The mechanisms of constructing trajectories of a laser robotic complex for 3d polygonal models

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Abstract. The article discusses the problems and methods of solving the digital design of the trajectories of the laser robotic complex on polygonal 3D models. The following mechanisms are implemented: preparation of a polygon 3D model, search and construction of the optimal trajectory on the faces of polygons. The method of application of the method of approximation of curvilinear part of a trajectory by means of an arc of a circle is described. On the basis of the obtained mechanisms, the mathematical method of transferring the coordinates of the model space to the working area of the ROBOGUIDE simulator of the industrial robot FANUC is applied

1. Introduction
Laser technologies are widely used in modern production for cutting, welding, thermal improvement of the surface layer, surfacing of material, and marking of products. The use of the laser has a number of advantages and provides a significant expansion of technological capabilities of enterprises and the choice of technical and design solutions [1].

The most technological means of delivering laser emission to the metal processing zone is the use of complexes based on industrial robots.

One aspect of the use of such laser robotic complex (LRC) is the lack of modern CAM systems solutions for the use of laser equipment in conjunction with industrial robots and the formation of appropriate command in the text of the control program.

Currently, there are many different types of systems — CAD-CAE-CAM, designed for use in various industries, as well as for research activities. However, in the field of emission technologies there is a clear lack of them [2].

The team of authors carried out the development and implementation of laser robotic welding complex (LRWC). LRWC includes an industrial robot and a positioner of the company named FANUC, ytterbium fiber laser of the company named IPG Photonics, automated supply systems of gas and compressed air, optical welding heads IPG FLW D50, the working place of the operator and the system of emergency shutdown of the laser emission into a complex.

Also there was developed and put into production the modular protective cabin illustrated figure 1 [3].

The control system of the LRWC (CS LRWC), which includes, in addition to hardware components, special application software CS LRWC (figure 2) was an important development for the complex. [4, 5].
Figure 1. Modular protective cabin of laser welding complex.

Also, the authors developed and implemented their own CAM computer-aided manufacturing LRWC - (further CAM) figure 3.

Development of CAM of robotic laser welding systems requires taking into account many technological features, such as: the construction of a trajectory strictly along the edge of the part, ensuring sufficient accuracy of positioning the laser focus, exposure to the orientation of the laser beam (laser emission delivery can be carried out at different angles to the surfaces, which can greatly affect the quality of the product), the requirements of taking into account the orientation and direction of the gas and air supply, as well as the location of technological sensors (pyrometer, triangulation sensors and profilometer) during the process. In turn, the development of mechanisms for the construction of welding trajectories on polygonal 3D models have difficulties associated with:
Figure 3. CAM LRWC.

- preparation of 3D model for design;
- search and construction of a trajectory on a 3D model, taking into account technological features;
- optimization of the constructed trajectory, taking into account technological features;
- transfer of coordinates of the CAM model of the space robot.

The purpose of this article is to describe the mechanisms of constructing the trajectories of laser robotic systems on polygonal 3D models obtained in the development of computer-aided design.

2. Problem statement

The source data for CAM is a three-dimensional model in STL format, prepared by the implementer in one or another third-party CAD software (for example, ASCON KOMPAS-3D or Dassault Systemes SOLIDWORKS). From a mathematical point of view, a model stored in an STL file is a set of planar polygons (usually triangles) and normal vectors defined in three-dimensional Euclidean space as an enumeration of the coordinates of the vertices of each such polygon and normal. Curved surfaces are approximated by a set of faces with the required level of detail (specified when the model is saved in STL format from CAD). For example, the approximation of the sphere is shown in figure 4.

However, it is worth noting that the polygonal three-dimensional models may have minor deviations from the real geometry of the part. This, in turn, can significantly affect the process of laser welding. After all, here the necessary component is the accuracy of delivery of the focused laser beam, with a spot size of about 50-200 µm. Deviations of the movement of the weld head by a value of about 1 mm from the joint of the parts can lead to qualitatively bad results. This feature of 3D models, in turn, requires the use of CAD models with an appropriate level of detail. As a result of increasing the level of detail, increasing the number of polygons, which in turn increases the search time and build a trajectory. This time factor is very important for the CAM user, as the time spent on the search should not exceed the intuitively-expected, fixed waiting value. The formulation of the CAM design problem, in this case, is as follows-to develop mechanisms for the preparation, search and construction of the trajectory on the polygonal 3D model, taking into account the requirements of the technological process of laser robotic
welding and time factors of information processing and to carry out the transfer of the trajectory of the model in the space of the LRC on the details.

Figure 4. The sphere is approximated using a polygon model. Flat triangles are used as graphic primitives.

3. Preparation 3D model
For the convenience of designing the trajectory of the robot, polygonal 3D model is considered as an undirected graph. The nodes of the graph are the vertices of the polygons, and the edges of the graph are the edges connecting the vertices of the polygon figure 5.

Figure 5. Polygon 3D model in vertex and edge view.

Let us have a graph $G = (V, E)$, where $V$ – is the set of vertices of the 3D model, $E$ – is the set of pairs of vertices (edges between vertices). Then, for the convenience of working with the model, we will represent the graph as an adjacency matrix:

$$ R = \left[ r_{i,j} \right]_{n \times n} $$

where $r_{i,j} = \begin{cases} 1, & \text{if vertices } v_i \text{ and } v_j \text{ are connection} \\ 0, & \text{if vertices } v_i \text{ and } v_j \text{ are not connection} \end{cases}$

In CAM, the definition of the nodes of the graph and the construction of adjacency matrix occurs during the initialization of the 3D model, in a distributed manner on multi-processor computers. This ensures stable and fast operation during motion path design.

From the point of view of the laser welding process, the trajectory of the robot passes along the joints of parts. As the joints of parts, obviously it is necessary to consider the faces of polygons. But most of the faces are not the joints of real parts and the smooth surface of the real part can be represented by the model as a set of polygons. For this CAM it is necessary to remove the edges of the graph, which do not correspond to the characteristics of the joint. As a sign, it is offered to use a method of comparison of angles of normals of polygons. The method is as follows. To determine the butt edge of two adjacent polygons, it is necessary to compare the difference between their angles of normal vectors, with a given value. If the difference between the angles of the normals is less than the specified value, then we assume...
that the edge is not butt and in accordance with this in the adjacency matrix of the graph, we specify the value 0. The optimal value of the difference in the angles of joint detection was determined empirically. The resulting optimal value should be considered average and for practical work, it is desirable to vary this parameter, depending on the specific details. The result of the method of determining the butt edge on the polygonal 3D model shown in figure 5, illustrated in figure 6.

4. Search and construction of the trajectories

One of the most obvious ways to construct a trajectory is to specify the start and end points. This method is intuitively convenient.

For the construction of trajectories, it is proposed to use the vertices of the 3D model polygons (graph vertices) as the start and end points, because they obviously characterize the beginning and end of the detail’s joint. The problem of constructing trajectories, where the start and finish points are the points of the faces of polygons, has a similar solution and it is to construct the trajectory between the vertices of the model.

On the graph from point A to point B, you can construct the path in a different way. On the graph from point A to point B, you can construct the path in a different way. For a more intuitive -expected, high-quality result, it is proposed to look for the shortest way. Considering these requirements, the task is to find the optimal path on the graph.

Since the speed of finding the optimal path is a key factor for the designer, the algorithm A* (A Star) was chosen to solve the problem. This heuristic algorithm is a modified algorithm for finding the shortest path of Dijkstra. The heuristic consists in the numerical estimation of the path for the vertex by the formula:

\[ l(v) = g(v) + h(v), \]

where \( v \) – the vertex of the graph, the function \( g(v) \) – is the path from the starting position to the vertex \( v \), \( h(v) \) – the heuristic approach from the vertex \( v \) to the finish. In this case, the path is guaranteed to be found in a finite number of steps, if there is a finite sequence of actions that leads from the initial situation to the solution [7].

The description of the algorithm can be reduced to the following steps:

1) Initialization and preparation. At this stage, two subsets of the search are created: \( O \) – open (the set of points that are associated with the current iteration point) and \( F \) – closed (the set of points that cannot be moved). You can do the start of the cycle until \( O \neq \emptyset \).
2) The search for the optimal vertex. On the set \( O \) choose the vertex \( v_0 \in O \), for which \( l(v_0) \rightarrow \min \).
   If \( v_0 \) – the finish, the search is over. The Euclidean distance function in three-dimensional space from the vertex \( v \) to the finish is used as a function \( h(v) \).
3) Making a list of adjacent vertices. If \( v_0 \) is not a finish, then we look for adjacent vertices for it (it is determined from the adjacency matrix). The result is a set of adjacent vertices \( V_0 = \{v_{i=0}^{i=k}\} \), where \( k \) – is the number of adjacent vertices..
4) Change search sets. For each element \( v_0 \) calculate the value of the function \( l(v) \). In the set \( F \) add the element \( v_0 \), and replace the set \( O \) with \( V_0 \). Return to step 2.

5) The end of the cycle.

The implementation of the algorithm \( A^* \) in CAM is distributed. This need was associated with the requirement of a time factor for information processing.

Several threads on a multiprocessor computer are used to find the optimal way to the finish line. The distribution consists:

- Adjacent vertices are searched for the «Start» vertex. The search result is written to the array \( S \).
- For each element of the array, the value of \( h(v) \) is calculated and sorted in the order of the shortest distance to the finish.
- Several \( T_N \) threads are created, depending on the computer processor architecture where \( N \) – the number of threads. Each thread is initialized by an array element \( S \), after that the search for the optimal path to the finish occurs in each thread. This operation provides you to search for a path in different directions.
- In each thread, \( T_N \) its own set \( O \) generates – the set of points in which it is possible to move.
- The points of the set \( F \) are common for each thread. If any of the threads were at the vertex \( v_f \in F \), then there is no need to go further.
- The search occurs until one of the threads finds the path.

As the output of the \( A^* \) algorithm, we obtain an array of points in the model’s three-dimensional space, connected by a straight line and representing in the aggregate the trajectory of motion.

The result of constructing the trajectory from point A to point B using the distributed algorithm \( A^* \) is illustrated in figure 7.

5. Path optimization

The trajectories obtained by using the \( A^* \) algorithm on the graph are segments. It turns out that sections with a curvilinear joint are an approximation from straight lines. The accuracy of matching the model and the real detail, in this case, will depend on the degree of detail of the polygon 3D model.

In most cases, a circular arc can approximate curved areas. Due to this, it is possible to reduce the number of nodes, as well as more accurately describe the sections of the trajectory.

The method of optimization the curvilinear trajectory by circular arc applied in CAM was described in work [8]. The essence of the method is a sequential search of the trajectory points and the construction of a circle between them on the basis of three points (beginning, middle and end of the arc). For each point inside the arc, the deviation from the constructed circle is calculated. The total error is calculated based on this deviation. Due to the calculation of the total error, the algorithm selects the best circle on the trajectory section.
For clarity, we illustrate the operation of the method in figure 8. It shows a section of the trajectory, represented as an array of points \( P[i] \), connected by a straight line. The area \([P[i], P[i + 4]]\) is approximated by the arc of the circle. In this area there are two inner points \( P[i + 2] \) and \( P[i + 3] \) not lying on the circle. For them, the distance to the arc is calculated, and on the basis of these values the approximation error of the area is calculated by the arc of the circle.

The method has limitations of application, in particular it requires the following:
- the parts of the trajectory should not intersect each other;
- approximation sections should be smooth curves.

These features of the method were identified during the development of CAM. Using the optimization method, you can automate the construction of a high-quality trajectory on a polygonal 3D model for laser robotic complexes. The result of the approximation of the curvilinear section is illustrated in figure 9.

Due to the specifics of polygonal 3D models, using the arc approximation algorithm allows to improve the quality of the trajectory on the real part figure 10.

Figure 10 shows that the optimization algorithm significantly smoothes the trajectory, which was originally presented as broken segments. But it is worth noting that there are no areas with broken segments on the real details, as a result of this, deviations of the LRWC movement can occur.

The using of the optimization algorithm allows to bring the trajectory to the real providing a better design result.
6. Transfer of coordinates to the robot space and verification of the result in the ROBOGUIDE system

One of the plans of the development of its own CAM is to implement the possibility of remote design of the trajectory of the LRC. In this case, the problem arises of accurately translating the three-dimensional coordinates of the trajectory points and the orientation of the instrument (laser beam, control sensors, systems, gas nozzles and cross-jet system) from model space to the space of the laser robotic complex.

This mathematical problem was solved in [9]. Thanks to it, it is possible to translate the coordinates of the trajectory points of virtual model space objects into the space of an industrial robot, taking into account technological requirements.

The method of calculating and transforming coordinates was applied to trajectories constructed in CAM. The ROBOGUIDE system, which emulates the functioning of Fanuc robots, was used as a test of compliance of the trajectory on the model and on the part in the form of primary testing.

Verification took place in the form of a series of tests on 5 different parts. 10 trajectories with 6 different tool orientations were built on each part.

After a series of tests of passing trajectories in the ROBOGUIDE system built in CAM, it has become obvious that the method of transferring the coordinates of the full extent ensures correct translation. The result of moving the trajectory to the ROBOGUIDE system is illustrated in figure 11.
For qualitative use of CAM in production it is necessary to conduct a series of tests and to reveal the degree of discrepancy between the trajectory of the model and the real detail. The team of authors is going to make such tests on real technical equipment and describe the results in 2018.

7. Results

The authors have developed CAM, which allows to create welding trajectories on the basis of polygonal 3D models, interacting with the technical capabilities of the complex in the process of laser welding. Mechanisms for preparing a polygonal 3D model, searching and constructing trajectories of a laser robotic complex for the laser welding process were proposed.

Also in the work the algorithm of trajectory optimization the with a circular arc was applied. It has allowed to improve the result of design the curvilinear trajectories of the robot movement in the laser welding process.

To transfer the coordinates of the trajectory from the model space to the robot space, a mathematical method of coordinate translation was applied. The result of coordinate transfer was verified in the ROBOGUIDE emulator.

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