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MACHINING ROBOT CONTROLED AND PROGRAMMED AS A MACHINE TOOL

Milutinovic D. [1], **Glavonjic M.** [2], **Slavkovic N.** [3], **Kokotovic B.** [4],
Milutinovic M. [5], **Zivanovic S.** [6], **Dimic Z.** [7]

Summary: *Industrial robots are promising cost-effective and flexible alternative for certain multi-axis milling applications. The paper describes machining robot for complex parts of light materials with lower tolerances having freeform surfaces. For the experimental configuration of a 5-axis machining robot modelling approach and prototype of developed control system with programming in G-code are shown. The experimental prototype of low-cost control and programming system has been verified by successful machining of several test work pieces of light materials.*

Key words: *Robot modelling, Control and programming system, Machining*

1. INTRODUCTION

Industrial robots are promising cost-effective and flexible alternative for certain multi-axis milling applications. Compared to machine tools, industrial robots are cheaper and more flexible with potentially larger workspace. For these reasons, the researchers, robot and CAM software manufacturers as well as people from machining shops are enthusiastic to replace machine tools by robots for some machining applications. These include milling materials, such as clay, foam, wax etc. for new product design, styling and rapid prototyping projects. Robotic machining of work pieces of traditional materials, such as wood, stone, aluminum etc. in which dimensional tolerances are low or even middle also produce satisfactory results [1,2,3]. It is well known that poor accuracy, stiffness and complexity of programming are the most important limiting factors for wider adoption of robotic machining in machine shops [1,4,5].

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[1] prof dr Dragan Milutinović, University of Belgrade, Faculty of Mechanical Engineering, dmilutinovic@mas.bg.ac.rs
[2] prof dr Miloš Glavonjić, University of Belgrade, Faculty of Mechanical Engineering, mglavonjic@mas.bg.ac.rs
[3] Nikola Slavković, University of Belgrade, Faculty of Mechanical Engineering, nslavkovic@mas.bg.ac.rs
[4] Branko Kokotović, University of Belgrade, Faculty of Mechanical Engineering, bkokotovic@mas.bg.ac.rs
[5] Milan Milutinović, Tehnikum Taurunum - High Engineering School Vocational Studies, mmilutinovic@gavrogroup.rs
[6] dr Saša Živanović, University of Belgrade, Faculty of Mechanical Engineering, szivanovic@mas.bg.ac.rs
[7] Zoran Dimic, LOLA Institute, Belgrade, zoran.dimic@li.rs

In order to contribute to efficient use of robots for machining applications, research and development of reconfigurable robotic machining system were initiated [6,7]. The research and development comprise two groups of problems. The first relates to the realization of a specialized 5-axis vertical articulated machining robot with integrated motor spindle in order to improve robotic machining accuracy. The second refers to the development of the machining robot control and programming system which can be directly used by CNC machine tool programmers and operators [8].

This paper describes the concept of machining robot for complex parts of light materials with lower tolerances. For the experimental configuration of a 5-axis machining robot, the modeling approach and prototype of developed low-cost control system with programming in G-code are shown. The experimental prototype of control and programming system has been verified by successful machining of several test work pieces.

2. CONCEPT OF THE MACHINING ROBOT

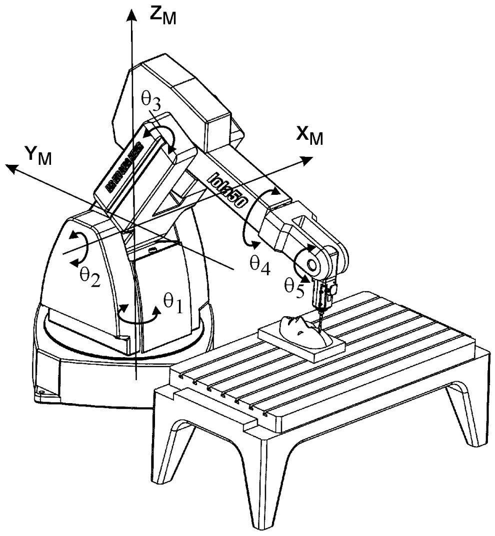


Fig. 1 *Conceptual model of 5-axis machining robot*

A basic module of the proposed concept of the robotic machining system consists of a specialized 5-axis vertical articulated robot, Figure 1, with integrated motor spindle, similar to [9] and with larger workspace, higher payload and stiffness. Due to its advantages in respect of stiffness [1] and singularities [10], such robot would operate as a specific vertical 5-axis milling machine (X, Y, Z, A, B) spindle-tilting type [11]. In addition to the mechanical structure shown in Figure 1, whose realization is in progress, the concept of this machining robot is based on:

- Low-cost control system based on PC real-time Linux platform and EMC2 (Enhanced Machine Control) software system [12,13] with programming in G-code;
- The possibilities of using the existing CAD/CAM systems and reverse engineering methods with implemented 3- to 5-axis machining for vertical milling machines (X, Y, Z, A, B) spindle-tilting type;
- Virtual machining robot configured in object-oriented programming language Python implemented in the control system for program simulation and verification.

As it can be inferred the basic idea of developing the control and programming system is that it should be a low-cost system directly applicable in machine shops by the personnel experienced in CNC technology and programming in G-code that is still widespread in industry [14]. For the development of experimental prototype of low-cost control system with programming in G-code, a 6-axis vertical articulated robot with payload of 50kg, Figure 2, was used as a testbed in a way that the sixth axis was blocked. The robot is equipped with high speed motor spindle with maximum speed of 18000 min^{-1}.

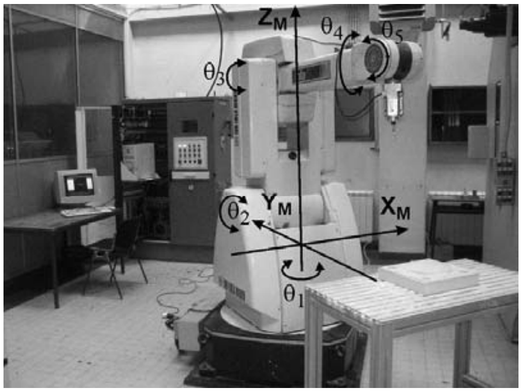


Fig. 2 *The experimental 5-axis machining robot in reference position*

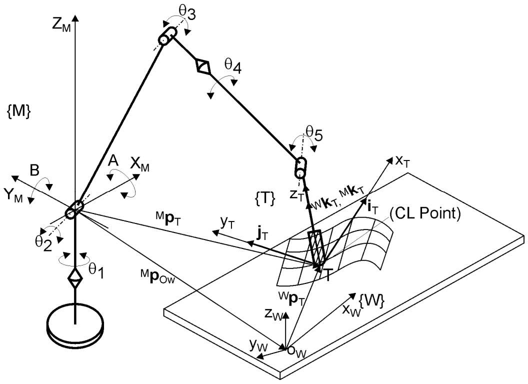


Fig. 3 *Tool position and orientation in robot reference frame {M} and work piece frame {W}*

3. MODELING APPROACH

As it was mentioned, the experimental 5-axis machining robot from Figure 2, will be considered in this paper as a specific configuration of the 5-axis vertical milling machine (X, Y, Z, A, B) spindle-tilting type [11]. Figure 3 represents a geometric model of the robot.

The robot reference frame {M} has been adopted according to the standard of this machine type [15]. The tool frame {T} is attached to the milling tool tip T in a way that axis z_T coincides with tool axis and the frame {W} is attached to the work piece. The thus configured machining robot, where machining is performed on a work table in front of the robot as well as limited motions in joints relative to the reference position allows for: taking into account only one solution of inverse kinematic, avoiding the robot singularities, conveniences related to the stiffness.

3.1 Joint and world coordinates

Joint coordinates vector for this vertical articulated robot is represented as $\boldsymbol{\theta} = [\theta_i]^T$ where $\theta_i, i = 1, 2, ..., 5$ are scalar joint variables controlled by actuators.

The description of world coordinates is based on tool path calculated by CAD/CAM systems defined by the set of successive tool positions and orientations in the work piece frame {W}, Figure 3. The thus calculated tool path is machine independent and is known as a cutter location file (CLF). A tool pose is defined by the position vector of the tool tip T in the work piece frame {W} as ${}^W\mathbf{p}_T$ and tool orientation is defined by unit vector of the tool axis as ${}^W\mathbf{k}_T$. In the general case, the tool tip position vector and tool axis vector in robot reference frame {M} can be expressed as

$$\begin{aligned} {}^M\mathbf{p}_T &= [X_M \quad Y_M \quad Z_M]^T = {}^M\mathbf{p}_{Ow} + {}^M_W R \cdot {}^W\mathbf{p}_T ; \\ {}^M\mathbf{k}_T &= [k_{Tx} \quad k_{Ty} \quad k_{Tz}]^T = {}^M_W R \cdot {}^W\mathbf{k}_T \end{aligned} \tag{1}$$

where ${}^{M}\mathbf{p}_{Ow}$ is the position vector of the origin of work piece frame {W}. Determining the position vector ${}^{M}\mathbf{p}_{Ow}$ and the orientation of the work piece frame {W} is conducted according to the standard procedure for 5-axis CNC machine tools. It should be noted that determining the orientation matrix ${}^{M}_{W}R$ in equations (1) is determined and executed later in control system without changing G-code. To complete the vector of world coordinates, it is also needed to determine the tool orientation angles A and B which define direction of tool axis z_T that also coincides with axis of the last link of the robot to which motor spindle is attached. Given that the robot has 5 DOF, only the direction of tool axis z_T is controllable, while axes x_T and y_T will have uncontrollable rotation about it. The position and orientation of the tool frame {T} relative to robot reference frame {M} can be described by homogenous coordinate transformation matrix 4x4 [16-19] as

$$ {}^{M}_{T}T = \left[\begin{array}{ccc|c} & {}^{M}_{T}R & & {}^{M}\mathbf{p}_T \\ \hline 0 & 0 & 0 & 1 \end{array}\right] = \left[\begin{array}{ccc|c} i_{Tx} & j_{Tx} & k_{Tx} & X_M \\ i_{Ty} & j_{Ty} & k_{Ty} & Y_M \\ i_{Tz} & j_{Tz} & k_{Tz} & Z_M \\ \hline 0 & 0 & 0 & 1 \end{array}\right] \tag{2} $$

where the rotation matrix ${}^{M}_{T}R$ represents the orientation, while vector ${}^{M}\mathbf{p}_T$ represents the position of the tool frame {T} with respect to the robot reference frame {M}. To bring the tool axis z_T to a desirable orientation with respect to frame {M}, the tool frame {T} must be rotated first about axis X_M by angle A, and then about axis Y_M by the angle B, as prescribed by the convention for 5-axis vertical milling machine (X, Y, Z, A, B) spindle-tilting type. As it is known, the rotation matrix ${}^{M}_{T}R$ specifying the orientation of tool axis z_T can be derived as

$$ {}^{M}_{T}R = R_{YM,B} \cdot R_{XM,A} \tag{3} $$

where $R_{XM,A}$ and $R_{YM,B}$ represents basic rotation matrices [17]. Using the equations (2) and (3) the angles A and B are determined as

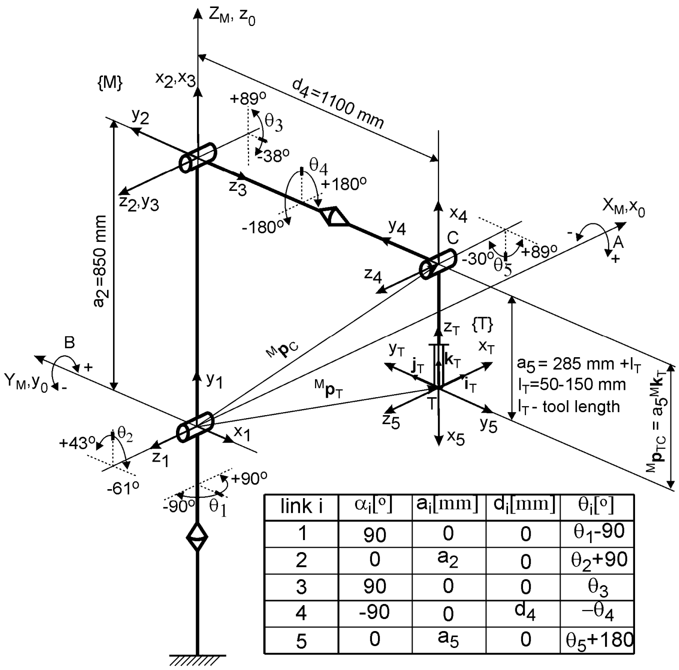
$$ A = A\tan 2(-k_{Ty}, \sqrt{1-k_{Ty}^2}) \qquad \text{and} \qquad B = A\tan 2\left(\frac{k_{Tx}}{\cos(A)}, \frac{k_{Tz}}{\cos(A)}\right) \tag{4} $$

Although for the angle A the second solution exists, by using the positive square root the single solution for which $-90° \le A \le 90°$ is always computed [11,18]. This way, the world coordinates vector can be expressed as $\mathbf{x} = [X_M \quad Y_M \quad Z_M \quad A \quad B]^T$.

3.2 Direct and inverse kinematics

To model the robot, the Denavit-Hartenberg (D-H) notation [16-18] was used. Figure 4 shows D-H coordinate frames and link kinematic parameters for the experimental 5-axis robot from Figure 2 i.e. Figure 3 in the reference position taking into account the ranges of joint motions.

Substituting D-H parameters of the links the transformation matrices ${}^{i-1}_{i}A, i=1,\ 2,\ ...,5$ are obtained first. As noticeable from Figure 4 the frame {T} can be described relative to the frame (x_5, y_5, z_5) by homogeneous transformation matrix ${}^{5}_{T}T$.



link i	α_i[°]	a_i[mm]	d_i[mm]	θ_i[°]
1	90	0	0	θ_1-90
2	0	a_2	0	θ_2+90
3	90	0	0	θ_3
4	-90	0	d_4	$-\theta_4$
5	0	a_5	0	θ_5+180

Fig. 4 *D-H link coordinate frames and kinematic parameters*

Now, as it is well-known [16-18], the tool position and orientation i.e. the position and orientation of frame {T} with respect to the robot reference frame {M}, Figure 4, for the given joint coordinates vector $\boldsymbol{\theta}$ and specified link parameters can be determined as

$$ {}^{M}_{T}T = {}^{0}_{1}A \cdot {}^{1}_{2}A \cdot {}^{2}_{3}A \cdot {}^{3}_{4}A \cdot {}^{4}_{5}A \cdot {}^{5}_{T}T \tag{5} $$

where for further consideration are of significance only

$$ \begin{aligned} k_{Tx} &= -s\theta_1 \cdot s\theta_{23} \cdot c\theta_4 \cdot c\theta_5 + c\theta_1 \cdot s\theta_4 \cdot c\theta_5 - s\theta_1 \cdot c\theta_{23} \cdot s\theta_5 \\ k_{Ty} &= c\theta_1 \cdot s\theta_{23} \cdot c\theta_4 \cdot c\theta_5 + s\theta_1 \cdot s\theta_4 \cdot c\theta_5 + c\theta_1 \cdot c\theta_{23} \cdot s\theta_5 \\ k_{Tz} &= c\theta_{23} \cdot c\theta_4 \cdot c\theta_5 - s\theta_{23} \cdot s\theta_5 \\ X_M &= -a_5 \cdot k_{Tx} + s\theta_1 \cdot (d_4 \cdot c\theta_{23} - a_2 \cdot s\theta_2) \\ Y_M &= -a_5 \cdot k_{Ty} - c\theta_1 \cdot (d_4 \cdot c\theta_{23} - a_2 \cdot s\theta_2) \\ Z_M &= -a_5 \cdot k_{Tz} + d_4 \cdot s\theta_{23} + a_2 \cdot c\theta_2 \end{aligned} \tag{6} $$

and where $\theta_{ij} = \theta_i + \theta_j$.

Through the vector ${}^{M}\mathbf{k}_T$ from equations (6) the angles *A* and *B* can be determined using equations (4). This way, the world coordinates vector has been completed i.e. direct kinematics problem is solved.

As noticeable from Figure 4, the last two joint axes z_3 and z_4 intersect at point C (wrist center). This fact and the above presented remarks and constraints make possible to consider this 5-DOF robot as a special case of 6-DOF robot with the last three joint axes intersecting at a point to which Pieper's method is applied [16,19]. As it can be concluded from Figure 4, the position of wrist center C is influenced only by joint coordinates θ_1, θ_2 *and* θ_3. For the specified world coordinates the position vector of the wrist point C can be calculated as

$$ {}^{M}\mathbf{p}_C = {}^{M}\mathbf{p}_T + {}^{M}\mathbf{p}_{TC} = {}^{M}\mathbf{p}_T + a_5 \cdot {}^{M}\mathbf{k}_T \tag{7} $$

Based on the calculated components of position vector ${}^{M}\mathbf{p}_C$ from equation (7), joint coordinates θ_1, θ_2 and θ_3 are solved using the geometric approach [8]. As it can be seen from equation (5)

$${}^{M}R_T = {}^{M}_{3}R(\theta_1, \theta_2, \theta_3) \cdot {}^{3}R_T(\theta_4, \theta_5) \tag{8}$$

As θ_1, θ_2 and θ_3 are solved geometrically from equation (8) θ_4 and θ_5 are solved analitically.

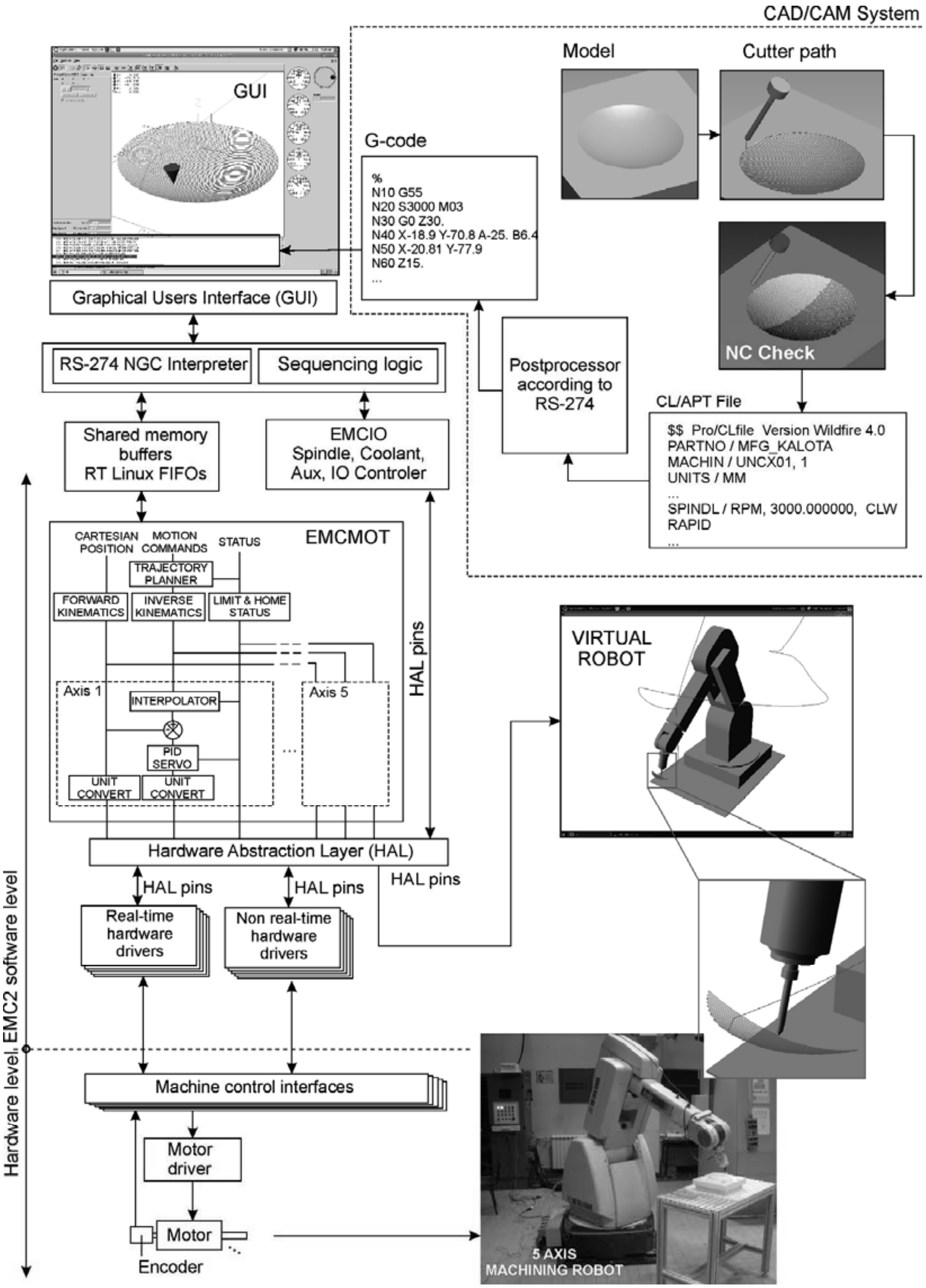
4. CONTROL AND PROGRAMMING SYSTEM

One of the distinctive features of the concept of machining robot, described in Section 2, is that it is applicable directly by CNC machine tool programmers by using the existing CAD/CAM systems and programming in G-code. Among several proposed OAC solutions, the development of the first low-cost control system prototype is based on PC real-time Linux platform with EMC2 software for computer control of machine tools, robots, parallel kinematic machines, etc. EMC2 was initially created by the NIST (National Institute of Standards and Technology) and is a free software released under the terms of the GPL (General Public License) [12,13]. The development of the machining robot control system prototype comprised a number of stages. For testing the functions of inverse and direct kinematics, robot off-line programming, control system behavior testing in real-time and collision detection, a virtual robot is configured.

Figure 5 shows a simplified structure of the first prototype of low-cost control and programming system where EMC2 software as a basic component is indicated. EMC2 software system [13] is composed of four modules:

- Motion controller (EMCMOT) is a real-time module. It performs trajectory planning, direct and inverse kinematics calculations and computation of desired outputs to motor drivers;
- Discrete I/O controller (EMCIO) handles all I/O functions, which are not directly related to the actual motions of machine axes;
- Task coordinating module (EMCTASK) is a task level command handler and program interpreter for the RS-274 NGC machine tool programming language, commonly referred to as a G-code;
- Graphical user interface (GUI). Among several user interfaces AXIS is the most advanced GUI, featuring interactive G-code previewer. It is expanded to specific application needs of the proposed robotic machining system.

Hardware abstraction layer (HAL) provides transferring of real-time data from EMC2 to robot control hardware or to virtual robot. During control system start up a choice is made for a corresponding configuration between real and virtual robot control, Figure 5. It is common to start up first the control system configuration for a virtual robot to visually detect possible collisions and to make final verification of the program. Connections to drivers from PC side are done via appropriate machine control interfaces including ADC, DAC and I/O channels. The virtual robot is configured using several predefined Python classes in EMC2. Based on inverse and direct kinematics equations, kinematic module is programmed in C language and is integrated in EMC2 software system, Figure 5.



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N10 G55
N20 S3000 M03
N30 G0 Z30.
N40 X-18.9 Y-70.8 A-25. B6.4
N50 X-20.81 Y-77.9
N60 Z15.
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$$ Pro/CLfile  Version Wildfire 4.0
PARTNO / MFG_KALOTA
MACHIN / UNCX01, 1
UNITS / MM
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SPINDL / RPM, 3000.000000,  CLW
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Fig. 5 *Structure of the control and programming sytem*

As obvious from Figure 5, the part programming is very conventional with the use of a postprocessor to convert CLF into G-code. This means that the programmer starts from the work piece CAD model in a common way, in this case in CAD/CAM system Pro/Engineer, generating CLF. The generated tool path is tested through the NC check (animated display of tool path and material removal). Using the configured postprocessor for the vertical 5-axis milling machines (X, Y, Z, A, B) spindle-tilting type, post-processing of CLF is done to obtain the robot program in G-code, which is transferred to the robot control system. If the robot is initialized and tool and work piece setting is done, the program can be tested in two ways. First, during G-code loading EMC2 software displays the programmed tool path. However, the second way is of crucial importance, because it employs a virtual robot. The virtual robot enables final verification of G-code. After these verifications, the program can be safely executed on the real robot.

5. EXPERIMENTS

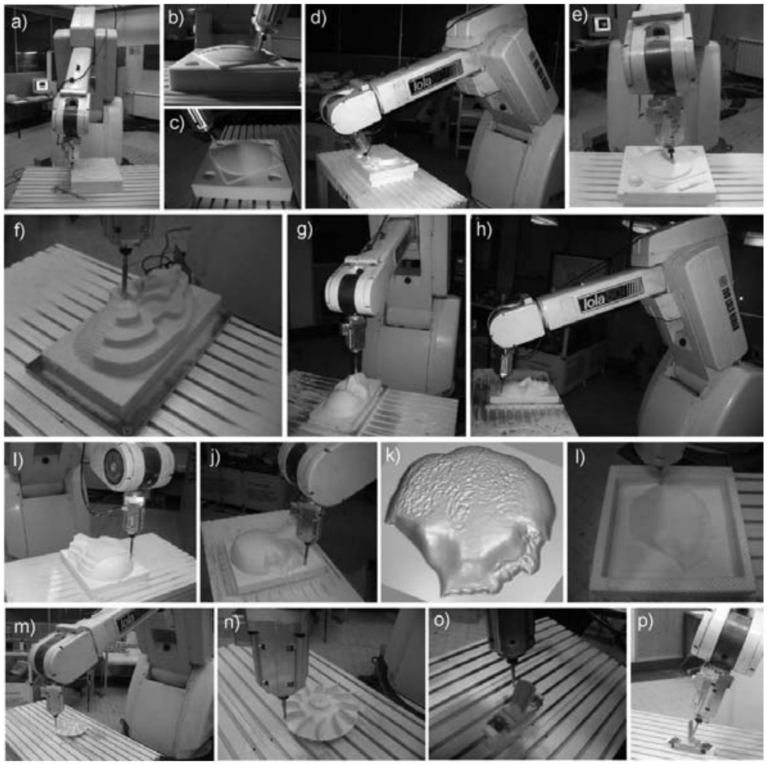

Fig. 7 Examples of test work pieces

Experiments were conducted to machine several test work pieces of light materials, Figure 7 using experimental robot from Figure 2. The setting of robot reference position and elementary calibration was performed by robot manufacturer's experts as their contribution to this research. The main goal of the experiments was to test capabilities of the developed control system prototype. The CAD/CAM system Pro/Engineer was used for the experiments with the idea that the programming of machining robot and machining itself is done in exactly the same way as it is done on a 5-axis vertical milling machine (X, Y, Z, A, B) spindle-tilting type. Prior to machining, the programs are tested in two ways:

- by graphical simulation of tool paths in EMC2, and
- on virtual machining robot to perform the final program verification.

The experiments were organized to embrace 3-axis and 5-axis machining of analytical and freeform (or sculptured) surfaces. For these examples of test work pieces, Figure 7, styrofoam and high-density polyurethane based material where used. For these experiments, specific flat endmills and ball-endmills [20] designed by one of the coauthor are used. These experiments confirmed that it is possible to realize machining robot with low-cost control and programming system for the complex-surfaces parts of light materials and lower tolerance, which can be directly used by CNC machine tools programmers and operators.

6. CONCLUSION

The paper describes the concept of machining robot for complex parts of light materials with lower tolerances. The 5-axis vertical articulated robot is considered as a specific configuration of 5-axis vertical milling machine (X, Y, Z, A, B) spindle tilting type. Robot modeling approach is shown in detail as well as the prototype of the developed low-cost control and programming system based on EMC2 software system. Verification of the experimental prototype of developed low-cost control and programming system is presented using the examples of machining of several test work pieces of light materials. The shown examples of test work pieces comprised 3-axis and 5-axis machining of analytical and freeform surfaces, where programming and the machining itself were performed according to the procedure applied for CNC machine tools. The developed and investigated experimental prototype of low-cost control and programming system indicates that such commercial system may be superior to the compatible robotic machining solutions, considering the G-code is still very widely used in industry. The subsequent stages of research will involve the development of specialized 5-axis vertical articulated machining robot and control system that will enable 3-axis and 5-axis machining by various combinations of robot's axes and additional rotational and translational axes.

7. ACKNOWLEDGEMENT

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