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VOLUMETRIC CALIBRATION FOR IMPROVING ACCURACY OF AFP/ATL MACHINES

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Abstract: *Automated Fiber Placement (AFP) and Automated Tape Laying (ATL) technologies are mostly used in aerospace industry. Deviations from predefined position and orientation of the AFP/ATL machine's end-effector may cause defects of the final product like gaps and laps of the laminate ply, tow end placement errors, pressure and temperature variations, etc. That makes clear the importance of accuracy of AFP/ATL machines. Calibration is needed to enhance accuracy.*

Development and implementation of a comprehensive procedure for volumetric calibration of three linear axes is described in this paper. According to ISO 230-1:2012 and ISO 230-2:2014 standards, 18 position dependent and 3 position independent (in total 21) errors of the 3 linear axes are considered. Measurements are performed using laser interferometer on ATL machine produced by company Mikrosam. Obtained data are used for calibration of that machine and validity of the results is verified by comparison with the calibration results obtained by TRAC-CAL software developed by ETALON AG.

Keywords: *AFP/ATL, volumetric calibration, accuracy, geometric errors.*

1. INTRODUCTION

Composites are often used in aerospace industry. Leading aerospace companies have already made airplanes with more than 50% of composites [1]. Because of that, it is necessary to develop automated manufacturing of large parts of composites for commercial and military airplanes.

AFP and ATL are the two crucial types of automated machines for that purpose. Difference between them is that Automated Fiber Placement (AFM) is more flexible allowing control of the tape width - different fiber tows could be cut in different time. That allows to use AFP machine for placing prepreg on more complex surfaces and to reduce the scrap, even to 5% [2]. Automated Tape Laying (ATL) mainly uses wider prepreg tape. It is very efficient for large parts with simple geometry.

Picture 1 shows fiber placement and Picture 2 shows tape lying.

AFP/ATL as technological process is related to the processes:

- Integration of the robot platform and AFP/ATL head
- Tape path generation and trajectory planning
- Process parameters control

Picture 1. Automated Fiber Placement

Picture 2. Automated tape layup

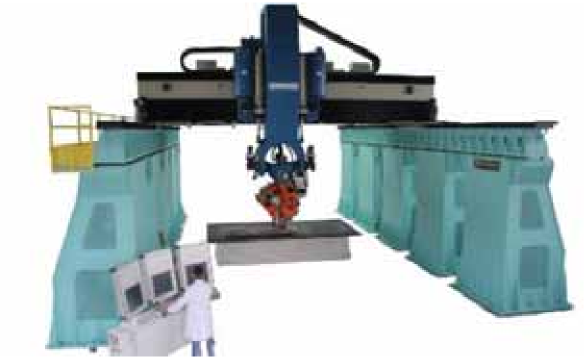
In [3] more details about technological process can be found.

The most sophisticated part of such machines is AFP/ATL head. It has to contain [2]:

- Prepreg delivery system
- Cutting and restarting system
- Roller and compression system
- Heat regulation system

Uniform working of compression system is important. That means, it is not sufficient to control only the position precisely, but as well the orientation of the AFP/ATL head.

To be able to produce 3D forms with complex geometry, AFP/ATL machine should be built as robotized system with 6 degrees of freedom (DOF). 6-axes ATL machine performed in gantry style, large as manufacturing of parts for aerospace industry requires is shown on Picture 3. All the measurements and testing the results for the calibration algorithm described in this paper, are performed on this machine.



Picture 3. ATL machine, produced by Mikrosam company

There are several factors for the AFP/ATL process end product quality: curvature variations of the surface used for laying on, prepreg properties, temperature etc. [4] Comprehensive review of defect types and the reasons for their appearing could be found in [5].

Picture 4. Gaps and overlaps

Avoiding defects of laminates during AFP/ATL process appeared due to deviations of the predefined position on laying path is emphasized in this paper. Such defects are: course/tape gaps, course/tape overlaps and tow/tape end placement errors of the layup [6].

To avoid such defects, it is very important to achieve high precision and accuracy of the AFP/ATL machines. For that purpose, comprehensive 3D volumetric calibration procedure used for compensation 3 linear axes errors is developed and presented in this paper.

In the future will be researched the opportunity for orientation errors calibration. Details about the importance of AFP/ATL orientation accuracy are given in [7].

2. VOLUMETRIC ERRORS

In traditional calibration methods, mainly separated measurements for each axis are performed and they are compensated in the same manner. Compensation of the axes are mutually independent, eventually some of the influence on dependence of kinematic configuration is included [1].

Some of the contemporary calibration techniques, developed for AFP/ATL machines are described in [6], [8] and [9].

To enhance the position accuracy of AFP/ATL head, it is necessary to include all of the 21 volumetric errors, according to the standards ISO 230-1:2012 [10] and ISO 230-2:2014 [11], as well to the ISO technical report [12].

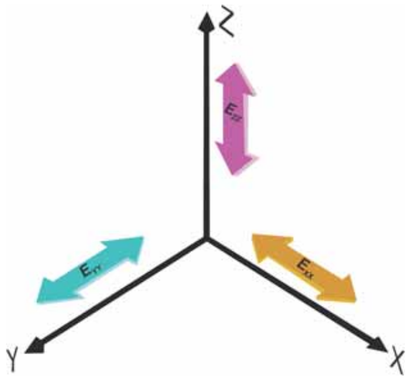
The volumetric errors appear due to some inaccuracies in machine manufacturing or installation [13]. These 21 volumetric errors concern only to the translational axes and their calibration can enhance accuracy only for the position of the machine's end-effector.

There are 18 position dependent geometric errors, 6 errors for each axis and 3 position independent geometric errors in a volumetric calibration procedure.

There are 3 displacement errors for each of the translational axes X, Y and Z - in total 9 such errors.

Displacements along the same axis as the measurement is performed are called positional errors (Picture 5.).

$$E_{XX}(x),\ E_{YY}(y) \text{ and } E_{ZZ}(z) \qquad (1)$$



Picture 5. Positional errors

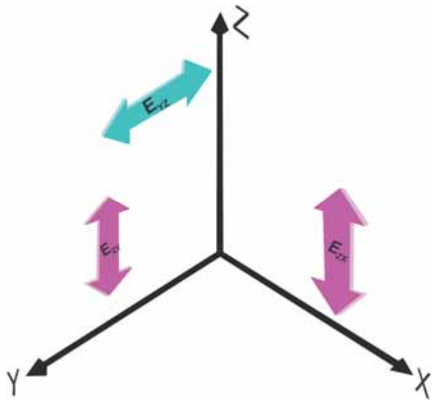
There are also 3 horizontal and 3 vertical straightness errors.

The horizontal straightness errors (Picture 6.) are denoted by:

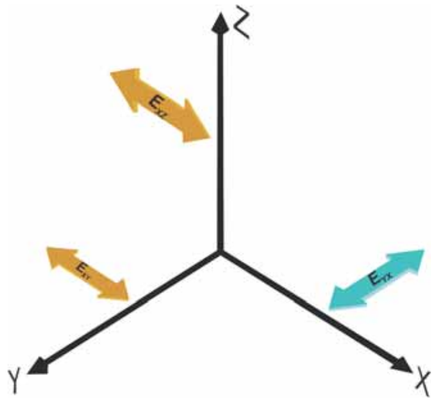
$$E_{ZX}(x),\ E_{ZY}(y) \text{ and } E_{YZ}(z) \qquad (2)$$

The vertical straightness errors (Picture 7.) are denoted by:

$$E_{YX}(x),\ E_{XY}(y) \text{ и } E_{XZ}(z) \qquad (3)$$



Picture 6. Horizontal straightness errors

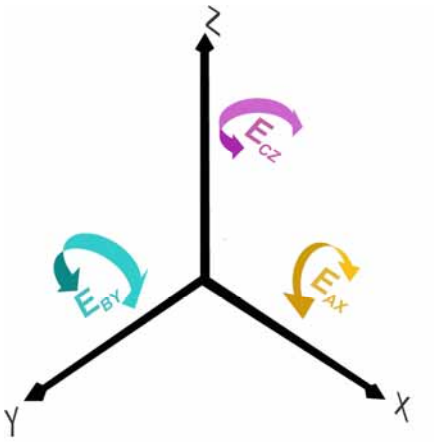


Picture 7. Vertical straightness errors

For every of translational axes X, Y and Z, there are 3 rotational errors as well. They are also position dependent. These 9 errors are classified in 3 groups: roll, pitch and yaw errors.

Roll rotational errors (Picture 8.) are denoted by:

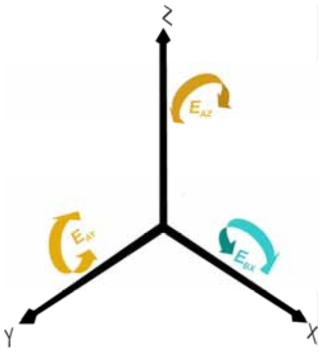
$$E_{AX}(x),\ E_{BY}(y) \text{ и } E_{CZ}(z) \qquad (4)$$



Picture 8. Roll rotational errors

Pitch rotational errors (Picture 9.) are denoted by:

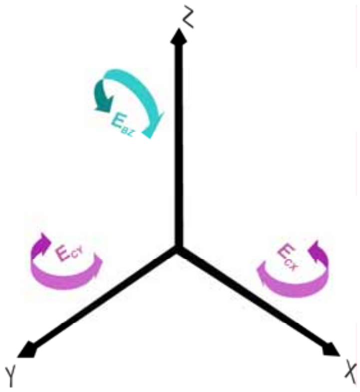
$$E_{BX}(x),\ E_{AY}(y) \text{ and } E_{AZ}(z) \qquad (5)$$



Picture 9. Pitch rotational errors

Yaw rotational errors (Picture 10.) are denoted by:

$$E_{CX}(x),\ E_{CY}(y) \text{ and } E_{BZ}(z) \qquad (6)$$

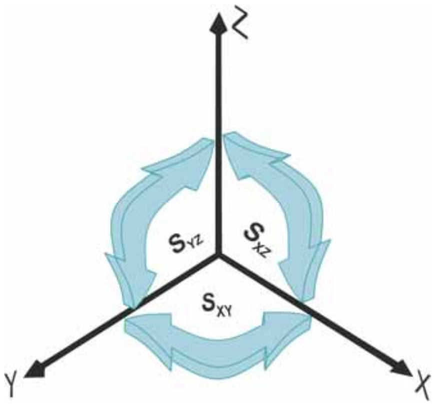


Picture 10. Yaw rotational errors

Nominally, translational axes are mutually perpendicular. In practice, there are small deviations from the right angle. Those deviations are called squareness errors (Picture 11.) and they are denoted by:

$$S_{XY},\ S_{YZ} \text{ и } S_{ZX} \qquad (7)$$

Squareness errors are position independent geometric errors. They are expressed with 1 number for each of them.



Picture 11. Squareness errors

3. 3D VOLUMETRIC CALIBRATION ALGORITHM

All the measurements of 21 volumetric errors were conducted on 6 DOF ATL machine (Picture 3.), produced by innovative company Mikrosam. A laser interferometer was used. Its resolution is 1nm, declared linear error between 2 and 3 µm and measurement rang of 15m. The experts from reputable German company AfM (Accuracy for Machines) made all the measurements in Institute for Advanced Composites and Robotics in Prilep, Macedonia in October, 2014.

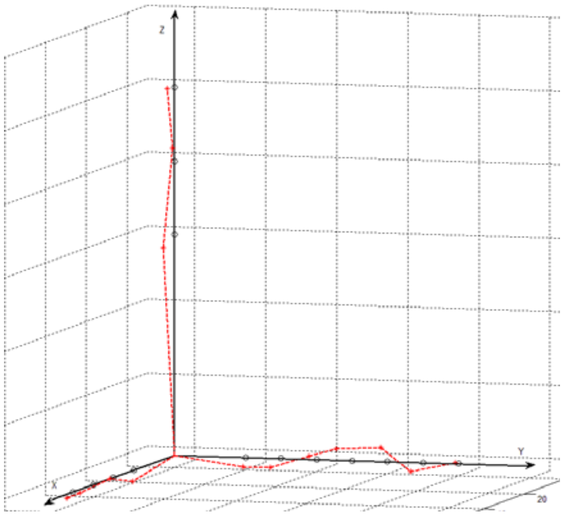
The measurement was time consuming and it was based on strategy which includes planning of the tracer positions and different combinations of reflector offsets and tool paths. The number of measured reflector positions depends on the statistical model for calculation the uncertainties. Interferometer only measures lengths of the beam for every tracer-reflector position in predefined measurement configuration. All collected data from measurement are used to obtain complete error map with estimations of all 21 geometric errors for every measurement points, using appropriate mathematical model and sophisticated software tool.

The number of measurement points and their ranges, for each axis separately are given in Table 1. Measurement points are uniformly distributed, with step of 25mm. The error estimation for some of them is obtained directly from measuring and for some of them using interpolation.

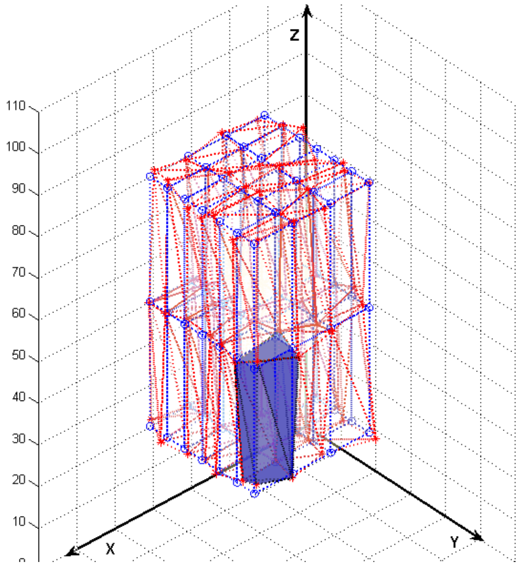
Table 1. Measurement points

	Number of measurement points	Min. (mm)	Max (mm)
X	322	940	8965
Y	142	520	4045
Z	50	-1200	25

This way, the machine's workspace is divided to 2,217,789 3D cells, using the measurement points. In the ideal coordinate system, each cell is shaped like ideal 3D box. Due to the geometric errors, in the reality axes are not mutually perpendicular straight lines, and they are "skewed" (Picture 12.).



Picture 12. The skewed coordinate axes



Picture 13. The skewed grid of the actual coordinate

Workspace's partition, this way is approximated with cells that geometrically are polyhedrons (Picture 13.).

For each knot of such grid, actual coordinates with measured errors included are calculated.

First, correction of position dependent geometric errors are made, using measured position independent geometric errors:

$$E_{XY}(y) \leftarrow E_{XY}(y) + S_{XY} \cdot y \tag{8}$$

$$E_{XZ}(z) \leftarrow E_{XZ}(z) + S_{ZX} \cdot z \tag{9}$$

$$E_{YZ}(z) \leftarrow E_{YZ}(z) + S_{YZ} \cdot z \tag{10}$$

For each knot, the nominal coordinates corrections are calculated using measured displacement errors, i.e. appropriate actual coordinates are calculated:

$$\mathbf{X_{act}} = \begin{bmatrix} x + E_{XX}(x) \\ E_{YX}(x) \\ E_{ZX}(x) \end{bmatrix} \tag{11}$$

$$\mathbf{Y_{act}} = \begin{bmatrix} E_{XY}(y) \\ y + E_{YY}(y) \\ E_{ZY}(y) \end{bmatrix} \tag{12}$$

$$\mathbf{Z_{act}} = \begin{bmatrix} E_{XZ}(z) \\ E_{YZ}(z) \\ z + E_{ZZ}(z) \end{bmatrix} \tag{13}$$

Finally, the actual coordinates of a skewed grid knot P_{act}, mapped to the appropriate ideal grid knot, given with its nominal coordinates $P_{nom} = [x,\ y,\ z]^T$ are determined by:

$$\begin{aligned} \mathbf{P_{act}} &= \mathbf{X_{act}} + \mathbf{R_x}^{-1}(x) \cdot \mathbf{Y_{act}} + \\ &+ \mathbf{R_x}^{-1}(x) \cdot \mathbf{R_y}^{-1}(y) \cdot \mathbf{Z_{act}} \end{aligned} \tag{14}$$

where, the matrices $\mathbf{R_x}$ and $\mathbf{R_y}$ include the rotational errors. They are given by:

$$\mathbf{R_x}(x)=\begin{bmatrix} 1 & E_{CX}(x) & -E_{BX}(x) \\ -E_{CX}(x) & 1 & E_{AX}(x) \\ E_{BX}(x) & -E_{AX}(x) & 1 \end{bmatrix} \quad (15)$$

$$\mathbf{R_Y}(y)=\begin{bmatrix} 1 & E_{CY}(y) & -E_{BY}(y) \\ -E_{CY}(y) & 1 & E_{AY}(y) \\ E_{BY}(y) & -E_{AY}(y) & 1 \end{bmatrix} \quad (16)$$

The total displacement error vector **E** for each grid knot could be calculated by equation:

$$\mathbf{E}=\mathbf{P_{act}}-\mathbf{P_{nom}} \quad (17)$$

The equation (8)-(16) depend on the robot configuration. Details can be found in [14] and [15].

If some point is inside a cell, the error is approximated expressing it as function of the coordinates and appropriate errors in the vertices of that cell. Linear fitting method is applied. The deviations are minimized using least square method as optimization approach.

This way, algorithm for total volumetric error approximation is designed, for any point over entire machine workspace, based on the measured geometric errors in the sampled points. This approach is non-parametric approach, or black-box approach. Details for non-parametric calibration and for error interpolation over workspace could be found in [16].

According to Mooring et al. [16], a comprehensive calibration algorithm includes forward calibration and inverse calibration. Calculation of the actual coordinates for all ideal grid knots and determining of the fitting polynomial coefficients for estimation of the total error for the points inside cells are carried offline. All the obtained data are stored.

Forward calibration means to find actual coordinates for any point over the workspace, given by its nominal coordinates. First, bisection method is used to determine appropriate ideal grid cell where the given nominal point lies. The fitting polynomial coefficients appropriate for that cell are loaded and they are used for estimation of actual coordinates of the given nominal point. Calculation of actual coordinates is performed in real time, for any given nominal point.

In practice, for enhancing the machine accuracy, the inverse calibration procedure is crucial. In fact, the compensation which should be commanded to the translational axes motors to obtained desired position is calculated in this step.

That means, if desired coordinates $\mathbf{Q_{des}}$ are given, the commanded coordinates $\mathbf{Q_{com}}$ should be determined. It is especially important to be able to calculate these compensations in real time, since a large number of points are sent to the controller, they are given by their desired coordinates and they should be compensated online.

If desired coordinates $\mathbf{Q_{des}}$ are given, first step is finding the proper cell in the skewed grid, such that the point Q_{des} is inside this polyhedron. The original algorithm based on linear algebra tools is designed to determine whether some 3D point is inside or not for polyhedron given with 8 vertices. Details for that algorithm are given in [1]. If some desired point is not inside the default cell, found using bisection method, 26 neighbor cells are checked additionally, until the proper cell in skewed grid is determined.

After that, appropriate polynomial coefficients for that cell are loaded. They are used to obtain linear system of 3 unknowns and its solution gives the commanded coordinates $\mathbf{Q_{com}}$.

Entire procedure for determining the commanded coordinates $\mathbf{Q_{com}}$ are performed in real time, including the search for the proper cell of the skewed grid.

4. RESULTS AND DISCUSSION

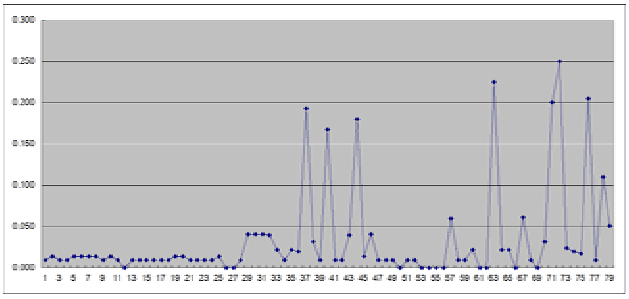
3D volumetric calibration algorithm is implemented in Matlab. Large number of measurement points given in table 1., are used to calculate and store the actual coordinates for all knots of the machine's workspace grid, and as well the fitting polynomial coefficients for approximation of the total 3D displacements for interior points, for all cells.

In Matlab is also implemented the inverse calibration procedure described in section 3. That way, comprehensive volumetric calibration procedure is implemented in Matlab.

Correctness of the implemented algorithm is done using comparative analysis [1]. The results obtained by this algorithm are compared against the results generated by TRAC-CAL software [17]. The software solution TRAC-CAL is established company Etalon AG's solution for 3D volumetric calibration and compensation.

There are 79 sampled points from the machine's workspace. For all of them, displacement along each dimension X, Y and Z is calculated, and the total vector deviations as well. The same calculation is done by the algorithm described in this paper and by TRAC-CAL.

The total vector deviations of both approaches are compared. Differences between two algorithms are depicted on Picture 14.



Picture 14. Deviations of error estimations in sampled points

The range of obtained differences is between 0 and 0.2 µm. The mean of this sequence is 0.033µm with standard deviation of 0.057µm.

Statistical t-test is used to establish if there is statistically significant difference between mean values of the sequences for each axis X, Y and Z, separately - the sequence obtained by the algorithm described in this paper and the appropriate sequence obtained by TRAC-CAL software. Two - tailed t-test is used 3 times for each of the axes X, Y and Z. In all three cases, there are no statistically significant differences in appropriate sequences. Using 95% confidence interval, it was showed that obtained values for both sequences have same means.

That means the precision this algorithm estimates total geometric error at arbitrary point from machine's workspace, for each of the axes X, Y and Z is close to the precision established TRAC-CAL software estimates.

That indicates the algorithm verified such way may be used for calculating compensations needed to be commanded to enhance position accuracy of ATL head of this machine.

After the verification, the algorithm is implemented in C++ and compensations are calculated in real time.

5. CONCLUSION

Description of AFP/ATL technologies and potential defects caused by their eventual inaccuracy is given at the beginning. That makes clear the need for volumetric calibration procedure for AFP/ATL machines.

The volumetric calibration algorithm described in this paper is tested on 6 DOF ATL machine, produced by company Mikrosam. Matlab is used for implementation. Only the three translational axes are calibrated, so only enhancing of the ATL head position accuracy may be achieved. The large amount of input data is used, obtained by measurements conducted by AfM company's experts. Commanded coordinates are calculated in real time, using the stored data and algorithm based on described black-box approach for non-parametric calibration. Results are verified using comparative analysis, comparing the obtained results against results obtained by TRAC-CAL software.

To achieve complete accuracy of AFP/ATL machine, the orientation of the head should be calibrated as well. Also, the geometric errors of rotational axes should be taken into account. In the future work, extension of this algorithm for calibration of all axes will be considered.

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