Robotic system for non-destructive testing of complex shaped objects

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Abstract. This article describes the positioning system of defectoscopic equipment for non-destructive examination of complex shaped parts made of polymer composite materials. The purpose of the system and features of the investigated objects are described. The rationale for the development of the system and the range of problems it solves are presented. The solution of the kinematics problem for a 5-DOF manipulator is considered. The original algorithms for solving the kinematics problem are demonstrated. Methods for resolving collisions for a manipulator system are described. The results obtained in the course of experiments and studies are presented.

1. Introduction

In the last 20 years, polymer composite materials have been widespread in the aircraft industry. Usage of composite materials can significantly reduce weight, improve environmental parameters and economy of the aircraft. Achievement of a competitive advantage with introduction of parts made of polymer composite materials in comparison with metal analogs is possible only with a reduction in labor intensity and quality assurance in a batch production. This, in turn, requires a high level of automation and robotization of the main technological processes in production manufacture, such as laying reinforcing material, machining, non-destructive testing. Non-destructive testing and defectoscopy of composite parts and assemblies take about 30% of the laboriousness of the technological process of production manufacture [1].

The design and specificity of the analyzed objects made of PCM make it difficult for a reliable defectoscopic to carry out the study without use of a specialized computer control and management tools.

Complex geometric shape of investigated products, as well as the relatively small size of internal defects that need to be recognized, imposes special requirements on the accuracy of the radiation emitter and receiver positioning relative to each other, and also with respect to the investigated object. An important parameter here is the angle between the central beam of rays and the perpendicular to the plane of the receiver (Fig. 1). The value of this angle affects the minimum defect size, which can be recognized in a series of images.
Thus, to automate the process of multi-angle microfocus radiography, it is necessary to develop a system that automatically moves the emitter and the receiver of X-ray radiation at a certain distance from the surface of the investigated object. As the manipulation proceeds, the computer system must analyze the data coming from the sensors, visualize them on the operator panel, and also indicate the locations and types of detected defects.

2. System Overview

The developed system should provide an opportunity to study all the specified types of objects, which include both relatively small products of complex shape and large parts. Reliable research of such objects is impossible without usage of robotic technical means. The concept of the developed positioning system includes several key components [2]:

1. Manipulator with a microfocus X-ray emitter installed on it. The manipulator must provide irradiation of the part at different angles with observance of the given distance. It is necessary to keep a strictly perpendicular orientation of the emitter relative to the surface of the radiation detector.

2. Frame construction with rails, providing positioning of the digital X-ray detector along three coordinates and its rotation in two planes.

3. Rotary table (large and small), on which the part is fastened using a set of clamps.

Figure 2 shows a computer model of a positioning system prototype. According to the proposed concept, the robotic complex synchronously moves microfocus X-ray emitter and a digital radiation detector near the investigated object, producing X-ray photography at various angles. To conduct a more complete flaw detection, the object can be subjected to a thermal or mechanical impact, which will allow one to describe the microstructure of the material of the structure, taking into account both technological defects and defects arising during operation.
According to the presented concept, the most complex component of the system (from the point of view of implementing mechanical designs and control algorithms) is the manipulator. The manipulator consists of the power elements of the structure and units including the link positioning mechanisms, the X-ray emitter, the main controller, the positioner’s sensors, etc. Figure 3 shows the scheme of the manipulator with the directions of rotation of each link. Each node is responsible for the angular displacements of the corresponding link.

In addition to the manipulator, one of the key elements of the proposed concept is the device that moves the X-ray detector. This device is designed based on the approach used in digital CNC machines, 3D printers, etc.
The digital X-ray detector is mounted on a special carriage that ensures its rotation; the carriage itself is located on the rails and can move along three axes. Rotation of the detector and carriage movement are provided by stepper motors with reduction gears, which are operated by the controller through the motor drivers. It should be noted that the ability to rotate the radiation receiver unit is necessary to provide wider positioning configurations.

In accordance with the presented description, the scanned object should be located between the manipulator and the frame structure on a special turntable. Fastening the investigated product to the turntable is carried out with the aid of a vise mechanism [3].

3. Kinematics
In order to provide the movement of system components to given points, it is necessary to solve the kinematics problem for each of them.

The corresponding kinematic scheme of specified manipulator is shown in Fig. 4.

![Figure 4. Kinematic scheme of 5-DOF manipulator](image)

The lengths of manipulator units will be denoted by L1 - L5. The emitter mounted on the manipulator is shown as a grip.

The direct problem of manipulator kinematics is solved by the matrix method of sequential construction of coordinate systems on the basis of the method proposed by Denavit and Hartenberg [4].

The solution of the direct kinematics problem is matrix T, which describes the position of the grip, which is determined by formula (1).

$$T = A_1 * A_2 * ... * A_i = \prod_{i=1}^{n} A_i \quad (1)$$

wherein

$$A_i = \begin{bmatrix} \cos (Q_i) & -\sin (Q_i) & 0 & 0 \\ \sin (Q_i) & \cos (Q_i) & 0 & 0 \\ 0 & 0 & 1 & L_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

where
Q1 - angle of rotation of the first unit; 
L1 is the length of the first unit. 
Similarly:

\[
A_2 = \begin{bmatrix}
\cos(Q_2) & 0 & \sin(Q_2) & L_2 \cdot \sin(Q_2) \\
0 & 1 & 0 & 0 \\
-\sin(Q_2) & 0 & \cos(Q_2) & L_2 \cdot \cos(Q_2) \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (3)

\[
A_3 = \begin{bmatrix}
\cos(Q_3) & 0 & \sin(Q_3) & L_2 \cdot \cos(Q_3) \\
0 & 1 & 0 & 0 \\
-\sin(Q_3) & 0 & \cos(Q_3) & -L_3 \cdot \sin(Q_3) \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (4)

\[
A_4 = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & \cos(Q_4) & -\sin(Q_4) & 0 \\
0 & \sin(Q_4) & \cos(Q_4) & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (5)

\[
A_5 = \begin{bmatrix}
\cos(Q_5) & 0 & \sin(Q_5) & L_4 \cdot \cos(Q_4) + L_5 \cdot \sin(Q_5) \\
0 & 1 & 0 & 0 \\
-\sin(Q_5) & 0 & \cos(Q_5) & -L_4 \cdot \sin(Q_5) + L_5 \cdot \cos(Q_4) \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (6)

All matrices are defined and substituting in (1); the coordinates and the position of the manipulator grip are found so the direct problem of kinematics is solved.

The inverse problem of kinematics determines, by the known kinematic scheme, such generalized coordinates of the manipulator (angles of rotation) that put the manipulator grip in the given position with a given orientation.

The problem was solved by a geometric method. This approach was chosen as the most demonstrative. Known values for solving this problem are the position and orientation of the manipulator grip, i.e. the vector of observation which is also known as a vector emanating from the emitter and directed at the object of study.

To solve the problem, let us denote reference points P1, ..., P5, shown in Fig. 5. Reference point P5 denotes the position of the manipulator grip.

![Figure 5. Reference points](image)

The P4P5 segment sets the direction of observation of the manipulator grip behind the object, which makes the position P4 known.
Point P3 in the five-DOF manipulator with the described kinematic scheme is calculated iteratively [5]. It is known that it is located on a circle with a center at point P4, radius L4; the plane, in which the circle lies, should be perpendicular to segment P4P5. The possible positions of point P3 are shown in Figure 6.

![Figure 6. Possible position of point P3](image)

With point P3 having some initial position, all generalized coordinates, starting with the first one, are calculated.

The first generalized coordinate, shown in Figure 7, is the angle between the X axis and the projection of point P3 defined earlier.

![Figure 7. Finding first generalized coordinate](image)

![Figure 8. Finding coordinates in plane P1P2P3](image)

The second and third generalized coordinates are found according to the scheme (Figure 8) and are defined as the angles of the triangle with known sides (L2 is the length of the second unit, L3 is
the length of the third unit that is known); the third side is located by the projection of point P3 on the X and Z axes.

To find O4 and O5, one needs to find the coordinates of point P4 in the coordinate system centered at point P3, i.e. to go to a new basis centered at point P3.

After the transformations, generalized coordinate O4 is equal to the angle between projection P4 on plane YZ and the Z axis (Fig. 9).

\[ \text{Figure 9. Definition of O4} \]

After that, generalized coordinate O5 is located at the angle between the X axis and point P4 as shown in Figure 10.

\[ \text{Figure 10. Definition of O5} \]

Iterations for the refinement of the position of point P3 on the circle are carried out analogously to [6].

The kinematics of the receiver is simpler in the description because its scheme can be reduced to a two-DOF manipulator (Fig. 11).
In this case, the plane of the receiver must be perpendicular to the grip (emitter), and its center (P4) is on the straight line passing through the grip (straight P4 P5 cm Fig. 5), and the distance between the emitter and the receiver is known in advance. Thus, there are enough data for the direct and inverse problem of the kinematics of the receiver.

4. Collision detection

When nodes of the system move, the problem of collisions between each nodes and the object arises. Thus, it becomes necessary to detect and prevent possible collisions.

In general, the collision detection problem consists in verifying a simple fact: if two objects intersect in space. In case objects intersect, additional information is often needed, such as finding the intersection volume, its approximation in a simple geometric object, the depth of interpenetration of objects.

The intersection of objects begins when the position of any part of the system changes. Initially, the AABB method is used, which requires the definition of the minimum and maximum points for each object. After determining them, the intersections of each part with each one (with the exception of those connected with each other) are searched.

AABB is conveniently represented as two points: points with minimum coordinates along all axes and points with maximum coordinates, which one will call the minimum and maximum points of AABB. To obtain these points, one must project the object on each axis. Figure 12 shows the construction of limiting parallelepipeds for some parts of the scanning installation.
If no intersections are detected, the next change in the position of the system is expected; otherwise, for intersecting objects (by the AABB method), the GJK method is searched, and when the intersection is detected, the user is notified.

The algorithm takes an arbitrary simplex and checks whether it contains the origin of coordinates. If it contains, then the shapes intersect; otherwise, using the reference function, an extreme point is calculated in the direction of vector \((-p)\), where \(p\) is the nearest point to the origin of coordinates. The calculated extreme point is added to the simplex, while the farthest opposite is removed from it. If the extremal point found is either one of those already deleted or one of those that already exists in the current simplex, then one finishes the calculations. There are two possible ways of completing the algorithm: the origin enters the current simplex so the shapes intersect, or the simplex containing the origin of coordinates was not found, then the distance between the figures is equal to the length of the vector \((-p)\).

To work with the GJK algorithm, convex hulls were created for all parts of the scanning system as shown in Figure 13.
5. Results and Discussion

As a result of this research, a model of the system for microfocus radiography was developed. Constructive solutions for creating a system prototype were implemented in practice and demonstrated its efficiency. It should be noted that two versions of the turntable were proposed: for small objects - a small rotary table, located between the emitter and the receiver; for large objects - a large turntable, covering the manipulator inside the ring. It is also important that the task of movement automating remains urgent for a large rotary table, since its rotation is carried out manually at the moment.

The problems of direct and inverse kinematics of a five-DOF manipulator and a radiation receiver were solved. Initially, the manipulator was assumed to be six-DOF and solution was completely analytical. However, the authors had to abandon one DOF (the rotation of the emitter around its axis) to allow the manipulator to get to hard-to-reach survey points located on the bottom of studied objects.

It was supposed to use Separating Axis Theorem, SAT, instead of GJK when solving the problem of collision. However, it showed rather low performance, despite the introduction of the preliminary AABB. In addition, there were problems associated with objects locating their facets in one plane without actual intersection. In this case, the SAT does not work properly and requires additional calculations to verify these cases.

There is a high-level software for controlling the real system being developed at moment, which will allow performing a full scan of an object. Current version allows simulating the process of detail scanning and controlling nodes of the system. In addition, the possibility of manual control of the real complex is being developed. Figure 14 shows the main program window with 6 camera angles for viewing the simulated scene.

![Figure 14. Main window of system controlling software](image)

6. Conclusion

As a result of the research, a model of a positioning system for defectoscopic equipment for nondestructive testing of complex shape parts from polymer composite materials was developed. A
solution and original algorithms for the kinematics problem for a 5-DOF solution are presented. Methods for resolving collisions for system objects are described. The results obtained in the course of experiments and studies are presented.

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References
[1] Anoshkin A, Zuiko V, Tashkinov M, Silberschmidt V 2015 Composite Structures 120 153–166
[2] Fayzrakhmanov R, Murzakaev R, Bakunov R, Mekhonoshin A 2016 Russian Electrical Engineering 11 32-36
[3] Fayzrakhmanov R, Murzakaev R, Bakunov R, Mekhonoshin A 2016 Information-mesuring and Control Systems. 9(14) 12-16
[4] Zhao J, Badler N 1994 ACM Transactions on Graphics 13 (4) 313–336
[5] Iliukhin V, Mitkovskii K, Bizyanova D, Akopyan A 2017 Procedia Engineering 176 498 – 505
[6] De X, Carlos A, Acosta C, John G, Huosheng H 2005 International Journal of Automation and Computing 2 114-124