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# Flexible Assembly Tooling Structure and Positioning Accuracy Analysis of Aircraft Fuselage Framework

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**Abstract.** Aiming at the problems of low efficiency, poor positioning accuracy and unreconstructible of the aircraft assembly process at present, according to the structure of the fuselage section of the aircraft, a flexible tooling for the fuselage frame is developed based on the modular idea. Positioning of different models of the fuselage is achieved by servo motor, manual adjustment and positioner. According to the way of the fuselage section, the structure of the flexible tooling is determined. At the same time, the layout of the automatic drilling and riveting system of the flexible tooling and the composite processing machine tool and the assembly process of the flexible tooling are introduced. Finally, the positioning accuracy of the flexible tooling test platform was analyzed, and the experimental verification was carried out through the experimental platform.

## 1. Introduction

In view of the characteristics of large number of aircraft parts, low stiffness, poor openness and high machining accuracy, a large number of tooling is needed to ensure its accurate geometric shape in the process of machining. The special fixture used in the traditional aircraft manufacturing process can not achieve the goal of rapid conversion and shortening the development cycle of new products [1]. Traditional rigid tooling usually adopts rigid structure and has poor reconfigurability: an aircraft product requires a large number of special tooling to be designed and manufactured. It has great disadvantages in the cost, cycle and storage space occupancy of aircraft manufacturing. With the increase of many new aircraft manufacturing tasks, tooling management and storage costs will become higher [2-4]. Flexible assembly tooling has high degree of digitalization and reconfigurability, which can realize the positioning of different sizes of different products; flexible tooling uses numerical control technology, so that the positioning accuracy is high, it is conducive to the realization of automatic assembly; product digital analog data source is the basis for tooling reconstruction to ensure the high positioning accuracy of flexible tooling [5-6].

Since the early 1990s, scholars have carried out a large number of research on flexible assembly technology of aircraft, the most representative of which are JAM (Jig less Aerospace Manufacture) and ADFAST (Automation for drilling, fastening, assembly, system integration, and tooling) projects. The automatic drilling technology has been studied and applied in the aircraft assembly, which improves the production capacity of aviation enterprises. The concept of box connection tooling [7] was put forward by Linköping University in Sweden. The box connection and passive parallel mechanism were combined to form a low-cost reconfigurable flexible tooling [8]. Flexible tooling

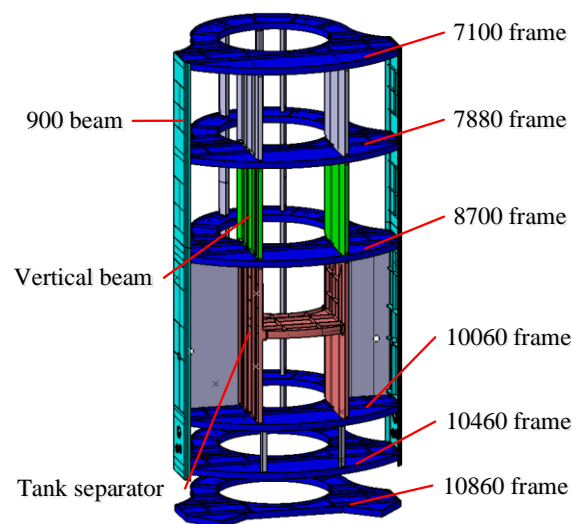


with high positioning accuracy and good openness can meet the use of various automation equipment [9], mainly used in aircraft panel and wing beam assembly [10-12]. M-Torres of Spain has developed a series of array multi-lattice vacuum sucker-type flexible tooling for positioning aircraft panel components, which is mainly used for assembling elastic curved surface components. The tooling consists of arrays of POGO column modules with vacuum suckers, by adjusting POGO column arrays and vacuum sucker-based adsorption clamps. Tight efforts to achieve product retention [13].

Based on the analysis of the fuselage structure characteristics, assembly coordination relationship and manufacturing process, a part-level digital flexible assembly worker is developed to meet the requirements of small fuselage size, complex coordination relationship, dense assembly parts and high requirement of openness in different aircrafts. Finally, the positioning accuracy of flexible tooling is analyzed.

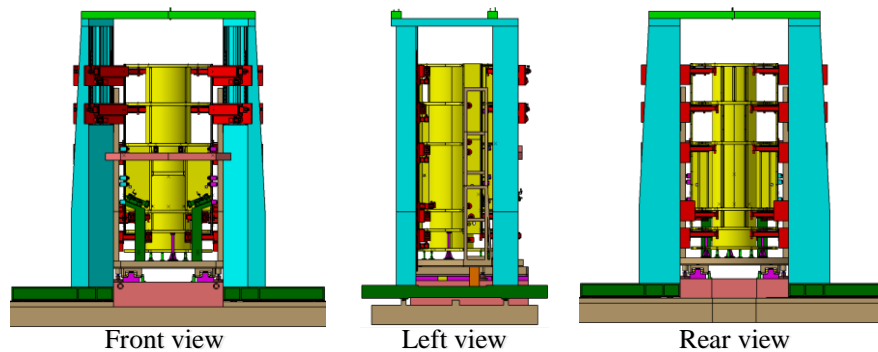
## 2. Flexible tooling structure for aircraft parts product skeleton

The parts that need to be located are generally the intersection holes on the fuselage frame and the fuselage beam, and the worker's operation space is fully considered when assembling. The mid-fuselage products are interchangeable. The front and rear fuselage are connected with the front fuselage and the rear fuselage respectively. The two sides are connected with the wing of the aircraft. The landing gear is located in the mid-fuselage abdomen and requires it to be retracted smoothly. The main structure after the fuselage is simplified is shown in Figure 1.



**Figure 1** The main structure of the aircraft fuselage after simplification

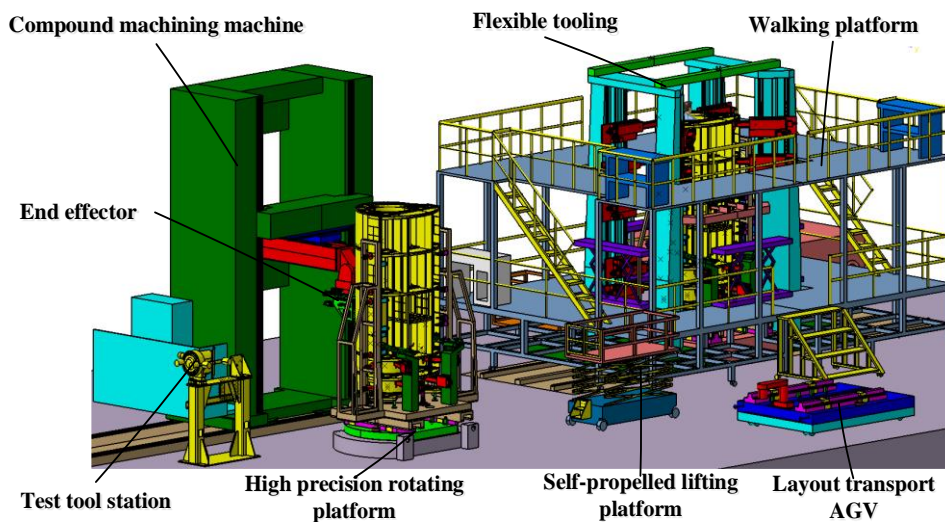
The flexible tooling developed in this paper adopts gantry structure. Based on the intersection holes in each area of the fuselage reinforcement frame, a gantry structure is formed on both sides. The gantry structure is connected by a snap, the positioning column structure of 900 beams is strengthened, the active rotating shaft is installed at the bottom of the tooling, and the positioning of 10460 frame and 10060 frame is close to the main rotating shaft. The positioner is a rigid positioner, and it is installed on the same supporting column as the main crankshaft positioner. The main guard plate positioner is installed on the 900 beam, and the positioner on the 8700 frame is a rigid positioner. The structure of tooling is shown in Figure 2. The scheme has the advantages of good openness, large worker operating space, strong rigidity, small tremor and high precision in the follow-up drilling process of the fuselage products, but its disadvantages are relatively low flexibility.



**Figure 2** Flexible tooling structure

### 3. Automatic layout of automatic drilling and riveting system

The automatic drilling and riveting system integrates the equipment of compound machining machine, multi-sensor fusion end-effector, flexible tooling, high-precision rotary positioning table, AGV parts transportation, tool testing station, ground auxiliary equipment, etc. The overall structure is shown in Figure 3.



**Figure 3** Overall layout of the automatic drilling and riveting system

Firstly, according to the information of the intersection holes on the product digital module and the tool digital module, the displacement of each moving unit along the guide rail and the distance between the left and right directions are planned, and then two gantry columns are moved to move a specified distance along the closure direction of the ground rail. After reaching the position, the guideway brake and the gantry latch are locked; secondly, the moving unit is controlled to move the specified distance along the planned path in front, back, up and down directions, and then locked after reaching the position; thirdly, the fuselage frame and the beam are installed; finally, the positioning of the rest of the components is completed. The assembly process of flexible tooling is shown in Figure 4.

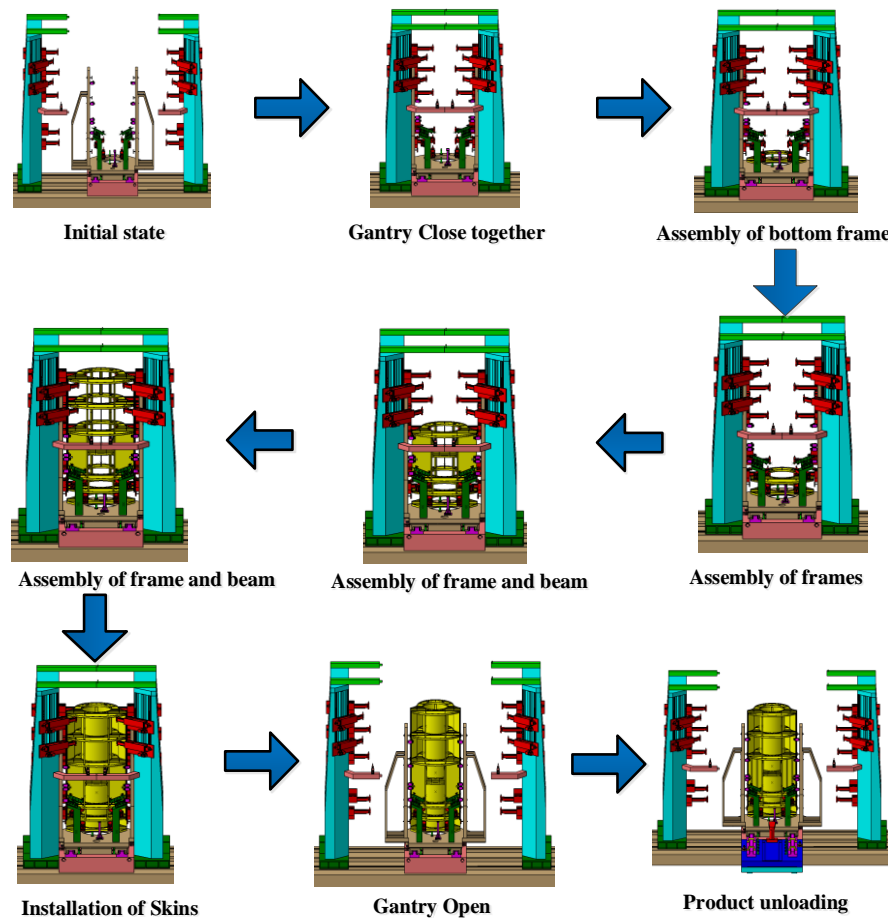


Figure 4 Assembly flow chart

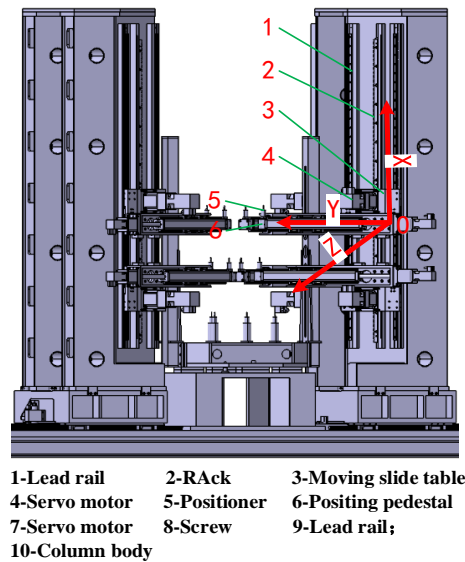
#### 4. Positioning characteristics of flexible tooling test platform

In order to reach the accuracy index and realize the accurate assembly and positioning of tooling and frame, it is necessary to make a comprehensive analysis of the factors affecting the positioning accuracy of flexible tooling. Taking a moving unit on a flexible tooling as an example, in order to improve the positioning accuracy of the center point of the locating pin for the quick-change connector of the moving unit, the laser tracker is used to set up the tool coordinate system, measure the actual position of the point, and establish the positioning error model of the moving unit in two moving directions. Combined with manual adjustment error, the comprehensive positioning error is calculated, and its value is compensated to the initial feed value of the positioning unit.

##### 4.1. Positioning characteristics of flexible tooling test platform

The modular design idea is adopted in the tooling test platform, and the flexible assembly of product samples is realized by using eight moving units. The moving unit is driven in two perpendicular directions (X direction and Y direction) by servo motors. On the X direction, the moving unit is driven by a gear and rack to slide on the guide rail. On the Y direction, the actuator cylinder is driven down by a screw. And on the Z direction, the U-shaped groove hole is used to fine-tune the quick-change connector, as shown in Figure 5. The positioning process is generally as follows: firstly, the fixture coordinate system is established, and then based on the positioning data generated in DELMLA simulation, the X-axis and Y-axis are driven to move to any positioning point in the XOY plane within the range of effective travel from the location of origin. At the same time, with the help of laser tracker, real-time measurement of the actual position of the point P of the quick-change connector is used to

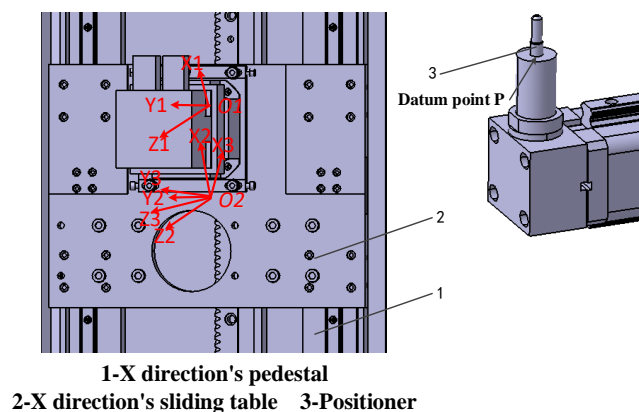
compensate the actual spatial position error by comparison. At last, the Z direction fine-tuning is realized by adjusting the positioning joint manually to achieve the positioning accuracy of 0.05 mm in space, and the intersection hole of the fuselage frame can be positioned.



**Figure 5** Flexible tooling test platform mobile unit

#### 4.2. Positioning accuracy analysis of moving unit in test platform

**4.2.1. Positioning error model in X direction.** A rectangular coordinate system  $D_1(O_1, X_1, Y_1, Z_1)$  is established at the symmetrical center of the pedestal of the moving unit, and a rectangular coordinate system  $D_2(O_2, X_2, Y_2, Z_2)$  is established at the symmetrical center of the sliding table, whose direction of the coordinate axis coincides with the direction of feed. At the symmetrical center of the slide table, a rectangular coordinate system  $D_3(O_3, X_3, Y_3, Z_3)$  is established, and its origin coincides with the coordinate system  $D_2$ , its coordinate axis is parallel to the coordinate axis  $D_1$ , and It does not rotate with the slide table's feed motion, as shown in Figure 6.



**Figure 6** Positioning error model in X direction

When there is no installation orientation error at the lead rail, the coordinate system  $D_2$  coincides with  $D_3$ . It is assumed that the coordinate of the datum point's position vector  $OP$  in  $D_2$  and  $D_3$  are  $(x, y, z)$ , and the coordinates of  $P$  in  $D_1$  are  $(x + x_0, y, z)$ . Due to the guiding error of the lead rail in actual motion, the position vector  $OP$  at the  $P$  point translates  $\Delta y$  and  $\Delta z$  along the  $Y_1$  and  $Z_1$

directions as the coordinate system  $D_2$  and rotates the angles  $\alpha$ ,  $\beta$  and  $\gamma$  around the axes  $X_1$ ,  $Y_1$  and  $Z_1$ , thus the spatial position of point  $P$  is offset and moves to  $P'$ , resulting in the positioning error, As shown in Formula 1:

$$OP' = R(X_3, \alpha)R(Y_3, \beta)R(Z_3, \gamma)OP = E_1 OP \quad (1)$$

Where:  $R(i, j)$  represents the rotation matrix that rotates the angle  $j$  around the axis  $i$ ,  $i = X_1, Y_1, Z_1, j = \alpha, \beta, \gamma$ . Since the angular displacement errors are all micro, As shows in Formula 2, rotation transformation matrix  $E_1$  can be obtained according to differential rotation transformation:

$$E_1 = \begin{bmatrix} 1 & -\gamma & \beta \\ \gamma & 1 & -\alpha \\ -\beta & \alpha & 1 \end{bmatrix} \quad (2)$$

In the formula, the signs of  $\alpha, \beta, \gamma$  are determined by the right hand rule. And the results are independent of the order of rotation around the axis  $X_3, Y_3, Z_3$ .

Ideally, when the sliding table moves to  $x_0$ , the actual coordinate of point  $P$  in the coordinate system  $D_2$  transformed to the coordinate system  $D_1$  is  $(x'+x_0, y', z')$ , as shown in Formula 3. The linear displacement error of point  $P$  transformed from angular displacement error is:

$$OP' - OP = (E_1 - I)OP = \begin{bmatrix} \Delta x_r \\ \Delta y_r \\ \Delta z_r \end{bmatrix} = \begin{bmatrix} z\beta - y\gamma \\ x\gamma - z\alpha \\ y\alpha - x\beta \end{bmatrix} \quad (3)$$

Considering the axial feed error  $\Delta x_i$ , the feed value  $x_0$  is input to the motion' direction  $X$  of the column positioning unit control system. And considering all the guiding errors and the linear displacement errors of the feed system, the linear displacement error  $\Delta X_p$  of point  $P(x, y, z)$  fixed on the positioning unit is shows as follows in Formula 4:

$$\Delta X_p = \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} = \begin{bmatrix} \Delta x_r \\ \Delta y_r \\ \Delta z_r \end{bmatrix} + \begin{bmatrix} \Delta x_i \\ 0 \\ 0 \end{bmatrix} \quad (4)$$

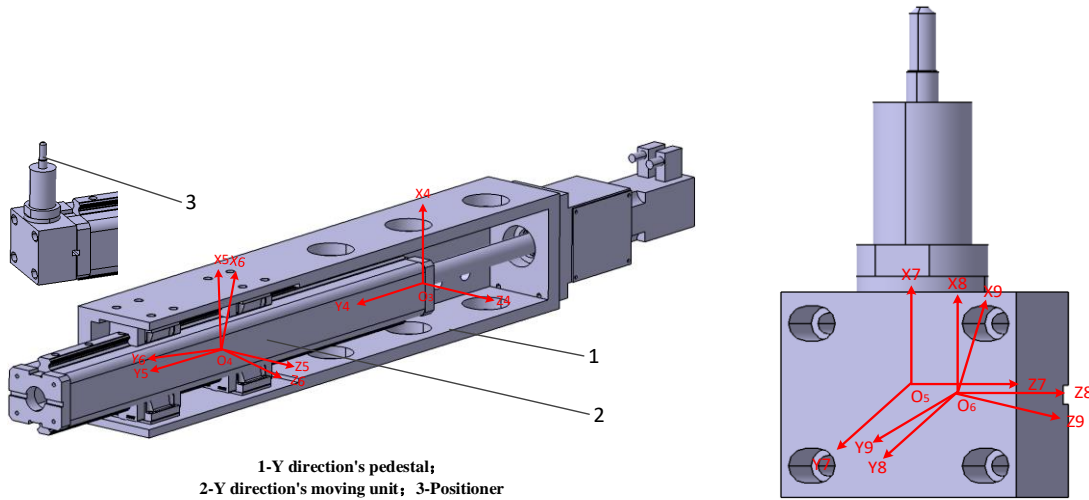
Similarly, by inputting the feed value  $y_0$  into the control system of the moving unit  $Y$ , as shown in Figure 7, the linear displacement error  $\Delta Y_p$  of the point  $P(x, y, z)$  fixed on the positioning unit is as follows in Formula 5:

$$\Delta Y_p = \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} = \begin{bmatrix} \Delta x_r \\ \Delta y_r \\ \Delta z_r \end{bmatrix} + \begin{bmatrix} 0 \\ \Delta y_i \\ 0 \end{bmatrix} \quad (5)$$

As shown in Figure 8, the linear displacement error  $\Delta Z_p$  of the point  $P(x, y, z)$  caused by manual operation in the direction  $Z$  is as follows in Formula 6:

$$\Delta Z_p = \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} = \begin{bmatrix} \Delta x_r \\ \Delta y_r \\ \Delta z_r \end{bmatrix} \quad (6)$$





**Figure 7** Positioning error model in Y direction      **Figure 8** Positioning error model in Z direction

**4.2.2. Spatial positioning error model.** The total positioning error of datum point  $P$  on the quick-change connector is the sum of the linear displacement errors caused by the direction of  $X$ ,  $Y$ ,  $Z$  to the datum point  $P$ . As shows in Formula 7, The error of the positioning datum points in each direction of motion is:

$$[\Delta X, \Delta Y, \Delta Z]^T = \Delta X_p + \Delta Y_p + \Delta Z_p \quad (7)$$

As follows in Formula 8, the difference between the location of the datum hole on the quick-change connector and the position in the digital module is:

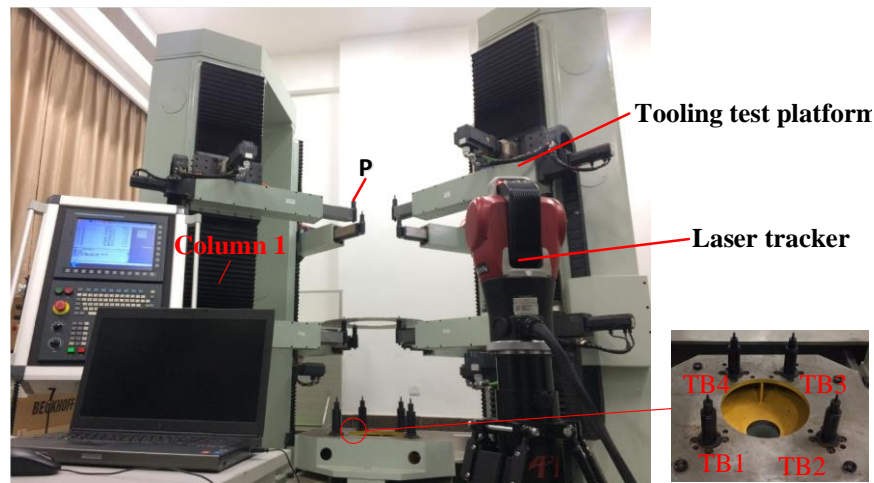
$$\Delta P = \sqrt{\Delta X^2 + \Delta Y^2 + \Delta Z^2} \quad (8)$$

#### 4.3. Experimental verification

Four laser tracker target sockets are installed on the pedestal of the test platform, and four target balls,  $TB_1$ ,  $TB_2$ ,  $TB_3$ ,  $TB_4$ , are placed on them. In the laser tracking and measuring system, the Cartesian coordinate system of the tooling is automatically generated according to the data of the four target balls. On the basis of the relationship between the tooling pedestal and the column 1, the coordinate system of the column 1 is established. The positioning accuracy of the moving unit before and after the measurement error compensation of the laser tracker is used to verify the correctness of the error model. The laser tracker measurement experiment is shown in Figure 9. Taking one of the datum point  $P$  of the moving unit as an example, the position accuracy of it in the column 1 coordinate system is measured to verify the accuracy of the error model. The specific experimental steps are as follows:

- Measure the coordinate value of the datum point  $P$  in CATIA digital model
- Measure the coordinate values of multiple sets of the datum point  $P$  at the origin of three coordinate axes by using the laser tracker, and then take their average values
- Compare the deviation between the coordinate value of the datum point  $P$  in digital model and the coordinate value at the origin of the actual axis, and then input the deviation value into the initial feed value of the control system
- Compensate the spatial error  $\Delta P$  calculated by the error model to the initial feed value of the control system
- Drive the moving unit to the theoretical spatial position, measure the positioning accuracy after compensation by using the laser tracker, and verify the correctness of the error model





**Figure 9** Laser Tracker Measurement Experiment

Through the measurement and calculation of the installation accuracy of the mobile unit, the orientation error of the rail mounting is obtained. The following is an error compensation process for the measurement of the positioning point of the mobile unit, as shown in Table 1.

**Table 1** Error compensation process of positioning datum point P

Theoretical coordinates (1334.686,847.886,382.875)	Mean value at origin (1284.371,767.245,382.343)	Initial feed value (50.315,80.641,0.532)
The coordinate of point P in D <sub>3</sub> in the motion of axis X (10.968,647.563,182.287)	The coordinate of point P in D <sub>3</sub> in the motion of axis Y (60.367,343.631,1.256)	The coordinate of point P in D <sub>3</sub> in the motion of axis Z (92.572,23.021,1.236)
The Linear displacement error of point P in the motion of axis X (0.061,0.230,0.131)	The Linear displacement error of point P in the motion of axis Y (0.045,0.085,0.023)	The Linear displacement error of point P in the motion of axis Z (0.012,0.013,0.022)
Spatial integrated error of point P (0.118,0.328,0.176)	Corrected feed value (50.433,94.092,0.708)	Location error value (0.021,-0.032,-0.025)

## 5. Conclusion

Aiming at the practical problems existing in aircraft fuselage assembly at present, this paper develops a gantry-type flexible tooling structure for machine tools, and designs a flexible tooling for fuselage skeleton assembly. The flexible tooling is suitable for aircraft products with a length of 3-5 meters. The assembly process of this kind of flexible tooling is introduced. Through Electronics Machine servo, manual adjustment and positioner adjustment to achieve the positioning of the new aircraft fuselage. The positioning accuracy of the flexible tooling system is analyzed, and the test bench verifies that the positioning accuracy of the whole flexible tooling system meets the design requirements.

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