:

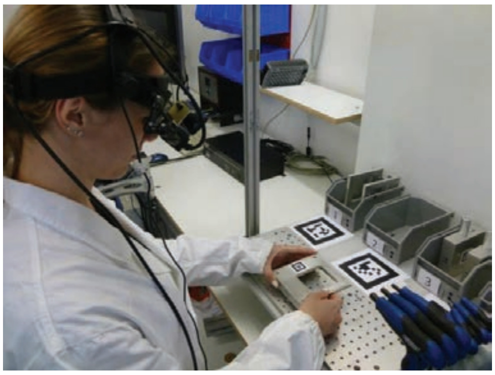


Fig. 5. Optical see-through approach.

- Video-mixing spatial display: the configuration is shown in Fig.1. The CCD camera mounted on the overhead frame captures the images from the real world, the visual aids are superimposed by the software and the resulting video stream is displayed on the PC monitor.
- Optical see-through apparatus: the configuration is shown in Fig.5. A head-mounted see-through display is used in connection with a CCD camera mounted on the same support. The captured images have the same optical view of the user's eyes, therefore, with respect to the previous one, this solution has the advantage of giving a more immersive sensation to the user. On the other hand, the portability is quite low and the user could suffer of eye strain after long periods.

In both approaches, the CCD camera performs two tasks:

- Recognition of marker positions and orientations in order to correctly place the visual aids in the real environment.
- Recognition of the assembly errors not distinguishable by the force sensor. The wrong orientation of the object is detected by using two different methods available in the adopted AR platform: a marker-based method, by means of small markers placed on the object faces (visible in Fig.5); a markerless method, by detecting the geometry of the part. The experimental results demonstrate that the former approach is obviously more robust, although it requires a preliminary marking of the parts to be assembled.

5. Case study

The described system has been tested using an experimental assembly set formed by 4 elements as shown in Figure 6. The presented case study is intentionally simple in order to clearly explained the concepts.

The assembly sequences has been divided in the following operations:

1. Picking of the object 1 from the container 1.
2. Positioning of the object 1 on the workbench.
3. Picking of the object 2 from the container 2.

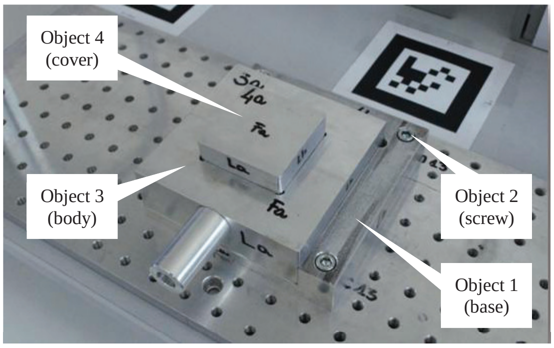


Figure 6: Case study: assembly set positioned on the workbench.

4. Insertion of the object 2 in the object 1 (steps 3 and 4 are repeated 3 times).
5. Screwing of the object 2 (repeated 3 times).
6. Tightening of the object 2 (repeated 3 times).
7. Picking of the object 3 from the container 3.
8. Positioning of the object 3 on the object 1.
9. Picking of the object 4 form the container 4.
10. Press fitting of the object 4 in the object 3.

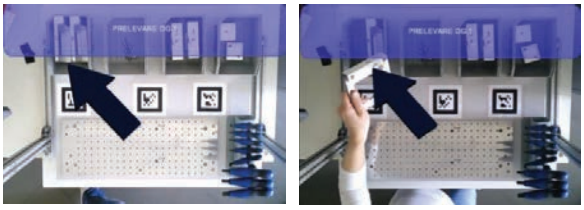
The assembly process succeeds when the whole set is positioned as shown in Fig.6.

Taking into consideration the operation n.1, the following probable events have been considered (the respective minimum and maximum limits of ΔF_1 are also reported):

- Event 1: picking of the object 1 from the container 1 (correct action), $m_{1,1}$ = 3.2 N, $M_{1,1}$ = 4.9 N.
- Event 2: picking of the object 2 from the container 2 (assembly error), $m_{1,2}$ = 0.0 N, $M_{1,2}$ = 0.6 N.
- Event 3: picking of the object 3 from the container 3 (assembly error), $m_{1,3}$ = 6.7 N, $M_{1,3}$ = 8.2 N.
- Event 4: picking of the object 4 from the container 4 (assembly error), $m_{1,4}$ = 0.8 N, $M_{1,4}$ = 1.6 N.

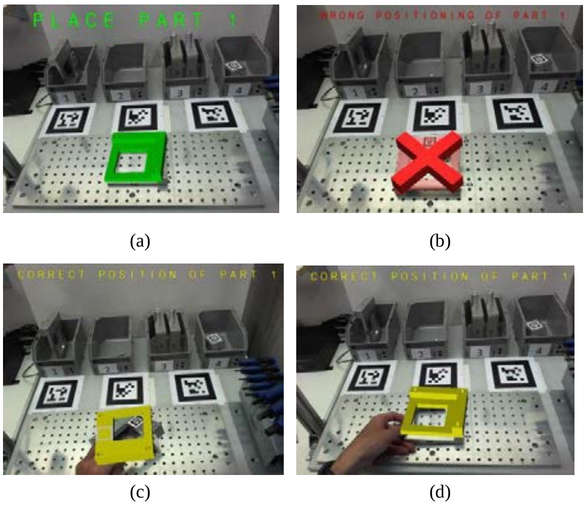
The different ranges do not overlap, therefore, by using the sensing device, each event can be detected without ambiguity. Fig.7 reports two screenshots taken during this operation when the event 1 is detected by the sensor: the measured value ΔF_1 is included in the range from 3.2 N to 4.9 N and therefore the AR software does not alert the worker with error symbols.

The operation n.2 is more critical and presents 20 different events which can be summarized as follows:



(a) (b)

Figure 7: Visual messages by using video mixing spatial approach in performing operation n.1: a) superimposition of operating instruction on the real workbench; b) manual performing of suggested operation.



(a) (b)

(c) (d)

Figure 8: Visual messages by using optical see-through in performing operation n.2: a) the AR system suggests to the worker the position of the object; b) the CCD camera detects the wrong orientation and the software displays an error symbol; c,d) the error recovery is suggested by an animated rotation of the part CAD model.

- Event 1: correct action.
- Events from 2 to 7: wrong positioning of the object on the workbench.
- Events from 8 to 20: wrong orientation of the object.

For this operation the physical quantities to be controlled are ΔF_2 ΔF_3. They change accordingly with the position (x_0,y_0) and the orientation of the object 1.

Due to the overlapping of the ranges characterizing some of the previous events, their detection by the sensing device is not possible. In particular, the event 1 is not distinguishable from the event corresponding to a wrong orientation (upside down positioning). This last event is therefore detected by the CCD camera of the AR equipment, as shown in Fig.8.b.

6. Conclusions

The paper describes an innovative manual assembly workstation able to assist an operator in previously planned assembly operations by a system combining a torque/force sensor and an AR environment.

The proposed system allows significant improvements compared with the currently used methods for prevention and corrections of human errors in industrial assembly processes. Such result is obtained by merging the properties described in Tab.1 and owned by the systems based on sensors and on AR techniques. The resultant three distinguishing features are:

- Capability of performing in-process error detection.
- Capability of selecting the recovery procedure.
- Ease of use due to the visual integration of the real environment, the instructions and feedback information.

Theoretically, there are no limits of applicability for the proposed system. It could be adopted both for simple assembly procedures, if a very low skill of the worker requests a constant support, and for complex and long procedures.

Nevertheless, the system is under development and some open issues or weaknesses still obviously exist. The most important of them is undoubtedly represented by the time consuming procedure needed for the system setup, especially for complex assembly sequences, that requires a high number of assembly tests for setting force/torque ranges used in error detection phase. A possible solution to this problem could be represented by the implementation of a self-learning procedure capable of recording the sensor output during a set of preliminary assembly sequences.

Other experimental tests have been planned for the future in order to face further open issues concerning: the wearability of the HMD device and its level of comfort after a long period of use; the robustness of the system in a real industrial environment.

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