CONSIDERATIONS REGARDING CAM TECHNIQUES FOR ROBOT MILLING

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ABSTRACT: Robotic milling is considered as an alternative solution for CNC milling. However, there are significant differences between these two processes. The work presented in this paper tackles some specific aspects regarding the CAM techniques used for robotic milling. The main types of parts which could be machined and the main methods of obtaining the 3D models of the machined parts are synthesized. Technological solutions from KUKA company, which was specifically developed for robotic milling are introduced. Finally, a case study of applying CAM techniques for milling a part with sculptural surfaces by means of a KUKA robot is presented.

KEY WORDS: CAM, industrial robots, milling.

1 INTRODUCTION

Until recently, industrial robots were mainly seen as equipment for pick-and-place tasks, such as handling, assembling, point welding and/or painting. However, due to the development of both CAD/CAM software solutions and robotic controllers' capabilities, machining operations, which require continuous path control (instead of point to-point control) can now be unfolded by means of industrial robots. Among these operations, milling is the most important one, but other operations are also considered, such as deburring.

Many authors (Chen & Dong, 2013, Lehman et al., 2012), based upon literature surveys and white papers issued by The Robotic Industries Association, consider that robot milling could be considered as an alternative for CNC milling, even if the accuracy of the machined parts is lower, mainly due the reduced rigidity of the robotic structures. Due to this fact, non-metallic materials or low hardness metals could are recommended for robotic milling. However, some methods for improving the accuracy of robotic milling when hard materials are machined are reported in the literature (Lehman et al., 2012, Abele, 2012, Halbauer et al., 2013). To improve the stiffness of the robotic structure, modeling and identification of the robotic structure was proposed (Abele, 2007). Robotic milling is also seen by many users as a solution for machining parts with sculptured surfaces (Chen & Hu, 1999).

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High speed machining (HSM) applied to robotic milling, mainly for aluminum alloys, was also taken into consideration by some research works (Coelho et al., 2011).

The energy efficiency of robotic systems used for machining tasks was also studied, to find the most recommended cutting parameters and the most energy-efficient toolpaths (Uhlmann, 2016).

2 PARTS MACHINED BY ROBOTIC MILLING

A synthesis regarding the parts machined by robotic milling is presented in figure 1. The shapes of the parts which could be machined by robotic milling can be divided into analytic and sculptural.

Analytic shapes (fig. 2) are specific for machine building industry and the 3D models of the parts are usually obtained by means of parametric modeling using specific CAD software packages. Machining the parts from figure 2 by means of robotic milling could be justified by several reasons.

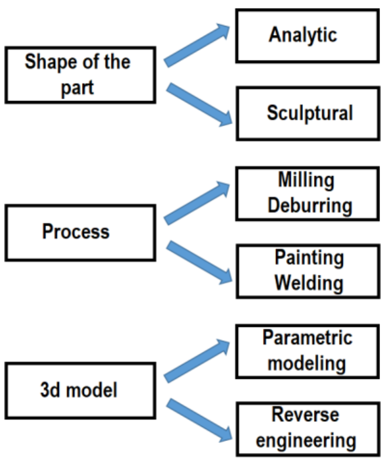


Figure 1. Parts and processes

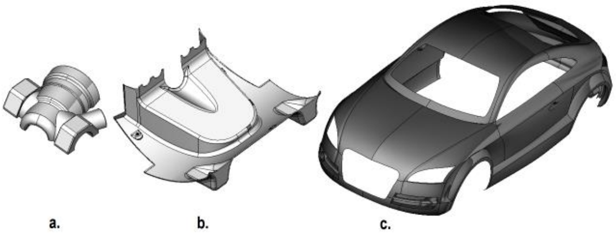


Figure 2. Parts with analytic shapes

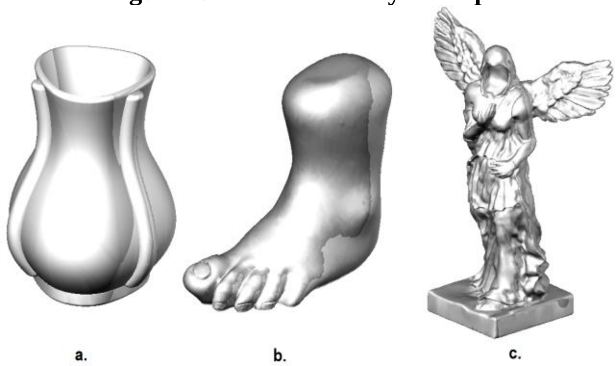


Figure 3. Parts with sculptural shapes

The part form figure 2a could be machined either by CNC milling or robot milling, depending on the required accuracy. The part from figure 2b is a complex car body element, with large overall dimensions. The machining process required by this part is deburring, and due the complex toolpaths and the large dimensions of the part, industrial robots are the most recommended technological equipment for the task. The part from figure 2c is a full car body which need either complex welding operations or painting, both requiring the end-effector (working head) to follow complex toolpaths. These requirements can be also fulfilled by using industrial robots as technological equipment.

The parts from figure 3 have sculptural shapes and are specific for artistic purposes as decorative elements and/or statues. The 3D models of these type of parts are mostly obtained by reverse engineering techniques, such as 3D scanning.

The part form figure 3a (https://grabcad.com) is recommended to be machined by robot milling due its relatively high overall dimensions. Machining this part is quite straight forward due its relatively simple consisting of revolution surfaces. The part from figure 3b (https://grabcad.com) has large overall dimensions and the machining complexity could be considered as medium according the complexity of its surfaces. The part from figure 3c (https://www.thingiverse.com) has both big overall dimensions and very complex shapes, while the required tolerances are quite low, making it suitable for robotic milling.

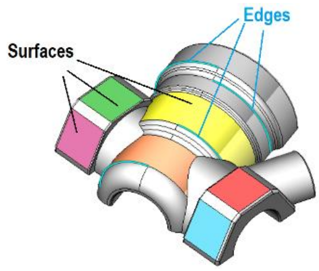


Figure 4. Parts file in iges and/or step formats

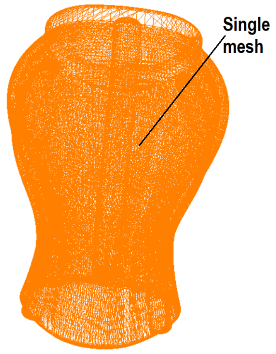


Figure 5. Part file in stl format

3D models for parts with analytic shapes are obtained by analytic modeling using CAD programs and are usually exported in neutral formats such as to be processed by CAM software packages. Among these formats, the most advantageous are iges (igs) and step (stp) (fig. 4), allowing the machining engineer to select geometrical entities of the model, such as surfaces and edges, which leads to a greater control of the machining process.

3D models for parts with sculptural shapes are obtained by 3D scanning and finally saved to the stl format to be processed by CAM software. The control of the machining process for stl files (fig. 5) is usually more complicated, because the whole part is represented by a single mesh, making difficult to assign limited machining areas.

3 TECHNOLOGICAL EQUIPMENT

There are many companies, worldwide, which manufacture industrial robots, such as ABB, Comau, Fanuc, Kawasaki, KUKA, Motoman, Nachi, Staubli. Some of them started to develop specific solutions for robotic milling, by adapting existing robotic structures and equipping them with additional modules (1-2 axes rotational positioning modules, milling units and tools magazines). Among these solutions, KUKA has developed the QUANTEC series, which are specifically developed for machining tasks. The QUANTEC robots are based upon the six axes KUKA serial kinematic structure (fig. 6, source KUKA download center), but having greater power density, reach and payload compared with other KUKA robots.

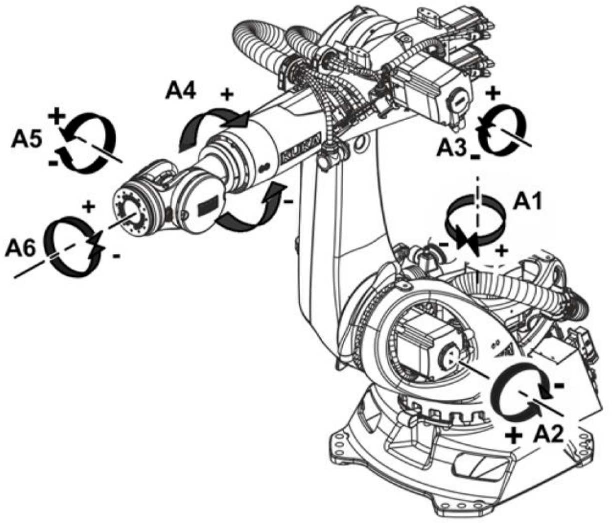


Figure 6. KUKA six axes serial robotic structure (source KUKA AG company website)

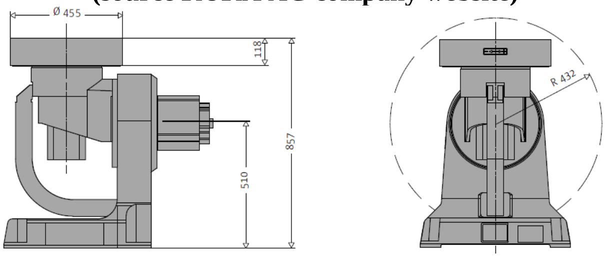


Figure 7. KUKA DKP 400 positioning unit (source KUKA AG company website)

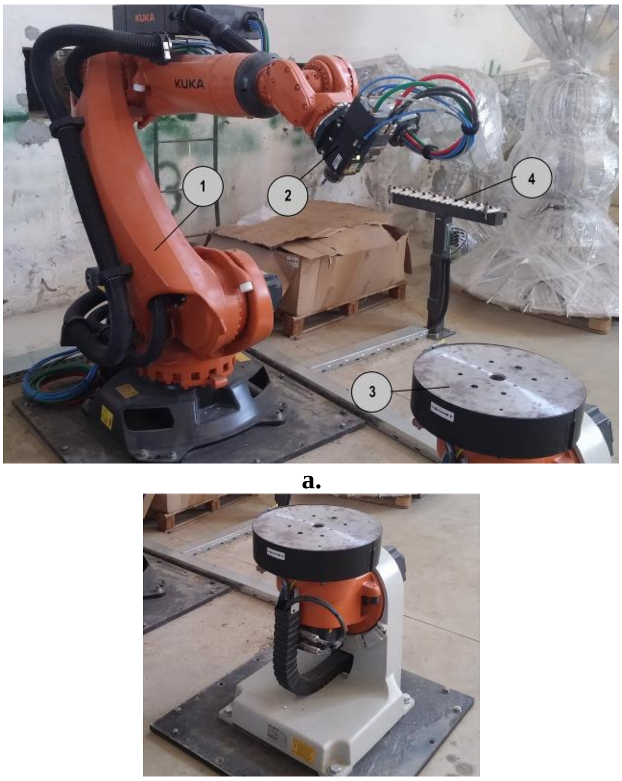
To extend the kinematic capabilities of the KUKA QUANTEC robots, the company has developed positioning units with 1-2 axes. The DKP 400 unit (fig. 7) is equipped with two external axes, a rotational axis (0° ÷ 360° range) and a tilting axis (-90°÷90° range).

By combining the KUKA QUANTEC robotic structures with milling units, positioning units and tools magazines, robotic machining cells can be structured.

Figure 8 presents a robotic machining cell, used mostly for milling operations, made up from the following modules:

- KUKA KR 210 R2700 extra robot (1);
- HSD ES 350L milling unit (2);
- DKP 400 positioning unit (3);
- tools magazine (4).

The robotic machining cell is in the endowment of the company MK Illumination S.R.L. (http://www.mk-illumination.ro), from Hunedoara, which uses it for machining mostly parts for artistic purposes (parts with sculptural shapes). Most of the machined parts have great overall dimensions, justified by the reach of the KR 210 R2700 robot, the most important geometric characteristic, of 2696 mm



a.

b.

Figure 8. Robotic machining cell (a), detail with DKP 400 positioning unit (b) (from MK Illumination S.R.L. company)

4 CAM SOFTWARE SOLUTIONS

Most of the commercially available general-purpose CAM software packages (Delcam, Mastercam, Mecsoft Visual Mill, NX CAM, SprutCAM, ZW3D) include modules for robotic milling. Usually, these modules generate the paths for the robot end-effector and the CL data file(s), based upon the 3D model of the machined part and the kinematics of the robotic structure.

These modules are able to simulate the machining process, to interactively control the positions of the robotic structure and to control external axes (from external positioning units such as DKP 400). Some of them have also the ability of solving problems related with singularities, collisions and/or reach limitations, which are specific to robot machining.

There are also on the market software solutions which target specifically robot machining, such as Robotmaster, which presents itself as CAD/CAM for robots.

The main problem of all CAM solutions from the market, yet to be solved, is that they do not take into consideration the dynamic properties of the robot structures, which, in contrast to CNC machine tools dynamics, heavily influences the machining accuracy.

Most of the authors (Chen & Dong, 2013) consider that even there are considerable similarities between CNC machine-tools programming and industrial robot programming, these two activities should not be considered similar. However, for the time being, robot path planning based upon robot kinematic is widely used by CAM solutions and consequently considered as industrial standard for programming robotic milling applications. Neither software packages specialized for robots (Robotmaster) do not take into consideration the dynamic features of the robotic structures used for machining tasks.

Academic research (Duma et al., 2011, Xiao et al., 2011, Chen, Yau & Lin, 2012) was also focused lately on developing software solutions for robot continuous path planning, tackling also the problems of the influence of the robot dynamic upon the machining accuracy, however, these researches have not yet issued solutions for commercial implementation.

5 CASE STUDY

In the following section, a case study regarding the simulated machining process of a part with sculptural shapes using CAM techniques on the machining cell presented in the previous paragraph will be presented. A commercially available general-purpose CAM solution, SprutCAM, was used for this approach. As presented in the second paragraph (fig. 3b), the part could be considered as medium complex, because it has sculptural shapes, while the 3D model was obtained by means of 3D scanning (stl file format).

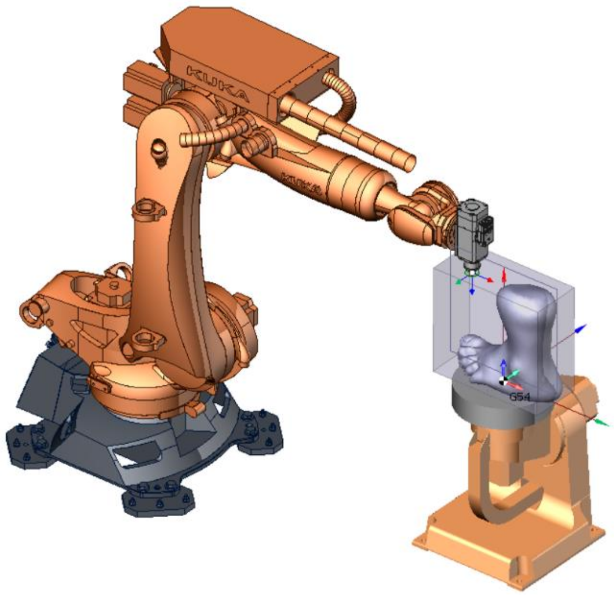


Figure 9. 3D model of the robotic cell, workpiece and machined part

The 3D models of the robotic cell, machined part and the workpiece is presented in figure 9. A box shaped workpiece was considered. The integration of the 3D model of the robot and its kinematic within the CAM software was presented in some previous papers (Bologa et al., 2015, Chicea et al., 2015).

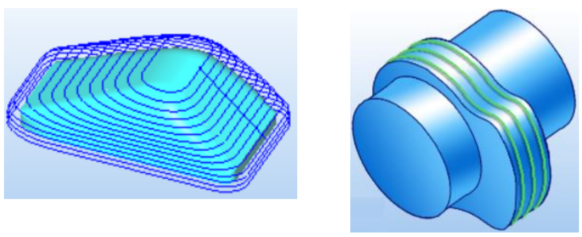
Due to the shape of the part, corroborated with the robotic structure reach, two machining strategy were used:

- Roughing waterline;
- Rotary machining.

Waterline roughing strategy (fig. 10a) implies the removal of stock material of a workpiece, which lies outside the 3D model. Milling is performed by using movements of the tool in successive horizontal (XY) planes. The shape of the area for machining at each Z-level is formed from curves created by intersecting the part with horizontal (XY) planes. This machining strategy is often used for primary rough machining of complex models, which have considerable geometrical difference to the workpiece.

Rotary machining strategy (fig. 10 b) is a 4-axis toolpath that removes the workpiece material layer by layer. It is similar to the roughing waterline strategy, except that the machining layers are not planes, but cylinders around the rotary axis. The rotary machining operation is used for the machining of the camshafts, crankshafts, worm shafts, paddles, decorate parts and so on. This operation can be used if the machine has at least one continuous rotary axis.

Due to the reach limitations of the KUKA KR 210 R2700 extra robot, the roughing waterline operation was divided into two separate operations, using an indexing movement of the part, by means of the DKP 400 positioning movement. Consequently, the first roughing operation was unfolded for 0° orientation (fig. 11a) of the part, while the second roughing operation was unfolded for 180° orientation of the part (fig. 11b).



a. **b.**

Figure 10. Roughing waterline strategy (a); rotary machining strategy (b)

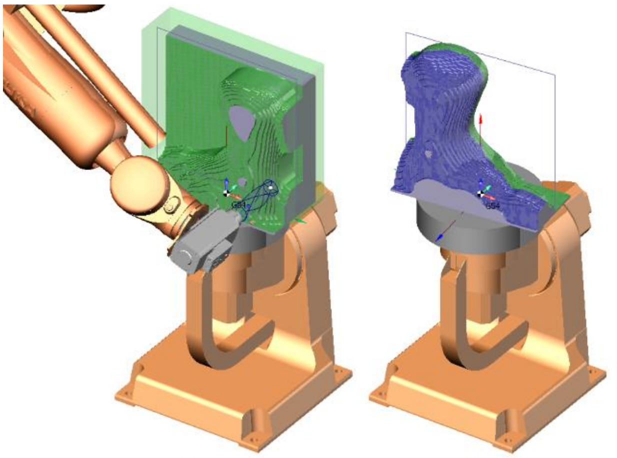
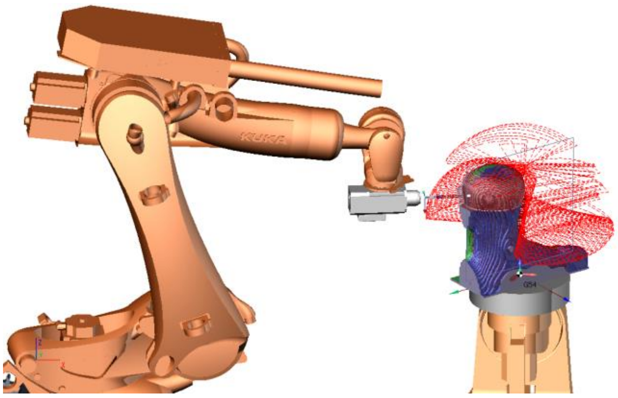


Figure 11. Roughing waterline strategy at 0°(a); and at 180° (b)

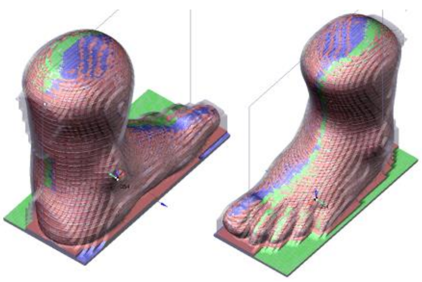
For both roughing waterline operations, a 63-mm diameter cylindrical mill was used as cutting tool, while the overall dimensions of the workpiece were 543 × 590 × 263 mm. A spherical mill of 12-mm diameter was used for the rotary machining operations.

The rotary machining operation was unfolded using the Z-axis of the WCS coordinate system as rotary axis. The trajectory was a spiral one, with a vertical step of 50% from the tool diameter (6 mm).

Figure 12a presents a screenshot taken during the simulation of the rotary machining operations (the toolpaths are also depicted in the figure), while figure 12b presents the final part.



a.



b.

Figure 12. Screenshot from rotary machining simulation(a); final part (b)

A short fragment of the generated code (src file) is presented below:

…………………………………………….…………..

```
$VEL.CP=0.167
LIN {X -424.077, Y -64.77, Z 224.507, A 98.842, B 89.906, C 90.002} C_DIS
LIN {X -422.98, Y -68.737, Z 220.356, A -81.158, B 89.773, C -90.001, E2 -19160.21} C_DIS
LIN {X -422.065, Y -72.601, Z 218.136, A -81.158, B 89.466, C -90, E2 -19171.99} C_DIS
LIN {X -421.362, Y -76.444, Z 217.932, A -81.158, B 89.163, C -90, E2 -19183.77} C_DIS
```

…………………………………………….…………..

It can be noticed that the code includes geometrical information with regards of the end-effector (tip of the tool – X, Y, Z and A, B, C) and the angle of supplementary axis E2 (the rotation axis of DKP 400 module).

By using the DKP 400 external module, the machining time was reduced (in any combinations of machining strategy) with at least 25%.

Moreover, without the use of the two supplementary external axes provided by the DKP 400 positioning unit, the automatic run of the machining strategies leads every time to singularities and collisions, which had to be removed manually by the user (a long and cumbersome process), or by means of a very expensive additional software module (Advanced Robotics).

Consequently, it can be stated that external modules added to robotic machining cells can dramatically improve the efficiency of the milling process, both in terms of time and costs. Also, it is noticeable that both robot manufacturers and software developers had understood and accepted the fact that industrial robots are nowadays well-suited for machining tasks, providing specialized tools for them (complete robotic machining cells and dedicated CAM modules).

6 CONCLUDING REMARKS

The work presented in this paper tried to synthesize some aspects regarding the use of industrial robots for machining applications. Shape of the parts, formats of the 3D model files, technological equipment and CAM software packages were considered. Finally, a case study emphasizing the main CAM techniques used for machining a part with sculptural shapes was presented.

7 ACKNOWLEDGEMENTS

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9 NOTATION

The following symbols are used in this paper:
CAD = computer aided design;
CAM = computer aided manufacturing/computer automated machining;
iges/igs = initial graphics exchange specification;
step/stp = standard for the exchange of product;
stl = standard tessellation language;
CL data = cutter location data;
CNC = computer numerical control;
WCS = world coordinate system.