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Path Planning for Industrial Robot Milling Applications

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Abstract

Recently, the use of industrial robots as an alternative to computer numerical controlled (CNC) workbenches has been increasing due to the lack of access capabilities of CNC, their large masses and costs. Computer-aided design (CAD) and computer-aided manufacturing (CAM) programs for industrial robot applications are still limited due to the following reasons. The trajectories in the CNC program are transformed into robot programs. Despite the wide-ranging capabilities of robots, the tooling orientation is not considered and the trajectory information is generated for commonly used blade geometries due to its suitability for CNCs. The robot configuration is not considered. When the industrial robots compared to CNCs, they have some disadvantages due to their articulated structure. They have difficulty in processing hard surfaces. In this study, a CAD program was developed for robotic milling to resolve the above-mentioned basic problems. Also, it can generate trajectories to increase the surface treatment quality. The program creates trajectory for IRBs from the graphic models in 3ds (3D Studio) format. The depth of the surface treatment can be controlled to increase the stiffness and reduce the geometric errors due to the robots are not rigid enough.

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Keywords: Robotic milling, Robotic manufacturing, Path planning, Off-line programming

1. Introduction

Machining is a basic necessity in the manufacturing industry. To meet the requirements different machining workbenches have been developed. These machines, which were as efficient as the operators' skills, are now controlled by computers. Although different types of materials can be produced in the mass production, the process can not be completely independent of the operator performance. Operators must create the position information for the tooling of the different workpieces, such as the cutter, driller, and polisher, taking into account the structure of the material to be machined and the geometry of the produced part. For machining parts with basic geometry such as cones, cube, cylinder, the position information of the end effector of the workbench can be calculated manually.

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However, routing information should be automatically generated from solid models prepared with CAD programs for complex geometries. In this operation the geometry of the process part is only the considered point. The geometry and the articulation points, which are usually 2 axes to 5 axes, which determine the degree of freedom of the CNC workbench to be used, should be included in the calculation. CNC machines may be considered as industrial robots in the form of Cartesian geometry. When CNC machines are cross examined in terms of cost, accessibility, large masses, the use of IRB has begun to be a good alternative in recent years. CAD-CAM programs are rather a recent applications for IRB stations.

The 6- degree of freedom industrial robots in articulated structure are more flexible but less stiff than CNCs. These case are highlighted [1]. In this study, it is pointed that articulated robot structures, can be advantageous over classical benches after the path compensation by accounting the forces. The stiffness of these jointed structures, flexibility of the IRBs has been studied [2] for the engraving of carbon fiber parts, which is a troublesome material. In this study KUKA KR500-2 with 500 kg carrying capacity is used and the effects of surface treatment direction is criticized. Distance errors are presented in the measurement results obtained with the laser interferometer.

It is subjected [3] to improve the follow-up mistakes by adding the estimated skewness of the stiffness to the planned path. It has been shown [4-5] that joint errors can be estimated in a similar way to reduce the errors in processing hard materials by adding the determined offset to the programs. Path compensation in another words, trajectory readjusting has also been suggested [6-7] to improve the tracing accuracy. The backlash and stretching of the joint links due to lack of stiffness during the processing of the hard materials limits also the load-carrying capacity of the robot. With the proper adjustment of the cutting tool orientation it is possible to achieve less resistance against surface handling. This can be done by considering the direction of the surface normal, service direction and the depth of etching in the same optimization function.

In these manuscripts different enhanced line scan geometries are recommended to use as an alternative to direct path formations. Another one [8] tried to overcome the strain and stiffness problem with surface scanning strategies. Heuristic algorithm based gradient scan methods are introduced [9] to provide maximum kinematic performance by superseding interlaced lines alternative to the intercepted and discrete paths. The hardness of the process part is rather high in the mold application. For this reason, [10] it is stated that unregulated cutter wear-outs can occur due to force undulation. A fixed surface treatment width and depth is proposed as a solution. Authors [11] had tried to reduce the encountered errors with the b-spline approach. In order to reduce force and errors, [12] geometric distance is calculated using triangular meshes.

The result that will be drawn from the literature survey made up to now is as follows: The follow-up mistake is one of the important barrier to the popularity of industrial robots in machining. Published technical papers in 2017 also shows the solution of the problem is not at the desired level of performance. Current solutions are just the addition of the planned path offsets in the sense that the joint resistance is measured by means of force sensors. Addition of small offsets to form a new follow-up paths is not a substantial solution.

In this work, manufacturing of models that are composed by 3d graphics processing programs such as 3D Studio, Maya, AutoCAD, CATIA, etc., in robotic milling station is subjected. The prepared software processes the model files in the ".3ds" format and generates applicable path data for the most common robot brands. The output of the prepared program was evaluated on the IRB 1600-8/145 series robot by ABB Robot Studio software and the success and applicability of the development was demonstrated.

In the following section, the definition of the problem and the current situation will be detailed. In the next section, basic objectives are mentioned and the proposed method is introduced. In this section, a sample application is given and the necessary steps of the process are pointed.

2. Definition Of The Problem

With the development of technology, CNC machines are rapidly taking the place of manual controlled machine tools. The production stages with the CNC machines are not completely independent of operator performance even though mass production is a big demand. In this process not only the geometry of the process part is considered but also shape of tooling, speed, machining depth should be taken into account. Due to the gantry structure of CNCs, their rigidity is excessive and not flexible. The path error is very small in surface treatment applications that require high power. Even if 5-axis CNCs are preferred due to the Cartesian geometry, there are access difficulties in 3D material processing. Parts may not be machined in the desired orientation. Serial robots in the 6-axis articulated structure can be the solution to this shortcomings. The IRBs are generally controlled by the operator via manual programming devices. Precise programming at shop level is not preferred with off-line programming software. Essentially access testing is done through these programs. Because of these and similar reasons, narrow field of IRB usage can not gain wide currency. Fig. 1 shows the interfaces of the robotics CAD-CAM programs. Within these programs, the advantageous of articulated manipulators such as agility and easy access through working path in case of overlying surroundings could not return profit. Quite the contrary, their weak stiffness arise when they are programmed as the same way with CNCs.

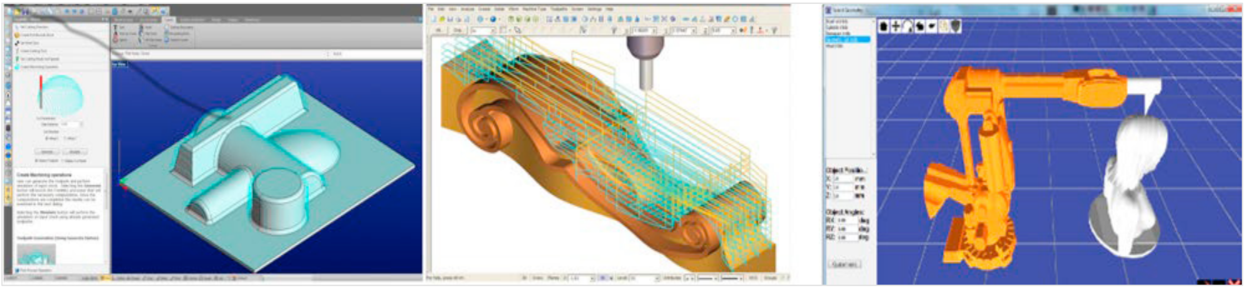

Figure 1. Robotic CAD-CAM programs, respectively Freemill [13] RobotMaster [14] and IrbCam [15]

If the cutting tool is not at the orientation in conformity with the normal direction of the surface of the work piece, the surface may not be machined to the desired quality. Stress of the manipulator over the planned path will result in an increase in follow-up errors. The body of the IRBs is generally thought to be rigid, inflexible. However, especially when positioned far away from the base point, the body will stretch away to the certain amount, as shown in Fig. 2. In this case the difference between the position found by the straightforward kinematic calculations and the actual value will increase. If there is a parameter deviation due to calibration errors already, the desired geometrical accuracy cannot be achieved for that additional effect alone.

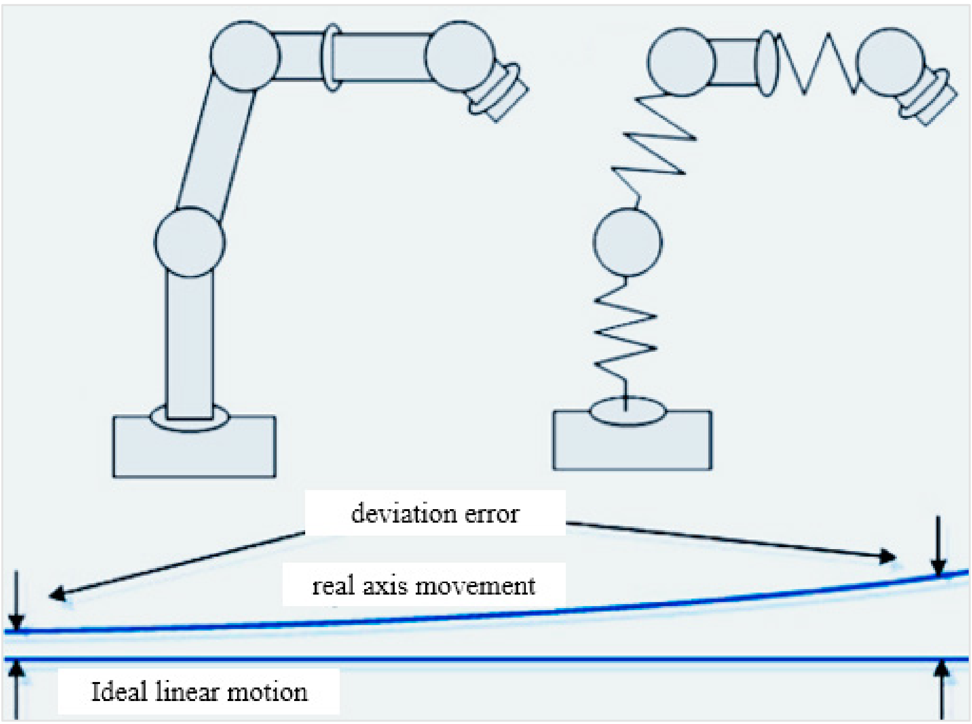

Figure 2. Illustrative robot posture and geometric problems [12]

In this study ABB IRB 1600-8/145 model is used. According to standardization ISO 9283:1998 namely manipulating industrial robots – performance criteria and related test methods, its linear path repeatability is 0.12mm, positioning accuracy is 0.42mm. Tests are done on a special linear trajectory where all axis must be moving, linear velocity is 1 m/sec and manipulator is carrying a fixed nominal load. Of course it is difficult to meet these catalog indicators. The reason of this is mostly from the dynamic forces due to velocity and posture changes along the trajectory. Interaction of the IRB with the work piece must also be considered in the surface treatment applications. Furthermore, standard calibration, without using extra equipment, positioning errors up to 6 mm can be also observed, as shown in fig. 2. This issue, which is insignificant in manual robot programming, is not known or evaluated by most programmers. When programming is done by manual point teaching method, because the reference target is the subjected teach point, positioning accuracy performance is surely high. However, when programming is done from the CAD data, calibration errors are important where the cartesian position data is processed up to the referenced coordinates located at somewhere in the external environment. Manipulators of ABB, without absolute accuracy optional package are regarded as normal with 6-10 mm positioning error, depending on the model.

3. The Purpose And The Method

As an alternative to CNC milling machines, the purpose of this work is to develop a CAD program that produces an optimal trajectory compatible with the process surface, in order to improve the tracking of the trajectory for robotic milling stations, which have recently become preferred over the last years. Using the models in ".3ds" format, developed program will be able to create robot motion commands for the robotic milling stations. For any kind of articulated arm structures of different brand industrial robots, it is available without the need for major changes. It is possible to improve the surface quality by orienting the robot cutting tools by evaluating the surface normal vector obtained from solid model information. The progressive chip removal paths will be determined by the surface normal vector considering requested path. In this way, it will be possible to process different challenging materials. Using the drawing models prepared on the computer, it is aimed to extract the path lines that will form the basis of the robot motion commands for the industrial robotic milling workstation. As a result of this work, a robotic milling station was installed. Models in 3ds file format were processed and path programs for industrial robots were created. The following functions have been carried out till now.

3.1. Organization Of The Graphical User Interface

In engineering education, when a topic related to industrial robots is being processed, a program that provides measurements of each manipulators independently of the robot brand and model has been introduced in the previous works of the author. Within this software essential linear, reorient and joint mode jogging can be performed, dynamic parameters of manipulators such as velocity, acceleration can be evaluated graphically and actions in the work space can be monitored in the screen tabs prepared with an OpenGL support. This program is coded in C++ by including Fox- Toolkit library which is an operating system and platform independent. Because the users are authorized to change link lengths by using interactive widgets, innovative designs can be created. Also limits of joint angles can be defined so as to visualize the manipulator's reach space.

The program shown in fig. 3 has the following basic features. Different interaction widgets and tabs for textual information, configuration alteration, limit redefinition, work space visualizing the reaching distance and graphic plotting exist together. Developed software's dynamic interaction widgets allows users to get inside the real robotic station in virtual reality. Just as many industrial robots commanding device, depending on the pulling rate of sliders, velocity of the joints and the robot's tool center point (TCP) changes proportionally. Manipulating the body can be done through the selected pattern such as joint, linear and orientation motions. With the help of this tab, user can move in the desired motion type. During these movements, angles of the joints and the position of the each links ends relative to arbitrary reference coordinates can be followed. TCP orientation information is also presented in this tab. It is also possible to manipulate graphic models by using relocation, reorientation and scaling options. Depending on the communication selection widgets, after confirming the safety rules, within a direct ethernet connection or via PLC bridge through the IRB, physically installed station can be observed and commanded.

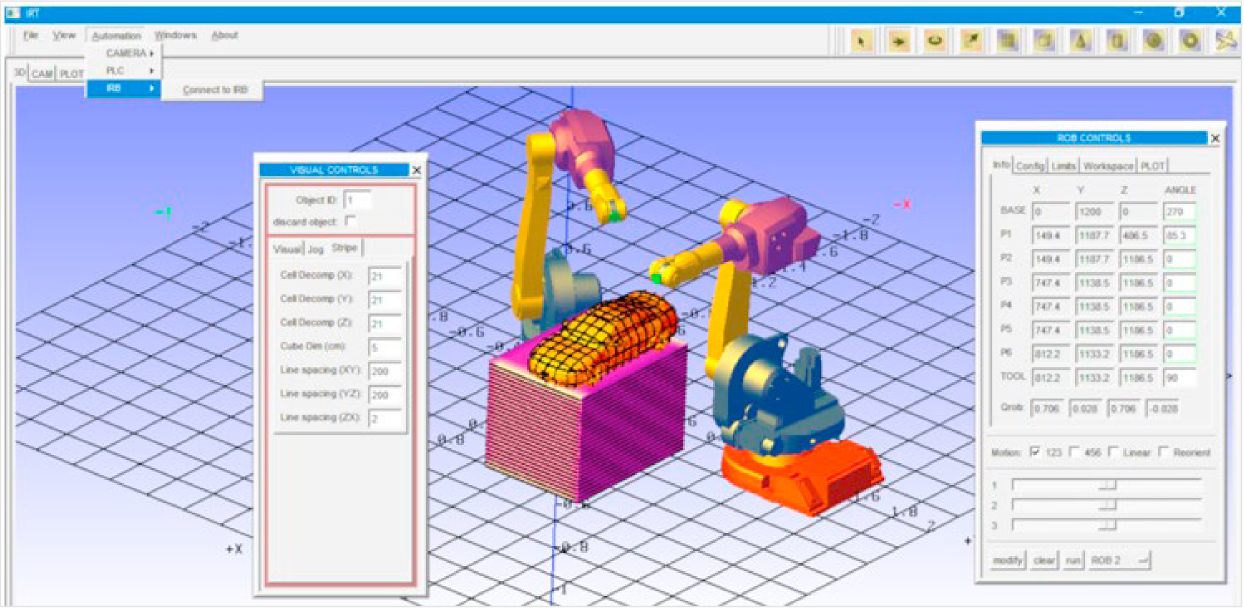

Figure 3. Overview of Developed Interface Program

3.2. Model Processing

In machining, the entire model is mostly not machined in a single pass. The most important reason for this is the need to remove too much material, depending on the geometry of the part to be machined. In this case, the bench is exposed to excessive force. Tooling wears out earlier. It is also possible that the process material is damaged. Of course, it is also very difficult to obtain the desired surface quality with only one pass. For this reason, it is preferable to reduce the size of the working block before reaching the target surface. This makes it possible to use more suitable rough tooling in the first pass and more precise tooling in the second pass. Basically two choices can be made for the coarse model. The scaling shown in fig. 4 is not the solution if it comes to mind first. In the case of scaling, the distance between the expanded model and the original model will be proportional to the geometric position. As a result of the scaling, the sharpness, the details will be preserved exactly. And the worse, it will be seen when concerned to the figure, that the enlarged model does not cover the basic drawing.

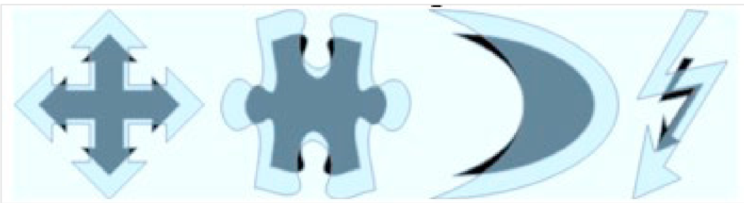

Figure 4. Scaling for larger rough models

The first possible solution is enlarging the model upon the source model in line with its surface directions as shown in fig. 5. This is not thought as scaling. It is the expansion of the desired pattern to a predetermined amount of distance. To make this manipulation, the model points have been extended by the average of the normal of their surface patches. Of course for edges of neighboring patches should be considered for smoothness reservations.

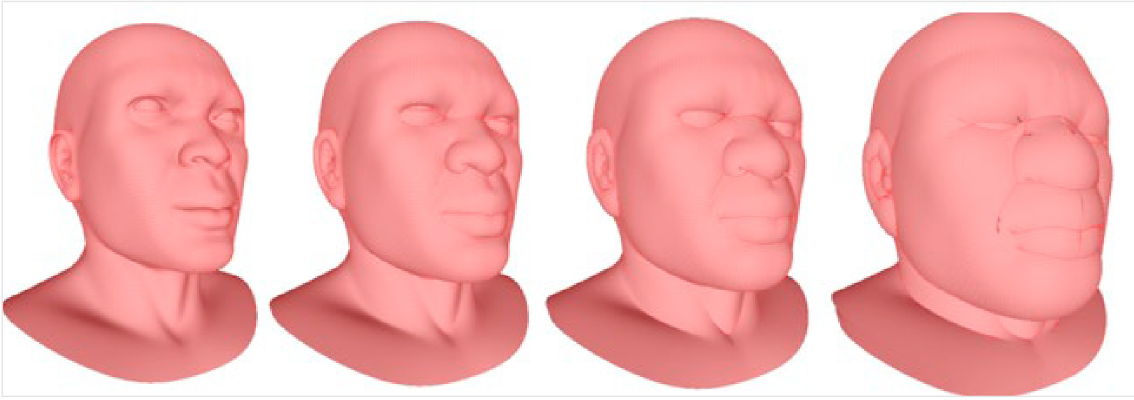

Figure 5. Enlargement of the model along the normal direction of the surface

The second alternative is presented in fig. 6. In this case, the coarse model was formed by dividing the working space into cells with predefined dimensions. Among all cells, those include the model vertex are marked as border. Respect to the center picture, it will be seen that the patches that make up the model can be very wide at some points. The method described roughly in the previous sentence will not work in this case. In this study, to deal with the mentioned problem, the arrangement shown at the far right is made. Additional points at equal distances on the surface were obtained and checked to see if the cells contained these points. Separation into cells should also be done for an additional purpose subjected the solid models. Models usually consist of sub-parts. Some of these parts will remain under the main structure after the surface is meshed. The lines passing through the remaining inside points must be canceled. This refinement process can be done by selecting border cells.

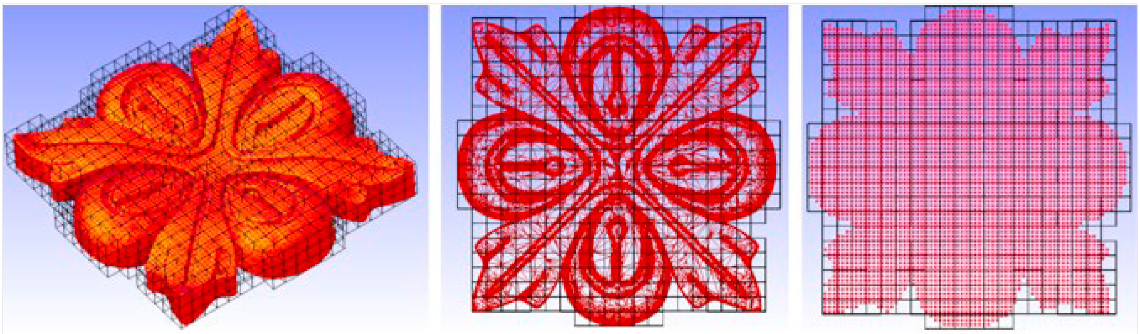

Figure 6. Rough model created by cell decomposition

3.3. The Workpiece Positioning

The workspace of industrial robots in articulated structure is not in canonical forms. Due to the rigid structure of the robot, there are areas in the interior that cannot been reached. It is difficult to envisage this volume as experiential or intuitive. For this reason, visualization option presented in fig. 7 is included in the developed software. For certain scan angles, the positions of TCP in the workspace are marked. The most suitable volume for access can be determined on this count. The robot will not make very high speed and accelerated movements in the machining process. Also, when the appropriate processing speed is selected, there will be no additional forces. When the dynamic model is evaluated it is known that the dominant force in this case is the gravity. For this reason, it is better to place the manipulator, which is slightly less stiff than the CNCs, near the base of the robot as much as possible in order to remove the positional errors of the manipulator.

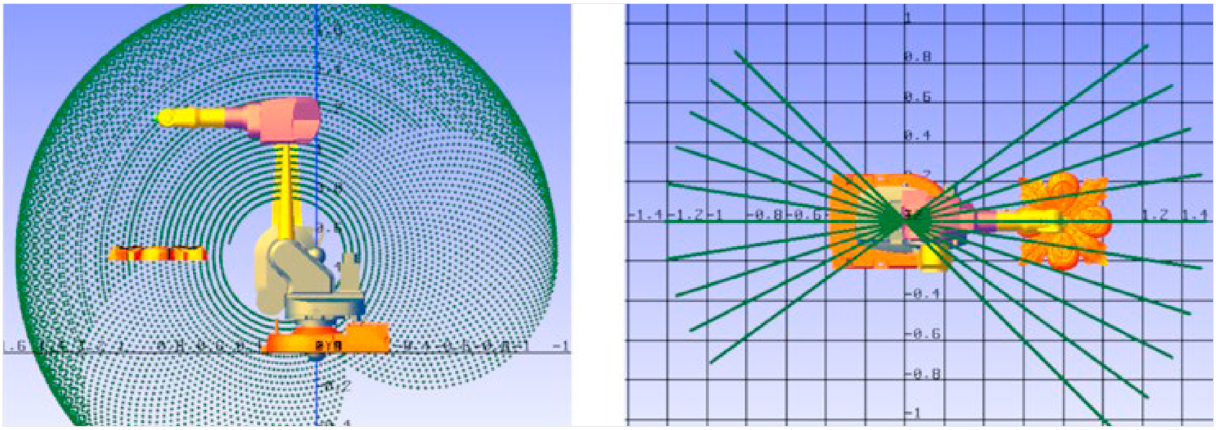

Figure 7. Selecting the optimum position in the workspace.

3.4. The Derivation Of The Machining Paths

Directional paths are show in fig. 8. These paths are composed by attaching short line segments. Segments are obtained by calculating the intersection lines of triangular patches forming the surface meshes with plane sections taken at xy, xz and yz planes. The point defining the path segments are the target position for robot. Robot target information includes also the orientation at these points. Orientation is the calculated direction of the normal vectors of the triangle patches. Of course these orientation needs to be interpreted to quaternion representation for ABB's robot programs. In the 3- 5 axis CNC workbenches, this direction information is not used and generally the cross-sectional plane, mostly the XY plane is used for machining and the direction is assumed to be unchanged. In the proposed software, the cross-sectional plane that is essential for scanning should not be twist with the robot orientation. The orientation obtained for segment endings are calculated from the belonging surface normal and independent from the cross-sectional plane.

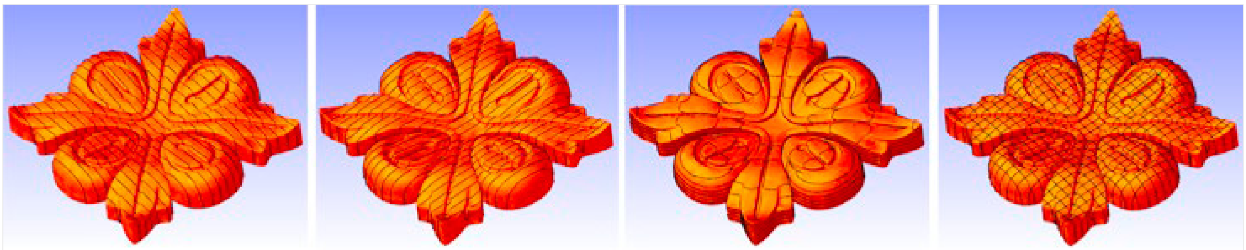

Figure 8. Deriving the screening lines from the surface meshes.

There are two other important steps between the creation of the scan lines and the creation of the path for the IRB. The segments are obtained from the surface patches and evaluated as a straight line with the two known end points. In computer drawings, patches are not at the specific order. Therefore, it is necessary to create a long path by adding the correct parts in succession. There are some special cases where segments are not co-boundary, the next segment may not start just end of the previous one as shown on the left side of fig. 9. Also, when the models are examined closely on the computer, it can be seen that there may be small apertures between the meshes. After the parts are attached together to form a parallel scanning lines, each single line are first needs to be extended towards the boundaries and then joined together into a single path. In order to increase the surface quality, the cross-sectional surfaces are combined to form the final processing path as shown in Fig. 10.

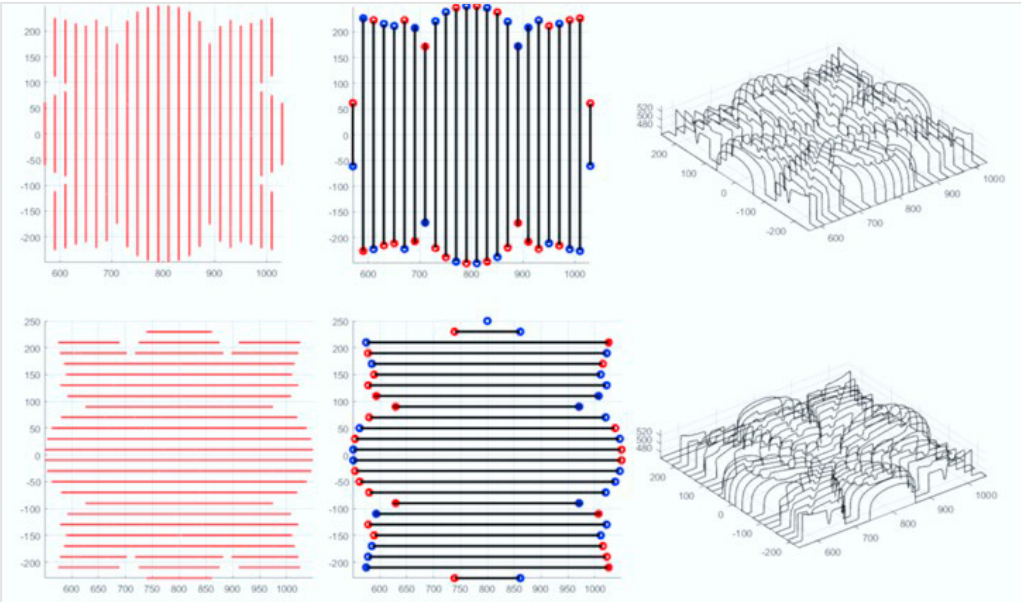

Figure 9. Linear justification of the path segments.

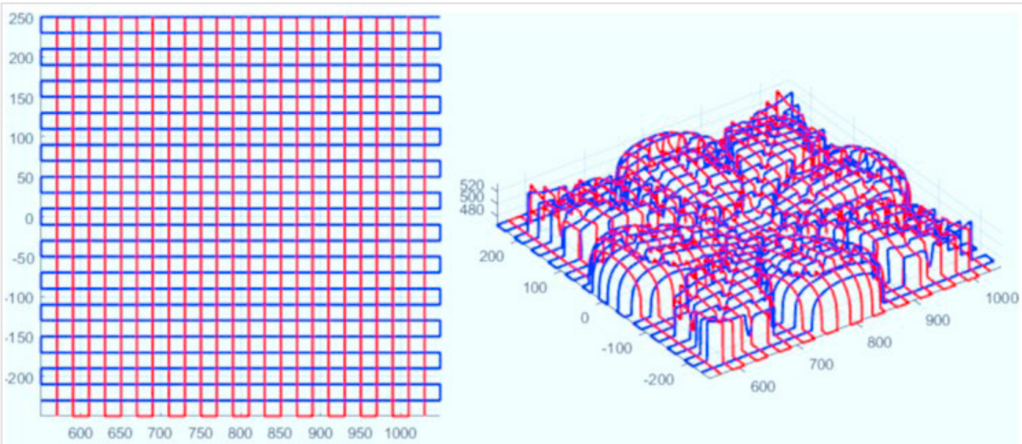

Figure 10. Merging the scan lines.

3.5. Interpretation Of The Representative Points For IRB Motion Commands

Up to this stage, the machining paths are extracted, which the positions and orientations of the points on them are known. It is now possible to determine whether these roads are feasible. Even though the placement of the parts is done diligently in the work space, access problems can also be experienced. The position specified in the desired orientation can not be reached. The existence of inverse kinematic solutions along the entire line should be investigated for this. Almost all commercial IRBs have the option of linear movement between the two positions. In the ABB Rapid language, The MoveJ command is used for joint motion and the MoveL is defined for linear motion. The position parameters of these commands are the axis angles defined by the JoinTarget variable name and the position and orientation values defined as RobTarget. It should also be kept in mind that the linear motion is implemented as joint movement by interpolation the straight segments into small intervals. The obtained target position datas were transferred to the IRB program as shown in Fig. 11. The access and collision tests were then performed.

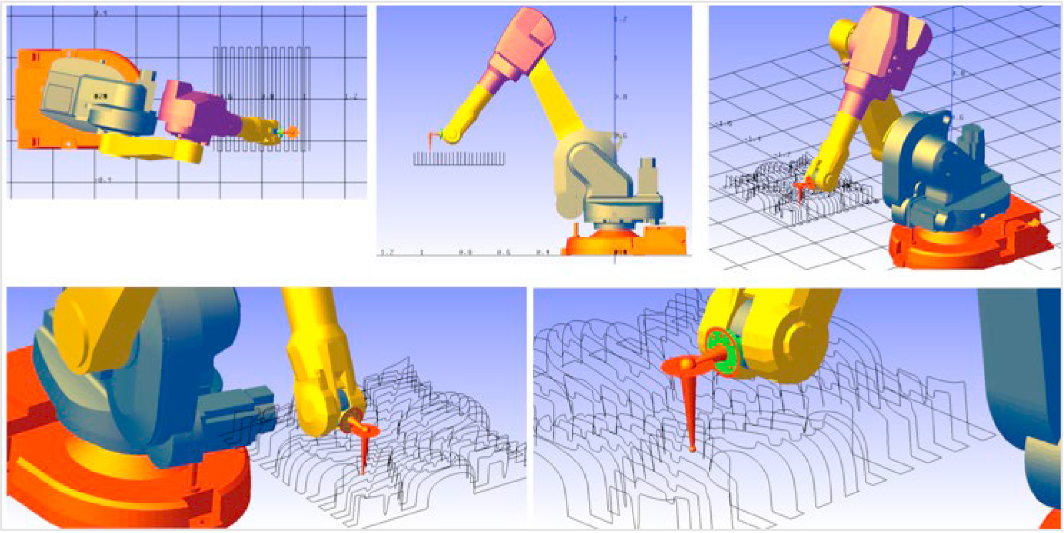

Figure 11. Robot access control.

3.6. Applicability Tests With The Commercial Off-Line Programming Software

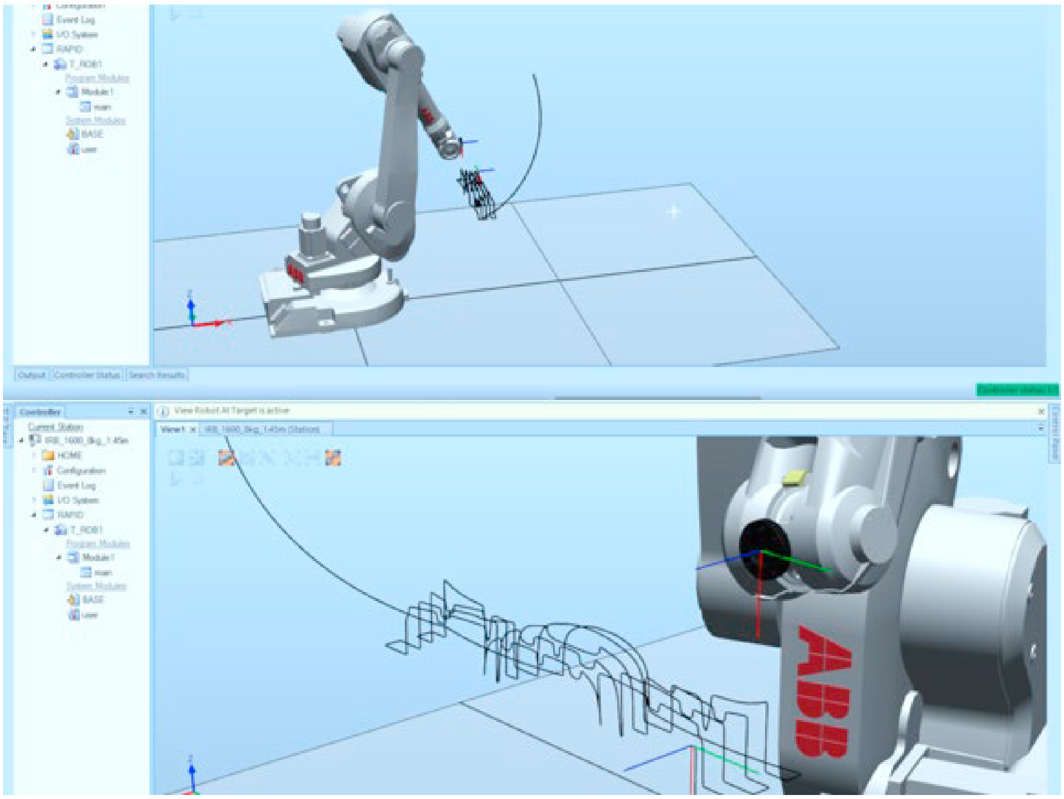

Figure 12. The conventional analysis of the robotic stations with ABB Robot Studio.

In this step, the IRB program which can be executed by the ABB robots is tested by transferring it to ABB Robot Studio software and the snapshots in fig. 12 are created. The prepared program should not be confused with the commercial software which is now the testing environment. By the proposed software, it is possible to obtain path points defined as targets for robots from computer drawings. In commercial software, however, this feature is not available. The purpose of this test is to check whether the output obtained is feasible or not, without the need for physical installation. As already mentioned, the difference in the distances between linear and joint motion at small intervals are very small. Motion may not be performed in the linear motion lines due to the orientation restriction. For this reason, as shown in the upper figure in fig. 12, joint motion is preferred. The paths have not been simplified yet. The line in the bottom picture is 10% of the total length, and the part up to here has 2000 lines of motion command. For this very frequent sampled path, there is no adverse effect of joint motion.

4. Conclusion

In this study, a new robotic milling software which creates 3D graphics models is presented. It is aimed to automatically generate paths for the robot machining tool in milling applications. The software was tested as real-time and compared with the commercial ones. Commercial software has been approved for replacement. There are also some parameters having in the software that need to be changed by the operators for milling applications. As a result, a fully automated process has not been developed. The cutting speed geometry, machining depths, machining depths, etc, needs to be developed. But, it is aimed to achieve full automatic process in the next studies.

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