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MATCHING A WELDING ROBOT COORDINATE SYSTEM WITH TECHNOLOGICAL EQUIPMENT DURING THE ASSEMBLY OF AIRCRAFT PIPES

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Abstract. Traditionally aviation engineering is considered as advanced and knowledge-intensive industry therefore it continuously utilizes advanced technologies and advanced software. The application of industrial robots may be an example of such advanced technologies. Their practical application causes some problems to engineering services of various enterprises. One of such problems is matching the coordinate systems of an industrial robot with other technological equipment. The paper considers the issue of matching the coordinate systems of technological equipment with a robot during welding of aircraft pipelines.

1. Introduction
Modern aircrafts contain multiple systems, including pipelines of various design and complexity, the manufacture of which requires different technological equipment.

It should also be mentioned that it is critical for the aircraft production, as well for any other industry, to ensure the design-technology production support [12-14]. The analysis of the assembly of aircraft pipeline systems [1] was carried out earlier, which proposed the idea of using a robotic welding station for the assembly of aircraft pipeline system [2].

However, the implementation of such complex leads to some problems caused by its programming and use.

The industrial robot programming employs two methods of control program design: online programming, when the program is designed in a workplace under direct interaction of a programmer or an operator with a robot and off-line programming, when the control program is designed in a workplace of a software engineer using special software and is then transmitted to a welding robot [3-6].

To ensure online programming beforehand there is a need for preliminary production support, which includes the development of special technological equipment [7] and pipeline fitting.
2. **The logic of industrial robot programming**

Let us consider the logic of online programming of a robotic welding station during pipeline assembly:

1. The first stage includes the installation of technological equipment to fix pipeline parts in a working zone of a welding robot. Thus, it is critical to fulfill the condition of welding points for a welding robot, otherwise the technological equipment shall be repositioned, which may lead to the increase in the error of coordinate assignment thus causing the need for more frequent adjustment of the control program.

2. The second stage includes installation and fixation of pipe joints into technological equipment.

3. The third stage includes matching of coordinate systems of the robot and technological equipment. For this purpose, the coordinates of fixed points on technological equipment are recorded via the laser tracker or the measuring probe, i.e. the equipment is positioned in relation to the robot.

4. At the fourth stage the operator of a welding robot sequentially links a pointing device to every welding point and saves coordinates of its position (Fig. 1).

5. The fifth stage includes verification of the control program with subsequent necessary adjustments. Then the control program is stored in the company DB for further reuse.

The main advantage of this programming method is the simplicity of a welding robot programming. There is either no need for profound knowledge of programming languages specialized for industrial robots or for expensive software. It is sufficient enough to demonstrate the sequence of the pointing device positions to a robot.

![Figure 1. Reading of fixed point coordinates of the equipment](image-url)
This yields the main disadvantage of this method, which includes considerable time for programming in case of a large variety of pipelines to be welded and high labor input related to entering the adjustments into the control program in case the design documentation for pipe fittings and assemblies is changed or the technological process is completed. Besides, the welding robot cannot be used while training [8].

Below let us consider the off-line programming.

The given method of the control program for a welding robot can be implemented without technological equipment and pipeline fitting but only via mathematical 3D models of pipeline fitting and jigs, fixtures and tools of a software engineer dealing with robotic welding station.

Let us consider the design of a control program via free open source parametric 3D FreeCAD modeler as an example of off-line programming.

The off-line programming logic includes the following stages:
1. Starting the FreeCAD.
2. Loading the kinematic robot model.
3. Loading the technological equipment with pipeline fitting.
4. Positioning the technological equipment with fitting in relation to the robot. This stage includes positioning of equipment in relation to the robot.
5. Setting the welding points and motion path by a software engineer of a control program.
6. Verification of the control program, introducing the necessary motion adjustments and saving the control program in the company database.
7. Piloting the control program on a first sample and introducing the necessary adjustments.

Figure 3 shows the example of a program window with a loaded kinematic robot model, technological equipment with fitting and a motion path.

**Figure 2.** Manual teaching of welding points
The final code of the control program for both programming methods will be identical and its fragment is given below:

```
&ACCESS RVP
&REL 1
&PARAM TEMPLATE = C:\KRC\Roboter\Template\ExpertVorgabe
&PARAM EDITMASK = *
DEF Trajectory( )
    ;------------- definitions ------------
    EXT BAS (BAS_COMMAND :IN,REAL :IN ) ;set base to World
    BAS (#INITMOV,0 ) ;Initialicing the defaults for Vel and so on
    ;------------- main part ------------
    $VEL.CP = 1.000000 ; m/s ; m/s
    LIN {X 16.231,Y -929.858,Z 1162.000,A 168.000,B 0.000,C 180.000} ; Pt
    $VEL.CP = 1.000000 ; m/s ; m/s
    LIN {X 240.702,Y -898.311,Z 1162.000,A -178.000,B 0.000,C 180.000} ; Pt1
    ...
    WeldStart
    WeldStop
    $VEL.CP = 1.000000 ; m/s ; m/s
    LIN {X 1121.685,Y -0.000,Z 372.192,A -84.845,B 11.951,C -66.460} ; Pt17
    ...
    ;------------- end ------------
END
```

The matching of coordinate systems between a robot, equipment and pipeline fitting to ensure the required accuracy of a pipeline to be welded is a typical problem for both programming methods applied to industrial robots. This problem is related to the probability of mismatching a welding path set by the program mainly caused by an error of positioning the welded surfaces in space due to
manufacturing errors, errors of installation into technological equipment, as well as installation errors of the technological equipment as such in relation to the robot.

![Figure 4. Displacement of equipment during installation](image)

In this case it is critical to adjust the programed motion path of a pointing device to the actual path through matching of coordinates of the robot and technological equipment.

3. **Matching of coordinates**

Let us consider the matching of coordinates of the pipeline fitting and the base coordinate system of the robot. The first step includes the definition of their relative orientation and position in space.

In general, the transfer matrix from the base coordinate system into the coordinate system of an object is as follows [9]:

\[
M = \begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix}
\]

(1)

where \( R \) – 3×3 rotation matrix transforming the base coordinate system into the coordinate system of a target point. It is formed by directional cosines and defines the rotation of the base coordinate system in relation to the coordinate system of an object;

\( T \) – 3×1 submatrix representing a position vector of the origin of coordinates of a turned reference system in relation to the base system.

It is advisable to apply the Euler angles to present the rotation matrixes. There are many various systems of Euler angles, all of which describe the orientation of a solid body in relation to some system of coordinates. For further consideration let us choose the following sequence of rotations:

1) rotation at an angle \( \psi \) around OX axis;
2) rotation at an angle \( \theta \) around OY axis;
3) rotation at an angle \( \phi \) around OZ axis.

The resulting rotation matrix for the chosen sequence is as follows [10]:

\[
R(\phi, \theta, \psi) = \begin{bmatrix}
\cos \phi \cos \theta & \cos \phi \sin \theta \sin \psi - \sin \phi \cos \psi & \cos \phi \sin \theta \cos \psi - \sin \phi \sin \psi \\
\sin \phi \cos \theta & \sin \phi \sin \theta \sin \psi + \cos \phi \cos \psi & \sin \phi \sin \theta \cos \psi + \cos \phi \sin \psi \\
-\sin \phi & \cos \theta \sin \psi & \cos \theta \cos \psi
\end{bmatrix}
\]

(2)
Knowing a 3D rotation matrix and considering the equality representing the expression of this matrix it is possible to define the corresponding angles $\varphi$, $\theta$, $\psi$ through the Euler angles. These expressions are well-known and will not be given for brevity.

The resulting transfer matrix connecting the base coordinate system and the coordinate system of pipeline fitting is as follows:

$$
M(\varphi, \theta, \psi) = 
\begin{bmatrix}
\cos \varphi \cos \theta & \cos \varphi \sin \theta - \sin \varphi \cos \psi & \cos \varphi \sin \psi - \sin \varphi \cos \psi \\
\sin \varphi \cos \theta & \sin \varphi \sin \theta + \cos \varphi \cos \psi & \sin \varphi \sin \psi + \cos \varphi \cos \psi \\
-\sin \psi & \cos \theta \sin \psi & \cos \theta \cos \psi \\
0 & 0 & 1
\end{bmatrix}
$$

where $X$, $Y$, $Z$ – coordinates of the center of a new axis of coordinates.

Let us consider next the introduction of the corresponding adjustments into the control program for welding.

In order to support the given objective, after the analysis of a pointing device motion along the welding path, it is possible to conclude that the main errors in the motion path of a pointing device are first of all caused by the discrepancy between estimated and actual values of the coordinate system of a part and a robot due to the setting error of technological equipment expressed as linear and angular deviations.

Hence, to match the coordinate axes of fitting and define the corresponding adjustments there is a need to find the following:

1) linear deviations expressed as longitudinal and lateral displacements;
2) angular deviations between the estimated position of an end face of a pipeline fitting (mathematical model) and actual in the assembly.

Once the adjustments are identified the control program will recalculate the coordinates for welding:

$$
X_{II} = X_p + \Delta X \\
Y_{II} = Y_p + \Delta Y \\
Z_{II} = Z_p + \Delta Z
$$

where $X_{II}$, $Y_{II}$, $Z_{II}$ – new coordinates taking into account adjustments;
$X_p$, $Y_p$, $Z_p$ – estimated coordinates;
$\Delta X$, $\Delta Y$, $\Delta Z$ – adjustment coefficients containing linear and angular displacements.

Let us consider next the method of matching the coordinate system in practice using the feedback system based on a laser tracker.

For this purpose, the fixed points are installed on the fitting base (at least 3) and using the wireless contact probe and a laser tracker the location of a robot in relation to a pipeline fragment is defined having previously determined the position of a laser tracker in relation to a welding pointing device through the installed fixed points.

Constructively, the fixed points may vary for different companies or divisions depending on the required accuracy, working environment and other parameters. Figure 5 shows an example of an alignment mark.

![Figure 5. Alignment mark](image-url)
The given alignment mark is installed on a fitting frame. Having defined the relative position of a robot and a pipeline fitting, the adjustment coefficients are introduced into the control program.

The operational scheme of a laser tracker with a robotic pointing device is shown in Fig. 7.

![Operational scheme of a laser tracker with a robotic pointing device](image)

**Figure 6.** The matching scheme of a robot with pipeline technological equipment using a laser tracker

Let us consider next the calculation example of the rotation matrix and adjustment coefficients.

4. **Example of recalculation of the coordinate system**

First, let us read from the electronic model the estimated coordinates of equipment position in relation to the robot located in fixed points. The drawing and the electronic model with point positions is shown in Fig. 7.

Let us write down the coordinates of fixed points located on the base. Three points are enough for the calculations:

\[
\begin{bmatrix}
440 & 860 & 440 \\
-1000 & -1000 & 1000 \\
15 & 15 & 15
\end{bmatrix}
\]  

(5)

Let us find the coefficients for the plane equation of the form \(AX+BY+CZ+D=0\) necessary for rotation matrix computation of the estimated system of coordinates in relation to the actual system.
Using the Cramer’s rule and the Scilab software package [11] let us find the equation coefficients: \( A=0, B=0, C=42, D=630 \).

Then, let us take the readings of coordinates of the installed equipment via the laser tracker. Matrix with coordinates of three points:

\[
\begin{bmatrix}
439,980,267,151 & 859,980,267,133 & 859,980,266,937 \\
-1,000,025,105,969 & -1,000,025,105,964 & 999,974,893,948 \\
14,992,031,640 & 14,987,633,410 & 14,968,434,789
\end{bmatrix}
\]  

Using the Cramer’s rule let us find the plane equation coefficients: \( A=8.7965, B=8.0826, C=842,000, D=12,619,000 \).

Knowing the plane equations and substituting the angle values in equation 3 it is possible to calculate the transfer matrix of the coordinate system for the considered case:
Besides, using old and new coordinates of the welding points it is possible to calculate the adjustment coefficients $\Delta X, \Delta Y, \Delta Z$ for three welding points of the first joint:

$$
\begin{bmatrix}
-0.0176 & -0.0184 & -0.0183 \\
-0.0271 & -0.0265 & -0.0265 \\
-0.0179 & -0.0179 & -0.0179 \\
\end{bmatrix}
$$

After finding the transfer matrix of the coordinate system it is possible to recalculate all welding points in the similar way.

5. Conclusions

The paper considers the matching of coordinates of the industrial welding robot with industrial equipment of an aircraft pipeline assembly using the feedback system of a laser tracker with a contact probe. It also provides the alternate solution to the matching of coordinate systems of the robot and equipment via the introduction of a rotation matrix and adjustment coefficients into an ideal motion path of a welding pointing device thus reducing errors caused by the positioning of the equipment in relation to the robot. The use of the welding robot will allow increasing quality, accuracy and stability of welding due to minimization of a human factor.

References

[1] Lebedev A V, Grishin M V, Pavlov P Yu, etc. 2014 Problems of pipeline production in modern aircraft industry. *In the world of discoveries* 4 (52) 71-82

[2] Pavlov P Yu 2014 Automation of pipeline welding at aircraft manufacturing enterprises via robotic welding units. *News of Samara Research Center of RAS*. 16, 1(5) 1521-1527

[3] Korendyasev A I, Salamandra B L, Tyves L I 2006 *Theoretical fundamentals of robotics. In 2 volumes, Vol. 1* (M.: Nauka)

[4] Korendyasev A I, Salamandra B L, Tyves L I 2006 *Theoretical fundamentals of robotics. In 2 volumes, Vol. 2* (M.: Nauka)

[5] Nakano E 1988 *Introduction to robotics*. (M.: Mir)

[6] Yurevich E I 2005 *Fundamentals of robotics*. (St. Petersburg: BH13 St. Petersburg)

[7] Pavlov P Yu, Sosnin P I 2016 Conceptual and algorithmic programming and modeling in design and production of aircraft systems. *Control automation* 1(43) 97-105

[8] Grigoriev S N, Andreyev A G, Ivanovsky S P 2013 Current state and prospects of industrial robotics. *Mechatronics, automation, control* 1 30-34

[9] Fox A, Pratt A 1982 *Computing geometry. Application in design and production* (M.: Mir)

[10] Sankin Yu N 2012 *Lectures on theoretical mechanics*. (Ulyanovsk: USTU)

[11] Alekseev E R, Chesnokova O V, Rudchenko E A 2008 *Scilab: Solution of engineering and mathematical tasks*. (M.: ALT Linux ; BINOM. Laboratory of knowledge)

[12] Maksarov V V, Khalimonenko A D, Matrenichev K G 2017 Stability analysis of multipoint tool equipped with metal cutting ceramics. *IOP Conference Series: Earth and Environmental Science* 7(8) 082030

[13] Krasnyi V A, Maksarov V V 2017 Improving wear resistance of friction assemblies of oil pumps having seals from directionally reinforced polymer composites, *Chemical and Petroleum Engineering* 53(1-2) 121-125
[14] Maksarov V, Khalimonenko A 2017 Forecasting performance of ceramic cutting tool. Key Engineering Materials 736 86-90