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Tracking Technologies to Support Virtual Prototyping of Manual Composite Lay-Up

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Abstract *Composite laminate manual lay-up operations and component quality inspections involve a variety of complex operations and instructions requiring highly-skilled operators, which can result in time-consuming and cost-inefficient processes. This research attempts to check the compatibility of Virtual Fabric Placement (VFP) and Microsoft Kinect to aid laminators and composite production. This research has investigated the feasibility of using this tracking technology to support the virtual prototyping of manual composite lay-up. It is concluded that, at the current stage of development, Kinect and VFP can be successfully used for virtual prototyping of large scale geometries while encountering only negligible tracking error with respect to mould size.*

1. Introduction

Fabric lay-up simulation software such as VFP can help to improve the quality of composite products by allowing designers to create a virtual prototype by devising the required manual composite lay-up actions virtually. Microsoft Kinect is a low cost skeleton tracking device used for gaming, with a great potential due to the unobtrusiveness of its operation. The major target for the case study was to provide some substantial information on any possible discrepancies between the ideal VFP model and final man-made product. In essence, the idealised outcome generated by VFP should be verified by the results obtained via Kinect. In addition the use of Kinect may provide data to improve the training given to inexperienced laminators.

Fabric lay-up simulation software such as VFP can help to improve the quality of composite products by allowing designers to create a virtual prototype by devising the required manual composite lay-up actions virtually. Microsoft Kinect is a low cost skeleton tracking device used for gaming, with a great potential for use in other areas due to the unobtrusiveness of its operation. A number of CAD programs such as CATIA or Virtual Fabric Placement (VFP) are capable of generating code to enable industrial machines to perform the lay-up of composite materials. However, the quality of such lay-up leaves a lot to be desired, for example, the surface of the final part is usually wavy, there are overlaps which do not meet tolerance standards and crucially the cross-section of a part typically contains numerous defects. According to author estimations, based on experience with industrial clients, it takes twenty years to properly train a lay-up worker. The aim of this work is to verify the use of Kinect and VFP in combination as a way to support manual lay-up process by dynamically predicting the quality of a final product.

2. Relevant Research

In the completion of this research it has been necessary to conduct a thorough review of literature in the area of composite layup techniques. Currently, automated processes involving composite distribution in a tool include: Automated Tape Laying (ATL), Automated Fibre Placement (AFP) and some Resin Transfer Moulding (RTM) preforming techniques as well as Filament Winding [1]. The components which might be produced as a result of these methods are restrained in terms of size and geometry. The size of a part cannot be too small and the geometry should be simple [1].
The rate of productivity achievable with automation is limited and there are numerous types of defects in the final product, such as tow gaps and steering overlaps [2]. Therefore, mechanisation does not support cost-effectiveness and manufacturers' profits. In the view of Long [3] no simulation software will be ever capable of accurately mimicking real lay-up. VFP (Virtual Fabric Placement) is licenced software which was developed at Bristol University and is used for manipulating, with 3D representation, woven composite cloth [4].
The software supports real time kinematic simulation and computation of drape and design of a given composite component. VFP is gaining in recognition by industry together with growing awareness about the linkage between manufacturing practicalities and further mechanical performance of a given component. The reason why the software does not support mechanical lay-up is the fact that even the best state-of-the-art machines cannot successfully manufacture good quality parts of complex geometry out of composite materials, except from non-continuous fibres [1].
Virtual prototyping (VP), which is also known as augmented prototyping, is a recently developed tool that allows for holistic design assessment prior to physical production or prototyping. It merges the functions and properties offered by computer aided design (CAD) and computer aided engineering (CAE) [5]. Research into the use of Microsoft Kinect [6] for industry purposes is exemplified by Esquivel et al. [7] who document a gesture driven technique for the

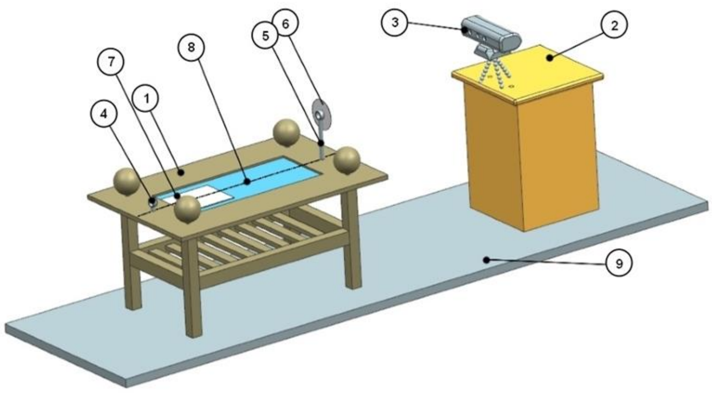
manipulation of CAD models using Kinect. It is clear from this review that there is only limited research devoted to the use of Microsoft Kinect in virtual prototyping, especially with commercially available software such as Virtual Fabric Placement.

3. Methodology

VFP is designed to digitally prototype the sequence of actions that must be followed by a layup worker. For a given geometry, VFP is used to generate coordinates of points where a worker must manually apply pressure, manipulate fabrics, and other actions related to composite lay-up. These points are associated with the location of the worker's dominant hand. Experiments are conducted whereby a Microsoft Kinect v1 is used to track the researcher's right hand as it follows these coordinates. Microsoft Kinect SDK v1.7 was used to drive the Kinect. Four case studies, each having up to ten experiments, were utilised to compare the output coordinates generated by means of VFP with the coordinates captured by Kinect during real life simulations. The case studies varied by size and orientation of Kinect tracking. This approach was chosen because it was able to deliver a wide scope of geometric and measuring cases which, due to their diversity, could provide a suitable background for stating a hypothesis concerning the compatibility of VFP and Kinect for use in manufacturing.

4. Experiment Design

The design of the experiments was an iterative and multistage process that determined concurrent case studies and the utilised data recording practice. It covered the establishment of the principal criteria and requirements for the investigation as well as positioning methods and procedures.



Key: Some of the elements of the set, which are listed in Table 1: 1. Table #2, 2. Table #1, 3. Kinect, 4. Hoop #1, 5. Hoop #2 (extendable), 6. Shield for Hoop #2 (optional), 7. Sheet of paper, 8. Longer axis of symmetry, 9. Ground.

Figure 1. Experimental Set Up

Figure 1 depicts the arrangement used to ensure the accuracy of the experimental set-up utilised in this research. The requirements concerning particular elements of the set-up shown in Figure 1 are enumerated and specified in Table 1 below.

Table 1. Experimental Set-Up Detailed Key

Elements of the experimental set	Requirements
Table #1	It should be stable and together with the Kinect tripod have at least the same height as Table #2.
Table #2	Should be shorter than the total height of Table #1 and Kinect tripod
Hoop #1	Its diameter should be consistent with the diameter of the laser beam, the length of its stand can be any but it must be shorter than the one of Hoop #2.
Hoop #2	Its diameter should be also consistent with the diameter of the laser beam and be as small as possible to assure greater level of precision which is based on geometrical principles; preferably its stand ought to be of adjustable height.

Sheet of paper	It can be of any kind but it should be of an appropriate size: the one which was utilized in the experiments was 300 x 500 mm. The piece of paper should contain a straight line coinciding with the longer axis of symmetry of the sheet.
Laser pen	The beam of light which is produced should be sufficiently focused and have little variation in diameter along its produced length. Its diameter must be compatible with the diameter of both hoops.
Laptop (or a PC)	Windows computer with Microsoft Kinect SDK 1.7 along with a program for hand(s) tracking
MS Kinect	Installed on a tripod with bubble level. There should be no contamination on either of the lenses as it could interfere with the quality and accuracy of data.

The assumptions regarding positioning are as follows:

- The surface of the floor/ground is smooth
- The surfaces of the table tops is smooth
- The tops of the tables are parallel to the floor and each other,
- The tripod bubble level which is an integral part of the Kinect Positioning
- All methods and procedures of positioning particular elements of the whole experimental set are highly accurate and do not accommodate significant 3D errors

The experimental set was placed in a room lit by sufficient electric lighting to ensure the same and appropriate conditions for every single reading irrespective of time of the day. Sunlight has much greater infrared spectrum, which could interfere with Kinect camera and sensors, which may be the cause of greater measurement errors and noise than artificial light. In their placement it was ensured that the experiments were conducted away from direct sunlight (with only the ambient daylight that may be present in a factory environment) and with the absence of brightly coloured objects in the vicinity of the set-up. A few positioning steps had to be executed to adjust certain distances and preserve specific relations like parallelism.

5. Case Study Results

The selection and detailed design of the four case studies was a crucial factor in the course of the research presented in this paper. The four cases generated for this research were: tape laying, a corner, a C-shape and a conical cylinder. There were four key factors in determining the selected case studies: VFP software only allows the modelling of simple geometries; each layup should be one that is in current industrial use; a number of different parameters should be represented in each case; the availability of objects which could serve the purpose of moulds for real life point readings. In determining the case studies interviews with case study organisation experts were completed to gain an insight into virtual and real life composite lay-up based on the implicit knowledge of professionals.

Case Study 1: Tape laying

This experiment set analyses a series of linear, straight-line hand motion, simulating lay-up motion at varying angles on a 2D plane (Figure 2). No VFP data was therefore necessary.

Table 2. Summary of the properties of case study 1.

Name	Dimensions	Aim of the case study
Tape laying	About 40cm long lay-up path. Lay-up carried out along 10 different paths: each having deflection by 10° greater than the previous one starting from collinear alignment with Kinect Z axis up to 90°. Spatial distribution of the coordinates of the captured points given in [m].	To investigate hand joint coordinates tracking accuracy with regard to orientation of the lay-up path.

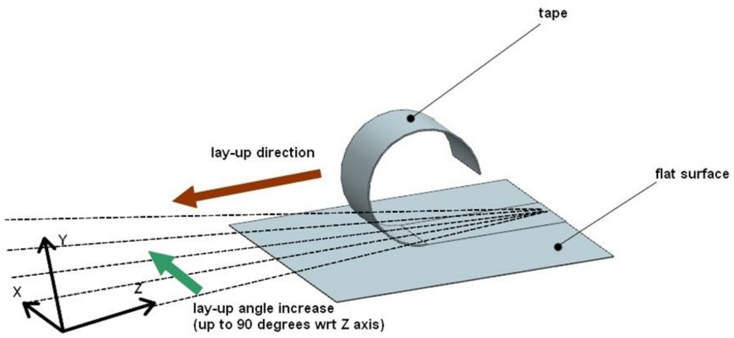


Figure 2. A 3D representation of the first case study, i.e. tape-laying performed on a flat surface, with regard to the Kinect coordinate system.

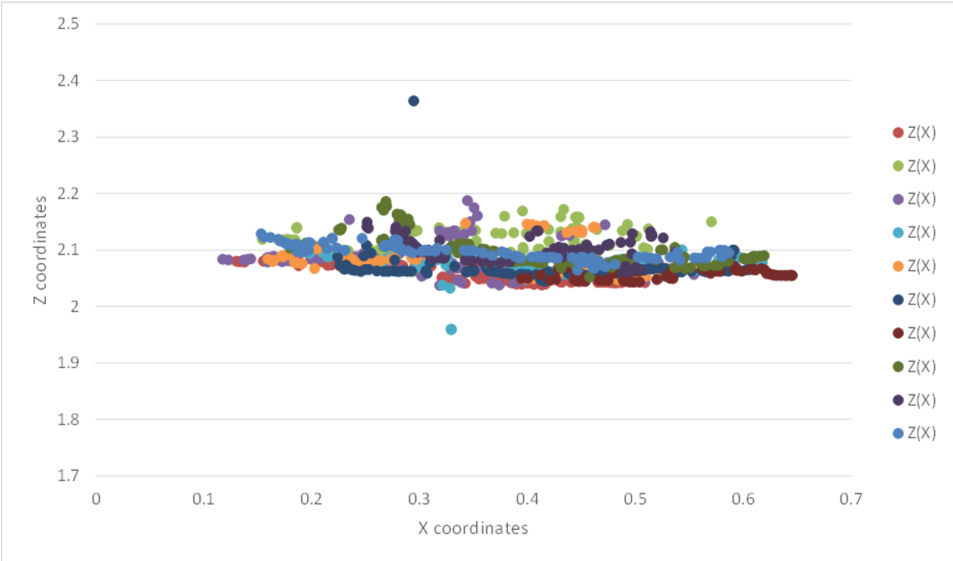


Figure 3. An instance showing 80 degrees of deflection from Kinect Z axis. Z coordinates are shown as a function of X coordinates.

Ten different instances of this case study were analysed, namely: the lay-up path was tilted from the Kinect Z axis by 10° until the position parallel to X axis was reached. The configurations of the lay-up paths for the landmark case of 80° of deflection from Z are plotted in Figure 3, with each dot representing a tracking point (coordinate) of a hand movement detected by Kinect. Common to the plots were randomly distributed points which could be categorised as noise. Taking into account the deviation of every single plot from the straight line and the presence of some erratically oriented points it can be stated that the noise was large. From this experiment set the lowest obtained value was 2cm +/- margin of error accuracy (margin of error for hand placement detection accuracy by Kinect) within in the X axis with 80° Z axis deflection (from the horizontal in depth) and the highest at 10cm +/- margin of error for 40°.

Case study 2: C-shape

This case study (summarized in Table 3) was utilised to check how accurate Kinect is with the recording of movement along variable curvature and variable path. The initial model geometry is presented in Figure 4 and the experiment set up in Figure 5.

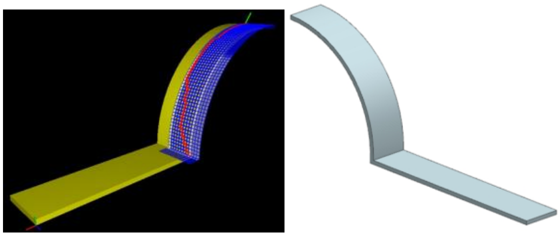


Figure 4. Modified C-shape which was finally used in the experiments and for VFP modelling (left) and its representation in NX8 (right).

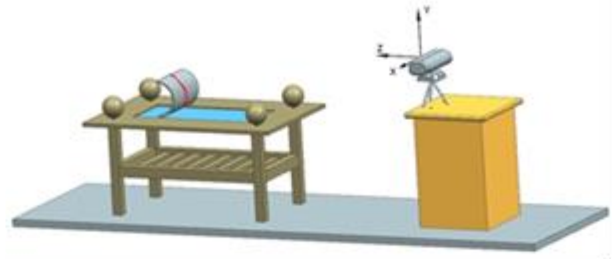


Figure 5. Vertical orientation of the C-shape during the Kinect-aided tracking.

Two instances were analysed based on this shape. One instance, for which the point recording was performed ten times, was the C-shape in vertical orientation with respect to the lenses of Kinect; the other instance, with the same number of recordings, was examined in horizontal orientation. The aim of this variation was to check how spatial position influences the quality and accurateness of hand joint tracing. The plots showing the results of C# based right hand joint coordinates gathering are displayed and described in Figure 6.

Table 3. Summary of the properties of case study 2.

Name	**Dimensions**	**Aim of the case study**
C-shape	• Spatial distribution of the coordinates of the captured points given in [m].	To check the impact of path complexity and curvature on the accuracy of Kinect performance.

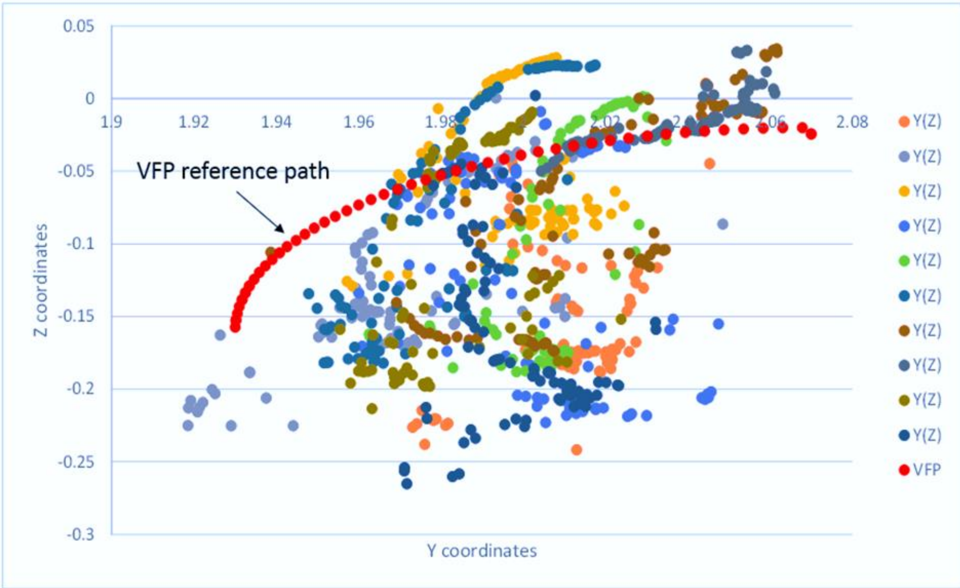


Figure 6. A function of Z(Y) coordinates which is the representation of the path of hand movement that was recorded.

Due to the fact that the lay-up was not performed along a standard curvature, such as a straight line or a circle, using the same method as in the case of the linear lay-up was impossible. However, it can be determined from Figure 6 above that the range of points reached 5cm +/- margin of error for this case study (the legend on the right of Figure 6 shows the points generated for each of the ten recordings).

Case study 3: Conical cylinder

This case study (summarised in Table 4) was also supposed to identify how well Kinect's tracking deals with simplified curvature. This case was less complex than the C-shape because the path, apart from having its own geometry, was not additionally curved in 3D. Specification of the employed geometry is given in Figure 7 and the stick path generated by means of VFP is visible in red in Figure 8.

Table 4. Summary of the properties of case study 3.

Name	**Dimensions**	**Aim of the case study**
Conical cylinder	In [mm], as shown in Figure 7 (right). Spatial distribution of the coordinates of the captured points given in [m].	To check the impact of path complexity, size and orientation on the accuracy of Kinect hand tracking.

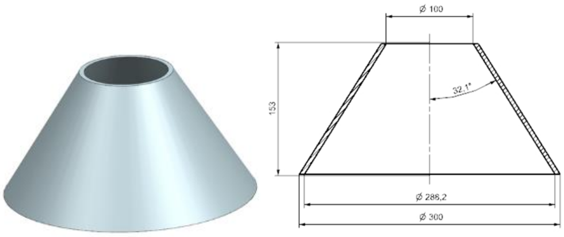


Figure 7. An image of a conical cylinder: a) a 3D view of the exploited geometry and b) its engineering drawing (all dimensions in millimetres).

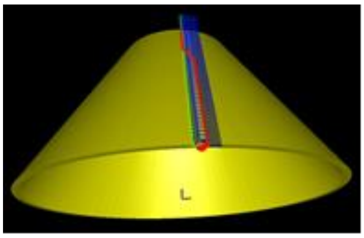


Figure 8. Stick path generated in VFP for the chosen geometry.

The Figure 9 shows a great deal of scattered points (with the circled points showing the majority of the outliers). The range within which the points might be found is about 12.5cm +/- margin of error for Y axis and 15cm +/- margin of error for X axis. This proves the findings obtained previously for a more complex geometry which was the C-shape hold also for this case. None of the paths even vaguely resembles the reference one.

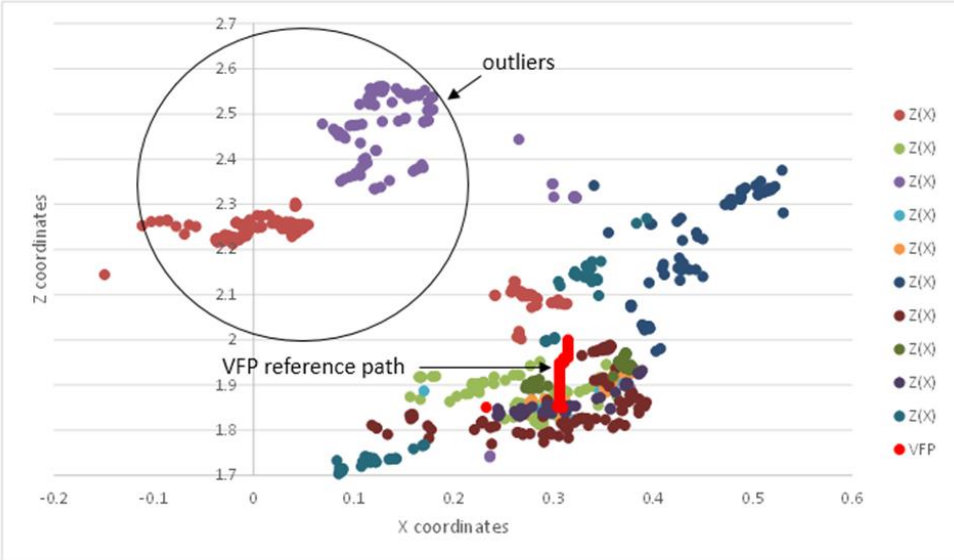


Figure 9. Ten recordings for horizontally oriented conical cylinder versus the path generated in VFP.

Case study 4: Large arc

The last case study that was selected was intended to display much larger geometry than the previous cases. Due to feasibility issues, i.e. the size of the arc and the fact that it was not movable, this case study was checked against only one spatial position with respect to Kinect. The results show that the discrepancy between ten sets of Kinect-captured points is comparable to the ones received in all cases discussed so far. The scatter is 5cm +/- margin of error but if one takes into account the size of the geometry used, it becomes less pronounced. The occurrence of noise is also not as clear as in case of smaller geometries. This phenomenon is illustrated by Figure 10 (with the set up summarised in Table 5).

Table 5. Summary of the properties of case study 4.

Name	**Dimensions**	**Aim of the case study**
Large arc	Spatial distribution of the coordinates of the captured points given in [m].	To check the impact of path complexity, orientation and size on the accuracy of Kinect-aided hand joint recordings.

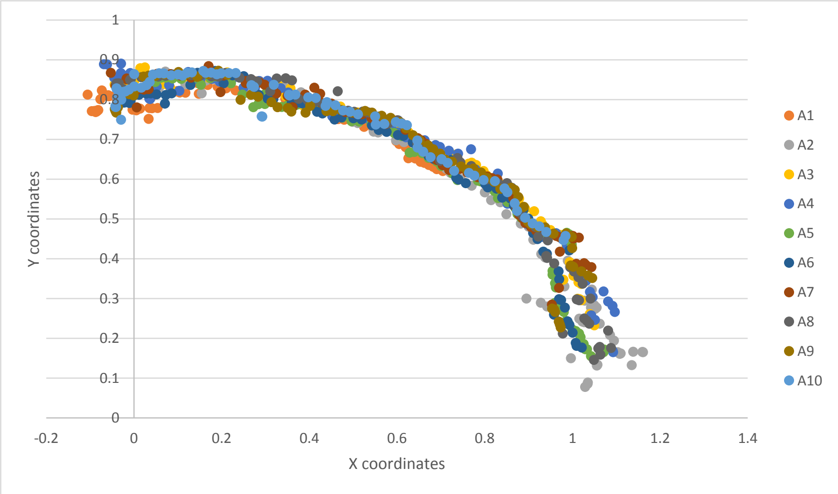


Figure 10. A set of points, in Y(X) function, which are a resultant of 10 readings that were performed by means of Kinect.

6. Discussion

The results revealed three main phenomena. In terms of mould size: The inaccuracy of Kinect-based measurements is less significant for assessing the lay-up of large geometries; If path complexity is taken into account Kinect is able to assess hands location at average accuracy of 5cm +/- margin of error so the more complex the path with respect to the area the greater inaccuracies occur. From the point of view of orientation of the lay-up path with respect to Kinect average distance to the real lay-up path is smaller the more aligned the path is to any of Kinect main axes. The tape-laying case study suggests that the results might have been about 30% better if one took 10° and 80° of deflection from Kinect longitudinal axis instead. The main conclusion which can be drawn from the experiments is that Kinect and VFP are compatible when it comes to modelling large moulds and capturing hand motion when composite lay-up is performed. For small scale geometries, the level of inaccuracies with respect to the size of a given object might be too great to allow successful use of Kinect. One of the assumptions characterising beneficial results is that any outcome which gives accuracy that fits the range of the width of human hand is acceptable. From this perspective, about 50% of the results from tape-laying instances and the same amount from the other case studies fit that criterion. Kinect works best for 2D lay-up path orientation. Best accuracies for the points were obtained for 10° and 80° of deflection from Kinect Z axis. The range may be decreased by increasing the distance of Kinect from the laminator's hands, though Kinect has its own limit of maximum distance from a given subject that should be respected if valid results are to be achieved.

7. Conclusions

Skeleton-tracking by consumer 3D camera is a relatively new principle which has been available on the market for the last few years. Due to this fact, its potential is not fully developed yet. The recent release of Kinect v2 has raised expectations on the level of accuracy obtainable from this system. The second generation Kinect uses a new time-of-flight sensor, providing greater depth resolution per pixel and a much improved signal-to-noise ratio. This should translate into much more accurate joint tracking in all three axes. Kinect and VFP combined performance can support virtual prototyping of manual composite lay-up, however, there are limits. The size and complexity of the workpiece lay-up path is restrained due to Kinect accuracy and its angle of orientation; these factors have a quantifiable impact on results.

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