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ORIGINAL PAPER

Natural interface for interactive virtual assembly in augmented reality using Leap Motion Controller

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Abstract

In this paper, an augmented reality methodology based on the use of a low-invasiveness hand tracking device is presented. The developed methodology, allows the user to be visually immersed into an augmented scene by means of a head-mounted display. He can interact with the virtual objects without any wearable sensor using the Leap Motion Controller that is able to acquire the pose of each finger of both hands by optical triangulation without markers. In this way, the interaction between the user and the scene can be considered "natural". The interaction between hands and objects and the assembling among objects is achieved by the modification of the Object Active Feature–Grasping Active Feature methodology, based on the use of algebraic kinematic constraint equations. The approach has been adapted to take into account the specific information coming from the tracking device. An example of implementation is reported and an experimental usability study discussed.

Keywords Virtual assembly · Natural interface · Leap motion · Augmented reality · User intent · Kinematic constraint

1 Introduction

In the current scenario of the deep change encouraged by the Industry 4.0 paradigm, virtual prototyping methodologies play a very crucial role. In addition, these methods are fuelled by the contribution of emerging virtual (VR) and augmented (AR) reality implementations that can be considered enabling technologies. In particular, AR is supporting several tasks related to the product design as geometric modelling, assembling and simulations [1]. By the combination of computer-aided design methodologies and augmented reality implementations, it is possible to arrange new and more efficient design environments. Most of the research is focused on the increase of interactivity between the user and the augmented scene [2,3]. A high level of interaction means that the user can be not only a spectator (i.e. he reviews and explores the scene) but he is able to actively interact with the contents of the scene.

In particular, the combination of AR and virtual prototyping in engineering has opened up a powerful array of tools to solve the assembly-planning problem. Instead of abstract, procedural assembly planning, a designer can plan, test and verify assembling procedure intuitively in an immersed virtual environment. By this way, the assembling and disassembling procedures can be simulated and optimized. For this purpose, a high level of interaction is welcomed because the implementations can mimic what happens in the real world in an accurate way.

According to the scientific literature, in the last years, several researchers investigated the possibilities of performing virtual assembling by the help of AR. The contributions may be divided into two main branches. Some studies are more focused on the use of AR rather than on the interaction which remains limited, some other are more focused on the way the user interact with the scene. As some recent examples, in 2003, Wiedenmaier et al. [4] described an AR application useful to support mounting procedure, replacing physical manuals with virtual contents. In 2006 Pang et al. [5] introduced an innovative implementation using AR for supporting the design of assembly features. One year later, Ong et al. [6] presented a methodology that integrates the assembly Product Design and Planning activities with the Workplace Design and Planning by using an augmented reality environment in order to improve the assembly procedures and layout. In 2008, Saaski et al. [7] described another interesting method for supporting assembly procedures using AR. One year later, Valentini [8] discussed and tested a method-

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ology for including an instrumented glove into an augmented reality scenario for assisting assembly operations. Although the presented methodology required the use of an invasive sensor, it includes a systematic approach suitable to be integrated into computer-aided design environments.

One of the crucial point in the implementation of AR assisted assembling is the user's interaction. In many cases, a high level of interaction is reached by the use of wearable sensors (gloves or other tangible or haptic interfaces) that are able to track the location on the user's hand in space and/or finger poses [8–10]. These devices are often invasive and uncomfortable to wear and may reduce the realism of the scene. In order to overcome this disadvantage, during the last years, the researchers have begun to develop the so-called "natural interface" concept [3,11]. The purpose of the natural interaction is to achieve the communication between the user and the computer without the use of invasive sensors to be worn. In this way, the user is more at ease and can communicate his intent using simple natural gestures and movements.

Especially for assembling tasks, the most important interface between the user and the virtual objects in the scene is the hand that is used to pick, grab, move, rotate, push and pull objects. For this reason, a robust and reliable hand tracking system has to be included in the scene. One of the emerging hand tracking device is the Leap Motion Controller which uses the stereoscopy for tracking the anatomic segments of both hands. Recent studies [12] witness that the accuracy of the device is adequate for reliable and robust tracking of user's hand in virtual environments. Katahira and Soga [13] proposed an integration of the Leap Motion Controller in an AR environment for implementing a realistic display and gripping. The possibilities in integrating Leap Controller and virtual reality is also explored in [14]. In 2017, another research [15] described the integration of the controller in a virtual reality environment focusing on mining industry requirements.

In all the above mentioned examples of integration between hand tracking and augmented or virtual reality, the purpose is focused on the simple capability of picking and moving objects (in some cases assisted by visual aids). On the other hand, for engineering purposes of virtual assembling, the picking and moving have to be correlated with mounting rules in order to respect the functionality of the mating surfaces. In other worlds, the manipulation of the objects has to be performed according with standard mating relationships, as it happens in computer-aided design environments [16].

Starting from this background, the purpose of the paper is to discuss an integration between the Leap Motion Control and an augmented reality architecture in order to implement an interactive virtual assembly methodology based on the use of the natural interface between the user and the virtual contents. This specific characteristic of the natural interface can give to the methodology a complete new way of interacting between the user and the virtual shapes and a wide field of application.

Firstly, the specific features of the hardware system are presented. Secondly, the interaction between the user and the virtual objects in the scene is discussed focused the assessment of the user's intent starting from the hand tracking data. Thirdly, the assisted assembly methodology presented in [8] is extended and adapted for the specific implementation using the Leap Motion Controller. Finally, an example is reported and discussed.

2 System implementation (hardware and software)

The implemented system is based on the integration between the Leap Motion Control and a standard video-see trough augmented reality architecture.

The Leap Motion Controller is a small box (about 12.7 × 12.7 × 5.1 cm) which can be connected via USB to a desktop/laptop computer. The device includes three infrared LEDs and two cameras and its tracking principle is the stereoscopy (the reflected light from the LEDs is seen from two different points of view and the distance from the sensor is computed accordingly).

Thanks to the proprietary SDK libraries, it is possible to retrieve tracking information of both hands in the space above the device in a height range of 15–60 cm. The library routines are able to recognize both hands and return information about the location and pose of each bony segment.

The augmented reality architecture is based on the use of an Head-Mounted display (Z800 3D visor by Emagin—http://www.3dvisor.com/) combined with a USB camera (Microsoft LifeCam VX6000) able to catch frames up to 30Hz with a resolution up to 10,247,68 pixels. The processing unit is an E4 Workstation, equipped with two Xeon 10-core E5-2680v2 processors, 128 Gb DDR3-1600 RAM and Nvidia Quadro K4000 graphic card. All the code is developed using Microsoft Visual Studio 2010. A patterned marker is included in the scene in order to compute the coordinate transformation between the camera and the real world. All the procedures about the recognition of the markers in the scene and the assessment of relative transformations between camera and each marker have been implemented using ARToolkit 5.3.2 libraries. Additional details about the new version of the ARToolkit libraries are freely available together with documentation at https://www.artoolkit.org/.

Figure 1 reports a picture of the implementation of the entire system. It is possible to notice that a Plexiglas plate is also included in the scene at a height of 200 mm from the Leap top surface. It allows a physical plane useful as a reference geometry for having the physical perception of a ground surface where unused objects can be picked and placed. Due

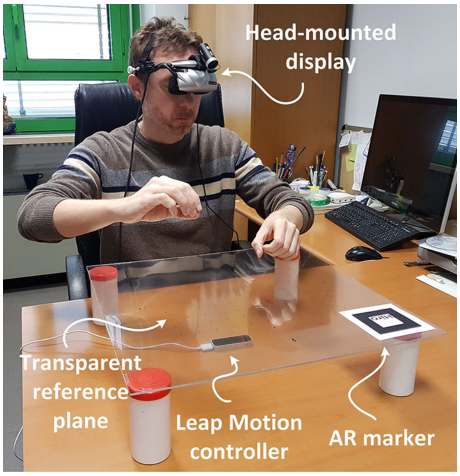

Fig. 1 An overall view of the implemented system

to the specific tracking range of the Leap Motion Controller, it is not possible to use the same plane where the device is located. Previous studies demonstrated the effectiveness of such solution [12] that does not affect the accuracy in tracking but requires a small correction of the tracked coordinates due to the refraction between air and Plexiglas.

The patterned marker is located on the Plexiglas plate near one of the top corners in order to be always seen by the camera. This position is necessary to avoid occlusion of the Leap projector and of the head-mounted camera in order to ensure a continuous perspective collimation of the real scene with respect to the camera.

3 Natural interaction with virtual shapes

The natural interaction between the user and the virtual objects in the augmented scene is the most important feature to be implemented. An effective and reliable interaction needs simple gestures, natural movements and easy actions, robust to be recognized.

The tracking of both hands and the recognition of relevant gestures make use of the Leap Motion Controller. The device is able to return information about the location and attitude of all the body segments. Two are the most important pieces of information to be collected from the sensor. The first one is the location of all the joints of the hand in order to build and pose a virtual hand (stick diagram) in the augmented scene. A virtual hand, superimposed to the acquired video stream in necessary to easily manage occlusions with other virtual objects and to give to the user a visual feedback of the tracking accuracy and robustness.

The other piece of information to be collected from the Leap is the pose of the fingers in order to assess the most common grasping poses. According to [8,16] and considering frequent hand operations, three gasping poses can be primarily considered: the cylindrical one, the spherical one and the pinch. Although the human hand possesses many degrees of freedom, it is possible to consider aggregate information in order to have acceptable estimation of the hand pose. With reference to Fig. 2, for each finger we can decompose the anatomical structure into four bones that are traceable by the Leap Motion controller: the metacarpal bone, the distal bone, the intermediate bone and the proximal one. For each bone, it is possible to define the orthonormal basis vectors: **x**, perpendicular to the longitudinal axis of the bone and exiting the sides of the finger; **y**, perpendicular to the longitudinal axis of the bone and exiting the top and bottom of the finger; **z**, aligned with the longitudinal axis of the bone.

The cosine of the relative angle ϑ_i between two segments i and $i+1$ can be computed as:

$$\cos\vartheta_i = \mathbf{z}_i \cdot \mathbf{z}_{i+1} \tag{1}$$

And then the angle ϑ_i can be computed considering that for the anatomical limits has to fulfil the constraint $0 \le \vartheta_i \le \frac{\pi}{2}$. Then we can define the mean attitude angle ϑ_{mean} of the finger's joints as:

$$\vartheta_{\text{mean}} = \sum_{i=0}^{2} \frac{\vartheta_i}{3} \tag{2}$$

Following the same criterion for user's intent recognition in [8], we can recognize the three most important poses by the interpretation of the angles ϑ_i for all the fingers because the difference among the three poses is in the flexion of the fingers. In the cylindrical grasping, all the fingers are bent except the thumb. In the spherical grasping, all the fingers are bent. In the pinch only the index and the thumb are bent. Looking at the signals from the Leap Motion Controller, the intent of grasping can be interpreted using threshold values [8]:

– Cylindrical pose: $\vartheta_{\text{mean}} \ge \frac{\pi}{3}$ for index, middle, ring and pinky fingers; $\vartheta_{\text{mean}} \le \frac{\pi}{6}$ for thumb;
– Spherical pose:

$$\vartheta_{\text{mean}} \ge \frac{\pi}{3} \tag{3}$$

for all the fingers;
– Pinch: $\vartheta_{\text{mean}} \ge \frac{\pi}{3}$ for index finger and thumb; $\vartheta_{\text{mean}} \le \frac{\pi}{6}$ for middle, ring and pinky fingers.

The interaction between the hand and the virtual objects is then implemented using the duality between the Grasping Active Feature (GAF) and the Object Active Feature (OAF) following the methodology introduced in [8]. Actually, that

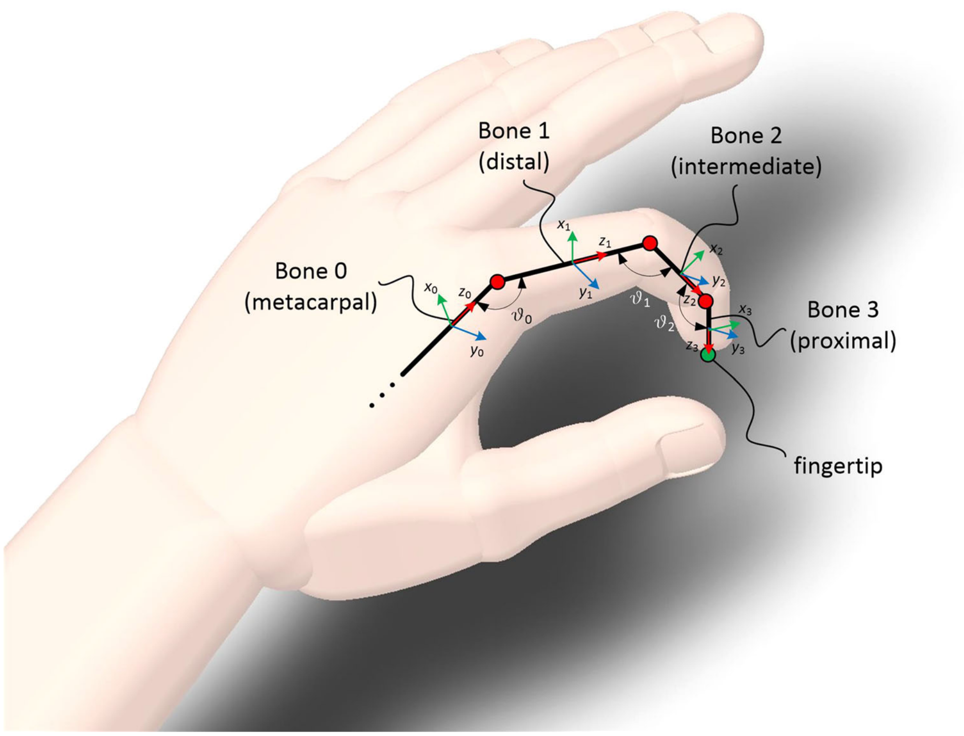

Fig. 2 Kinematics of the fingers

methodology was initially developed for glove-based interaction and therefore it has to be adapted in order to be suitable to the natural interface interaction and to the data collectable from the Leap device.

In particular, the GAF–OAF methodology is based on the definition of some relevant geometrical features (points and vectors) on both human hands and graspable objects, in order to algebraically impose mating relationships between vectors and points as it happens in multibody kinematics studies [17].

For each of the three grasping poses, it is necessary to define the following Grasping Active Features:

Cylindrical pose

The cylindrical pose is the pose used for grabbing cylindrical objects (see Fig. 3). In this case, it is necessary to compute the location and direction of the axis of the grasping, by defining a spatial vector $\mathbf{z}_{cyl}$ and a point $\mathbf{C}_c$. The vector $\mathbf{z}_c$ can be computed as:

$$\mathbf{z}_c = \mathbf{f}1_m - \mathbf{f}2_m \tag{4}$$

where $\mathbf{f}1_m$ and $\mathbf{f}2_m$ are the centres of the circumferences passing through the midpoints of the distal bone, the intermediate bone and the proximal bone of index and middle finger, respectively:

$$\begin{array}{l} \mathbf{f}1_m \rightarrow \text{centre of circumference passing through } \{\mathbf{d}1_m \quad \mathbf{i}1_m \quad \mathbf{p}1_m\} \\ \mathbf{f}2_m \rightarrow \text{centre of circumference passing through } \{\mathbf{d}2_m \quad \mathbf{i}2_m \quad \mathbf{p}2_m\} \end{array} \tag{5}$$

where $\mathbf{d}1_m \quad \mathbf{i}1_m \quad \mathbf{p}1_m$ are the midpoints of the distal bone, the intermediate bone and the proximal bone of the index, respectively and $\mathbf{d}2_m \quad \mathbf{i}2_m \quad \mathbf{p}2_m$ are the midpoints of the distal bone, the intermediate bone and the proximal bone of the middle finger, respectively.

The point $\mathbf{C}_c$ can be considered as the midpoint between the centres of the two above introduced circumferences and therefore its coordinates can be computed as:

$$\mathbf{C}_c = \frac{\mathbf{f}1_m + \mathbf{f}2_m}{2} \tag{6}$$

Spherical pose

The spherical pose is the pose used for grabbing spherical objects (see Fig. 4). In this case, it is necessary to compute the location of the centre of the virtual sphere, by point $\mathbf{C}_s$. The coordinates of the point $\mathbf{C}_s$ can be computed as:

$$\mathbf{C}_s = \frac{\mathbf{f}1_m + \mathbf{f}2_m}{2} \tag{7}$$

where $\mathbf{f}1_m$ and $\mathbf{f}2_m$ are the centres of the circumferences passing through the midpoints of the distal bone, the intermediate bone and the proximal bone of index and middle finger, respectively:

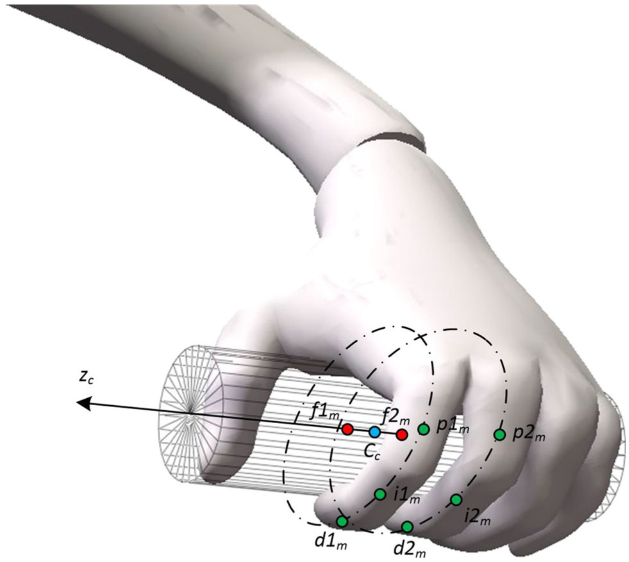

Fig. 3 Cylindrical pose geometrical entities

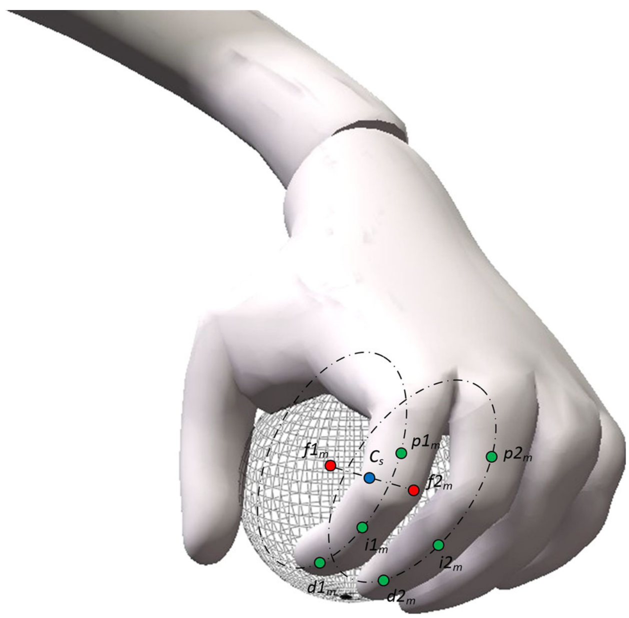

Fig. 4 Spherical pose geometrical entities

$$\begin{array}{l} \mathbf{f}1_m \rightarrow \text{ centre of circumference passing through } \{\mathbf{d}1_m \quad \mathbf{i}1_m \quad \mathbf{p}1_m\} \\ \mathbf{f}2_m \rightarrow \text{ centre of circumference passing through } \{\mathbf{d}2_m \quad \mathbf{i}2_m \quad \mathbf{p}2_m\} \end{array} \tag{8}$$

where $\mathbf{d}1_m \quad \mathbf{i}1_m \quad \mathbf{p}1_m$ are the midpoints of the distal bone, the intermediate bone and the proximal bone of the index, respectively and $\mathbf{d}2_m \quad \mathbf{i}2_m \quad \mathbf{p}2_m$ are the midpoints of the distal bone, the intermediate bone and the proximal bone of the middle finger, respectively.

Fig. 5 Pinch pose geometrical entities

Pinch pose

The pinch pose is the pose used for grabbing objects using index and thumb fingertips (see Fig. 5). In this case, it is necessary to compute the pinch location, by point $\mathbf{C}_p$. The coordinates of the point $\mathbf{C}_p$ can be computed as:

$$\mathbf{C}_s = \frac{\mathbf{t}1 + \mathbf{t}5}{2} \tag{9}$$

where $\mathbf{t}1$ and $\mathbf{t}5$ are the fingertips of index and thumb, respectively.

Starting from the knowledge of the GAFs, it is possible to impose mating constraints between human hand and virtual objects by using algebraic constraints [17]. According to the GAF–OAF methodology [8] each relevant feature of a graspable object (i.e. planar surfaces, pins, etc.) may be associated to an Object Active Feature, using a local reference frame (see Fig. 6).

The mating relationship between GAF and OAF can be imposed using algebraic constraints involving coincidence between points and perpendicularity between unit vectors. In particular, for each of the grasping pose we can have:

Cylindrical pose → cylindrical grasp/constraint

$$\begin{aligned} &\mathbf{z}_c \cdot \mathbf{x}_{OAF} = 0 \\ &\mathbf{z}_c \cdot \mathbf{y}_{OAF} = 0 \\ &\mathbf{x}_{OAF} \cdot (\mathbf{C}_c - \mathbf{O}_{OAF}) = 0 \\ &\mathbf{y}_{OAF} \cdot (\mathbf{C}_c - \mathbf{O}_{OAF}) = 0 \end{aligned} \tag{10}$$

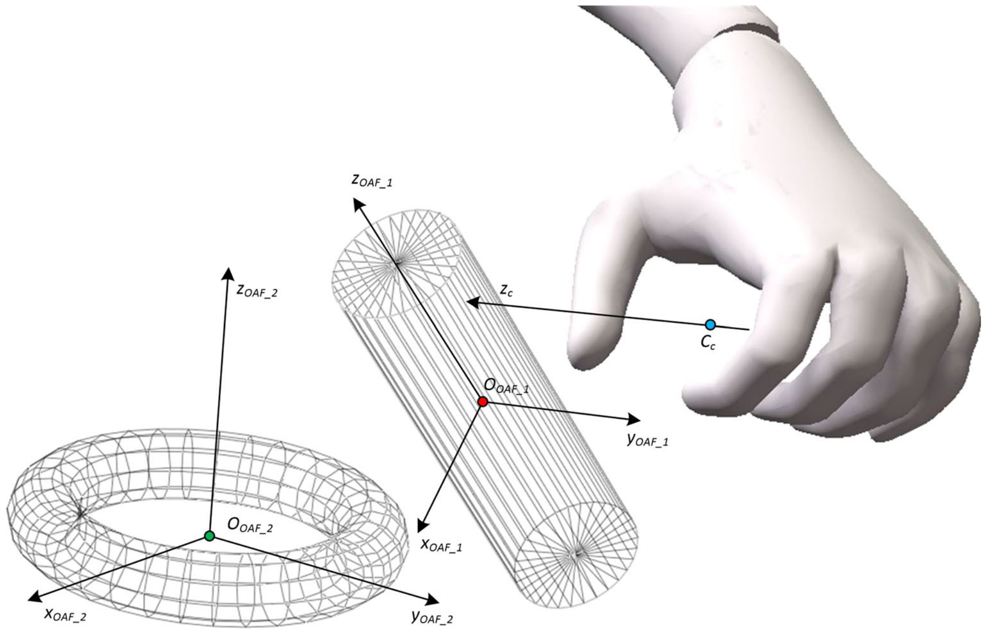

Fig. 6 Relationship between OAF and GAF

Spherical pose → coincidence grasp/constraint

$$\mathbf{C}_s - \mathbf{O}_{OAF} = \mathbf{0} \tag{11}$$

Pinch pose (general case) → coincidence grasp/constraint

$$\mathbf{C}_p - \mathbf{O}_{OAF} = \mathbf{0} \tag{12}$$

If the pinch pose occurs without other existing constraints, it can be modified in order to include the ability of lock the object rotation simulating a tight pinch with friction, imposing the following more complex equations:

Pinch pose (without other active constraints) → coincidence grasp/constraint and orientation lock

$$\begin{aligned} &\mathbf{C}_p - \mathbf{O}_{OAF} = \mathbf{0} \\ &\mathbf{x}_{OAF} \cdot (\mathbf{t}1 - \mathbf{t}5) = 0 \\ &\mathbf{z}_{OAF} \cdot (\mathbf{t}1 - \mathbf{t}5) = 0 \end{aligned} \tag{13}$$

The possibility to impose one of the above mentioned constraints depends on two conditions: the first one is that one of the GAF is recognized [by using the threshold of Eq. (2)], the second one is that the OAF and the GAF are close. This condition can be checked by evaluating the Eqs. (10), (11) and (12) substituting the equalities with inequalities considering a tolerance tol . This second set of conditions is necessary to interpret the user's intent in a proper way ($i.e.$ the user wants to grab an object if the pose of the hand is nearly compatible to the grasping action). For the three poses, we have:

Cylindrical pose intent check

$$\begin{aligned} &|\mathbf{z}_c \cdot \mathbf{x}_{OAF}| \le tol \\ &|\mathbf{z}_c \cdot \mathbf{y}_{OAF}| \le tol \\ &|\mathbf{x}_{OAF} \cdot (\mathbf{C}_c - \mathbf{O}_{OAF})| \le tol \\ &|\mathbf{y}_{OAF} \cdot (\mathbf{C}_c - \mathbf{O}_{OAF})| \le tol \end{aligned} \tag{14}$$

Spherical pose intent check

$$\|\mathbf{C}_s - \mathbf{O}_{OAF}\| \le tol \tag{15}$$

Pinch pose intent check

$$\left\|\mathbf{C}_p - \mathbf{O}_{OAF}\right\| \le tol \tag{16}$$

4 Mating of virtual shapes

The mating between virtual objects can be imposed in the same way of the mating between user's hand and virtual objects. In this case, the mating relationships involve two Object Active Features, one of each mating body (for example, OAF_1 and OAF_2 in Fig. 6). The first condition to be fulfilled is the closeness of the two reference systems of the two objects:

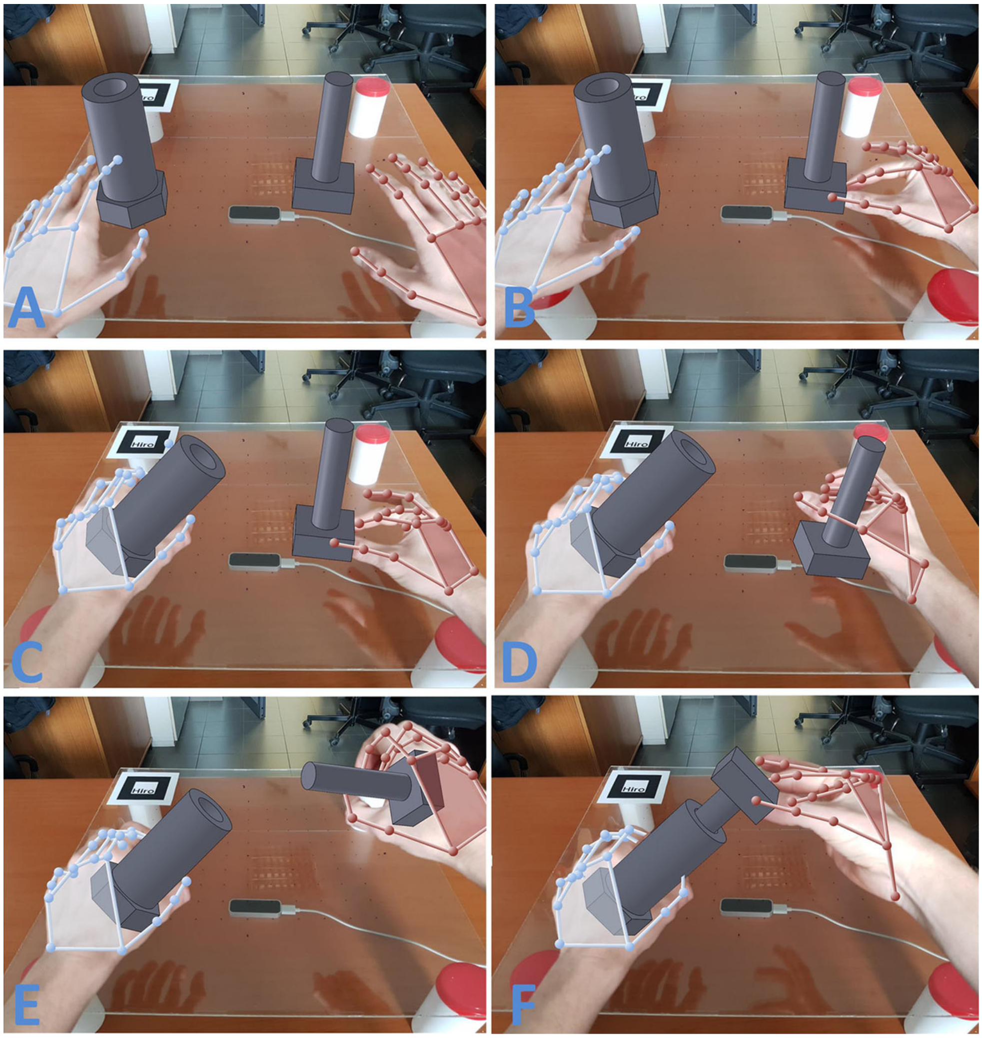

Fig. 7 Six snapshots from the discussed example of application

Cylindrical mating closeness check

$$\begin{aligned}
&|\mathbf{z}_c \cdot \mathbf{x}_{OAF2}| \leq tol \\
&|\mathbf{z}_c \cdot \mathbf{y}_{OAF2}| \leq tol \\
&|\mathbf{x}_{OAF2} \cdot (\mathbf{O}_{OAF1} - \mathbf{O}_{OAF2})| \leq tol \\
&|\mathbf{y}_{OAF2} \cdot (\mathbf{O}_{OAF1} - \mathbf{O}_{OAF2})| \leq tol
\end{aligned} \tag{17}$$

Spherical mating closeness check

$$\|\mathbf{O}_{OAF1} - \mathbf{O}_{OAF2}\| \leq tol \tag{18}$$

Surface/surface coincidence closeness check

$$|\mathbf{z}_{OAF2} \cdot (\mathbf{O}_{OAF1} - \mathbf{O}_{OAF2})| \leq tol \tag{19}$$

If one of the above-mentioned inequalities is satisfied, the corresponding mating relationship can be enforced:

Cylindrical mating constraint

$$\begin{aligned}
&\mathbf{z}_c \cdot \mathbf{x}_{OAF2} = \mathbf{0} \\
&\mathbf{z}_c \cdot \mathbf{y}_{OAF2} = \mathbf{0} \\
&\mathbf{x}_{OAF2} \cdot (\mathbf{O}_{OAF1} - \mathbf{O}_{OAF2}) = 0 \\
&\mathbf{y}_{OAF2} \cdot (\mathbf{O}_{OAF1} - \mathbf{O}_{OAF2}) = 0
\end{aligned} \tag{20}$$

Spherical mating constraint

$$\mathbf{O}_{OAF1} - \mathbf{O}_{OAF2} = \mathbf{0} \tag{21}$$

Surface/surface coincidence constraint

$$\mathbf{z}_{OAF2} \cdot (\mathbf{O}_{OAF1} - \mathbf{O}_{OAF2}) = 0 \tag{22}$$

The OAF–OAF relationships have the priority in the solution with respect to the OAF–GAF relationships since the

Table 1 Results of the questionnaire: number of occurrence for each query (for each query: 1—very poor; 2—poor; 3—fair; 4—good; 5—very good)

Questions	1	2	3	4	5
Comfort of the head mounted display (wearability)	0	5	10	25	0
Comfort of the visor (image, resolution, focal length, etc.)	1	10	24	5	0
Comfort of the hand tracking device	0	0	5	10	15
Familiarity of the environment	0	3	20	7	0
Easiness in perceiving the three-dimensional space	0	3	20	7	0
Easiness in reaching and picking virtual objects	0	5	18	5	2
Easiness in manipulating virtual objects	0	7	21	2	0
Easiness in imposing assembly constraints	1	8	16	5	0

correct assembly has to be ensured in any conditions (it is a functionality issue). In case of both OAF–OAF and OAF–GAF relationships, the assembly configuration can be solved enforcing the OAF–OAF relationships $\psi_{OAF-OAF}$ and minimizing the OAF–GAF relationships$\psi_{OAF-GAF}$.

In particular, in case of both OAF and GAF relationships, the numerical problem to be solved is the following:

$$\begin{cases} \min \psi_{OAF-GAF} \\ \psi_{OAF-OAF} = 0 \end{cases} \quad (23)$$

5 An example of application

In order to present the details of the proposed methodology, we developed a simple but complete example of application. It deals with the virtual simulation of the insertion of a pin into a hole of another component (see Fig. 7). Both components have two Object Active Features which allow the pinch of their base (hexagonal and prismatic features) and the grabbing of their cylindrical surfaces. The Fig. 7 shows seven snapshots taken from the augmented projection of the user. The augmented reality scene includes a stick representation of the hands' bones and joints in order to facilitate the recognition in the scene and avoid a wrong occlusion between the real and virtual objects. The representation is computed directly from the data coming from the Leap Motion recognition.

In the first part of the simulation (snapshot A), both the virtual objects are located on the working plane and the user can freely navigate the scene moving his hands. In a second part (snapshot B), the user move the right hand toward the second object (that on the right) and reach with the fingertips the object active feature at its prismatic base. The user's intent to pinch is checked using the formulas in (3) and if the inequality in (16) is satisfied, the pinch constraint is established using the Eq. (13) since the pinch is the only active constraint of the object. From this point, the second component can be moved attached to the index and the thumb of the user until the pinch pose is recognized. At the same time (snapshot C), the left hand of the user is posed fulfilling the cylindrical intent check in (3) near the corresponding object active feature of the first object (on the left), until the (14) are satisfied. From this point on, the (10) are enforced and the user grabs the object till the cylindrical pose is recognized.

In the snapshot D, the user repeated the same procedure for the second component on the right and grab it by its cylindrical active feature. At this time, both objects are grabbed and are moved attached to the user's hands (snapshot E). In the final step (snapshot F), the user places the two objects so that the cylindrical mating closeness check is fulfilled (Eq. 17) and the corresponding constraint enforced (Eq. 20). Then the user releases the cylindrical constraint with the second component. At the final step, the user establishes a pinch constraint (Eq. 12), since now the cylindrical constraint is already present) and moves in order to push the pin inside the hole till a surface/surface constraint is enforced (Eq. 22).

6 Usability tests

The effectiveness of the methodology has been assessed using experimental tests on field. A group of 30 people (18 men and 12 women in the range of 20–40 years old) took part in the experiment. None of them have had previous experience with the Leap Motion or navigation in AR scenarios. A preliminary five-minute free acquaintance to the hardware system has been arranged for each subject in the study in order to get familiar with the head mounted display, the field of view and the usage of Leap. Each subject has been asked to repeat the sequence described in the example of the previous section and then asked to fill a multi-choices questionnaire about the experience.

The results of the questionnaire are reported in Table 1.

The interpretation of the results of the test showed that most of the user are at ease in the augmented reality environment reporting some difficulties in the comfort of the visor due to the limited resolution and angle of view. Most of them reported a good of very good comfort in the low-invasive tracking device. The easiness in the manipulation of virtual object is fair/good without any remarkable difficulties. On the other hand, some complications arose in the imposing of mating constraints between virtual objects, mainly due to the difficulties in aligning the reference systems before enforcing the constraint equations [proximity conditions in (17) and (19)].

7 Conclusions

A methodology for implementing virtual assembling using natural interface has been presented. The methodology makes the combined use of augmented reality and low-invasiveness hand tracking device and it is based on the use of Leap Motion Control. The methodology uses the information coming from the bone segment recognition in order to track the user's hands in the scene, interpret their pose and infer the user's intent. The augmented reality is necessary to superimpose the virtual objects to the real scene. Three general grabbing poses have been studied and implemented: the cylindrical pose, the spherical pose and the pinch. They allow managing a large set of assembly conditions. The equations to enforce the grasping and the assembly constraints have been deduced using the OAF–GAF methodology able to produce algebraic equations which constraint the virtual objects' degrees of freedom, similarly to that for the multibody kinematics investigation. The simultaneous presence of object–object and object–hand constraints is resolved by introducing minimization strategy. The discussed example and the in-field testing demonstrate that the integration between augmented reality and natural interface is feasible and the methodology is suitable for building interactive applications. The proposed method can be considered a general approach to substitute or help the standard assembling procedures included in common computer-aided design environments. It can be considered as a substitute or helper of the standard assembling procedures included in common computer-aided design environments. This gives the ability to be easily applied to solve real industrial problems is a general way, using the same modular approach. The methodology is extendable by including a larger set of assembling constraint between OAFs and GAFs and between OAFs and OAFs, including more complex gestures and constraints.

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