ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
UDC/UDK 621.865.8:004.896

KINEMATIC CONSTRAINTS AND OFFLINE PROGRAMMING IN ROBOTIC MACHINING APPLICATIONS

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Original scientific paper

Robotic machining applications are becoming more and more frequent in the world of industrial robots. However, their kinematic complexity still offers many challenges. This work presents an overview of kinematic constraints, which are important for the offline programming of industrial robots for the use in machining applications. The three possible solutions for overcoming kinematic constraints (end-effector rotation, part translation, and part rotation) are presented. The computer algorithm for avoiding such constraints was developed, programmed and tested with a case study. Results show that kinematic constraints can be automatically avoided by implementation of developed avoidance algorithm into the offline programming software for robotic machining.

Keywords: *constraint, industrial robot, kinematic, machining, offline programming*

Kinematička ograničenja i izvanmrežno programiranje kod robotskih obradnih programa

Izvorni znanstveni članak

Robotski obradni programi postaju sve učestaliji u svijetu industrijskih robota. Međutim, njihova kinematička složenost još uvijek nudi mnogo izazova. Ovaj rad daje pregled kinematičkih ograničenja, koja su važna za izvanmrežno programiranje industrijskih robota za uporabu kod obradnih programa. Prikazana su tri moguća rješenja za prevladavanje kinematičkih ograničenja (end-effector rotacija, djelomična translacija i djelomična rotacija). Razvijen je računalni algoritam za izbjegavanje takvih ograničenja, programiran i testirani analizom slučaja. Rezultati pokazuju da kinematička ograničenja mogu biti automatski izbjegnuta primjenom razvijenog algoritma izbjegavanja kod izvanmrežnog programiranja softvera za robotsku obradu odvajanjem čestica.

Ključne riječi: *industrijski robot, izvanmrežno programiranje, kinematički, ograničenje, strojna obrada*

1 Introduction

IFR Statistical Department [1] reports that there are more than 1 million industrial 6-Degree-Of-Freedom (6-DOF) robot manipulators used worldwide. By rapid expansion of industrial 6-DOF robots they are not used exclusively for pick-and-place operations any more. Robotic machining is one field where they are becoming more and more present. Even robot manufacturers have noticed the change in perception of industrial robots and they have already started to offer models intended for specific usage in machining applications. There are many reasons for the expansion of industrial robots into the CNC world [2]. Two main reasons that should be exposed are the greater flexibility of industrial robots compared to conventional CNC machines and the lower price of robotic machining cells compared to conventional CNC machines with similar work envelope. When comparing the programming solutions between pick-and-place operations and robotic machining, one difference becomes evident among others: complexity of tool trajectories. Trajectories for robotic machining can be much more complex and many times contain thousands of toolpath points. In [3] Pan and Zhang and in [4] authors have already recognized that this complexity means that the only practical way to generate such programs would be offline programming using CAD/CAM software modules. Kinematic constraints of the 6-DOF robot manipulator are one of the main drawbacks for the further expansion of robot machining. As previously published by Pan [5] Computer Aided Manufacturing (CAM) systems, currently used for programming CNC machines, do not yet include algorithms that would enable the automatic avoidance of these constraints. The lack of adequate tools to automatically avoid kinematic constraints, when preparing a program for the robotic machining means that the programmer has to solve them mainly by trial-and-error method. This method is time-demanding and sometimes does not allow finding optimal solution in a given timeframe.

The work is organized as follows. An overview of kinematic constraints and related work is shown in Section 2. Section 3 addresses different methods to avoid kinematic constraints. The algorithm for finding, visualizing and avoiding kinematic constraints is covered in Section 4. Application and experimental results are presented in Section 5 and finally, the conclusion follows in Section 6.

2 Robotic machining via offline programming and kinematic constraints

Offline programming is the technique of generating a robot program without using a real machine. As reported by Carvalho in [6] it presents several advantages over the online method, some of which are described below:

- NC programs are prepared without interruptions of robot operation, resulting in reduction of robot down time.
- Programmer is removed from potentially dangerous environment, as most of the program development is executed away from the robot.
- Because offline methods include a simulation of the process there is a greater possibility for optimization of the workspace layout and the planning of robot tasks.
- New programs can include previously developed routines.
- Program changes can be done quickly by substituting only the necessary part of the program.

- Information from the environment (i.e. computer integrated manufacturing system; CAD/CAM systems) can be incorporated into programs which can increase the accuracy of the process.

When using offline programming to create complex trajectories that are intended for machining with industrial robots we come across constraints that are much more evident with 6-DOF industrial robots than with conventional CNC machine tools. As stated by [7] these constraints are a direct result of industrial robots kinematic structure with 6 rotational joints. The main issue with such kinematic structure from the CNC programming standpoint is that moving of these joints during movement along toolpath cannot be easily predicted without using precise simulation of robot movements. There are three main kinematic constraints of industrial robots that can greatly complicate the programming of toolpath trajectories: joint limits, singularities and workspace limits.

Joint limits induced kinematical constraints are the consequence of mechanical construction of robot joints, where the working limit for each of these joints rarely exceeds -/+ 360 degrees. Chen and Sheng [8] have recognized that the main reason for this limitation is the construction of the end-effector and its electrical power and/or compressed air supply rather than the mechanical construction of the joint. Electrical cables for end-effectors power supply and pipes for compressed air or coolant supply are most often mounted on the outside of the manipulator arm and they do not allow joint rotations that are larger than -/+ 360 degrees.

Singularity position is a position of the robot end-effector in the robot workspace, where the mobility of the robot is reduced and the inverse kinematics may show infinite solutions. Small end-effectors velocities may cause very large joint velocities [9]. As shown by Hayes and Husty [10], there are generally 3 types of singularity positions: elbow, shoulder and wrist singularity.

Working space limitation is another important factor in offline programming for robotic machining. The main issue regarding the workspace is the fact that the shape of working space for the 6-DOF industrial robot is not in the shape of a block compared to conventional CNC machines. Reachability constraint becomes important when a robot arm cannot reach the point that is out of the working envelope of the robot.

In order to successfully finish the robotic machining the trajectory must be free of all three previously described kinematic constraints.

3 Overview of methods to avoid kinematic constraints in robotic machining

When dealing with kinematic constraints of industrial robots used in machining operations, we limited possible solutions to only those that did not require changing position or orientation of a tool in a part coordinate system for any toolpath points that were previously calculated by the CAM software. This means that the toolpath trajectory cannot be changed in order to overcome kinematic constraints. The proposed solutions have also been used by several authors [11, 12, 13].

3.1 End-effector rotation

The first method is the rotation of the end-effector around the tool symmetry axis. The motion of the end-effector usually required by a task is the full 6-DOF. However, many robotic industrial tasks, including robotic machining, require less than 6-DOF, because of the presence of a tool symmetry axis. Huo and Baron [12] proved that the general task of machining requires 3-DOF for the displacement of the end-point of the tool, but only 2 additional DOF for its orientation. The rotation of the end-effector around the tool axis is clearly irrelevant to the view of the task to be accomplished. By rotating the end-effector around the tool symmetry axis we can change the position of all six joints of the robot arm and at the same time do not change the position and orientation of the tool according to the part. This solution can greatly improve the possibility to successfully finish the toolpath that was previously unachievable due to kinematic constraints.

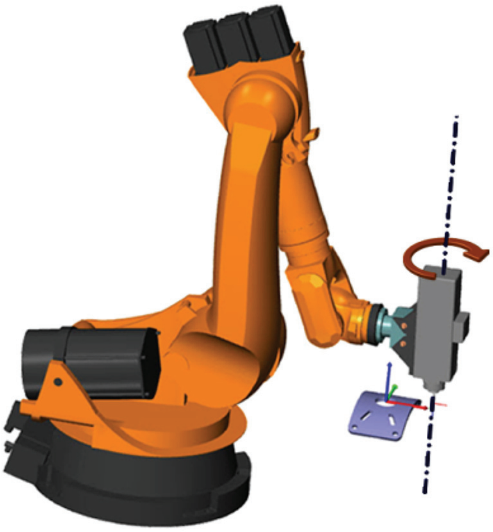


Figure 1 Method for solving kinematic constraints by rotating end-effector around tools symmetry axis

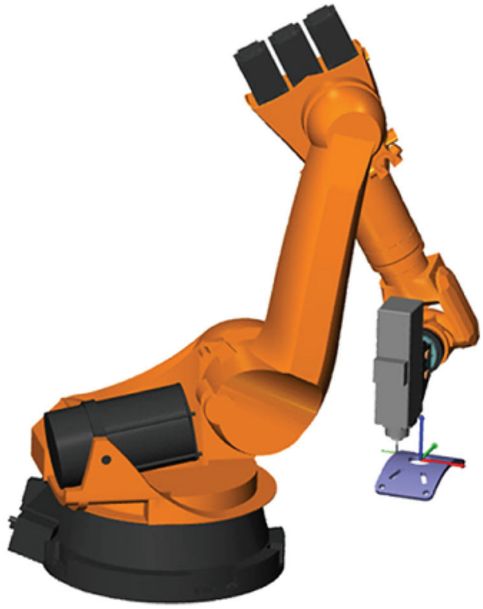


Figure 2 After applying the method of rotating the end-effector around tools symmetry axis the part can be machined

Fig. 1 shows a part which is placed at such a position in a robot workspace that machining is not possible due to the robots joint limits. By rotating the end-effector around the tool symmetry axis (Fig. 2) the same part at the same position becomes reachable and can now be machined.

3.2 Part translation

The second method for resolving kinematic constraints is the change of the part position in the robot workspace. Fig. 3 shows that at the beginning the part is being positioned too close to the robot base and is therefore unreachable to its end-effector. By repositioning of the part away from the robot base it becomes reachable to the end-effector and can be machined (Fig. 4).

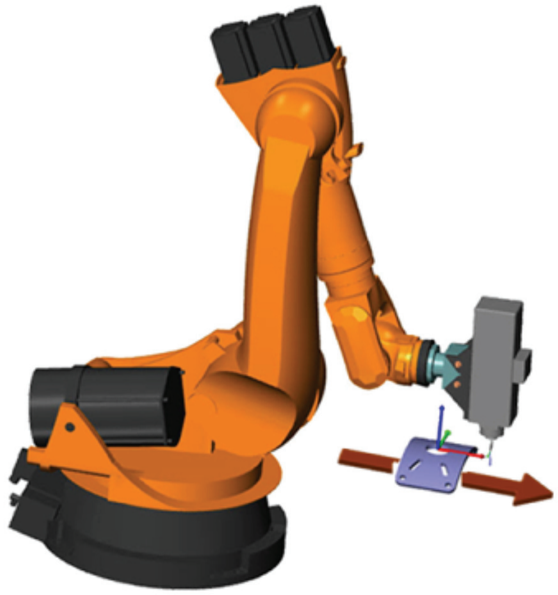


Figure 3 Method for solving kinematic constraints by repositioning the part

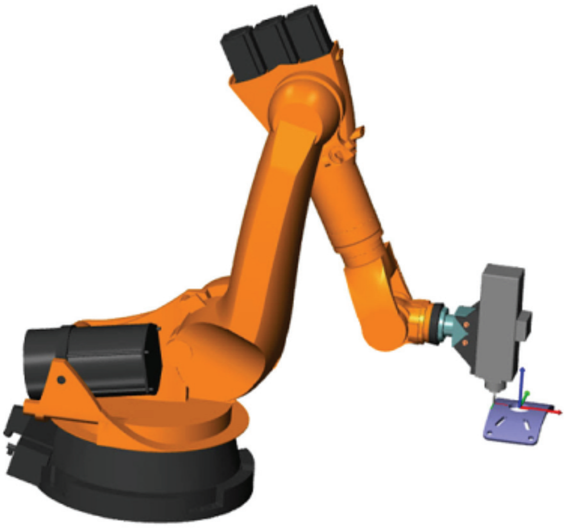


Figure 4 After applying the method of repositioning the part can be machined

3.3 Part rotation

The third valid method to solve kinematic constraints is the part rotation. This solution is presented in Fig. 5, where a part is positioned too close to a robot base in order to be successfully reached and machined. By changing its orientation the robot can successfully finish the toolpath (Fig. 6).

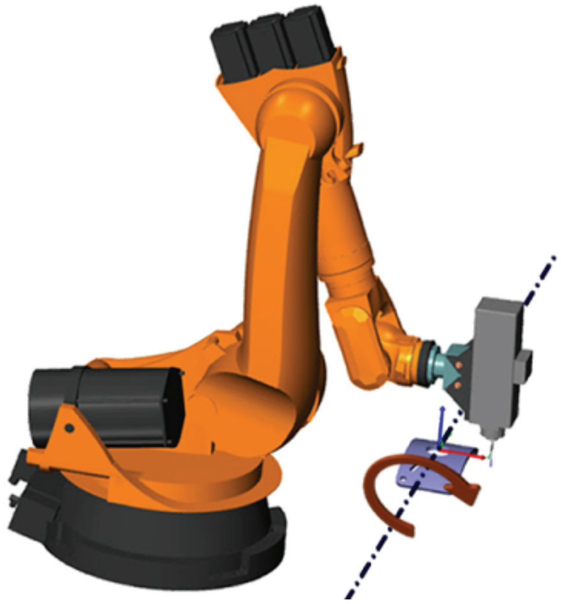


Figure 5 Method for solving kinematic constraints by reorienting the part

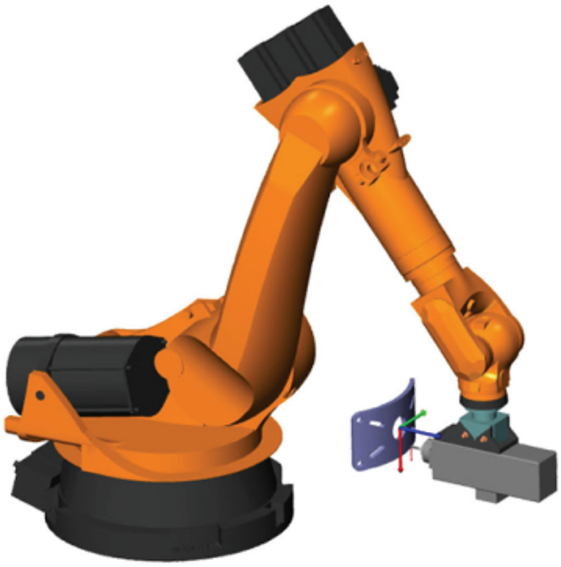


Figure 6 After applying the method of reorienting the part can be machined

4 Algorithm for avoiding kinematic constraints

The intention of this algorithm is to implement previously described methods for avoiding kinematic constraints in order to successfully complete the programmed trajectory for machining a part. Kamrani [13] has stated that the toolpath is admissible if the end-effector of the robot can reach all the points on the toolpath in the predefined configuration. The main methods we used in the developed algorithm were discretization and solution method ordering.

4.1 Discretization

As previously described by Zacharias [14] the theoretically possible workspace of the robot arm can be encapsulated by a cube with a side length of two arm lengths centered at the robot arm base (Fig. 7). The work of Kamrani [13] and Zacharias [14] has shown that the best practice to calculate the admissibility of the toolpath when it is placed at different positions in the robot workspace is to discretize the encapsulated cube into smaller blocks. The calculation then checks the admissibility of the given toolpath placed at each corner of the sub block. Similarly, we also use discretization of the robot end-effectors rotation around tool axis and part rotation around global *X*-, *Y*- and *Z*-axis.

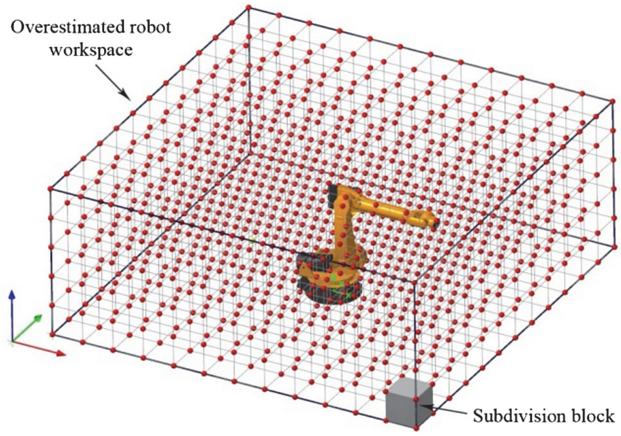


Figure 7 Robot workspace is overestimated and subdivided

4.2 Ordering of the solution methods

Our work aims to address the issue of finding the machining configurations (orientation of the end-effector, part location, part orientation) where the machining is possible. We propose to use the specially ordered combination of all previously mentioned solutions which will be further explained in the following paragraph.

The main reason for this approach is the need to minimize the calculation time and to maximize the number of possible configurations which are checked for admissibility. To minimize the calculation time we decided to order possible combinations by the number of DOF that each solution takes. In robotic machining applications it is preferred that the part predefined position and orientation changes as little as possible from the predefined position. Every additional DOF the proposed solution uses means that the change in position and/or orientation complicates the clamping of the part. For instance, the solution with the end-effector rotation does not necessarily require movement of the clamped part. It therefore requires 0 DOF. Part reposition can require one, two or three DOF which in real world requires re-clamping of the part. If the part must be reoriented this solution can take up to 6 DOF what in reality often means that a new clamping device must be constructed. The first solution method with rotation of the end-effector around its axis is therefore more preferred than the repositioning or reorienting the part. After taking these characteristics of the possible solutions into consideration we have prepared Tab. 1 that recognizes the most important types of kinematic constraints and the order of each solution taken into consideration for solving these constraints.

Table 1 Proposed methods to avoid kinematic constraints and their proposed order

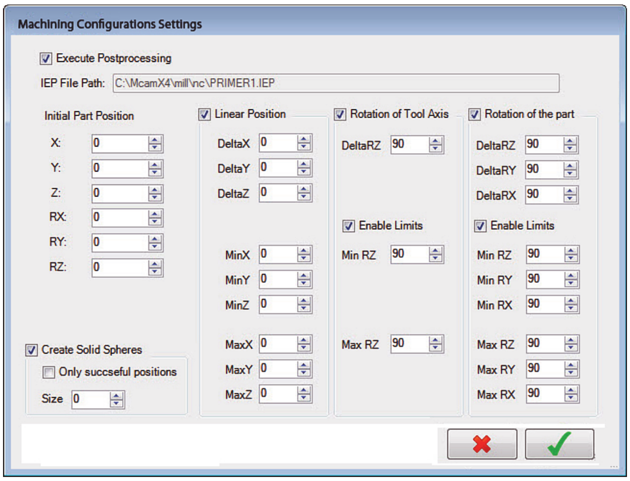
Method	Method description
1	Rotate end-effector around tool axis
2	Reposition the part
3	Rotate the part

By using this matrix in a developed algorithm we predicted that each level of solution methods would be used after a previous level method was found to be unsuccessful. If the previous level solution returned an admissible configuration all higher level solutions would be discarded from the calculation process.

4.3 Description of the developed algorithm

The flow of the developed algorithm is depicted in Fig. 8. The algorithm first imports the CL (Cutter Location) data which have been previously calculated by a CAM (Computer Aided Manufacturing) program. At the same time the Machining Configurations Settings window (Fig. 9) is shown. In this window user can set additional limitation parameters. Tab. 2 shows all the additional parameters that can be specified in order to set the discretization parameters of algorithm. We also have an option to minimize the calculation time by omitting the inverse kinematics calculation at some of the configurations. For instance if it is predicted that the part will be clamped on the working table we can input the parameters in such a way that only configurations with parts *Z*-coordinate at the top of the clamping table are used and calculated.

After the parameters are input and confirmed the algorithm calculates the reverse kinematics for the toolpath at the initial part position (Fig. 8). The role of the inverse kinematic calculation is to check each point in the toolpath for possible kinematic constraints [15]. If all the points in the toolpath can be reached without any reported kinematic constraints the toolpath at the current configuration is marked as admissible (valid).


Machining Configurations Settings

☑ Execute Postprocessing

IEP File Path: C:\McamX4\mill\nc\PRIMER1.IEP

Initial Part Position
X: 0
Y: 0
Z: 0
RX: 0
RY: 0
RZ: 0

☑ Create Solid Spheres
□ Only succseful positions
Size 0

☑ Linear Position
DeltaX 0
DeltaY 0
DeltaZ 0
MinX 0
MinY 0
MinZ 0
MaxX 0
MaxY 0
MaxZ 0

☑ Rotation of Tool Axis
DeltaRZ 90
☑ Enable Limits
Min RZ 90
Max RZ 90

☑ Rotation of the part
DeltaRZ 90
DeltaRY 90
DeltaRX 90
☑ Enable Limits
Min RZ 90
Min RY 90
Min RX 90
Max RZ 90
Max RY 90
Max RX 90

Figure 8 User interface window for entering additional parameters

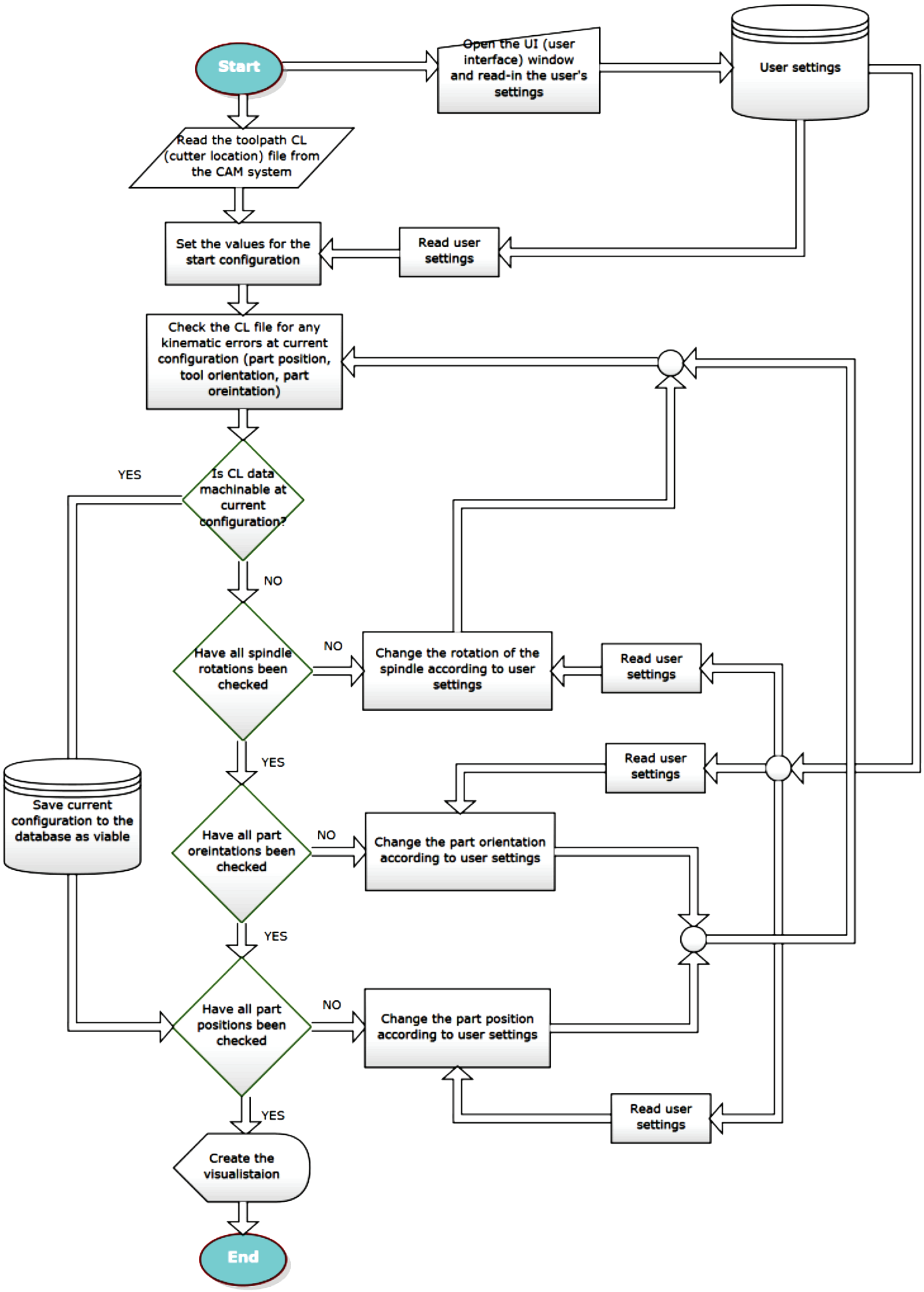

Start
Open the UI (user interface) window and read-in the user's settings
User settings
Read the toolpath CL (cutter location) file from the CAM system
Set the values for the start configuration
Read user settings
Check the CL file for any kinematic errors at current configuration (part position, tool orientation, part oreintation)
YES
Is CL data machinable at current configuration?
NO
Have all spindle rotations been checked
NO
Change the rotation of the spindle according to user settings
Read user settings
YES
Read user settings
Save current configuration to the database as viable
Have all part oreintations been checked
NO
Change the part orientation according to user settings
YES
Have all part positions been checked
NO
Change the part position according to user settings
Read user settings
YES
Create the visualistaion
End

Figure 9 Flowchart diagram of the algorithm

Table 2 The user interface input parameters overview

Part repositioning discretization parameters			
Minimum part position values	*Min X* / mm	*Min Y* / mm	*Min Z* / mm
Maximum part position values	*Max X* / mm	*Max Y* / mm	*Max Z* / mm
Subdivision block size	*Delta X* / mm	*Delta Y* / mm	*Delta Z* / mm
End-effector rotation discretization parameters			
Minimum end-effector rotation value	*T Min RZ* / mm		
Maximum end-effector rotation value	*T Max RZ* / mm		
End-effector rotation step	*T Delta RZ* / mm		
Part rotation discretization parameters			
Minimum part rotation values	*P Min RX* / mm	*P Min RY* / mm	*P Min RZ* / mm
Maximum part rotation values	*P Max RX* / mm	*P Max RY* / mm	*P Max RZ* / mm
Part rotation step	*P Delta RX* / mm	*P Delta RY* / mm	*P Delta RZ* / mm

If this calculation returns an invalid solution the algorithm continues the iteration process and checks all the configurations with rotated end-effector. If this additional iteration through all the preset end-effector rotation configurations still returns no admissible solution the algorithm continues with iterating through all the preset part orientation configurations. After the completion of the iteration the inverse kinematics solution is recorded into the database for later use. If the valid solution is found at any of the previously described steps the algorithm increments the parts position and starts iteration process for all the predefined configurations at the new part position.

When all the configurations at each of the predefined part positions have been checked the process is stopped and the visualization module is run. This module reads the data from previously saved database and presents the results on the screen.

4.4 Results visualization

Visualization was used to clearly represent the algorithm results in order to help locating the configurations where machining of the part is viable. Each calculated configuration is presented by a reachability sphere [14] where the coordinates of the reachability spheres center represent the position of the part origin in the robot base coordinate system (Fig. 10).

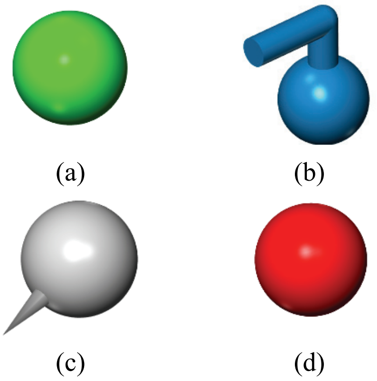


Figure 10 Graphical representation of several types of algorithm results

In addition to the spheres we also use additional geometry and colors to represent different types of solutions:

- Green sphere (Fig. 10a) represents a valid solution with no need to rotate the end-effector or the part.
- Blue sphere with added cylinder (Fig. 10b) represents the part position in robot coordinate system which becomes valid by implementing tool frame rotation around tool axis (the rotation of the cylinder also represents the tool frame rotation angle).
- Grey sphere with added cone (Fig. 10c) represents the part position in robot coordinate system which becomes valid by implementing part rotation (the rotation of the cone also represents the axis and the angle of parts rotation).
- Red sphere (Fig. 10d) represents the part position in robot coordinate system where no valid solutions can be found. Part cannot be machined when placed in this position.

5 Experimental implementation and results

The developed method was implemented using Visual C#. The results were visualized using Mastercam^{TM} and Robotmaster^{TM}. For the calculations and simulations we used the data and a 3D model of the Kuka KR-150 industrial robot. The Denavit-Hartenberg (D-H) parameters of the test robot definition are presented in Tab. 3.

Table 3 D-H parameters for the inverse kinematics calculations

α / °	r / mm	θ / °	d / mm
90	350	0	–750
0	1250	–90	0
90	–55	0	0
–90	0	0	–1100
90	0	0	0
180	0	180	230

5.1 Test case: machining of small part on a working table

The test case represents the machining of a relatively small and simple part which was predicted to be clamped on a fixed working table (Fig. 11). Using the algorithm we calculated all the admissible configurations where the part would be clamped on the table (Fig. 12). In order to achieve that the values of the repositioning coordinates were limited to the extents of the table in the *X*- and *Y*-axes. In the *Z*-axis we limited the calculations only to the value of the height of the working table (Tab. 4).

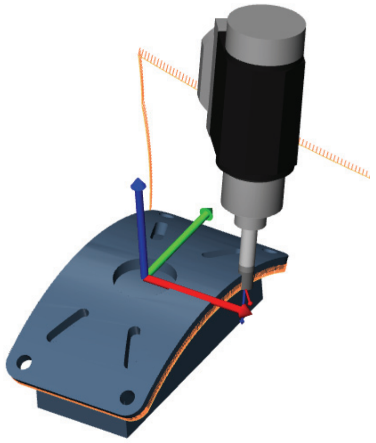


Figure 11 A 3D model of the test part with test toolpath simulation

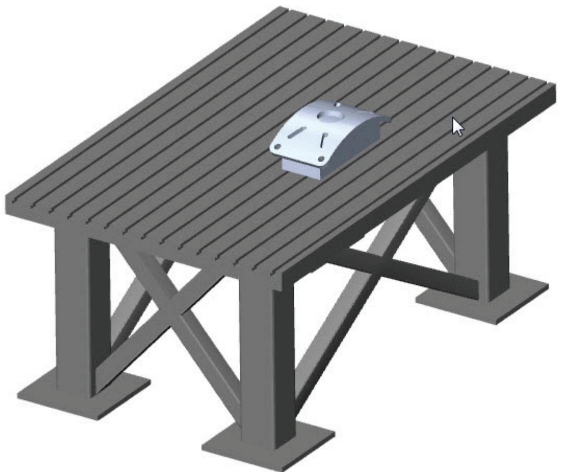


Figure 12 Position of the test part on the working table

Table 4 Algorithm discretization parameters used for test case

Part repositioning discretization parameters			
Minimum part position values	*Min X* = 800 mm	*Min Y* = –800 mm	*Min Z* = 950 mm
Maximum part position values	*Max X* = 1900 mm	*Max Y* = 800 mm	*Max Z* = 950 mm
Subdivision block size	*Delta X* = 100 mm	*Delta Y* = 100 mm	*Delta Z* (not used)
End-effector rotation discretization parameters			
Minimum end-effector rotation value	*T Min RZ* = 0°		
Maximum end-effector rotation value	*T Max RZ* = 360°		
End-effector rotation step	*T Delta RZ* = 90°		
Part rotation discretization parameters			
Minimum part rotation values	*P Min RX* (not used)	*P Min RY* = 0°	*P Min* RZ (not used)
Maximum part rotation values	*P Max RX* (not used)	*P Max RY* = 360°	*P Max RZ* (not used)
Part rotation step	*P Delta RX* (not used)	*P Delta RY* = 90°	*P Delta RZ* (not used)

Using the Intel® Core^{TM} i7-2860QM processor at 2,5 GHz the calculation time was 4 min 42 s. To compare automatic and manual method we also tried to find one admissible configuration by manual trial-and-error method and this test took us 9 minutes to find only one viable configuration. This comparison clearly shows that automatic method can return a larger number of admissible configurations in a shorter period of time compared to manual method.

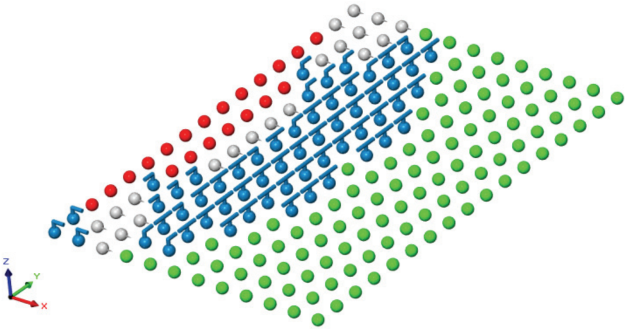


Figure 13 Graphical representation of the results for the test case

Graphical representation of results (Fig. 13) shows that the number of admissible configurations was as follows:

- 105 part positions were valid for machining with just part repositioning (green spheres).
- 58 part positions were valid for machining by rotation of the spindle around the tools axis (blue spheres). 40 of these positions offered 2 valid configurations (rotation of the spindle by 90° and 270°). This method therefore offered 98 valid configurations.
- 20 part positions were valid for machining by rotating the part around Y-axis (grey spheres).
- 20 configurations were not valid for machining (red spheres).

The results also show that the best region for clamping the part is on the far side of the table (larger X-axis position) regarding to the robot base coordinate system where no end-effector or part rotation is necessary to successfully machine a part.

The results of the algorithm were tested using Robotmaster^{TM} simulation module. As seen in Fig. 14a, Fig. 14b and Fig. 14c all three groups of results proved to be correct and can be used in actual machining process.

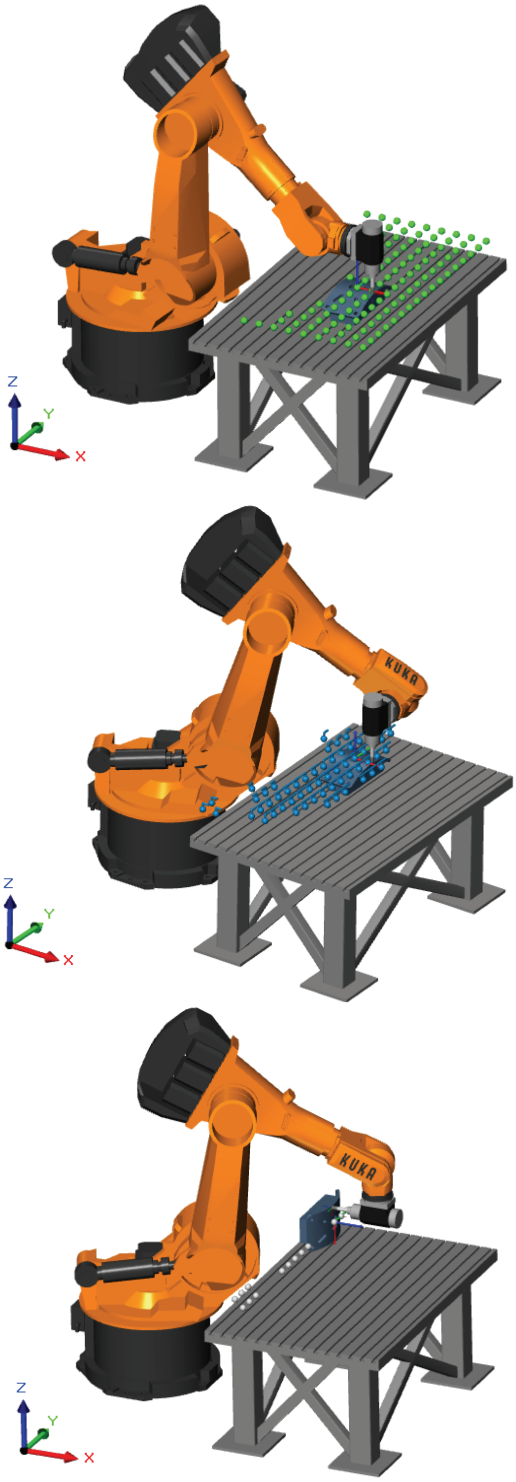


Figure 14 a) Simulation test of the solution group 1, b) Simulation test of the solution group 2, c) Simulation test of the solution group 3

6 Conclusions

The presented research shows that kinematic constraints of industrial robot for machining applications can be avoided by implementing end-effector rotation around tool axis, part repositioning and/or part reorientation. The algorithm for calculating valid configurations using these solutions was developed and programmed using Visual C++. It was successfully tested on an industrial case and the results were confirmed by the Robotmaster^{TM} robot simulation software. The main advantage of the proposed method compared to the state-of-the art in the offline programming, is synergetic implementation of three separate methods into one algorithm. By combining all three methods kinematic constraints can be resolved reliably and much faster. The main advantage lies in the fact that all three methods are considered synchronal. Additionally, the developed visualization helps the user to better recognize positions of critical zones and by this the final solution can be significantly closer to the optimal part position. Implemented algorithm (Fig. 9) also allows the user to set the input parameters in such a way that only a part of the robot workspace is being checked. This enables further shortening of the calculation times, while the inverse kinematics does not have to be calculated over the whole robot workspace.

The proposed method has been tested on the case study. Results of the test show that the algorithm can significantly improve the speed and quality of calculating the valid configurations/tool path for robotic machining compared to manual trial-and-error method.

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