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Procedia Manufacturing 11 (2017) 1263 – 1270

Procedia MANUFACTURING

27th International Conference on Flexible Automation and Intelligent Manufacturing, FAIM2017, 27-30 June 2017, Modena, Italy

On immersive Virtual Environments for assessing human-driven assembly of large mechanical parts

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Abstract

Application of immersive Virtual Reality is advocated for assessing human-based assembly of large mechanical parts, including assembly jigs and fixtures as well as tools used and procedures followed. The primary aim is to enable subjective/customised assessment of the assembly system by the participating human. The secondary aim is to allow recording of the human's main movements in order to analyse them with standard ergonomics tools. Proof-of-concept was sought by a case study, i.e. aircraft wing assembly by riveting, involving a real human worker holding a real tool, whilst all the rest, i.e. avatar, wing, fixtures and factory were virtual. Health risk from assembly tasks was subjectively assessed via a questionnaire. Assembly equipment and procedure were preliminarily assessed by interpreting and applying RULA and REBA protocols. The potential to automate such a tedious task was demonstrated by automatic calculation of body postures from avatar's kinematics.

Peer-review under responsibility of the scientific committee of the 27th International Conference on Flexible Automation and Intelligent Manufacturing

Keywords: Immersive Virtual Reality; Assembly planning; Ergonomic assessment

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Peer-review under responsibility of the scientific committee of the 27th International Conference on Flexible Automation and Intelligent Manufacturing
doi:10.1016/j.promfg.2017.07.253

1. Introduction

Industrial assembly spans a wide range of products in terms of types (e.g. mechanical, electromechanical, mechatronic), technology levels (trivial to very sophisticated) and even sizes (from mm to m scale) and has invariably attracted the manufacturing community's attention due its universal applicability as the last operation manufacturing plan. Despite extensive automation, human involvement in assembly is still extremely important [1].

Human-driven assembly of products was one of the first domains where, initially, Virtual and, then, Augmented Reality (VR/AR) techniques were applied [2], mainly because the human involvement introduced both complexity and uncertainty that needed sophisticated tools to study quantitatively [3]. Such study can be classified according to its aim, namely: to test feasibility of assembly concepts [4] and methods [5], to check performance of the human in the assembly tasks [6], to assess suitability of the assembly workstation and equipment provided [7], to train the human in the assembly tasks [8], to guide the human while performing such tasks [9] etc. In many of these tasks ergonomics is involved as either a conspicuous [10] or an underlying issue [11]. Parameters of interest are visibility of assembling parts, posture of workers and reachability of assembly regions [12].

VR hardware, especially haptics, trackers of human body motions and displays allowing freedom of user movement have enabled recording of individual motions with respect to the assembled objects [13] and subsequent analysis using dedicated software applications [14]. At a research level, intelligent processing of such information on / off-line can seek patterns and assess them against formal or empirical knowledge [15]. At a commercial level, maturity of VR elements is high, especially regarding scene creation, scenario development and interaction with the user, but research to apply them to real manufacturing industries and create suitable analysis tools is needed [16].

In this work, immersive Virtual Reality is advocated for assessing assembly tasks pertaining to large mechanical parts, including assembly jigs and fixtures as well as tools used and procedures followed by the human, before these are physically materialized. The main idea is two-fold: to enable subjective/personal assessment of the assembly system by the participating human and to allow recording of the human's main movements, in order to analyse them with ergonomics tools and obtain an objective assessment. A proof-of-concept prototype of a virtual environment for assessing assembly processes for large parts (VAPA-LP) was created pertaining to aircraft wing riveting. This is an example for human-driven large part assembly under existing stringent requirements [17]. A game authoring engine, Unity™ served as the development platform. The concept of the system is presented in Section 2. The most important details of system development are outlined in Section 3. Preliminary results are demonstrated in Section 4, whilst Conclusions are summarised in Section 5.

2. Virtual Assembly Process Assessment for Large Parts (VAPA-LP)

2.1. The concept

Assembly of large parts differs from assembly of smaller mechanical parts in various aspects: part size, task complexity and movement accuracy. The area covered by the human is substantial compared to the almost static assembly of small parts and main movements are adequately described by operator postures at the body rather than at the finger level. Therefore, a system supporting the assessment of the assembly of large parts should primarily focus on accommodating the whole area of the assembly workstation(s) and on tracking the main, as opposed to subtle, movements of the human operators. In terms of assessing the assembly procedure, both subjective and objective assessment is possible. The former requires that assembly tasks are performed with tools as close to the real ones as possible. Objective assessment requires that movements are recorded in detail and then subjected to analysis based on established ergonomics protocols.

A Virtual Environment (VE) does address all requirements stated above. The advocated system is depicted in Fig. 1(a). Immersive capabilities of the Environment ensure realism of the human movements and behavior in general, whilst the use of real tools ensure realistic task performance. At the centre of the environment lies the concept of the avatar, which, through sensors tracking the human, duplicates the movements performed in real time. The coordinates of the avatar's kinematic chain can be recorded continuously and therefore, in principle, any patterns associated with fatigue, injury risk or simply discomfort can be discovered. Such patterns are defined in standard ergonomics protocols, such as Rapid Upper Limb Assessment (RULA) [18], Rapid Entire Body

Assessment (REBA) [19] and Hand Arm Vibration (HAV) Calculator [20]. However, the ability to test the assembly workstation by personal participation is a unique advantage of VEs and is considered to be at least equally informative as the 'objective' study through ergonomics protocols. The latter capability is routinely provided by CAD suites such as CATIA™ , thus the only advantage of including it in the VE is that avatar motion is more natural since it follows that of the human.

Depending on the results of the subjective and objective assessment of the assembly process, several actions may be decided: (i) redesign of the assembly workstation layout (ii) redesign of assembly jigs and fixtures (iii) replacement of assembly tools (iv) re-engineering of assembly procedures (v) special training of human operators.

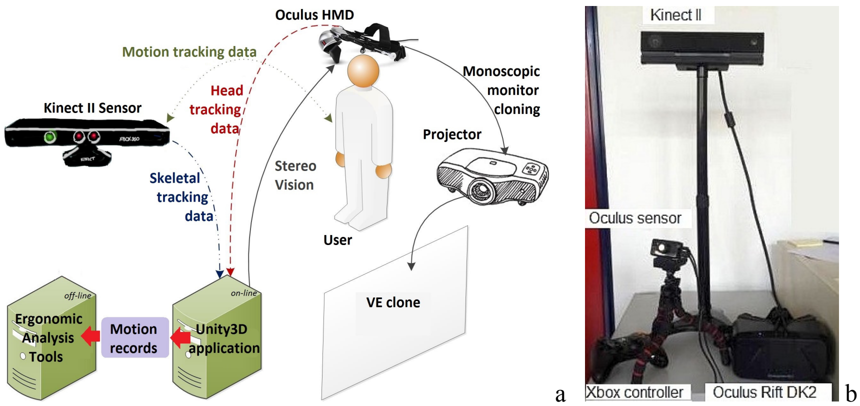

Fig. 1 (a) Virtual Assembly Process Assessment for Large Parts; (b) Sensors employed

2.2. Ergonomics assessment

RULA and REBA protocols are considered to be of general applicability in assembly process assessment because upper limb and entire body of the human operator have to be observed in essentially all tasks concerning large parts. Thus, shoulders, wrists, elbows, neck, trunk and legs are the object of observation. There are six steps to follow: (i) Observe the task, (ii) Select postures for assessment – worst vs. most frequent, (iii) Score the postures, (iv) Process the scores, (v) Determine final score, (vi) Confirm action level.

Scores are computed according to distinct rules. For instance, RULA distinguishes five possible ranges for upper arm (elbow) angle with respect to the vertical, namely ±20°, <-20°, 20-45°, 45-90° and >90° and these ranges are assigned scores: 1, 2, 2, 3, 4 respectively. There are also combinatorial and conditional scoring rules, as well as others that take into account load and time of application. Scoring scale is 1-7 for RULA and 1-15 for REBA.

Corresponding actions are foreseen. For RULA such actions involve: do nothing since posture is acceptable (1-2), investigate further (3-4), change soon (5-6), change immediately (7). For REBA action necessity is: none (1), maybe (2-3), required (4-7), required soon (8-10), required now (11-15). The discerning reader is referred to [18] and [19] for further details regarding RULA and REBA and to [21] for an illustrative application example.

In some assembly environments special ergonomics protocols may be applicable. In essence such tools provide tabulated data based on observations and clinical experience. For example, when vibratory tools are used HAV protocol is applied to calculate a score reflecting health risk from tool vibration. In this case, this depends on the acceleration level induced, as looked up in standard tables per tool type, and on exposure duration per 8-hour shift.

2.3. Implementation platform

The Virtual Environment could be implemented on various platforms of which Unity3D™ was selected due to its maturity, user / developer community and zero acquisition cost. This is a platform for game creation including a game engine and an Integrated Development Environment (IDE) with good online documentation [22], as well as a graphical environment for project programming. Components and scripts are attached to GameObjects to control their behaviour. Components can be: transforms, cameras, colliders, particles, rays, rigid bodies, audio sources etc. Transforms determine the position, rotation and scaling of a GameObject relatively to its parent. Scripts were programmed mainly in C#. In particular, in every class a Start script is called once before the play mode begins, and an Update script is handled during the frame update in play mode, involving movements, action triggering, responses to user actions etc.

VAPA-LP development involved: (i) creating or importing the virtual objects (ii) creating an avatar with appropriate kinematics (iii) adding interactions between the user and the assembled objects (iv) scripting the scenario for testing. So far, the application's total size is 209MB containing 11 original C# scripts to model the scenario activities as described in Section 3.

The hardware used, see Fig. 1(b), is (i) a microsoft Kinect II^{TM} sensor as an input device for skeletal tracking of the user employing microsoft Kinect SDK v1.8 for communication with the Virtual Environment. (ii) a stereoscopic HMD (Oculus Rift DK2^{TM}), comprising a headset and a sensor camera, as an immersive output device, and as an input device for head motion tracking, employing an SDK for connecting to the Virtual Environment. Note that the distance between the user and the Kinect was about 2.5 m and between the user and Oculus sensor was about 1.5 m.

2.4. The case study

Small to medium aircraft wings are built by first laying out spars along a suitable jig, see Fig. 2(a), and then riveting sheet metal skins on them, see Fig. 2(b),. Riveting is often performed by technicians, see Fig. 2(c), using pneumatic tools, see Fig. 2(d). Depending on the size of the wing or wind section being built it is possible to configure the assembly jig as well as the assembly workstation in different ways, corresponding to different technician postures, different working distances from the floor, different needs for main and auxiliary equipment etc.; such design decisions are expected to have an impact on productivity, safety and cost. Thus, a Virtual Environment (VE) is considered to be advantageous in designing and trying out alternatives at low cost.

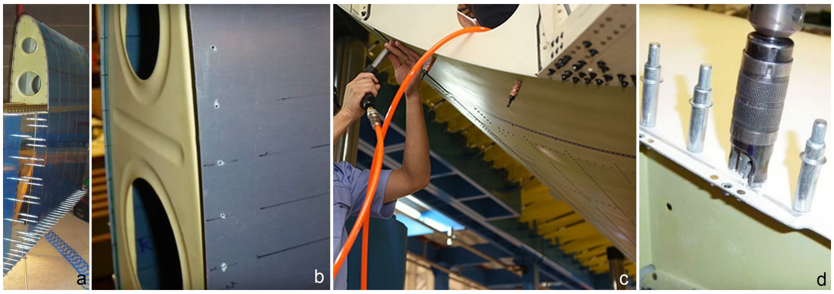

Fig. 2 Riveting process (a) frame (b) skin riveted to spar (c) typical work snapshot (d) pneumatic tool closeup

3. Application development

3.1. Virtual world

The virtual world incorporates (i) a number of original 3d models forming the virtual wing assembly-cell, (ii) the skinned model of an avatar with a biped attached to it, (iii) real-time data exchange with the tracking device, (v) interaction scripts mainly concerning collision and ray-casting, child/parenting functions and skeletal tracking of avatar joints, (vi) real-time shadows, rendering and lighting, and (vii) image and audio textures enriching the working space.

An assembly jig for holding the wing with the desired orientation was designed in CATIA 5^{TM} system as the main part of the assembly workstation, see Fig. 3(a). 3D models of the wing (spars, skins and rivets) as well as of various objects of a wing assembly factory, such as hoists, cranes, shelves etc. stemming from web model bases were suitably modified, certainly in terms of scale, before being input into the virtual scene, see Fig. 3(b).

A skinned, fully functional male avatar model was created in the Evolver™ avatar builder as a textured mesh model of 11000 polygons, with a custom face (clone) and a body animation rig. A biped was attached to the avatar model, making it kinematically functional.. An avatar is essential in a first-person shooter application, to enhance sense of presence and association of the user with the virtual body through tracking, because the user is wearing an HMD and the real world is completely blocked from his view. The main camera is attached to the avatar's head as a child of the head transform, at eye height and with ±60 degrees field of view about the local vertical axis. A capsule collider bounds the avatar's torso whereas the upper body is enclosed in another capsule and two smaller capsule colliders are attached to its hands and forearms. Rigid body physics is also added in the avatar's hands, head and torso. 20 avatar tracking points (Unity Transforms) are used for skeletal tracking, see Fig. 3(c).

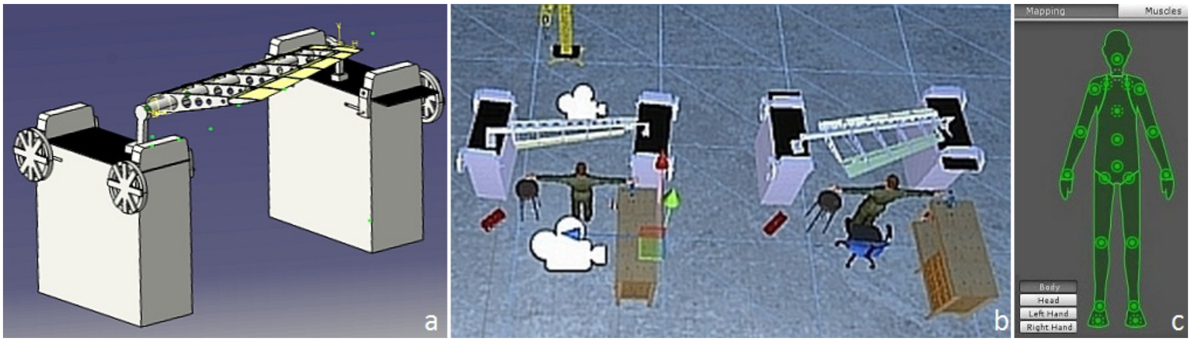

Fig. 3 (a) Designed assembly jig holding wing spar frame (b) General view of the virtual scene (c) Avatar tracking points

3.2. The simulation scenario

The scenario that has been modelled requires the human operator to take a rivet, put it in the required pre-drilled hole on the wing skin and the corresponding spar below it, then take the pneumatic tool from the bench, align it with the rivet, move it to so as its hollow head makes full contact to the rivet head, allow compressed air to hammer the rivet, disengage the tool from the rivet head and return it to the bench. The same cycle is repeated for as many rivets in a sequence as required. Fig. 4 presents characteristic snapshots of typical application execution

Fig. 4 Characteristic snapshots of the application scenario execution with upper / lower arm positions marked (right)

In the current version, some tasks are fully supported in a realistic way whilst others are modelled as metaphors. For instance, the rivet hammering task is not realistic enough yet, since it is not supported by haptics, i.e. the reaction to the holding pressure applied against the jig is not felt by the user. Yet, the weight of the tool is actually felt by the user, since a real riveting gun is used instead of a mock-up or any other substitute.

Selection, manipulation, navigation and system control are interaction tasks accomplished with the use of a variety of natural interaction schemes. Ray-casting and collision-based pointing techniques are used for selection. Direct-virtual-hand, real hand gestures, collision, and child/parenting techniques are used for manipulation. For instance, a ray casting script is attached to the avatar's index fingers and the pneumatic tool's head, which casts a small, invisible ray towards all colliders, and returns a true Boolean value when the object with the desired tag is hit, which, then, becomes a child of the hand's or the tool's transform. Alignment and positioning of the tool with respect to the rivet on the wing skin is accomplished by analogous collision detection techniques. Primitive shape colliders (or combination of them) are preferred to complex mesh colliders, for execution speed and for maintaining a steady frame rate. Collision detection can initiate rigid body physics actions (onCollisionEnter function), or just trigger events and call another function (onTriggerEnter function).

Navigation is implemented with simple physical motions and real walking techniques, through head and body tracking, taking into account space limitations imposed by the sensors and connecting cable.

Neither Graphical User Interfaces nor physical tools are used for system control, but mainly tracking-driven virtual hand interaction (select, manipulate) and specific objects trigger a system state change. For example, when the user's virtual hand interacts with the pneumatic tool, e.g. the user walks to, approaches his hand and finally collides with it, a function is triggered that moves subsequently the tool with the user's hand. Conventional system control is restricted to the posture commands technique applied during calibration. Mouse and keyboard are used for minor system control tasks, e.g. application termination, settings typing at start and motion data logging.

3.3. Motion information recording

A special script was written in order to continuously record the Avatar Position as well as the transforms of specific avatar members, namely: Shoulder, Arm, Elbow, Wrist, Middle Finger (left and right), Spine, Neck. Table 1 presents a sample of this data recorded every 10 frames, depicting data comparison in close and distant frames.

Table 1 Sample recorded orientation data for three avatar members

Frame - Time.time (sec)	1- 0.5798939			41- 1.275033			451- 10.23379		
	X	Y	Z	X	Y	Z	X	Y	Z
Transform_RightShoulder (localRot)	-0.0479	-0.0409	0.7584	-0.0479	-0.0409	0.7584	-0.0951	-0.1432	0.8701
Transform_RightArm (localRot)	0.0009	0.0116	-0.0776	0.0009	0.0116	-0.0776	0.0767	0.0420	0.2821
Transform_Neck (localRot)	0.0000	-0.2648	0.0000	0.0000	-0.2648	0.0000	0.0350	-0.2479	0.1858

An alternative also offered by the system concerns recording of the scene during application execution through Unity3D^{TM} plugin "AV Pro Movie Capture". Four different cameras were employed: one for viewing the wing, one for the avatar legs, another for the avatar neck and back and the last one for the avatar shoulders, wrists and elbows.

Fig. 5 Riveting in the immersive virtual environment (a) human operator (b) corresponding avatar

4. Preliminary test results and discussion

A preliminary test of the system and assessment of results was conducted with a sample of 9 unskilled operators, see Fig. 5. The test is conducted as follows: each participant tries the manipulation in turn. They wear the virtual reality headset and stand in front of the Kinect II™ and the Oculus™ sensor camera. Before starting the test the sensor camera has to be calibrated for operator height. In these tests two tasks were focused on: handling of the tool and the rivet, and riveting as such: the avatar will put the rivet in the hole and will use the rivet gun to hammer it. This was repeated for a complete rib comprising 20 holes to be riveted, which lasted about 4 minutes. The wing was held by the jig in the vertical position, see Fig. 5(b).

First, common sense checks, such as comfortable reach of all rivet holes were performed in order to verify acceptability of the designed jig, wing orientation and the associated tool and method.

Subjective evaluation of the assembly method and tools was also sought through a questionnaire. The users were asked to (i) mark on a 1-10 scale any physical discomfort felt at 11 possible parts of his/her body, e.g. shoulder, elbow, wrist etc., and assign their cause in terms of tasks performed (ii) present the tasks performed and explain the pertinent difficulties encountered (iii) report any headache and its intensity after using the Oculus Rift. According to the results obtained, most painful limb is the right shoulder (8/10), right wrist (7/10) and right elbow (5/10), whilst, the less painful are the knees, legs and left hand and elbow (0-1/10). No clear answers were obtained for question (ii) whilst in question (iii) some dizziness was reported.

Then, the most important of the motion data captured were assessed according to RULA [18] and REBA [19]. Motion patterns were detected by the analyst by observing the full scenario as recorded in Unity3D™ video, see Fig. 4. This involved approximate estimation of the angles at joints of interest and scoring according to the pertinent rules, see Section 2.2. This manual procedure involves stopping the video frame-by-frame and is arguably tedious and prone to errors, but it was used as a substitute to automated motion pattern detection, which has not been implemented yet. The scores obtained regarding main riveting posture, see Fig. 5 were: 6 (medium risk. change soon) for RULA and 6 (required) for REBA. Indicative results for RULA are shown in Table 2. Application of HAV [20] protocol involved measuring the total duration of rivet hammering subtasks in the recorded scenario (2.4 hrs per 8 hr shift) looking up riveting tool in a standard table for vibration data (5.6 m/sec^2) and entering this data to the HAV calculator that yields the Total Exposure Points, in this case: 157, meaning some changes to be undertaken.

Table 2 Indicative results for RULA regarding main riveting posture

Group	A						B				C	Final score
Body part	*U*pper *A*rm*	*L*ower *A*rm*	*W*rist*	*W*rist *T*wist*	*M*uscle*	*F*orce/ *L*oad*	*N*eck*	*T*runk*	*M*uscle*	*F*orce/ *L*oad*	*L*egs*	
Score	5	2	3	1	0	1	2	1	0	1	2	6

* UA: Angle 45-90°: +3, Shoulder raised: +1 , Upper arm abducted: +1, LA: Angle>100°: +2, W: Angle: ±15°: +2, bent from midline: +1, WT: twisted in midrange: +1, M: posture repeated <4X/min: 0, FL: 4.4-22 lbs intermittent, N: Angle <10 : +1, side bending:+1, T: upright:+1, L: not supported:+2. (Table A score: 6, Table B score: 3 [18], www.ergo-plus.com)

To improve the situation in riveting, where it was found that the tool weight and the upper arms position present a problem, the jig may be turned to hold the wind at a horizontal position under the operator, the tool may be suspended from a spring etc, but any solutions need re-assessment as above before being adopted.

5. Conclusions and further work

In assembly of large parts, such as aircraft wings, it became possible to try out the methods and tools prescribed in a low cost Virtual Environment. Although basic motions and interaction were successfully modelled, there is still room for future refinements for attaining higher fidelity in motion by further exploiting the game engine's functionality. The VR equipment is deemed adequate regarding accuracy, with some reservation concerning stability of viewing through the HMD and freedom of movement due to the sensor ranges and cable connection.

The avatar (manequin) employed has enough joints to model basic but not subtle movements. Capabilities for finger tracking through wearable IMUs are currently being considered to rectify this discrepancy.

All assessments performed so far concern reach and posture ergonomics as based on kinematics in 3D space. Haptic feedback of the equipment is an obvious future extension. Subjective assessment of the assembly setting by the participating human is advocated as equally important to objective assessment based on ergonomics protocols.

Currently human operator motion is recorded on video and this is studied manually to detect patterns of undesired postures according to established rules in RULA and REBA protocols. However, recording of avatar's skeleton transformations has been achieved, enabling automatic identification in the near future.

The ultimate aim is extensive use of the application in order to compare alternative wing assembly cell designs with a large sample of users, including experienced operators and similar use in further large part assembly tasks.

Acknowledgements

J. Deville's stay at NTUA was financed by the Erasmus+ programme and 'Bourse de mobilité international étudiante de la Région Rhône-Alpes'.

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