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Development of An Augmented Reality Equipped Composites Bonded Assembly and Repair for Aerospace Applications

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Development of An Augmented Reality Equipped Composites Bonded Assembly and Repair for Aerospace Applications

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Abstract: The prosperity of aircraft transportation together with revolutionary promotion of composite components used in commercial aircraft pose enormous challenges to the aircraft composite assembly and repair (especially uncertainties associated with polymer process parameters control, barely visible defects and non-destructive inspection capability to inspect zero-thickness defects). Therefore, an industry solution owning merits on reliability and repeatability of assembly process is at high demand. Augmented Reality (AR), a human computer interaction technology, possesses its exclusive superiority on its capability of inflicting digital mock-up into physical environment. The above property of AR provides colossal opportunities to be utilised into industrial applications to contribute the realisation of automated, efficient, streamlined and reliable process and assembly. The current ongoing research aims at developing an AR System integrated into aircraft composite bonded assembly and repair as a guidance tool to instruct technicians' repairing operation, mitigate human errors, and reduce duration of repair and assembly. Upon the accomplishment of the System, the researchers would aim to investigate the incorporation of machine learning and deep network algorithms to enable and significantly improve the interactions between the multitude of process parameters involved in the composites assembly control procedures, solely relying upon the AR geometric data. This will ultimately lead to dramatic reduction of sensors in aircraft assembly, mitigation of in-process analysis time, reduction of process and post-process inspection time, and a higher quality assembly. Stepped scarf composite repair embedded with soft composite patches was selected as the archetype to be brought into effect though hard patches were partially examined as well. The AR System has focused on composite patches assembly and vacuum bagging process to address the predicament of miscellaneous steps and fibre directions.

Keywords: Composite bonded assembly, Scarf repair, Aerospace, Augmented reality, Digital mock-up

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1. INTRODUCTION

Thanks to the prosperity of global economy and progress on materials and manufacturing, airplanes have dominated the transportation market with ascendant performance on safety and speed. Tthe expenditure spent on aircraft Maintenance, Repair and Overhaul (MRO) sector is currently at USD 46bn level (Doan 2015). On the other side, composite materials leaped into the favourite of aircraft designers considering its virtues on the ratio of weight and performance.

The prosperity of air transportation, together with the dominant proportion of composite component in commercial aircraft, address immense challenges to the MRO industry of composite scope as to commercial aircraft. Accompanied with enormous opportunities and interests, the global aircraft MRO market is expected to be USD 680bn by 2021 (Company 2019). In response to the above, a competitive industry solution which bears merit on efficiency, and also provides accessibility to explicitly instruct the operations of MRO engineers and operators is highly demanded. Several challenges exist in processing and performance of composite laminates and bonded assemblies, acting as barriers for their reliable utilisation and scalability. The effects from improper process parameters control on the performance can be significant, e.g. poor bond quality of composite assembly induced by improper surface preparation or insufficient cure (Bhanushali, Ayre et al. 2017, Liu, Lemanski et al. 2018, Yazdani Nezhad, Stratakis et al. 2018), which are difficult to detect via non-destructive inspections (Deane, Avdelidis et al. 2019, Sirikham, Zhao et al. 2019). On the other hand, composite laminates are susceptible to impact events induced during maintenance, known as barely visible impact damage (Gonzalez, Maimi et al. 2012, Nezhad, Merwick et al. 2015).

Augmented reality (AR), a human computer interaction technique which has been under development nearly half a century (Fernández del Amo, Erkoyuncu et al. 2018), has started to attract enormous attention during the past two decades. Attempts have been implemented in variety of industries such as construction (Hernández, Lerones et al.

2018), medical treatment (Sielhorst, Feuerstein et al. 2008), manufacturing (Rukubayihunga, Didier et al. 2015).

The current research aims at providing an effective solution of instructing the operating process for composites bonded assembly and repair by utilising the aforementioned AR technique. Functions expected to be realised were:

- Process knowledge embedment, i.e. the designed application is able to embed relevant operation requirements and parameters (e.g. fibre direction and diameter of patches) of composite bonded repair.
- Modifiable parameter setting, which means the value of the process parameters can be changed depending on different models of aircraft.
- Instruction functionality, which means the developed AR system is capable of being utilised as a process instruction to guide technicians' operating.

2. METHODOLOGY

The methodology consisted of gap analysis, composite assembly concept design, manufacturing of composite patches and panel, development of AR algorithms, and integration of the algorithms to the assembly procedure. Further analysis was implemented to have visual representation of the gap between existing AR industry applications and the composite bonded repair process.

The specific steps aimed to be integrated into AR applet have been finalised. The applet operating sequence has been defined. Detailed design on models have been implemented, under which, software, platform and programming language were employed to proceed further development. Out of the above, application developing ranged from importing image target, building up digital mock-ups until creating user interface has been the major parts of the implementation.

3. COMPOSITE BONDED ASSEMBLY AND REPAIRING

Multifarious inducer such as lightning strike, improper ground and process activities (e.g. low-velocity impact damage (Nezhad, Merwick et al. 2015) and process-induced bond defects (Bhanushali, Ayre et al. 2017)) and environment corrosion will bring about many composite defects in commercial aircraft operating circumstances. Thus, a basic exposition of frequently-used composite repairing methods was investigated. Further on, scarf repairing which gains good graces in aircraft repairing industry was interpreted:

3.1 Composite Bonded Repair Steps

Basically, there are two types of methods that are commonly used in case of composite repairing, that is Resin injection repair and Patch repair (Soutis and Hu 1997):

Resin Injection Repair, as its literal meaning, is a method that transfuses resin into the defect area, which is a temporary solution to prevent damage propagation (Katnam, Da Silva et al. 2013). Patch repair which is a commonly used repairing method can be treated as a perpetual industry solution. Different branches still exist based on the choices of removal damage material or not, accessing from one side or both, shape of removal temper (Katnam, Da Silva et al. 2013). Scarf patch repair's virtues on providing aerodynamically smooth surface and effective stress transfer attracts high attentions in the aircraft composite repair industry (Wang and Gunnion 2009), and has been considered in our research case.

3.2 Scarf Based Repair Major Steps

Three major steps are necessary to accomplish bonded repair:

Material removal: It is the process of removing materials of defect zone to create a hollow cavity for embedded patches. This stage has been skipped as the defect hole area was intentionally considered in the panel manufacturing to start research from the post material removal stage.

Surface preparation: This is an imperative process to guarantee the mechanical properties of laminate in the way of guaranteeing required adhesion force, especially for the composite repairing process, a new surface (scarf surface or stepped scarf surface) of which had been created by the previous machining process, which is also compulsory e.g. regulated by the European Aviation Safety Agency (EASA). This new created surface needs to be treated to achieve surface uniformity and wiping off any debris, dusts, or any other contaminant generated from the preceding process or caused by the ambient (Baldan 2004, Hart-Smith 2011). Misunderstanding on surface preparation exists that deems a clean surface as the exclusive surface requirement to achieve fine bonding quality. Surface wetting occurs on the condition that the surface energy of the adhesive applied for bonding is lower than that of adherend. Abrasion/solvent cleaning, and peel-ply treatment have been implemented to relatively enhance the adhesion strength via promoting surface energy, augmenting surface roughness and surface chemistry.

Repair execution: To acquire a robust and reliable patch repair structure, suitable material matrix (herein thermoset polymer adhesive) and controlled curing conditions are duple systems to be taken into account, where the material matrix refers to materials such as patch materials, resins, adhesives together with temperature and pressure are elements to be paid attention on, in case of curing conditions (Whittingham, Baker et al. 2009, Caminero, Pavlopoulou et al. 2013). Aerospace grade carbon fibre-reinforced thermoset composite patches were cured via autoclave pre-preg manufacturing at 7 bars and 180°C, and bonding using aerospace grade adhesive film (Cytec FM94) at 0.28MPa and 120°C.

4. COMPOSITE MATERIAL AND PROCESS

As per commercial aircraft repairing strategy, time spent on repair bearing highly dependence on aircraft downtime has to be taken into consideration in the aspects of operation and cost. Adhesive material which can be stored in room temperature and possess low curing temperature and short curing time is consummate in case of the above operational considerations. Nevertheless, the compatibility with its mother (composite) panel which will contribute to the continuity of the repairing structure is a determinative factor.

4.1 Curing conditions

A good compaction of composite plies was guaranteed by adaptive temperature, pressure and vacuum conditions enabling curing reaction (Katnam, Da Silva et al. 2013).

Curing pressure: an appropriate curing pressure helps enhancing consolidations and decreasing porosities by providing proper bondline thickness, enabling adhesive flowing and wetting the surface and squeezing out trapped air (Chester and Roberts 1989, da Silva, Adams et al. 2004, Tzetzis and Hogg 2008). Vacuum bagging and mechanically fixtures are alternative ways to apply pressure in case of composite repairing, the earlier was used in our research.

Curing temperature and time: Curing temperature is a key factor to be controlled to realize a fine bonded patch. Conundrums still exists on eliminating thermal gradient because of the poor thermal conductivity in the through thickness direction of composite laminates (governed by polymer's poor conductivity) which can cause non-uniform stress transfer and ineffective bonding. A heat blanket is the most frequently-used method for situ repairing.

Vacuum bagging: This is a popular technique adopted among aircraft composite repairing industry to achieve a uniform curing pressure, also used in this research. The uniform mechanical clamping force is obtained from pressure differential between normal ambient and sealed vacuum system. The sealed vacuum system is achieved by utilising vacuum pump to extract detained air and using sealant tape to create isolated interspace. It serves functions such as squeezing out air trapped between laminate layers, reducing humidity, enabling efficient force transmission and disabling fibre orientation twisting by compacting fibres, and optimizing fibre-to-resin ratio which is a key parameter to obtain strength-to-weight superiority of composite matrix.

Sealants were used, crucial to achieve airtight bagging.

Bagging system is a combination of diverse layer of auxiliary materials whose functions ranged from easy peel-off, absorbing until isolation. The composition of bagging layers is not universal but case-by-case depending on the factors of material, temperature and equipment employed. The PTFE types were used in this research.

Heating system used for curing requirement of the resin was adopted. However, aircraft composite manufacturing industry employs heating system very frequently ranging from autoclave, oven until heating blanket. In case of repair terrain, heating blanket is the minion considering its virtues on manoeuvrability and cost-effectiveness.

Another non-negligible unit in heating system is the thermal couple which is employed by being distributed into different locations of the panel to be cured to monitor the curing temperature. Three thermal couples allocated respectively into part centre and tail end are mandatory according to most of the aircraft manufactures' specifications, which were used for temperature monitoring across the surface of the patches.

5. AR INTEGRATION IN COMPOSITE BONDED ASSEMBLY AND REPAIR

AR, compared with virtual reality which is a thorough virtual interface isolating from physical ambient, enhances human beings' perception of realistic surroundings by combination digital perceptual information with physical existence (Caudell and Mizell 1992), therefore acts as a user-digital mock-up interactive interface. These computer-generated sensorial information can be overlaid in two formalisations that is constructive and destructive, where the constructive means additional digital data being inflicted into natural surroundings, however, the destructive means the computer-generated sensorial information will override the related physical subsistence. Four types of AR can be classified based on the technique adopted for positioning, which are Maker Based, Markerless (our research case herein), Projection Based and Superimposition Based. Three typical representatives of AR's application into aircraft industry are MiRA Technology developed by Airbus Group Innovation, IRIS Integrated AR developed by Safran Composites (Sauer, Khamene et al. 2001), and Composite Adaptable Inspection and Repair (CAIRe) by Lufthansa Technik.

5.1 AR equipped Composites Process Design Scenario

Stepped scarf combined with soft patches was selected as the prototype method as per the aerodynamic and stress transfer benefits. Figure 1 is the process flow generated based on the type of repairing method selected. Laying up together with vacuum bagging process was selected as the target processes to be casted into program, to guarantee almost identical fibre orientation between the repaired panel and scarfed patches to realise the continuity of mechanics (stress transfer). It will also be an intricate process in case of dozens of plies to be applied together with the disparate orientation requirement. It is highly possible that technicians operate incorrect or improper during these laying up and vacuum bagging process. It should be noted that the AR-process integration strategy developed for the soft patches would be very much applicable to hard patch scenarios as well. To concentrate more on the design and developing of the application itself, the panel and patches' dimensions of an aerospace research scenario were inherited and utilised. The panel was designed as a 300mm×300mm flat square carbon fibre-reinforced composite laminate. The thickness was 6.8mm. The defect was assumed to be at the centre of the laminate with dimension 68mm×72mm (Table 1). The quantity of the patch steps was designed as three to avoid repeated programming, and to mimic a 6° recommended angle of scarf repair.

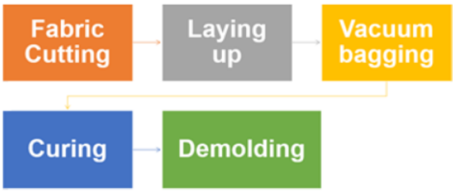
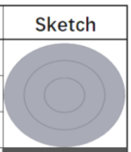


Figure 1: Soft patch scarf repair process

Apart from the adhesive film and carbon composites, a set of auxiliary materials functioning as absorbing excess resin, demoulding and sealing was mandatory to be applied to assist the entire curing process. Figure 2 illustrates the combination of auxiliary materials to be applied in our scenario, among which *Dry Peel Ply* was utilised for easily splitting all the consumable materials above it from the cured composite entities, *Perforated Release Film* was employed to isolate other auxiliary materials from laminates, *Absorbing/Breather Fabric* wrapped below and above the thermal blanket was applied for absorbing excess resin and protecting the thermal blanket from being contaminated by chemical liquid, *Thermal Blanket* was utilised for heating source other than any auxiliary materials, and *Bagging Film* functioned as sealing the whole system to guarantee vacuum condition together with preventing contaminations from ambient.

Table 1: Panel and patch dimensions

Unit: mm		Diameter/Sides Length	Thickness	Sketch
Patches	Patch 1	76	2.1	
	Patch 2	138	2.35	
	Patch 3	200	2.35	
Panel		300	6.8	

Also, thermal couples were utilised to monitor and control the curing temperature, together with vacuum networks consisting of vacuum pump (not relevant to lay-up however) vacuum tubing, connectors, vacuum gauge, etc.

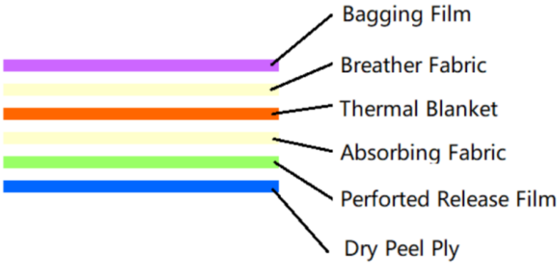


Figure 2: Auxiliary material layup sketch

Equipped with the mentioned layers and facilities, the entire vacuum bagging system was set up as shown in Figure 3.

5.2 Functionality Design

The primary functions expected to be realised in the research were user interface, user interaction with system and stepwise instruction. User Interface was comprised of the step buttons. The layout of the step buttons (Figure 4) was designed to be standing in one horizontal line. These buttons were built up from left to right following the operating sequence. Each button was named as the material or equipment it indicates, except for carbon layers in which additional information on lay-up direction (0°, 45°, 90°) are presented on the buttons.

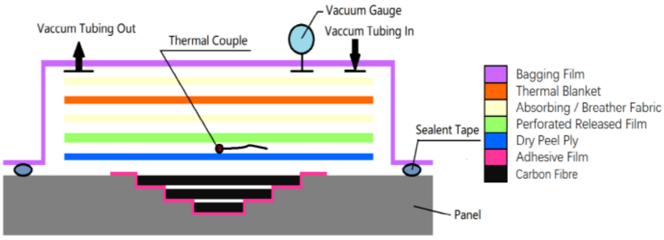


Figure 3: Schematics of vacuum bagging system

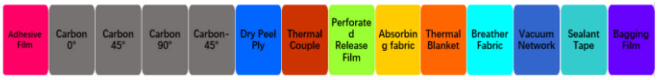


Figure 4: Button layout

Digital Model of each entity was employed during laying up and bagging process, to allow operators bearing directly perception on the dimension and position of each material or sensor to be applied. Once the pre-set marker is recognised, the virtual matrix emerges in front of operator's view.

Interaction between user and system was built up through the trigger events set up above each button. In our case, the virtual mock-up of each layer was colorised once its related button is triggered. The colour rendered to each layer is not uniform but in accordance with the colour of its respective button to intensify identification function.

Stepwise Instruction was realised through the massive bulk of process information, split and endowed into each button.

6. IMPLEMENTATION AND RESULTS

6.1 Hardware Configuration

The entire developing process was divided into two phases based on the different output equipment, which are Tablet Based and HoloLens Based. During the Tablet Based Phase, the only hardware employed is a digital camera embedded tablet computer. The digital camera was exerted to capture the feather points of the image target to enable positioning the digital mock-ups. The tablet computer was utilised to operate the system and as the output termination to display the combination scene between virtual mock-ups generated from computer and physical operating circumstance captured by the embedded digital camera. Further on, Microsoft HoloLens was introduced into the system as the output terminal to substitute the original tablet screen terminal. Thus, the image target is captured by the digital camera embedded on the HoloLens, and the synthetic scene presents directly in front of operator's view via Microsoft HoloLens.

6.2 Developing Environment Configuration

The primary developing platform was selected as Unity (Version 2018.3.14 f1 64-bit) equipped with Vuforia Engine considering the wide-range compatibility on operating system guarantees extensive client base, formidable and sophisticated computer graphic technique, broad user base and user-friendly, compatibility to external resource realised by drag and drop functionality, and supportability on scripting Programming Interface (API) in C# by plugin.

Apart from Unity, a set of associative configuration was equipped into computer to drive Microsoft HoloLens, which are Windows 10 PC operating system with developer mode, Visual Studio 2019 (Version 16.1 or Higher) to compile code, debug, test and deploy, Windows 10 Software Development Kit (Version 10.0.18362.0) to assist the building of HoloLens, and Mixed Reality Toolkit (MRTK v2) for certain advanced and intermediate functions.

6.3 Development Process

Based on the presupposed function to be realised under the current system, stages were undertaken (see video here):

Stage 1: Import Image Target to Enable Graphic Recognition.

Stage 2: Build up 3D Models representing diverse materials and facilities to be applied under Image Target as its child. Thus, once the image target was captured by the digital camera and recognised by the system, these child objectives emerge at the pre-set position. Figure 5 exhibits the pre-set image target and the matrix of digital mock-ups build upon the marker. A perpendicular view was deliberately designed to be presented in front of users' view to allow the operator possessing global view of the whole set of stages.

Step 3: Creating canvas to put user interface elements inside.

Step 4: Setting up Render Mode and Layout. A horizontal layout was built up to indicate a left-to-right sequence of operating. Here Horizontal Layout Group tool was employed.

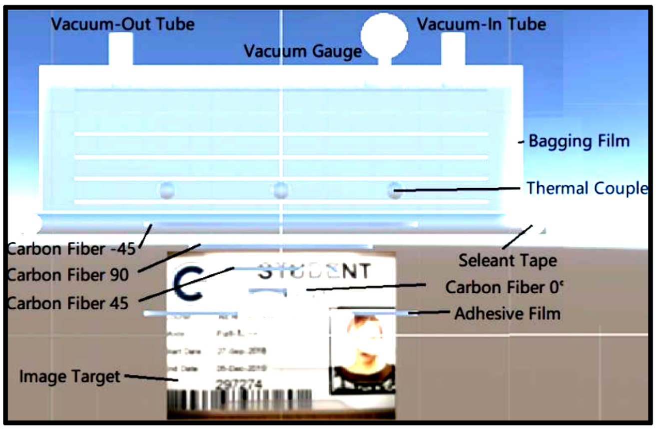


Figure 5: Shot of digital mock-up built under image target

Step 5: Create Interactive Components – Buttons representing each step were built up to realises the interaction between user and system. Relevant virtual mock-up were colorised once its indicating button clicked by setting up click event to each button (Fig. 6). Especially, the rendering of digital mock-ups of carbon fibre composites were set to be the textures and orientations which equip the operator with an instinct view the exact fibre orientation to be initiated. Diverse colours were endowed to indicate different stage of each button like normal, highlighted, pressed and disabled colour. The normal colour of the button and the render colour of its related digital models were set as a matched colour to build up another potential linkage between both.

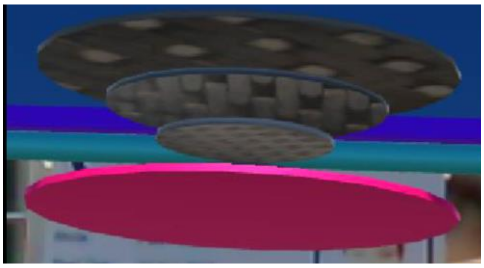


Figure 6: Carbon composite rendering texture

Step 6: Building up an indicator to trace the current steps. Fifteen buttons have to be established due to the tremendous steps of materials and equipment to be applied. To avoid any labyrinth, a tracker was designed to stand at the top of current operating button.

Step 7: Conversing the output terminal from tablet screen into HoloLens: Further attempt was made to transform the output platform into Microsoft HoloLens which bears superiorities on offering immersive ambient to user and hands liberation. Some modifications had to be made to coincide with Microsoft HoloLens Configuration: 1- Image Target was placed obliquely instead of a perpendicular view during tablet based output. 2- Stepwise process information were presented by activating the pre-set mock-up to indicate disparate operating steps, which means the monolithic mock-ups will be split and come up one after another based on the button clicked instead of being colorised brick by brick. 3- Materials were rendered as the texture of its physical entity to reinforce the function of virtual mock-ups, which caused the cancellation of the potential colour linkage between buttons and its related process (Fig. 7). 4- Step Tracker was abandoned. Dynamic floating text was introduced to instruct operator the current step with its name broadcasting at the top of user interface. A typical image comparing physical and virtual carbon composite patches is shown in Figure 8. 5- Four Buttons functioned respectively as previous steps, next steps, reset and remote view.

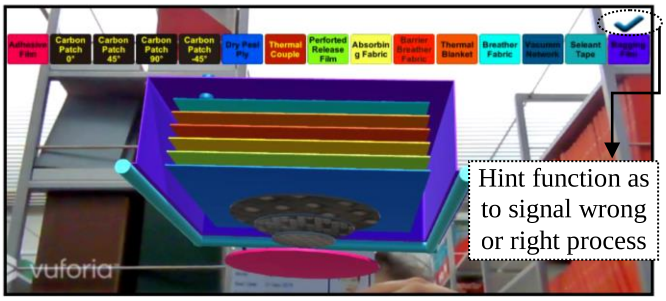


Figure 7: Real-time running shot of tablet based program

6.4 Program Validation

There are existing reports proved that the implementation of AR technique into aerospace manufacturing instructing area facilitates substantial promotion and upgrading on productivity and quality. A 90% increase in first-time quality and a 30% decrease in operating time was announced by Boeing by exerting AR technique instructing to install electrical wiring of airplane. This was to assist engineers installing electrical wiring on aircraft via providing a real-time, hands-free, 3D wiring diagrams before engineer's eyes.

The current program will be validated through two separate directions: functionality validation and effect validation.

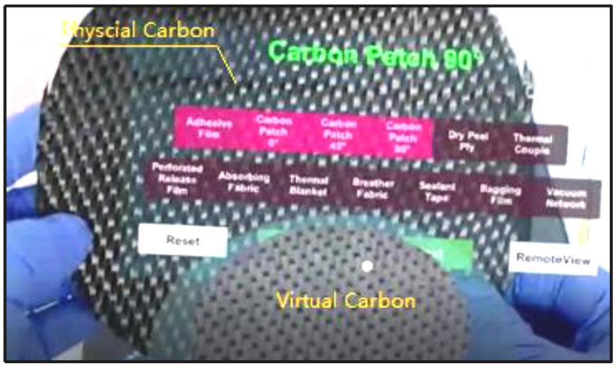


Figure 8: Contrast between physical and virtual patches

7. DISCUSSION AND CHALLENGES

The currently developed AR toolkit provides a digital and automatic way of instructing composite bonded assembly and repair process. Compared with the conventional pattern in which process instruction is delivered through paperwork instruction and 2D repairing sketches, our toolkit exhibited superiorities such as Processing Time Reduction, Process Reproducibility Fortification, Products Quality Promotion, and Threshold of Operators' Skill Descending.

Challenges still exist in the current system which is under development in aspect of image recognition, position accuracy, system synchronism and scenario's compatibility such as Image Recognition, Accuracy of Position, System Synchronism, and Scenario Compatibility.

8. CONCLUSIONS

The current research accomplished an attempt on applying AR technique to realise a real-time instruction of aircraft composite bonded assembly and repairing process, specifically for composite scarf bonded patch repair. Patch installation and bagging process was selected as the target process to be pitched into the AR application design. An aerospace grade composite repair was selected as prototype to accommodate system's concept design and as the foothold to generate system's operating flow. Bagging scenarios were designed based on this specific scenario. Digital mock-ups to indicate different implementation of materials and facilities were created. User interface was designed and built up. User and system interaction was realised through creating interactive buttons and endowing trigger event to the related buttons. The blend between digital mock-ups and physical panels and patches was realised through pre-set image target recognition. Dual output terminals (Tablet screen and Microsoft HoloLens) were also realised. Functionality validation was executed through putting use into a laboratory demonstration. Effect validation route was designed.

The developed application contributes to exploiting routes to employing AR technique into commercial aircraft maintenance, repair and overhaul industry and exhibiting potential capability and space to be pitched into industrial environment to remit the increasing workloads brought about from continuous incremental adoption of composites in aircraft assembly through an efficient, reliable and reproductive platform. Further utilisation and validation of such capability would enable integration of machine learning and/or deep learning algorithms in future for reliable automation of high valued composite assembly and repair.

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