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ARTICULATED ROBOTIC ARM SIMULATION AND CONTROL

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Abstract: In this paper is presented the mathematical model for five degrees of mobility robot using cinematic direct and inverted method. Based on this model is designed the hardware-in-the-loop (HIL) simulation. Using the mathematical model and the simulation results a software controller is written and tested. The robot is controlled by software implemented on a PC connected to the robot by an electronic interface. Mathematical model and the software allow generating very precisely robot elements trajectories and easily implementing advanced algorithms. At the end of the paper there are presented two applications to control an educational robot based on direct and inverted models.

Keywords: robot models, cinematic direct and inverted method, HIL-simulation

1. GENERAL PROBLEMS

In fig.1 is presented an articulated five degrees of mobility robot. In order to control the joints movement of this robot there must be used methods to generate the approximate trajectories.

In the case of industrial robots, this method, together with the classical ones, like “teach-in” or “play-back”, has good results. In the case of intelligent robots or in order to implement advanced control algorithms, like adaptive, optimal or intelligent control, these methods are not applicable. In this case there are necessary very accurate mathematical models of the mechanical movement of the robot. From these reasons, is mandatory the cinematic inverted model. This inverted cinematic model must deal with big difficulties related to the presence of nonlinear equations. The approximate solution is not always acceptable, due to the weak convergence and to the real-time operating necessity.

Using such structures there can be achieved by program almost any type of diagram, using the appropriate software.

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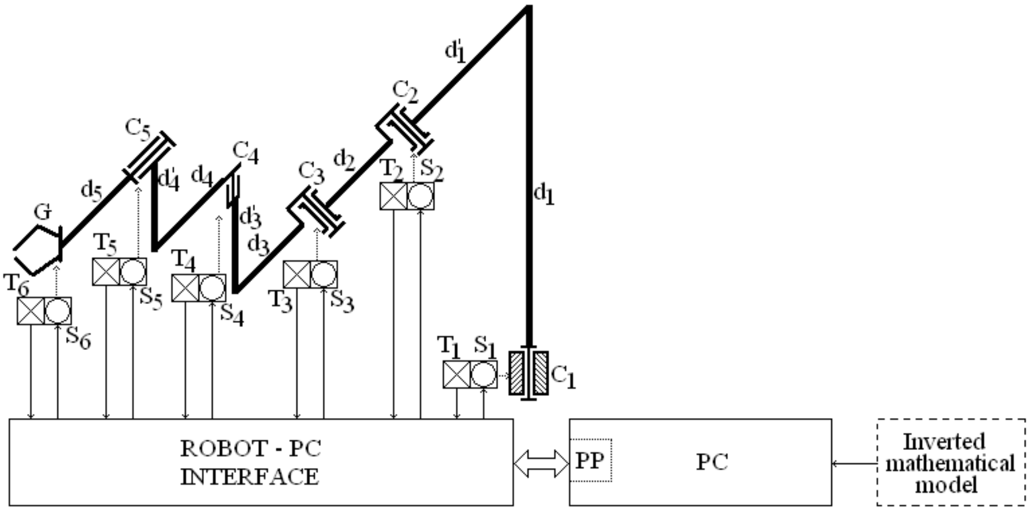


Fig. 1. Mini robot block diagram

In this paper is determined an exact solution for the cinematic direct and inverted model of a complex structure articulated robot with five degrees of mobility and there are solved the exceptions that appear to the bounds of the working domain.

The model is then simulated in MatLab-Simulink and are determined the trajectories, the working domain and the behavior for the existing exceptions. Using an educational robot connected to a PC by an appropriate interface there is tested the real working, based on HIL (hardware-in-the-loop) method. This simulation allowed the design and implementation of a software controller using object oriented programming technique for real-time control of the robot. In order to achieve all the above tasks, there was used a mini-robot, having five elements, named d_1, d_2, d_3, d_4, d5, five revolute joints, named c_1, c_2, c_3, c_4, c_5 and the gripper G. Each joint and the gripper are controlled by a DC servomotor S_i and a rotation sensor T_i.

There is used an intelligent interface that closes each servomotor position control loop. The servomotor can move with prescribed acceleration and speed and have software imposed movement limitations. The interface is connected to the PC by the parallel port or an acquisition card and allows the control of the robot based on the direct and inverted cinematic model.

2. MATHEMATICAL MODEL AND HIL SIMULATION

In order to determine the mathematical model of the five degrees of mobility articulated robot was first analyzed the mechanical structure based on Denavit-Hartenberg formalism (Pop et al., 2001).

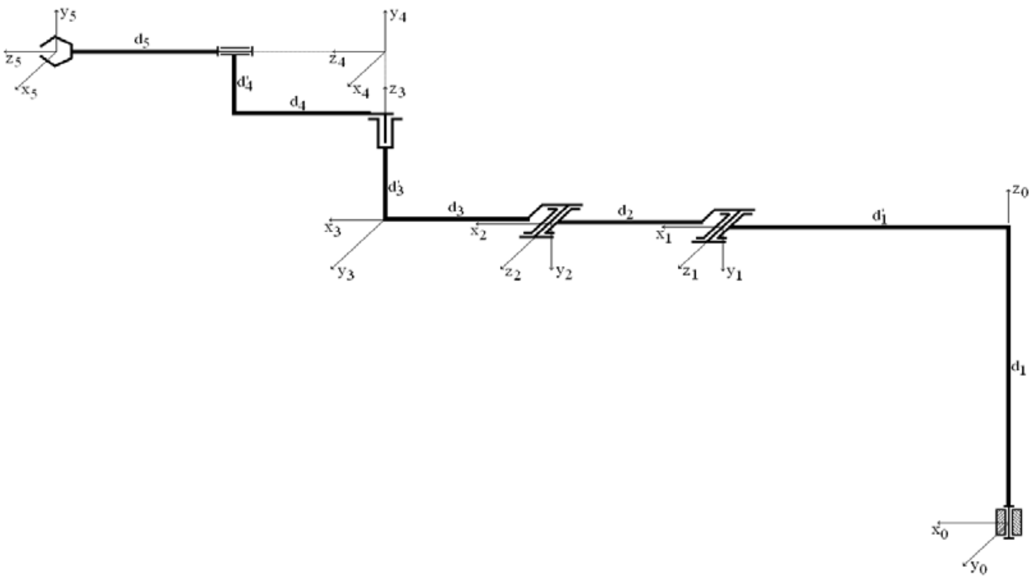


Fig. 2. Robot diagram

In figure 2 is presented the diagram of the robot that led to the movement matrix below, where n_i, o_i, a_i, p_i; i = 1, 2, 3 are the orientation and position vectors presented below:

$$T_{0,6} = \begin{bmatrix} n_1 & o_1 & a_1 & p_1 \\ n_2 & o_2 & a_2 & p_2 \\ n_3 & o_3 & a_3 & p_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix} = \begin{bmatrix} \cos\theta_1 \cdot \sin\theta_4 \cdot \cos\theta_5 \cdot \cos(\theta_2 + \theta_3) + \cos\theta_1 \cdot \sin\theta_5 \cdot \sin(\theta_2 + \theta_3) - \sin\theta_1 \cdot \cos\theta_4 \cdot \cos\theta_5 \\ \sin\theta_1 \cdot \sin\theta_4 \cdot \cos\theta_5 \cdot \cos(\theta_2 + \theta_3) + \sin\theta_1 \cdot \sin\theta_5 \cdot \sin(\theta_2 + \theta_3) + \cos\theta_1 \cdot \cos\theta_4 \cdot \cos\theta_5 \\ -\sin\theta_4 \cdot \cos\theta_5 \cdot \sin(\theta_2 + \theta_3) + \sin\theta_5 \cdot \cos(\theta_2 + \theta_3) \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} o_1 \\ o_2 \\ o_3 \end{bmatrix} = \begin{bmatrix} -\cos\theta_1 \cdot \sin\theta_4 \cdot \sin\theta_5 \cdot \cos(\theta_2 + \theta_3) + \cos\theta_1 \cdot \cos\theta_5 \cdot \sin(\theta_2 + \theta_3) + \sin\theta_1 \cdot \cos\theta_4 \cdot \sin\theta_5 \\ -\sin\theta_1 \cdot \sin\theta_4 \cdot \sin\theta_5 \cdot \cos(\theta_2 + \theta_3) + \sin\theta_1 \cdot \cos\theta_5 \cdot \sin(\theta_2 + \theta_3) - \cos\theta_1 \cdot \cos\theta_4 \cdot \sin\theta_5 \\ \sin\theta_4 \cdot \sin\theta_5 \cdot \sin(\theta_2 + \theta_3) + \cos\theta_5 \cdot \cos(\theta_2 + \theta_3) \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} \cos\theta_1 \cdot \cos\theta_4 \cdot \cos(\theta_2 + \theta_3) - \sin\theta_1 \cdot \sin\theta_4 \\ \sin\theta_1 \cdot \cos\theta_4 \cdot \cos(\theta_2 + \theta_3) + \cos\theta_1 \cdot \sin\theta_4 \\ -\cos\theta_4 \cdot \sin(\theta_2 + \theta_3) \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} p_1 \\ \\ \\ p_2 \\ \\ \\ p_3 \\ \\ \end{bmatrix} = \begin{bmatrix} (d_4+d_5)\cdot\cos\theta_1\cdot\cos\theta_4\cdot\cos(\theta_2+\theta_3)+d_3\cdot\cos\theta_1\cdot\cos(\theta_2+\theta_3)+ \\ +(d_3'+d_4')\cdot\cos\theta_1\cdot\sin(\theta_2+\theta_3)-(d_4+d_5)\cdot\sin\theta_1\cdot\sin\theta_4+ \\ +d_2\cdot\cos\theta_1\cdot\cos\theta_2+d_1'\cdot\cos\theta_1 \\ (d_4+d_5)\cdot\sin\theta_1\cdot\cos\theta_4\cdot\cos(\theta_2+\theta_3)+d_3\cdot\sin\theta_1\cdot\cos(\theta_2+\theta_3)+ \\ +(d_3'+d_4')\cdot\sin\theta_1\cdot\sin(\theta_2+\theta_3)+(d_4+d_5)\cdot\cos\theta_1\cdot\sin\theta_4+ \\ +d_2\cdot\sin\theta_1\cdot\cos\theta_2+d_1'\cdot\sin\theta_1 \\ -(d_4+d_5)\cdot\cos\theta_4\cdot\sin(\theta_2+\theta_3)-d_3\cdot\sin(\theta_2+\theta_3)+ \\ +(d_3'+d_4')\cdot\cos(\theta_2+\theta_3)-d_2\cdot\sin\theta_2+d_1 \end{bmatrix} \tag{5}$$

This matrix represents the direct cinematic model of the articulated robot. Based on these equations there was designed and implemented the MatLab-Simulink simulation model. In fig.3 are presented the model and simulation results for the direct cinematic model control.

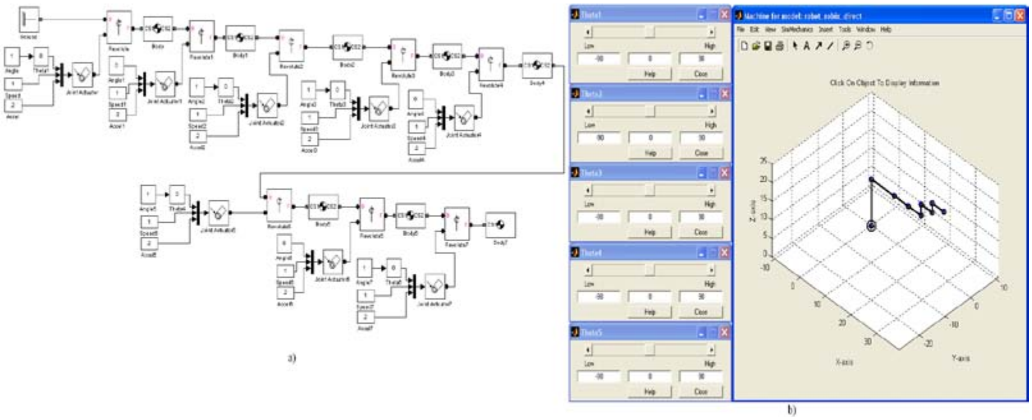


Fig. 3. Direct control:
a) Simulation; b) Results

The direct control method is usable only in simple applications, like play-back or teach-in. In the case of complex applications that require complex advanced algorithms implementation it is absolutely necessary the inverted cinematic model of the robot.

For this, there are known the desired gripper position (x, y, z) and orientation (RPY) matrix. Based on the mathematical model there must be determined each joint rotation angle in order to reach the imposed point (Pop and Leba, 2001).

Solving the system of equations presented above, will be obtained the angles θ_I, i=1..5 by the relations representing the inverted cinematic model:

$$tg\theta_1 = \frac{B}{A};\; tg\theta_2 = \frac{o_1 \cdot B - o_2 \cdot A}{n_2 \cdot A - n_1 \cdot B} = \frac{o_1 \cdot tg\theta_1 - o_2}{n_2 - n_1 \cdot tg\theta_1};\; \sin\theta_4 = \frac{a_2 \cdot A - a_1 \cdot B}{\sqrt{A^2 + B^2}} = \frac{a_2 - a_1 \cdot tg\theta_1}{\sqrt{1 + tg^2\theta_1}} \quad (6)$$

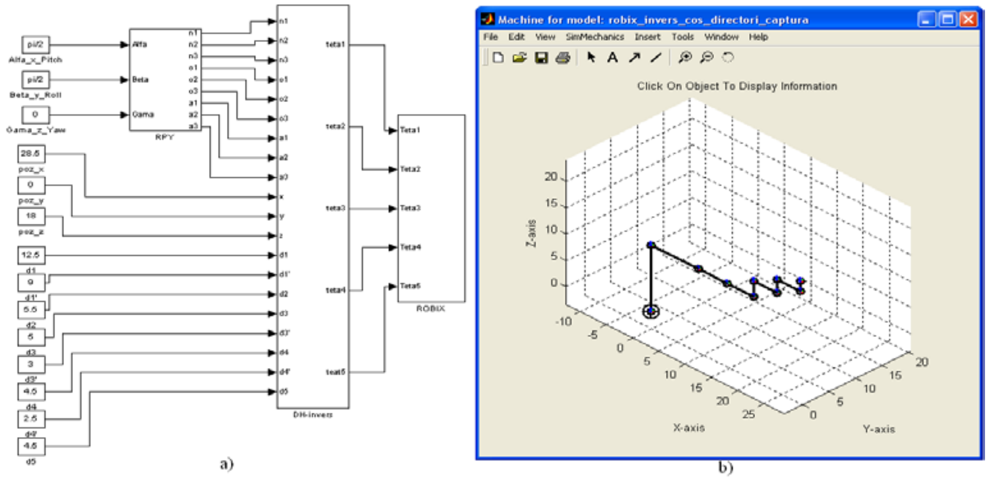
$$\sin\theta_2 = \frac{d_1 - z + \dfrac{a_3 \cdot (d_4 + d_5) \cdot \sqrt{A^2 + B^2 - (a_2 \cdot A - a_1 \cdot B)^2} + a_3 \cdot d_3 \cdot \sqrt{A^2 + B^2} + (d_3' + d_4') \cdot (a_1 \cdot A + a_2 \cdot B)}{\sqrt{(a_1 \cdot A + a_2 \cdot B)^2 + a_3^{\,2} \cdot (A^2 + B^2)}}}{d_2} \quad (7)$$

$$tg(\theta_2 + \theta_3) = -\frac{a_3 \cdot \sqrt{A^2 + B^2}}{a_1 \cdot A + a_2 \cdot B} = -\frac{a_3 \cdot \sqrt{1 + tg^2\theta_1}}{a_1 \cdot (1 + a_2 \cdot tg\theta_1)};\; tg\theta_3 = \frac{tg(\theta_2 + \theta_3) - tg\theta_2}{tg(\theta_2 + \theta_3) \cdot tg\theta_2 + 1} \quad (8)$$

where, A and B are:

$$A = x - a_1 \cdot (d_4 + d_5);\; B = y - a_2 \cdot (d_4 + d_5) \quad (9)$$

This inverted model was implemented in MatLab-Simulink and was obtained the results presented in figure 4.b.



a) b)

Fig. 4. Inverted model: a) Simulation; b) Results

3. SOFTWARE CONTROL

Based on the simulation results, was designed a control software, which allows the movement of robot by direct and inverted cinematic model. The software was written in Visual C++ as a Win32 application, using the MFC library of Windows operating system.

There are used the following classes: CRobixView, CControlRobix, CDlgHistory, CDlgCinematicDirect, CDlgCinematicInvers.

The CRobixView class (Fig. 5.a) consists of a working formulary that deals with the visual part of the program. The 3D graphical animation was done using the Direct3D from DirectX 9.0 library (Luna, 2003).

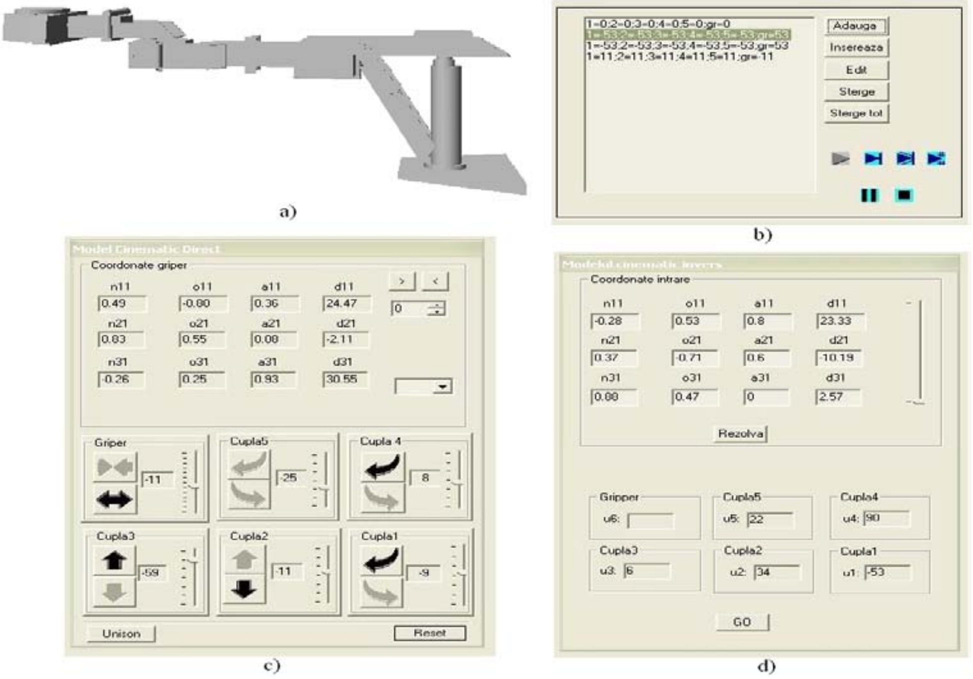
The CControlRobix class allows the real-time robot control, using an electronic interface for joints motor drives. In order to control each motor of the robot there is used the dedicated software driver library Rascal.dll.

The CDlgHistory (Fig. 5.b) class was necessary for direct cinematic model information storage. For this reason are used the controls: list; command button; play, pause, stop buttons.

The CDlgCinematicDirect class (Fig. 5.c) manages all the direct model dialog box controls to display the gripper coordinates, according to the joints movement control panels. This class implements the direct cinematic model equations, presented above in paragraph 2. The inputs of this class are the joints movement angles and the outputs are the position and orientation coordinates of the gripper.

The CDlgCinematicInvers class (Fig. 5.d) implements the inverted cinematic model using as input the position and orientation coordinates. The outputs of this class are the joints movement angles.

For direct and inverted cinematic models the movement angles are converted in command pulses sent to the electronic interface, that drives the joints motors.



a)

b)

1=0;2=0;3=0;4=0;5=0;gr=0
1=53;2=53;3=53;4=53;5=53;gr=53
1=-53;2=-53;3=-53;4=-53;5=-53;gr=53
1=11;2=11;3=11;4=11;5=11;gr=11

c)

n11	o11	a11	d11
0.49	-0.80	0.36	24.47

n21	o21	a21	d21
0.83	0.55	0.08	-2.11

n31	o31	a31	d31
-0.26	0.25	0.93	30.55

0

Griper: -11
Cupla5: -25
Cupla 4: 8
Cupla3: -59
Cupla2: -11
Cupla1: -9

d)

n11	o11	a11	d11
-0.28	0.53	0.8	23.33

n21	o21	a21	d21
0.37	-0.71	0.6	-10.19

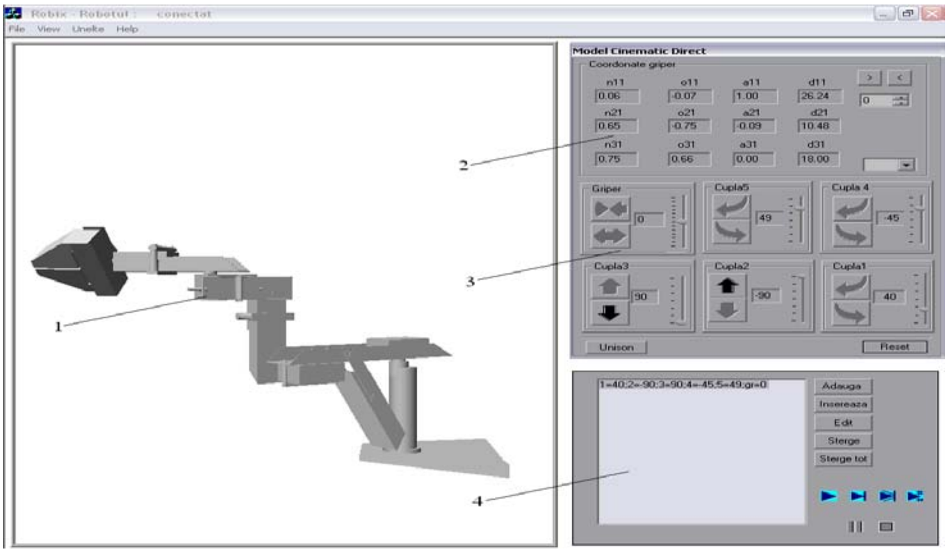
n31	o31	a31	d31
0.88	0.47	0	2.57

Gripper u6:
Cupla5 u5: 22
Cupla4 u4: 90
Cupla3 u3: 6
Cupla2 u2: 34
Cupla1 u1: -53

Fig. 5. Interface classes:
a) CRobixView; b) CDlgHistory; c) CDlgCinematicDirect; d) CDlgCinematicInvers

4. APPLICATIONS

The graphical user interface (GUI) allows the achievement of complex applications based on the two cinematic models software classes' implementations. The GUI (Fig. 6) consists of the following windows: animation display (1), inverted cinematic model panel (2), direct cinematic model panel (3) and play-back or teach-in storage data and panel (4).



n11 0.06
o11 -0.07
a11 1.00
d11 26.24
n21 0.65
o21 -0.75
a21 -0.09
d21 10.48
n31 0.75
o31 0.66
a31 0.00
d31 18.00
0
Griper 0
Cupla5 49
Cupla 4 -45
Cupla3 90
Cupla2 -90
Cupla1 40

1=40;2=-90;3=90;4=-45;5=49;gr=0

Fig. 6. Working screen

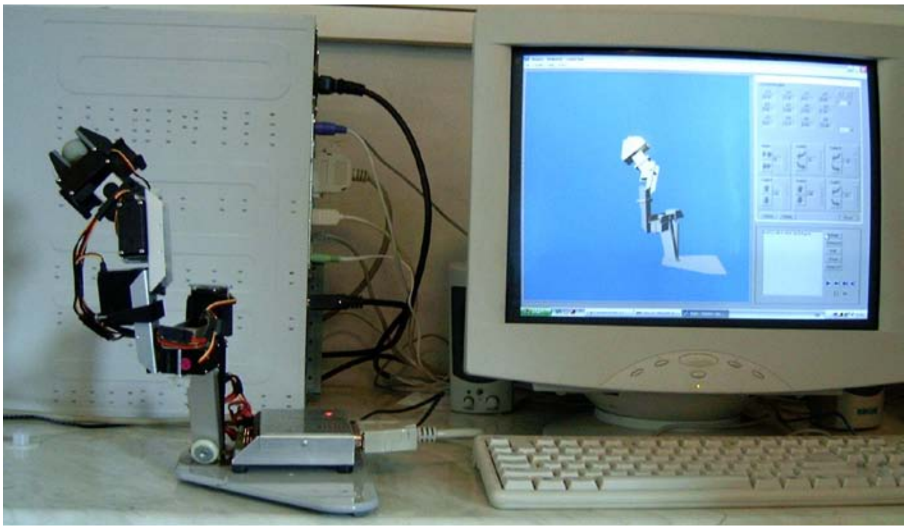


Fig. 7. Real-time application

A first application of this program is for five degrees of mobility robot control using play-back method. In this case it is used the direct cinematic model. The robot executes the movements imposed previously by the user. The movement of the real robot is done synchronously with the animation on the graphic interface.

The second application allows moving the robot gripper based on a positions map using the inverted cinematic model. The inputs are the position and orientation coordinates for each point that the gripper must reach. The outputs are the movement angles determined from the cinematic inverted model. In figure 7 is presented the real-time working scene.

5. CONCLUSIONS

In this paper the direct and inverted mathematical model for five degrees of mobility articulated robot is determined.

Based on the models there is done the HIL simulation in MatLab-Simulink platform, obtaining the working space, the rotation angles and the characteristic point position.

There is designed in Visual C++ the real-time control software and then implemented on a PC interfaced to an articulated educational robot.

The developed methods are applied for a play-back control robot and for a complex movement control by a positions map.

The advantages of this control methods based on mathematical model are obvious regarding the accuracy, speed and advanced control algorithms implementation.

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