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## Intelligent Composite Layup by the Application of Low Cost Tracking and Projection Technologies

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### Abstract

Hand layup is still the dominant forming process for the creation of the widest range of complex geometry and mixed material composite parts. However, this process is still poorly understood and informed, limiting productivity. This paper seeks to address this issue by proposing a novel and low cost system enabling a laminator to be guided in real-time, based on a predetermined instruction set, thus improving the standardisation of produced components. Within this paper the current methodologies are critiqued and future trends are predicted, prior to introducing the required input and outputs, and developing the implemented system. As a demonstrator a U-Shaped component typical of the complex geometry found in many difficult to manufacture composite parts was chosen, and its drapeability assessed by the use of a kinematic drape simulation tool. An experienced laminator's knowledgebase was then used to divide the tool into a finite number of features, with layup conducted by projecting and sequentially highlighting target features while tracking a laminator's hand movements across the ply. The system has been implemented with affordable hardware and demonstrates tangible benefits in comparison to currently employed laser-based systems. It has shown remarkable success to date, with rapid Technology Readiness Level advancement. This is a major stepping stone towards augmenting manual labour, with further benefits including more appropriate automation.

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### 1. Introduction

Despite the rise of automation within composites manufacturing, hand layup has remained the dominant forming process for a number of years due to the inability of those automated processes to form complex geometry and mixed-material components. Those structures that are successfully formed through automation still require hand layup for some of its processes. In hand layup, the desired output form of a ply over a complex surface, is provided to the laminator within a Manufacturing Instruction Sheet (MIS). However, the route by which they achieve this form is largely undefined, aside from providing a starting datum and sometimes an initial tangent of direction. The successful manipulation of a broadgood carbon or glass prepreg ply presently relies on the skills and experience developed over a

number of years, and the chosen process route and result often varies between laminators [1]. There are a number of material properties which contribute to the time and quality of the layup, including flexural rigidity, tack, and shear stiffness [2]; while material variability further introduces a level of complexity to the process [3]. But it is clear that ambiguity in the MIS leads to interpretation, and so variability between laminators and components, creating difficulty for a true benchmark of time, cost, and quality to be achieved (as well as understanding capability).

It is envisioned that applying Augmented Reality (AR) through the use of affordable tracking and projection technologies, in order to guide the laminator during hand layup, will lead to improvements in quality and standardisation alongside reductions in time and labour costs. Manual layup is conducted by highly experienced and

qualified crafts-people, which reportedly leads to labour becoming the single biggest contribution to direct costs [4]. The breakdown of tasks, and understanding of processes, may aid the development of more appropriate automated systems in the longer term. As identified by [5], the sources of error that are introduced within a manufacturing process stem from either mistakes made by "the human element", or a lack of process understanding. Composites manufacture could be argued to be hindered on both sides of the argument, despite many facilities striving for tools such as six-sigma or lean philosophy [6].

If the characteristics of Fig. 1 (moving towards future automation) are reviewed, it can be seen that classical automated systems may help increase production volume and batch size, while reducing the flexibility and variation of the process [7]. When the value and restrictions of a process are properly understood, a shorter development cycle should be realised as a smoother translation from the design office to the shop floor is envisioned, and components can be produced with a higher quality from the outset [8]. This understanding will enable the development of a true Design for Manufacture framework for composite materials.

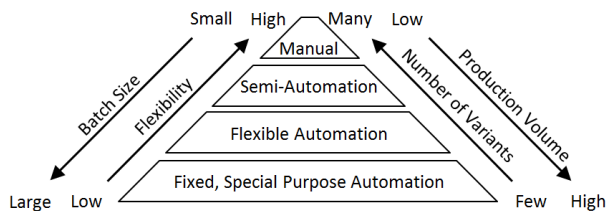


Fig 1. Characteristics of automation, from [7].

### 1.1. The difficulty of layup

The forming of a composite ply over a tool surface with some degree of geometrical complexity requires the application of deformation load paths to achieve the correct shape in the first instance. Broadgoods are typical within hand layup as such cloths possess reversible deformation characteristics; with major deformation occurring mainly by in-plane scissor shear of the warp and weft tows (other in-plane and out-of-plane processes are also possible). A unique pattern of shear deformation is witnessed dependent on the route by which a ply is constrained to a tool, but this pattern can also be unintuitive for complex geometries. Furthermore, the material properties and variability of a prepreg introduces difficulty into these operations, increasing the likelihood of defects. Wrinkling and bridging are regarded as the major drape quality metrics [9], and can result from an inability to apply sufficient shear to form the material due to its inherent stiffness. Poor technique is also responsible for their occurrence. The tack of the prepreg material directly influences the number of forming operations required, with repetition about a feature stemming from an inability of the ply to stick to the tool surface, or remain locked in place once forming continues beyond its location.

The tacit knowledge on how best to drape a ply is developed within an individual, through repeating work and

gaining experience on how best to approach a particular feature. Over time this translates into a laminator learning a component's layup by addressing each feature sequentially, leading to a feature by feature approach to drape of the ply and the component. This probably inhibits drape instruction detail in the MIS, as a designers experience base is unlikely to be as extensive as those of the laminators tasked with achieving the component. Thus, there is a difficulty witnessed in understanding this developed knowledgebase, even though better understanding of it could have knock-on advantages [10-11]. For example, reducing the number of actions to layup a composite broadgood, and decreasing the learning curve for new components, could lead to large cost reductions and increased productivity. Yet despite the importance of hand layup, it is still poorly understood and informed.

### 1.2. Layup guidance

The guidance received by laminators for a given component is contained within the MIS, which is also a traveller pack of manufacturing information and record sheets for that component, and for layup relates to the location and orientation of each ply within the finished component. In the main this is now automatically generated in Product Lifecycle Management (PLM) software for hardcopy (MIS, record), and softcopy (ply shape, positioning etc.) records. The resulting layup documentation is often open to interpretation. Physical templates and Optical Laser Ply Alignment (OLPA) is used to control the positioning of a ply, but does not provide feedback or information for the deformation route. A study by Crowley et al. [9] reviewed the typical acceptance criteria used in composites layup, and found that the strict limits imposed upon the process make it impossible to manufacture acceptable components. Further work [12] made suggestions to alter the acceptance criteria in a way that would reduce ambiguity and improve understanding.

The overall route to manufacture of a composite component formed by hand layup is shown in Fig. 2 [15]. Prepreg material is received and then kit cutting is carried out by a number of possible systems including manually cutting templates, die-stamping, or Computer Numeric Control (CNC) cutter beds (which are more popular). This is followed by tool preparation, involving the application of release agents to the tool surface (type dependent on the tool material). Hand layup is then conducted, as shown in Fig. 3, which adds the most significant amount of value to that component. It is evident that the alignment of the ply is the only step with any real guidance - the drape of the ply over the tool by folding and/or shearing around features, and the smoothing of it, is not accompanied by process guidelines and so may occur by a number of ways. Removal of the cloth's protective films is excluded from the Fig. 3 process, although works such as [13-14] recently explored this. The way in which drape occurs is heavily dependent on the skills, experience, and preferences of the laminator. The quality of these operations, or rather the effect on quality that these operations may have, is not truly assessed until after cure during Non-destructive Inspection (NDI), at which point no remedial action can be taken, only concessionary works of rework, repair, or scrapping.

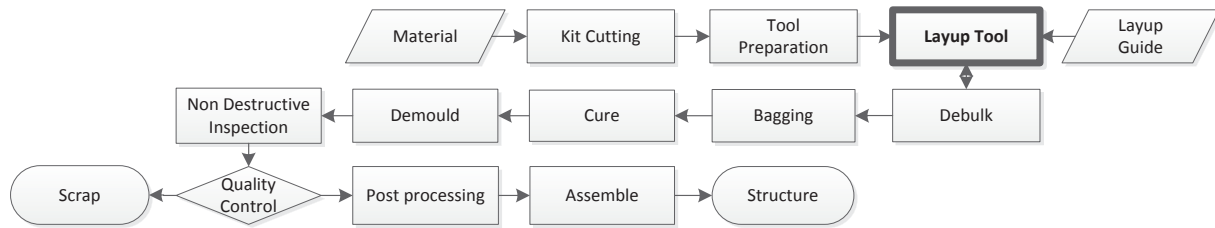


Fig. 2. Layup process overview, adapted from [15].

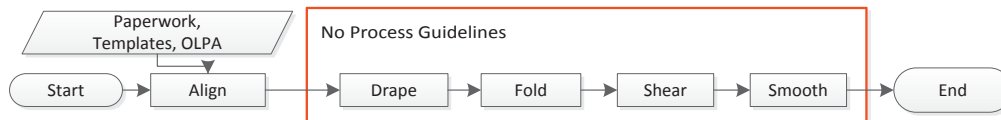


Fig. 3. The layup process, simplified.

For ply alignment, OLPA systems and/or software are developed and supplied by a number of companies including Laser Projection Technologies, LAP Laser, Virtek, SL Laser, Assembly Guidance Systems, and Magestic [16-21]. Generally, the system involves a ply outline being projected onto the working tool surface by laser lines being steered through a specific set of points, to visually provide the laminator with the layup area to work in. Most require more than one projector mounted onto a framework above the layup with retro-reflective targets at a number of defined positions on the tool, alongside support media (computer & peripherals) [22]. Projection accuracies of  $\pm 0.1\text{mm/m}$  with respect to the projection distance, and a beam width of  $0.5\text{mm}$  appear to be typical, but some systems now advertise greater flexibility. For example in-process inspection tools that verify the ply for material type, ply presence, sequence location, and fibre orientation (under specific lighting conditions) [23].

Other options include [24], where electronically identifiable tags are incorporated into the prepreg at kit cutting. These can be scanned to check ply ID and location, and enable the use of laser displacement sensors to validate the ply by assessing defects following layup [25-26]. The problem with these assessment techniques is that they are carried out following layup, as opposed to concurrently, which can only lead to component reworking or scrap rather than feedback to better inform the process.

PlyMatch™ provides a similar ability to align plies in the correct order, but offers a unique approach by overlaying live video of the tool with the desired placement area(s) [27]. [28] has recently developed a similar method, in which the tool sits on a table and is tracked with regards to height and rotation, to overlay ply placement on a live video feed. In reality these offer no more functionality than OLPA methods, and despite offering functionality in terms of working within interiors, scalability and applicability appear somewhat limited. The defining issues for all these methods are the high cost of implementation which can restrict their uptake, application to smaller businesses, and use in more flexible product lines.

### 1.3. Future direction

As the current industry standard relies on only informing placement and orientation, there is still significant development space available to provide more information to the laminator through the use of an augmented system [29]. For example, during the design phase of a component simulation tools are used to assess the geometry for drapeability, develop the MIS, and provide a fixed datum from which to layup. That information could be transferred with sufficient detail to documentation to better inform the layup. Recent work in this area has been conducted by the authors, although their use and application has not been reported within this paper. It is important to outline the process, to aid future implementation, as this may introduce a paradigm shift into composites manufacture. The authors have aimed 'to provide unambiguous instructions to laminators by the use of AR systems'. There are human factor issues which also need to be resolved, as noted by [30]. However the evaluation of a system which addresses perceptual needs and benefits cognitive tasks cannot occur until such a system exists. The interaction with the AR system should be conducive to an efficient clean room working environment. The building blocks of an AR system involve identifying working places, augmented contents, tracking module, and a method of display.

There have been a number of reviews into the applications and future trends of AR applications, such as [31-32], including within a Design & Manufacturing context [33]. For example, work by [34-36] investigated the conditions under which AR manuals are effective in work situations. But these studies involved the use of head mounted displays or tablets, so are not addressed further in this work. Research by [37] involved studying experienced fabricators during a contact moulding process, by tracking movement and vision. This is also not addressed further in the present work as it is not felt to significantly progress process understanding at this time. If similar methods were used to study hand layup, there would be a large variation in the order of techniques witnessed,

which could become difficult to distil. Other literature examples are available but have not been reviewed owing to space limitations.

A technology lag is evident with employed systems as accuracy and robustness is strived for, demanding a higher price and long development cycles. As technology progresses, the issues of accuracy and robustness may decline with development. But an application deficit is often found with technologies used in manufacturing. Technology innovation supersedes technology uptake at a large rate, and since it is undervalued, a deficit is evident between potentially useful technology and the user capability to apply it. This is shown in Fig. 4 with a dotted line to represent the increasing user capability to reduce the application deficit. This work seeks to address the lack of standardisation and information provided to laminators during the hand layup process by use of an AR system, and which may address this application deficit.

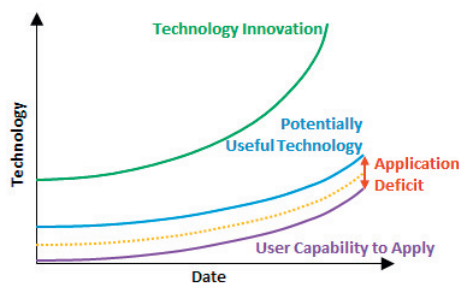


Fig 4. The application deficit for technology innovation within manufacturing, adapted from [5].

## 2. Understanding Layup

In order to test the practicalities of the desired system, a U-Shaped tool which imitates many of the complex features available to a typical composite panel was chosen for layup trials. The tool was 25mm tall with a 30° ramp angle and required a ply size of approximately 600mm x 400mm. The layup of this geometry is made difficult due to the central cut-out region and the shearing required for the ply to form around the ramp corners. If the layup is not conducted properly then a number of areas may be susceptible to wrinkling, bridging, and waviness, such as that noted in [11].

The geometry was assessed for formability using Virtual Fabric Placement (VFP) [38-39]. VFP is a kinematic model using pin jointed net behavior, allowing detailed drape instructions to be generated as the user controls each drape simulation step in the Graphical User Interface (GUI). Further information can be found in [40]. In practice a typical laminator would work the cut-out first, so creating significant shear that would need to be worked out to the free edges of the cloth. The VFP approach of Fig. 5 by contrast, sticks material into the cut-out, limiting the work and so time to drape. Previous works has been shown that lay-up time can be halved by the VFP approach [11], and even enable laminators to compete with automated processes [10]. But such a drape simulation output is unintuitive to most laminators and so methods of creating unambiguous instructions were required.

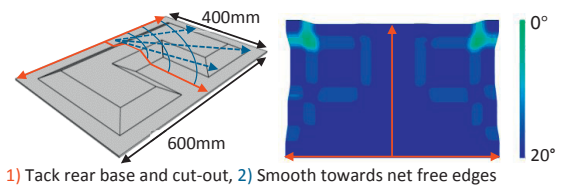


Fig. 5. User optimised drape path and shear distribution, adapted from [40].

Developing the projected instruction set involved a number of layup trials conducted by an experienced laminator (known herein as expert), interpreting the VFP output to inform the layup process of a plain woven glass prepreg. The expert had previous exposure to VFP. This was important as the kinematic solution for in-plane scissor shear in the simulation is of a global ply deformation mode rather than the feature by feature approach referenced earlier. The trials were recorded and studied as per the work of [1], in order to understand the techniques used at various features during the layup process. The advised route begins at the rear of the tool with the first action to tack the ply to the base. Layup then progressed towards the cut-out, while making sure to shear and smooth the opposite sides of the ply sequentially. The last actions involved significantly shearing and smoothing the exterior corner features to run out excess length in the material. It was noted during the trials that if it is assumed that the same instruction set is provided, this order of operations remains constant but the precise number of manipulations is dependent on the laminator and material properties. The introduction of a heat gun and dibber tools was allowed to aid the layup process, but their influence on the ease of manufacture was not under investigation. Following consultation with the expert, this layup process was broken down into 15 discrete features, which are addressed sequentially, as shown in Fig. 6.

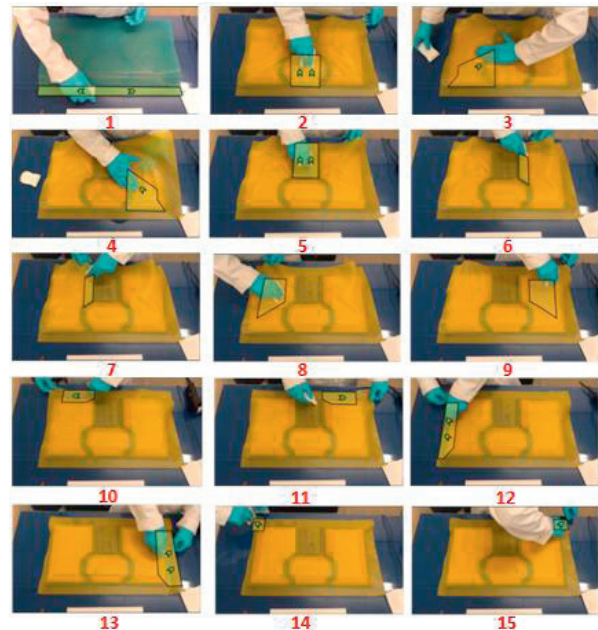


Fig. 6. Sequential regions required for feature by feature layup procedure.

### 3. Materials and Methods

#### 3.1. Design methodology

The success of the system relies on providing information to the laminator which introduces process standardisation and reduces the learning curve for an activity. The key to this relies on overlaying useful data onto the working surface which is more informative than currently employed. The amount of useful data is hard to quantify and preference may vary between users. Alongside this it must allow for intuitive interaction to guide the process, and be unobtrusive in the clean room environment. Projection onto the working surface is used within this work, in a similar manner as seen within OLPA methods. It was the position of the authors that the alternative of watching the layup progress on an AR video feed was not a scalable technology, disruptive, and conflicting with the current process.

The LightGuide system [41] projects instructions directly onto the user's hands to indicate required physical movements. Movements can be controlled much more accurately with this implementation. However if the layup instructions were created with this resolution in mind, in order to control every articulation, the system would lose flexibility by being dependent on the laminator and material system. Thus early concepts in this work focused around wearable computing and projection technology in order to make the system flexible. This was conceptually similar to the "Wear Ur World" interface [42], and would allow the user to move around the work space calling up the appropriate instructions. The use of Pico-projectors may allow this interaction, as seen within the LightBeam project [43]. The design for wearability guidelines as proposed by Gemperle and Kasabach [44] were consulted, and it was concluded that there was not an unobtrusive way to mount a projector upon a laminator which would provide adequate projection and natural interaction.

As a result this demonstrator system used near-tool but fixed overhead projection onto the working surface, by sequentially highlighting target features and indicating smoothing direction, as previously demonstrated in Fig. 6. A Microsoft Kinect™ [45] was used as an affordable depth sensor to enable instruction progression, as opposed to relying purely on standardised timings. Since their introduction in 2010, and the subsequent release of the Kinect for Windows [46], there has been a large amount of third-party development. This includes a number of projects, both commercial and academic, aiming to utilise the technology for reasons other than gaming. The accuracy and constraints of the depth data impose a limit on the effective range and environment in which a Kinect™ can be used [47]. There have been a number of studies into object recognition [48-49] and hand pose estimation [50-52], including hand interaction with an object [53] or surface [54] utilising the Kinect™ and/or similar affordable Red, Green, Blue, plus Depth (RGB-D) sensors. From this comes an understanding of the developing ability for marker-less tracking of hand articulations and interactions based on depth data of an affordable sensor, and the predictive capability to allow occlusion by an object (in this instance a composite ply). This

is also located off-body, in contrast to the Digits sensor [55], and is less invasive or disruptive of the working environment compared to body mounted sensors. The marker-less tracking provided by the Kinect™ depth data is able to locate hands on a person when the upper torso is visible, and provides a predictive capacity when hands are occluded. The accuracy of this tracking ability will impose a restriction on the resolution of the output instruction set.

Future implementations could make use of multiple projector setups in order to allow for a greater area of coverage than afforded by a single fixed projector. Mounting projectors onto pan-tilt platforms, as within the Beamatron project [56], might also provide more flexibility. Generally as technology progresses more substantial hardware will become available, and so in the short term the techniques for knowledgebase capture and instruction set delivery should be addressed and improved on. An overview of the system interactions is shown within Fig. 7, with the development set-up shown in Fig. 8.

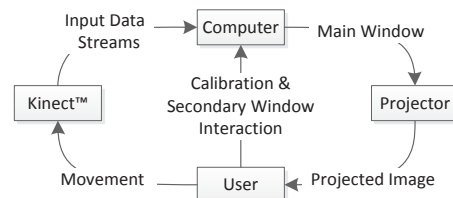


Fig. 7. Simplified system interactions showing data passed between system elements.

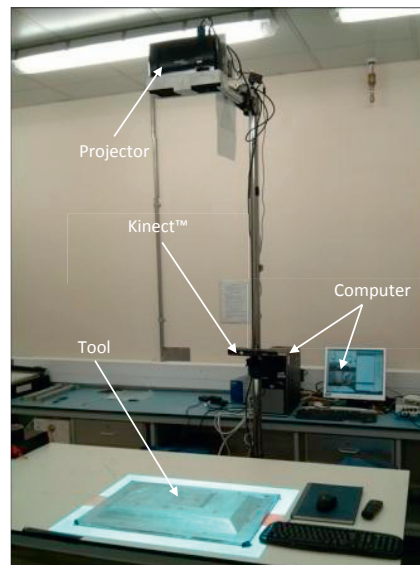


Fig. 8. System set-up within a clean room environment.

#### 3.2. Hardware

One of the first challenges to address was the ability to project onto a prepreg surface. An Acer C120 [57] and a Microvision Showwx+ [58] was used for initial projection trials. These were both Pico-projectors with the latter being a

laser based projector with 10 lumens output, compared to 100 for the former. Initial tests showed that projection onto a glass fibre prepreg was much more visible with a lower number of lumens. In order to further understand the reflected intensity in different prepreg systems, and the dependency on a number of variables, an experimental set up was designed to allow for qualitative comparison. A camera recorded images of the prepreg while a white light source of known 26 lumens intensity, at a fixed distance of 220mm, was directed at the prepreg from a number of different angles (at 15° intervals) relative to the surface normal. A PixelFly PCO [59] with a HR 2/3" F1.4/8mm lens was used for image acquisition, and a custom LabVIEW VI program [60] to control camera settings.

Most literature on reflectivity and reflectance focuses on creating accurate computer rendered images or designing lighting systems within architecture. To that end it becomes difficult to investigate the reflectivity of prepreg as they are heterogeneous, demonstrating a mixed mode reflection, and reflectivity will be dependent on a number of variables. Captured images were post-processed within Matlab [61] by recording image histograms across a 256 grayscale. These histograms were then thought to provide a qualitative comparison of reflected intensity, as a large histogram count of brighter pixels signifies greater reflective ability.

In general terms, carbon fibre prepreg had a much poorer reflected image than witnessed on glass fibre prepreg systems. This could be due to the absorption by the black carbon fibres instead of the transparent glass. Tow width influenced the reflection with a thinner tow leading to less scatter. Similarly, the style of the broadgood had an influence - twill weave was thought to provide more scattering than plain weave. The resin colour for the glass fibre prepreg also had an affect which although not under investigation in this instance, it will require flexibility in the projected output colour. It is unclear if thickness or surface quality had an effect since it was difficult to standardise those parameters. The prepreg systems varied greatly between each other on a number of parameters which made standardisation and idealisation of the experiment difficult to achieve. In general terms the understanding derived from the experiment showed that plain woven glass fibre prepreg provided the ideal system for projection, whereas a thick tow twill woven carbon fibre prepreg would provide the worst case scenario (useful for benchmarking the later system in trials and development).

When the full system was tested, an Eiki LC-XB28 [62] was positioned overhead in a laboratory clean room (providing an output of 3000 lumens) with sufficient throw to project a window measuring 800mm x 500mm. An Optoma DS211 [63] with a 2500 lumen output was also set-up in a similar manner for subsequent testing. Keystone correction was used with the tool in place to correct the shape of this projected window. The Kinect™ was offset to this, just above the height of the table, in order to record the torso of the user and locate the hands, as in Fig. 8. Several trials were initially conducted at reduced light levels, which was later deemed unnecessary for visualisation. The ability to reduce the ambient light levels within a working environment was noted, by controlling the light levels of the working volume addressed by the projection.

### 3.3. Program and operation

Programming was driven by use of the Microsoft Kinect SDK v1.8 [64] and supplemented by bespoke code written within C# [65], with early system design inspired by the "Simon Says" project [66]. Reduced logic for program operation is shown in Fig. 9. In operation, the main program window is projected onto the tool surface and the hands are tracked relative to this. The program is started by placing hands over either side of the tool to initiate the layup sequence, which then plays through and highlights the order in which features are tackled. A datum is provided to enable positioning of the ply and an outline shows the expected deformed ply edge. An annotated main window display is shown in Fig. 10.

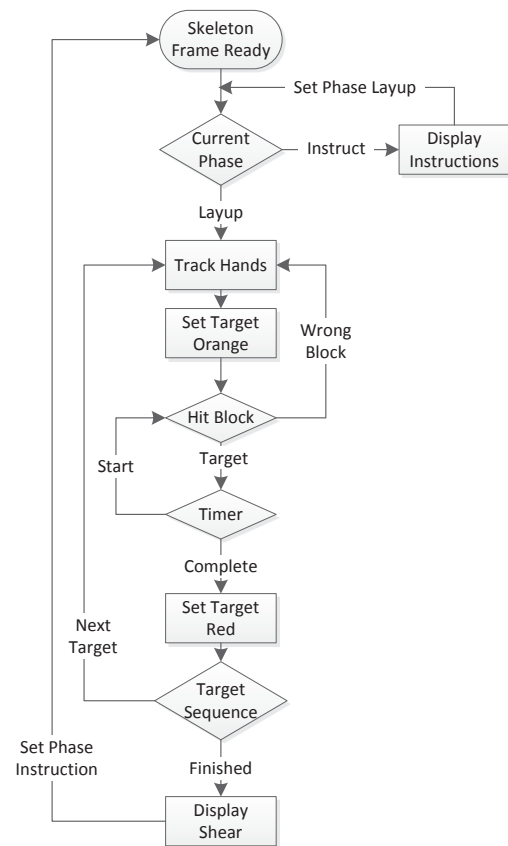


Fig. 9. Program logic.

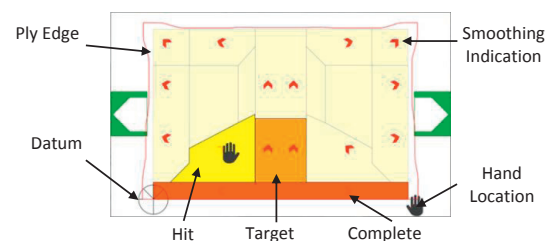


Fig. 10. Window display as projected onto a working surface.

$$\begin{bmatrix} x_{k1} & y_{k1} & z_{k1} & 1 & 0 & 0 & 0 & 0 & x_{k1}x_{p1} & y_{k1}x_{p1} & z_{k1}x_{p1} \\ 0 & 0 & 0 & 0 & x_{k1} & y_{k1} & z_{k1} & 1 & x_{k1}y_{p1} & y_{k1}y_{p1} & z_{k1}y_{p1} \\ x_{k2} & y_{k2} & z_{k2} & 1 & 0 & 0 & 0 & 0 & x_{k2}x_{p2} & y_{k2}x_{p2} & z_{k2}x_{p2} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & x_{kn} & y_{kn} & z_{kn} & 1 & x_{kn}y_{pn} & y_{kn}y_{pn} & z_{kn}y_{pn} \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ \vdots \\ q_{11} \end{bmatrix} = \begin{bmatrix} x_{p1} \\ y_{p1} \\ x_{p2} \\ \vdots \\ y_{pn} \end{bmatrix} \tag{5}$$

When layout commenced, the target block was set to orange and contact with this block was monitored. Timings based on the layout trials of the expert were used to assess when a block was set to complete. As this happened, the block changed colour to red and the next block in the sequence changed colour to orange to instruct the laminator to move on. At any point during the layout, forward and backward buttons either side of the tool could be used to progress or regress layout. These were implemented as the tracking of the hands sometimes did not accurately prompt the next block, or a laminator could not meet the expected timings. Gestural interaction was experimented with to enable this progression, but was not fully implemented in the demonstrator set-up.

Timings could easily be scaled to allow for performance by less experienced laminators, but it was felt that users could be motivated to follow the program timings, thus increasing productivity [67]. Once the sequence was complete, and all target features had been contacted for sufficient time, the shear distribution as presented within VFP was overlaid over the tool to provide some qualitative assessment of the result. A secondary window projected onto a nearby surface allowed for display of tool and material data, alongside a ply-book which was digitally signed throughout the layout. This reduced the amount of paperwork on the shop floor, and an annotated secondary window is shown in Fig. 11.

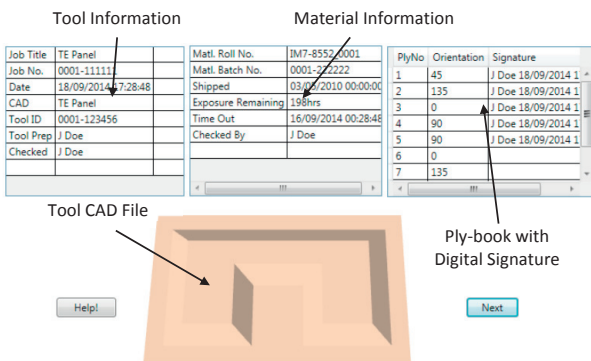


Fig. 11. Example of the secondary window display used.

The Kinect-projector calibration and human-mapping was performed by solving a system of linear equations as demonstrated by [68]. Kinect™ coordinates ( $V_k$ ) and projector coordinates ( $V_p$ ), which are captured by placing a hand and mouse point at the same location on the working surface, are defined by Equations 1 and 2.

The Kinect™ coordinates were converted to orthonormal projector coordinates and orthonormal coordinates converted

to projective beamer coordinates, as Equations 3 and 4, seen with unknown coefficients  $q_1 \dots q_{11}$ . Two equations now existed for every coordinate pair and the system could be shown using matrix notation, as Equation 5.

$$V_k = (x_k, y_k, z_k) \tag{1}$$

$$V_p = (x_p, y_p) \tag{2}$$

By solving the system of equations of the form  $Ax = b$  for  $x$ , designers were provided with the coefficients ( $q_1 \dots q_{11}$ ). These equations were then used to process the location of the user's hands in relation to the working surface. Calibration could be verified by simple commands such as following the line of a projected circle. Results of this are shown in Fig. 12 with the positions of the hands plotted every 1ms represented by red ellipse for the right hand and blue ellipse for the left hand. Large linear errors could be corrected by applying offsets to the raw data, while other corrections can be made through the use of smoothing parameters.

$$x_p = \frac{q_1x_k + q_2y_k + q_3z_k + q_4}{q_9x_k + q_{10}y_k + q_{11}z_k + 1} \tag{3}$$

$$y_p = \frac{q_5x_k + q_6y_k + q_7z_k + q_8}{q_9x_k + q_{10}y_k + q_{11}z_k + 1} \tag{4}$$

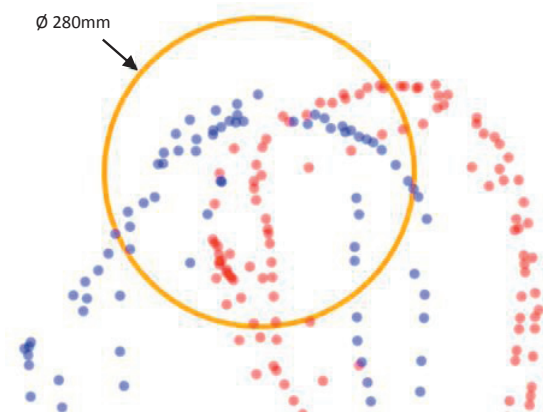


Fig. 12. An example of the Kinect-projector calibration verification for hand tracking.

As the Kinect™ was introduced as a gaming device it works much better with understanding gestures as opposed to poses [69]. In order to minimise jitter of the joint tracking there are a number of smoothing parameters that can be used to transform the skeleton data stream. The smoothing filter used is based on the Holt Double Exponential Smoothing method and has five parameter inputs of Correction, Smoothing, JitterRadius, MaxDeviationRadius, and Prediction [70]. It is difficult to find the ideal set of parameters for a use case and applying heavy filtering introduced latency into the joint tracking. Initial values used in this work were Smoothing = 0.7, Correction = 0.3, Prediction = 1.0, JitterRadius = 1.0, and MaxDeviationRadius = 1.0.

#### 4. Proof of concept

The results of the best and worst case scenarios for the projector system are shown in Figs. 13 and 14 respectively. The glass fibre prepreg allowed for very clear projection of target areas and smoothing indication, whereas projection onto carbon led to some loss of information as the resulting image was less clear. The discrete areas standardising the order of operations were found to be useful, and triggering those blocks allowed for easy progression. There was not much difference between the time taken to perform layup with or without this system for experienced laminators, but it did reduce the learning curve for the tool and standardised the layup between them. A user with little experience in lamination had a vastly reduced layup time when the system was used, closer to that of a laminator of 15+ years' experience. The impact of this could mean a shorter timeframe to develop experienced staff to meet production needs. But it was somewhat difficult to quantify the full range of knock-on effects that could be witnessed in this initial work.

When the system was trialled, the smoothing parameters were used to create smooth joint tracking data, which did introduce some latency. This was thought to be not too much of a disadvantage when the speed at which a laminator works, and the accuracy of the hand tracking, was taken into account. The system tracks the location of the hands with reasonable accuracy whereas quick movement was disregarded.

Block timings, based on recordings of an expert at work, were a useful indicator for the relative time taken to layup up a feature. Early work with hit detection led to the program uncontrollably cascading, as blocks were quickly triggered one after the other when timings were not implemented. The progression buttons allowed users to work at a comfortable pace as they could progress forward and backwards as needed. If implemented, simple waving as gestural interaction was preferred - progression buttons were easy to trigger at the ply edge. The continually projected ply edge was a useful tool for prompting the laminators for the required final ply shape. Although the projected shape would be taken out following trim after curing, it instructed where the shear in the cloth should be applied to produce the form and shape.

The secondary display window provided useful data and was a helpful tool for following layup progression, by being able to digitally sign-off each ply. The information in these

data tables could perhaps be populated by scanning Quick Response codes in the future. It is imagined much of the paper work now found on the shop floor within the MIS could be digitally displayed. A help button was experimented with through this window. If the laminator was unsure of progression at a particular point in the layup, a call-up button brought up a step-by-step recording showing the feature in lamination. Full implementation of this would require a test panel in layup to be conducted, and recordings made in order to generate those images.

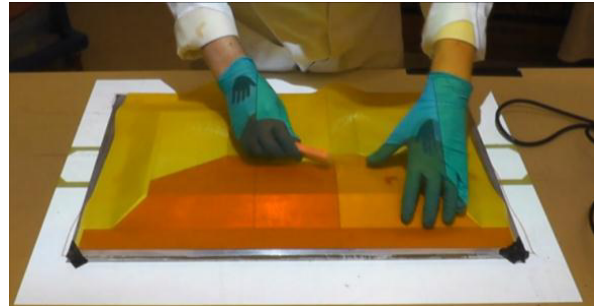


Fig. 13. Best case layup scenario - plain woven glass prepreg.

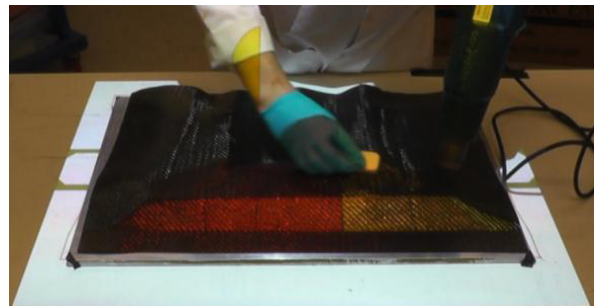


Fig. 14. Worst case layup scenario - twill woven carbon prepreg.

#### 4.1. Further work

The keystone correction, for projection of the appropriate size and shape window for calibration and program use onto the working surface, was unsatisfactory. Future work may involve the use of computer vision methods in order to recognise the tool and output a more appropriate projected window, or incorporate optical glyphs to capture the tool corners. Trials using examples such as [71-72] were made and found to be promising; although the setup required the Kinect™ or another camera to be placed at the same location as the projector in order to apply appropriate corrections. The resolution of the Kinect™ camera also experienced some difficulty with recognising optical glyphs from a distance, and the distorted video feed experienced greater latency through this mapping technique.

A secondary camera positioned at the same point in space as the projector may open up capabilities for further quality control. Although not expected to have the ability to detect ply edge misalignment, it may be possible to detect object inclusion and/or paper backings that are not properly



removed, and such technology is already employed in some OLPA methods [16, 23]. The Kinect-projector mapping relied on (slowly) capturing eight points during set-up. The use of more robust optical glyphs in a framework, overlaid onto the tooling, may reduce the time taken to perform this calibration.

Naturally there are a number of limitations on the components which can have guided layup by this single projector system. The tooling must fit within the output window, where the size of the output window is limited by the lumens and elevation of the projector. The size of the tooling is also limited by the range of the Kinect™ as the user must remain within viewable range. But these disadvantages are very much suppressed due to the components requiring complex layup procedures, which would be aided by this system, being relatively small. Multiple projectors would address problems with shadowing and complex geometry assuming appropriate system connectivity. Future implementation may also require the use of a head mounted display in order to circumvent problems experienced with projection onto particular prepreg types or tooling systems.

It is also thought further study would be used to understand in depth the outcomes of standardising the layup process. At the component level, testing may indicate improved mechanical properties due to fewer defects in critical areas, and this may also help reduce the NDI burden within composites manufacturing. Further study may also explore the capability of factory operational outputs in terms of time and quality capture. At this stage of the research the authors suggest the system has witnessed rapid Technology Readiness Level (TRL) advancement, and is to undergo rigorous testing within a manufacturing environment to proof the concept in a real-world working scenario.

## 5. Conclusions

Hand layup is still poorly understood and misinformed. But this issue can start to be addressed by detailed analysis of the route to manufacture, and in use of systems such as that which has been demonstrated; that guides a laminator in real-time during the layup of a complex component. The developed system that has been reported has shown that it is possible to:

- Use and project a predetermined and unambiguous instruction set. Based on an optimum tool path, this can impart minimum variability in the expected global shear by addressing a skilled laminator's knowledgebase. This presents a much more informative data application direction than witnessed by any currently employed laser alignment system
- Significantly improve the standardisation of produced components between laminators, as the same order of operations and features is used for layup between them. Although the production time may not be shorter for those experienced laminators, the learning curve would be reduced for newer components. Less experienced laminators should experience increased productivity, and transferable skills across geometries, to enable skills and training development

- Deliver a layup system that is agile in regards to positioning and tactile in its collaboration with the user; although in this case issues for robustness and resolution remain, and truly flexible and discrete operation was not fully realised. Future developments in hardware will help address issues of hand tracking, projection accuracy, and system robustness. Future technology may also open up the possibility of discrete wearable systems

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