Stop Planning of Teleplatform for Large Civil Aircraft Painting with Industrial Robot

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Abstract. An efficient automatic aircraft manufacturing system needs to be developed to respond to the rapid development of civil aviation in China. Whole aircraft painting is the last process of manufacture. Painting quality is an important guarantee for flight safety and longevity. Manual painting has difficulties meeting the quality and efficiency requirements. In this study, the stop planning of teleplatform is investigated for automated aircraft coating with industrial robots (IRs). First, the automatic painting system composed of a teleplatform and an IR is introduced. Next, the high-quality workspace for IR is established, with focus on the requirement of terminal precision. Next, the aircraft surface is considered to be composed of flat, cylindrical, and conical surfaces for simplicity. Painting work units are proposed. Finally, the stop planning of teleplatform for advanced regional jet for the 21st century is accomplished. The developed stop planning method is convenient and practical and could be applied further to the automatic painting of other aircrafts and rockets.

1. Introduction
China’s civil aviation industry has achieved rapid development based on the successful flights of advanced regional jet for 21st century (ARJ21) and C919 jets. Automation requirements are enhanced for aviation manufacturing. The final process of aircraft manufacturing is the painting of the outer surface to prevent corrosion and to ensure flight safety and longevity. The required workspace for the painting operation of large aircrafts usually exceeds 38 m × 36 m × 10 m. Painting relies mainly on artificial, semi-automatic operation. The operation efficiency and quality are dependent completely on the skills and state of workers. The requirements of the booming civil aviation industry cannot be met because of poor stability and low efficiency of the process. The existing aircraft automatic painting solution focuses mainly on part and small fighter aircraft painting, adopts 1D or 3D rigid motion platforms to realize the synchronized motion control of the industrial robot (IR). The motion platform has limited workspace and cannot be applied to large civil aircraft.
The teleplatform robot system, which integrates the large-space teleplatform and IR, provides an automation solution for the painting of large civil aircraft [1]. The teleplatform is cable-driven and has a huge workspace with reasonable cost. However, the stiffness and precision of the teleplatform is weak. The IR is attached to the teleplatform to carry out precise local painting. During the painting operation, the teleplatform docks at planned stops one by one. At each stop, the IR finishes the painting of the local small area, which is the painting work unit (PWU). PWUs should be defined, and the stop planning should be investigated to realize automatic painting.

Existing research on paint planning focuses mostly on the continuous trajectory planning of the IR with the fixed base or bases that can be controlled synchronously with the IR. Chen [2] proposed the optimization algorithm of painting trajectory using time and painting uniformity as the goal. Kohrt [3] proposed an online trajectory planning and programming system to improve the efficiency of painting. Meng [4] proposed a large-space positioning technique and optimized the planar painting trajectory. Other studies addressed the optimization of the relative pose between the IR and the workpiece. Ren [5] proposed a method for selecting the base location based on the available location analysis of the IR base. Lin [6] used stiffness as an index to optimize the workpiece location for robotic machining. Seriani [7] proposed a coverage index and used genetic algorithms to obtain the optimal layout of multiple irregular PWUs in a plane. However, no practical way to carry out stop planning of teleplatform exists for large civil aircraft painting using IR.

Defining the PWU, which is determined directly by the IR workspace, is the basis of stop planning of teleplatform. Yang [8] proposed a collision-free reachable workspace to avoid obstacles. Zhao [9] defined a dexterous workspace that considers link lengths, joint rotation angles, and singularity. Asada [10] proposed acceleration ellipsoid indices to optimize the dynamic performance of the manipulator. Considering the low stiffness of the teleplatform and the IR terminal accuracy, reaction ellipsoid indices and local conditioning index (LCI) are adopted to define the high-quality workspace (HQW) of the IR.

Aiming at the automatic painting of the ARJ21, the HQW of the IR attached to the teleplatform is determined. A practical stop planning method of teleplatform for large civil aircraft painting is developed, and the stop planning for the ARJ21 is deduced on the basis of the defined PWUs. Subsequent contents are arranged as follows: Section 2 introduces the research object. Section 3 shows the HQW of the IR. Section 4 establishes the PWUs of flat, cylindrical, and conical surfaces. Section 5 completes stop planning of teleplatform based on PWUs and concludes the study.

2. Research Object

![Figure 1. Teleplatform robot system.](image1)

![Figure 2. Aircraft model.](image2)
3. Analysis of the HQW

The mechanical structure of the IR can be divided into two parts, namely, positioning and orienting mechanisms. The orienting mechanism determines the terminal posture and is small in size and mass with high accuracy. The positioning mechanism consists of 1, 2, and 3 joints from the base and determines the volume of reachable workspace. The positioning mechanism is the main factor of the IR terminal accuracy. The teleplatform is low in stiffness and can vibrate due to external disturbance. In this teleplatform system, the only disturbance comes from the reaction force and torque of the mounted IR. The accuracy of the IR and the teleplatform vibration should be considered together to improve terminal accuracy of the teleplatform robot system.

The accuracy of the IR is analyzed on the basis of the LCI. Teleplatform vibration is controlled by limiting the reaction force and torque of the IR. Reaction ellipsoids are proposed to describe the reaction force and torque of the IR exerted on the teleplatform by considering the unit IR terminal acceleration. The values of long axes of reaction force ellipsoid and reaction torque ellipsoid are the reaction force index (RFI) and reaction torque index (RTI), respectively. As mentioned previously, positioning mechanism is analyzed. For IR, joints 2 and 3 determine the boundary of the reachable workspace on the XOZ section, and the entire reachable workspace is formed with the rotation of joint 1. Thus, only the value distributions of the aforementioned indices on the XOZ section of the reachable workspace, which are shown in Fig. 4, must be analyzed.
Figure 4. Index values distribution on reachable workspace section. (a) LCI. (b) RFI. (c) RTI.

The value ranges of the aforementioned indices can be determined according to the terminal precision requirements of the teleplatform robot system. In this study, the LCI, RFI, and RTI values are $\geq 2.5$, $\leq 90$ N, and $\leq 120$ Nm, respectively. The HQW of the IR can be obtained by considering the intersection of the corresponding workspace boundaries of the aforementioned index requirements. Fig. 9 (See 5.2) shows that the HQW is the space between the inner and the outer concentric spheres with radii of 1.1 m and 1.935 m, and the center is located at the origin of the O1-X1Y1Z1 coordinate system.

4. PWUs

This section defines typical PWUs based on deduced HQW. The IR will paint the area of the PWU with each stop of the teleplatform. The PWU and teleplatform stop correspond to each other. Fig. 2 shows the outer surface of the aircraft can be considered to be composed of flat, cylindrical, and conical surfaces for simplicity. PWUs are defined with the following basic surfaces.

4.1. Flat Work Unit (FWU)

FWU is defined for the painting of large flat surface. Figure 5 shows the pose relationship between the target flat plane and the IR is discussed in the coordinate system O1-X1Y1Z1. With the motion of the teleplatform, the IR can be located to make the Y1O1Z1 plane parallel to the flat surface that needs to be painted. When the inner sphere of the HQW tangents to the flat surface, the maximum intersecting circle can be obtained, and its radius is $R_s = \sqrt{R_0^2 - R_i^2}$. RO is the radius of the outer sphere of the HQW, whereas RI is the radius of the inner sphere. Considering working efficiency and easy splicing, square and hexagon are selected as the FWU.

Figure 5. FWU. (a) First. (b) Second. (c) Third.

Fig. 5(a) shows the vertices of the maximum inscribed square of the intersecting circle area are points P1, P2, P3, P4. The sides of the square are parallel to Y1 and Z1 axes, and the side length is
\[ L_p = \sqrt{2 \left( R_0^2 - R_1^2 \right)} \]

On the basis of the square, two hexagon FWUs can be defined further. Fig. 5(b) shows that points P5, P6 are the end points of the diameter that parallels the Z1 axis. The second FWU is obtained by connecting points P1, P5, P2, P3, P6, and P4 in sequence. Similarly, the third FWU can be deduced, as shown in Fig. 5(c).

The first FWU is simple and flexible to arrange, but the usage efficiency of the HQW is low. The second and third FWUs have advantages along different directions. The second FWU increases the stop span in the Z1 direction, whereas the third FWU increases the stop span in the Y1 direction. A reasonable choice of second and third FWUs facilitates the reduction of stop numbers and improves painting efficiency.

4.2. Cylindrical Work Unit (LWU)

LWU is defined for the painting of large cylindrical surface with radius of \( R_c \), length of L. With the motion of the teleplatform, the Y1 axis of the IR is parallel to the axis of the target cylindrical surface, and X1 axis intersects with the cylindrical axis. When the inner sphere of the HQW tangents to the cylindrical surface, the maximum intersecting area can be obtained. If we unfold this intersecting area, then it becomes a flat ellipse. The largest inscribed rectangle can be determined as the first LWU, which is marked with P1, P2, P3, P4, as shown in Fig. 6(a). The long sides of the rectangle are parallel to the Y1 axis. Similar to the previous section, the second and third LWUs are defined, as shown in Figs. 6(b) and 6(c).

The parameters of the LWUs are deduced as follows. The length of P1, P2, can be described as

\[ L_* = \sqrt{2 \left( R_0^2 - R_c^2 \right)} \]  

The cylindrical central angles of the LWUs can be written as

\[ \alpha_1 = \arccos \left( \frac{(R_i + R_c)^3 + R_c^2 - R_i^2}{2(R_i + R_c)R_c} \right) \]  \hspace{1cm} (1)

\[ \alpha_2 = \arccos \left( \frac{4(R_i + R_c)^3 + 4R_c^2 - (R_i^2 + R_c^2)^2}{8(R_i + R_c)R_c} \right) \]  \hspace{1cm} (2)

In addition, \( \alpha_{61} = \alpha_{62} = 2\alpha_2 \), \( \alpha_{63} = \alpha_4 + \alpha_2 \), and \( \alpha_i \) is the coverage angle of \( i \)-th LWU along the circumference.

Figure 6. LWU. (a) First type. (b) Second type. (c) Third type.

The first LWU is simple and flexible to arrange but its area is less than the second or third LWU. The second LWU increases the stop span along the circumference, whereas the third LWU increases the stop span along axial direction.
4.3. Conical Work Unit (CWU)

CWU is defined for the painting of a large conical surface with radii of RT and Rt (RT > Rt), the angle between the generatrix and the large end face is denoted as θ and length of LC. This conical surface is divided into several small conical surfaces and their CWUs are defined.

The Y1 axis is kept parallel to the axis of the target cone by adjusting the teleplatform, and the X1 axis intersects with the cone axis. Fig. 7(a) shows the i-th section of CWU. Consider a cylinder with the same radius as the large end of the cone. Length L can be deduced as shown in the last section. Move the teleplatform and make the distance between the large end and the X1O1Z1 plane equal L_2.

The intersection points P1, P2 of the outer sphere can be determined when the inner sphere of the HQW tangents to the cone surface. Two generatrices from points P1 and P2 intersect with the outer sphere on points P3, P4.

X1O1Z1 is translated L_2 in the negative direction of Y1 axis to obtain reference plane 1, and the projection of the intersection of the cone surface and HQW on reference plane 1 is shown in Fig. 7(b).

\[ |EF| = \frac{2R_i L_i \cos \theta}{2 \sin \theta} \]
\[ \alpha_i = \arccos \left( \frac{4|EF|^2 + 4R_i^2 - 3R_o^2 - R_t^2}{8|EF|R_t} \right) \]

Where \( \alpha_u = 2\alpha_i \), \( \alpha_i \) is the coverage angle of i-th section of CWU along the circumference, and RTi is the radius of the big end of i-th section of CWU.

The solution method of Lsi is introduced using O1-X1Y1Z1 as the reference coordinate system:

\[ P_i (x_1, y_1, z_1) = \left( |EF| - R_i \cos \alpha_u, \cos \frac{L_s}{2}, R_i \sin \alpha_u \right) \]
\[ B (x_2, y_2, z_2) = \left( |EF| - \frac{L_s}{2 \tan \theta}, \cos \alpha_u, 0, \left( \frac{L_s}{2 \tan \theta} \right) \sin \alpha_u \right) \]

Linear equation of space can be established by \( P_i \), \( B \), as follows:

\[ \frac{X-x_2}{x_2-x_1} = \frac{Y-y_2}{y_2-y_1} = \frac{Z-z_2}{z_2-z_1} \]
The outer surface equation of the manipulator’s HQW is:

\[
X^2 + Y^2 + Z^2 = R_0^2
\]  \tag{8}

\[
R_0^2 = \left[\frac{(Y-y_1)(x_2-x_1)}{(y_2-y_1)} + x_1\right]^2 - \left[\frac{(z_2-z_1)(Y-y_1)}{(y_2-y_1)} + z_1\right]^2 - y_2^2 = 0
\]  \tag{9}

Solve the aforementioned quadratic equation regarding \(Y\), where a positive solution is \(L_{si}\). Thus:

\[
L_w = L_{ri} + \frac{r_0}{2}
\]  \tag{10}

Where \(L_{ri}\) is the coverage width of \(i\)-th section of CWU. The value of the variable \(R_{Ti}\) can be updated continuously to calculate \(L_{ri}\) and \(\alpha_i\) of every CWU because the radius of the big circle of the remaining conical surface is a known condition.

5. Stop Planning of an Entire Aircraft

In this section, the surface of an entire ARJ21 aircraft is considered to be composed of flat, cylindrical, and conical surfaces. Stop planning is accomplished using the previously defined PWUs.

5.1. Stop Planning of wings, vertical tail, and Horizontal Tail

The wings, vertical tail, and horizontal tails of the ARJ21 can be approximated as flat planes. FWUs are used for stop planning. The wing surface is simplified as a quadrilateral plane with side lengths of 0.41, 10.10, 4.40, and 10.77 m. When the third type of FWU (\(RP=1.592\) m, \(LP=2.251\) m) is adopted, the stop number of the teleplatform is the lowest and is equal to 6. The two wings of the aircraft have four surfaces, and the total stop number for the wing painting is 24. Fig. 8(a) illustrates the arrangement of FWUs and corresponding teleplatform stops.

The vertical tail is considered a plane surrounded by four straight lines with lengths of 5.36, 3.70, 4.67, and 3.66 m. The horizontal tail can be approximated as a plane surrounded by four lines with lengths of 0.80, 5.29, 2.01, and 5.55 m. Their stop numbers and locations are illustrated in Figs. 8(b) and 8(c). A vertical tail of an aircraft has two surfaces, and has a total of eight stop numbers for the vertical tail. Two horizontal tails of the aircraft have four surfaces, and the total stop numbers for the horizontal tail painting are 12.

5.2. Stop Planning of Fuselage

The fuselage of the ARJ21 can be simplified as the cylindrical surface with radius \(RC=1.67\) m and length \(L=18.3\) m. When the first or third LWU is used for stop planning, \(\alpha_1 = \alpha_3 = 60.6^\circ\). When the second LWU is used for stop planning, \(\alpha_2 = 73.7^\circ\).
Analysis shows that when the third LWU is used for stop planning, the required stop number is the least number. With $\alpha_3 = 60.6^\circ$, the fuselage can be surrounded by six LWUs in the circumferential direction. The stop number and locations are shown in Fig. 10. The total stop number for fuselage painting is 42. Furthermore, the engine of ARJ21 is small and can be covered by a single HQW of the IR.

![Figure 9. HQW of the IR](image)

![Figure 10. Stop planning for painting fuselage.](image)

5.3. A subsection Stop planning of aircraft head and tail
The aircraft head of the ARJ21 can be approximated as partial cone (RT=1.67 m, Rt=0.21 m, LC=3.95 m). From the large end, the number of CWU in each section is reduced with the diameter of each section. The aircraft head needs to be divided into two sections according to its size parameters. The stop number for the first and second sections is 5 and 3, respectively, and the total stop number is 8. Fig. 11(a) shows the adopted parameter values are $\alpha_1 = 80.1^\circ$, $\alpha_2 = 127.2^\circ$, $L_1 = 1.85m$, and $L_2 = 2.11m$.

The aircraft tail of the ARJ21 can also be simplified as partial cone (RT=1.67 m, Rt=0.21 m, LC=7.79 m). The aircraft tail is divided into four sections. Stop numbers for each section are 5, 5, 3, and 2, and the total number is 15. Fig. 11(b) shows the adopted parameter values are as follows: $\alpha_1 = 72.0^\circ$, $\alpha_2 = 89.2^\circ$, $\alpha_3 = 120.8^\circ$, $\alpha_4 = 157.6^\circ$, $L_1 = 2.02m$, $L_2 = 2.07m$, $L_3 = 2.17m$, and $L_4 = 2.45m$.

Since sum of $\sum_{i=1}^{4} L_i = 8.71$ has exceeded the total length ($H = 7.79m$) of the aircraft tail, the last section of CWU can be moved in the direction of aircraft tail’s axis to increase the coverage angle $\alpha_4$. After the manual optimization, it can be concluded that painting the last section of partial cone should move teleplatform two times.

![Figure 11. (a) Stop planning for painting aircraft head. (b) Stop planning for painting aircraft tail.](image)

6. Conclusion
This study decouples the complex optimization problem of stop planning for the teleplatform robot system into two simple steps, namely, deducing the HQW of the IR and stop planning of the teleplatform. A convenient and practical stop planning method is developed using the simplified
geometric surface, avoiding complex optimization analysis and calculation. Typical PWUs are established, and the overall stop planning for the ARJ21 aircraft is completed by considering flat, cylindrical, and conical surfaces. Analysis shows only 111 stops are required to complete the entire aircraft painting operation. The method proposed in this study can also be extended to stop planning and optimization for other aircrafts and rockets. The IR trajectory optimization for typical PWUs will also be investigated.

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