Engineering

NEW APPROACH FOR FORWARD KINEMATIC MODELING OF INDUSTRIAL ROBOTS

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Adrian NICOLESCU[2]

ABSTRACT: *DESIGNING AND CONTROLLING INDUSTRIAL ROBOTS INVOLVES DETERMINING THE POSITION OF ITS KINEMATIC CHAINS IN RELATION TO A FIXED COORDINATE SYSTEM – THE ABSOLUTE POSITION OF THE ELEMENTS AND THE RELATIVE POSITION – REVEALED BY GENERALIZED COORDINATES. MOST OF THE WORK AVAILABLE REGARDING THIS ISSUE IS BASED ON DIRECT KINEMATICS USING THE DENAVIT-HARTENBERG (D-H AND D-H MODIFIED) CONVENTION, WHICH LEADS TO PARTICULAR GEOMETRIC MODELS AND WHICH ARE EQUIVALENT TO A CERTAIN EXTENT BUT DO NOT CORRESPOND TO THE COMPLETE DESCRIPTION OF THE REAL ROBOT. IN ORDER FOR THIS PURPOSE, KINEMATIC MODELING USING A FULL SET OF GEOMETRIC PARAMETERS OF THE REAL ROBOT ARE MANDATORY FOR THE DEVELOPMENT OF APPROPRIATE GEOMETRIC MODELS, ESPECIALLY IF SOFTWARE COMPENSATION IS DESIRED FOR ERRORS SUCH AS THERMAL DEFORMATIONS. A NEW UNIVERSAL APPROACH FOR DIRECT KINEMATICS MODELING (APPLICABLE TO ANY TYPE OF ROBOT) WHERE THE REFERENCE SYSTEMS OF EACH JOINT MAINTAIN THE SAME ORIENTATION ON THE ENTIRE STRUCTURE AND IN WHICH THE REAL GEOMETRIC PARAMETERS CAN BE USED IS PRESENTED IN THE PAPER. THIS METHOD ALSO FACILITATES THE INTEGRATION OF ERROR PARAMETERS IN THE GEOMETRIC MODEL IN ORDER TO COMPUTE THE ERROR COMPENSATION. A COMPARISON BETWEEN USUAL DH MODELING, THE UNIVERSAL MODELING PRESENTED IN THIS PAPER, AND THE VALIDATION USING A VIRTUAL MODEL AND CAD SOFTWARE IS ALSO PRESENTED.*

KEY WORDS: *INDUSTRIAL ROBOTS, DIRECT KINEMATICS, ORIGINAL MODELING APPROACH.*

INTRODUCTION

The study of the movement of the robot's mechanical elements (without regard to masses and forces) is called „kinematic modeling". The movement is relative, and for this reason, the motion and position of a material system is determined in relation to a reference system by means of angles and distances. Solving the problems of designing and conducting industrial robots involves determining the position of its kinematic chains in relation to a fixed coordinate system – the absolute position of the elements and the relative position – revealed by generalized coordinates. In the specific literature, these problems bear the name of the direct problem and the inverse problem (direct kinematics and inverse kinematics). The meaning of direct problem is the determination of the position and orientation of the characteristic point (of the last mobile element) and the inverse problem is the determination

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of the movements in the kinematic joints when the position of the characteristic point is known. The results of solving these problems are used both for controlling industrial robots and for designing them[3]. In this paper, only the direct issue (direct or forward kinematic) of industrial robots (IR) is discussed. In practice and in the related literature, the matrix method is preferred for developing kinematic model along with the D-H convention. To describe the position of an element within the kinematic chain relative to the previous element, we need to consider 6 transformation parameters. By D-H formalism[4] the relationship between elements can be described using four parameters by applying constraints related to the positioning of the coordinate systems[5]. The result is that in modeling and in the kinematic scheme, references systems are sometimes constrained to be in positions that are non-obvious or even do not match real physical elements. Choosing coordinate systems is not unique. For the same robot, different individuals can obtain different kinematic schemas but still correct because they lead to the same expressions of the end-effectors position relative to the robot base[6]. Also in D-H modeling the dimensions of the joints are neglected, fact that leads to deviations from the real model of the IR and the impossibility to correctly evaluate IR's elastic and thermal behavior as well as to apply appropriate software compensation procedures.

CLASSIC APPROACH (DENAVIT-HARTENBERG)

The main confusing issue in D-H kinematic modeling is that for the same robot, different people can get different kinematic schemas (Table 1), but still correct because they lead to the same expressions of the end-effectors position relative to the base[7]. This is true to said "correctly", but only in the conditions in which in the theoretical study it’s important only the position of the end-effectors without taking into consideration other real constructive and functional aspects, aspects that radically influence the way in which the mathematical model must be elaborated. Only few specific papers present some kinematic models ready to be directly implemented on a real scale IR or to assess the kinematic behavior of a specific IR model[8]. This is usually due to inconsistencies in modeling, the most frequent of which is the incomplete formalization of the entire set of real constructive and functional parameters (which is mandatory to be considered in case of a specific model of real IR), the ignorance of some specific aspects (such as actual dimensions of structural elements and joints) leading to the wrong localization of the coordinate systems used to express the homogenous coordinate transformations, as well as the lack of a validation procedure able to verify the correctness before being implemented on the real robot controller.

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[3] Alexandru, Dorin; Tiberiu, Dobrescu; Nicoleta, Pascu.; Ioana, Ivan; *Cinematica robotilor industriali,* Bucuresti: Bren, 2011

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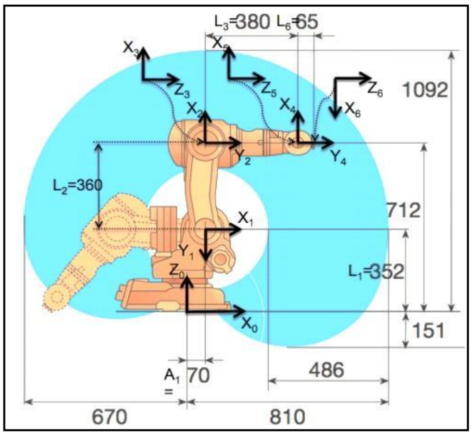
****http://www.petercorke.com/doc/rtb_dh.pdf*

[7] ***ABB Product specification IRB120; Document ID: 3HAC035960-001; Copyright 2010-2017 ABB; www.abb.com/robotics

[8] Nicolescu, A.F.; Ilie, F.M.; Alexandru T.G.; *Forward and inverse kinematics study of industrial robots taking into account constructive and functional parameters modeling; Proceedings in Manufacturing Systems, Volume 10, Issue 4, 2015, 157−16; ISSN 2067-9238;* Cezara, A.; Strajescu E.; *Research on structural and functional optimization of IR's numerically controlled axes in order to increase their performances; PhD. Thesis - , University “Politehnica” of Bucharest; faculty IMST - 2014*

Table 1: Example of different modeling using DH for the same robot (ABB IRB140)

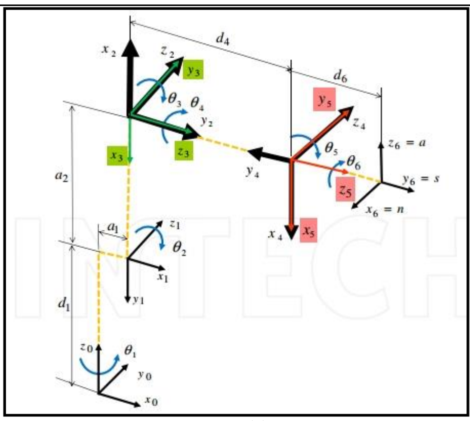
Frame assignment | **DH parameters**



[9]

Joint	Θi	di	ai	αi
1	q1	352	70	-pi/2
2	q2 - pi/2	0	360	0
3	q3	0	0	-pi/2
4	q4	380	0	pi/2
5	q5	0	0	-pi/2
6	q6 + pi/2	65	0	0

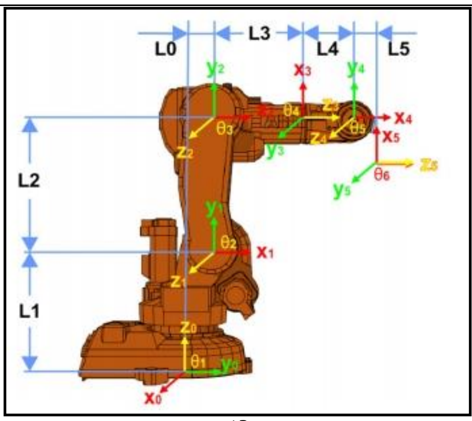
[10]



[11]

Joint	Θi	di	ai	αi
1	$\Theta_1 = 0^0$	d1	a1	-90^0
2	$\Theta_2 = -90^0$	0	a2	0^0
3	$\Theta_3=180^0$	0	0	90^0
4	$\Theta_4 = 0^0$	d4	0	-90^0
5	$\Theta_5 = 0^0$	0	0	90^0
6	$\Theta_6 = -90^0$	d6	0	90^0

[12]



[13]

Joint	Θi	di	ai	αi
1	Θ_1 + pi/2	L1	L0	pi/2
2	Θ_2 + pi/2	0	L2	0
3	Θ_3	0	0	pi/2
4	Θ_4	L3+L4	0	- pi/2
5	Θ_5	0	0	pi/2
6	Θ_6	L5+d	0	0

[14]

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[11] Djuric, A; Urbanic, R. J.; *Utilizing the Functional Work Space Evaluation Tool for Assessing a System Design and Reconfiguration Alternatives*; University of Windsor; Intech, Canada
[12] Djuric, A; Urbanic, R. J.; *Utilizing the Functional Work Space Evaluation Tool for Assessing a System Design and Reconfiguration Alternatives*; University of Windsor; Intech, Canada
[13] Baquero-Suárez, M; Ricardo Ramírez, H.; *Kinematics, Dynamics and Evaluation of Energy Consumption for ABB IRB-140 Serial Robots in the Tracking of a Path; 2nd International Congress on Mechatronics Engineering and Automation, Universidad de la Salle. Bogotá D.C., Colombia*

A new and different solution is presented for the first time in[15] for a gantry robot and continued in[16] for articulated arm robots, solution that involves a new approach in forward and inverse kinematics modeling based on a full set of constructive and functional parameters of IR. The importance of this modeling was especially emphasized in[17] for taking into account the real constructive and functional parameters, parameterization of the geometric errors and of errors due to deformations, in the correct (real) elaboration of the mathematical model to determine the loads applied to an IR, in developing of the mathematical model for the calculation, selection and verification of the actuators and in the evaluation of the IR's volumetric precision as well as in the elaboration of some software compensation procedure for the geometric and kinematic errors due to thermal deformations of structural components.

THE NEW KINEMATIC MODELING APPROACH

Instead of using classic DH in this paper is presented and suggested applying of the homogenous coordinate transformations following two specifications: 1) the final goal of this study is developing a universal mathematical model applicable for any IR architecture type, mathematical model that must correspond to the real physical IR and which to take account of the real constructive and functional parameters and error parameters (geometric and due to thermal deformations) with the possibility of software compensation of these errors by implementing this mathematical model in the robot controller; 2) a particular case is when referring to robots with a closed kinematic chain (e.g. ABB IRB 460) where the number of transformation matrices is higher because of the influence of the passive joints and closed kinematic chain elements that affect the position of the other couplings and this must be taken into consideration.

Five steps are proposed to be followed: 1) Develop mathematical model equivalent to D-H using the new approach for a IR with bilateral symmetry (ABB IRB120) and for one without symmetry (ABB IRB140) and to compare results obtained by new approach modeling with results from D-H modeling and with a virtual modeling using a CAD software (CATIA). 2) Applying new approach for developing a mathematical model equivalent to D-H for a IR with closed kinematic chain (ABB IRB460) and to compare results with the D-H and also with the virtual model (in a second following paper). 3) Improve the above mentioned models by adding real constructive and functional parameters and to compare results with D-H and with the virtual model. 4) Develop a mathematical model with the constructive and functional parameters and plus error parameters (especially errors due to thermal deformations) following the study of the influence of the thermal deformations on the positioning precision and repeatability of the IR (study in progress in PhD thesis). This mathematical model should be used for compensation of these errors by implementing it on the robot's controller. 5) Compare theoretical and experimental results and validation with dedicated software for programming and offline-simulation of ABB robots, "ABB Robot Studio".

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[14] Baquero-Suárez, M; Ricardo Ramírez, H.; *Kinematics, Dynamics and Evaluation of Energy Consumption for ABB IRB-140 Serial Robots in the Tracking of a Path; 2nd International Congress on Mechatronics Engineering and Automation, Universidad de la Salle. Bogotá D.C., Colombia*

[15] Nicolescu, A.F.; Ilie, F.M.; Alexandru T.G.; *Forward and inverse kinematics study of industrial robots taking into account constructive and functional parameters modeling; Proceedings in Manufacturing Systems, Volume 10, Issue 4, 2015, 157−16; ISSN 2067-9238*

[16] Cezara, A.; Strajescu E.; *Research on structural and functional optimization of IR's numerically controlled axes in order to increase their performances; PhD. Thesis - , University "Politehnica" of Bucharest; faculty IMST - 2014*

[17] Nicolescu, A.F.; Ilie, F.M.; Alexandru T.G.; *Forward and inverse kinematics study of industrial robots taking into account constructive and functional parameters modeling; Proceedings in Manufacturing Systems, Volume 10, Issue 4, 2015, 157−16; ISSN 2067-9238*

Further on in this paper is presented the first stage of the above, with the continuation of studies and the presentation of the results in the future in the doctoral thesis and other papers on this topic.
For each robot, link dimensions were taken from official ABB Product manuals[18].

Table 2: DH parameters and NEW APPROACH parameters

<table>
<tr><th>Denavit-Hartenberg</th><th>New approach</th><th>Robot Model</th></tr>
<tr><td>

Joint	Θi	di	ai	αi
1	q1	290	0	-pi/2
2	q2 -pi/2	0	270	0
3	q3	0	70	-pi/2
4	q4	302	0	pi/2
5	q5	0	0	-pi/2
6	q6+pi/2	72	0	0

</td><td>

Joint rotation angles		Translations			
			Pe X	Pe axa Y	Pe axa Z
Θ_0	0	Sis. Ref 0	0	0	0
Θ_1	0	Sis. Ref 1	0	0	0
Θ_2	0	Sis. Ref 2	0	0	290
Θ_3	0	Sis. Ref 3	0	0	270
Θ_4	0	Sis. Ref 4	134	0	70
Θ_5	0	Sis. Ref 5	168	0	0
Θ_6	0	Sis. Ref 6	72	0	0

</td><td>IRB 120</td></tr>
<tr><td>

Joint nr.	Θi	di	ai	αi
1	q1	352	70	-pi/2
2	q2 - pi/2	0	360	0
3	q3	0	0	-pi/2
4	q4	380	0	pi/2
5	q5	0	0	-pi/2
6	q6+pi/2	65	0	0

</td><td>

Joint rotation angles		Translations			
			Pe X	Pe axa Y	Pe axa Z
Θ_0	0	Sis. Ref 0	0	0	0
Θ_1	0	Sis. Ref 1	0	0	0
Θ_2	0	Sis. Ref 2	70	0	352
Θ_3	0	Sis. Ref 3	0	0	360
Θ_4	0	Sis. Ref 4	254	0	0
Θ_5	0	Sis. Ref 5	126	0	0
Θ_6	0	Sis. Ref 6	65	0	0

</td><td>IRB 140</td></tr>
</table>

The general form of the homogenous coordinate transformation matrix (4x4) composed from 4 separate sub-matrices, is the following:

$$T = \begin{pmatrix} R & p \\ \eta^T & \sigma \end{pmatrix} \tag{1}$$

where: R = fundamental rotational matrix (3x3)

p = translation vector (3x1)

η = perspective vector (1x3) (in kinematics is the null vector)

σ = scale factor (usually = 1)

For kinematic modeling two steps must be followed: 1) the translation matrices are applied on directions X, Y, Z from joint "i" to joint "i+1" (without any change in the orientation of the reference frame). 2) rotational matrix is applied for joint "i+1". Axis system of joint "i+1" will rotate around one of its own axis (depending which one is the rotation axis).

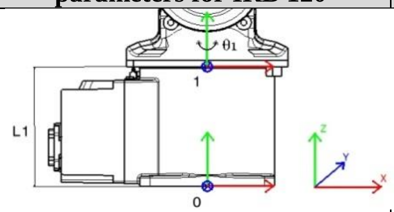
Table 3: Transformation matrices and frame assignment for robot joints in the new approach

<table>
<tr><th>Transformation matrix</th><th>Frame assignment and parameters for IRB 120</th><th>Frame assignment and parameters for IRB 140</th></tr>
<tr><td>

T01

$$\begin{pmatrix} cos\theta 1 & -sin\theta 1 & 0 & 0 \\ sin\theta 1 & cos\theta 1 & 0 & 0 \\ 0 & 0 & 1 & L1 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{2}$$

</td><td>



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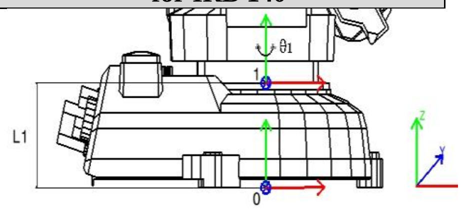
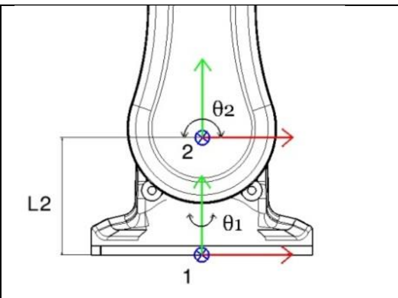
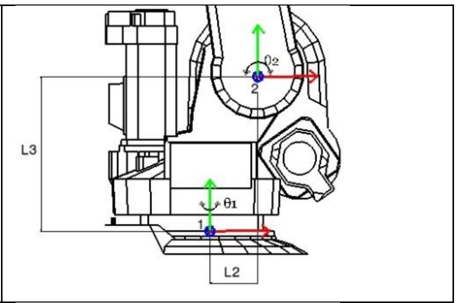
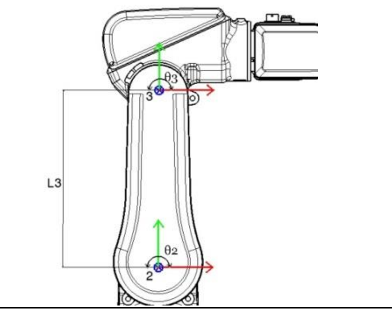
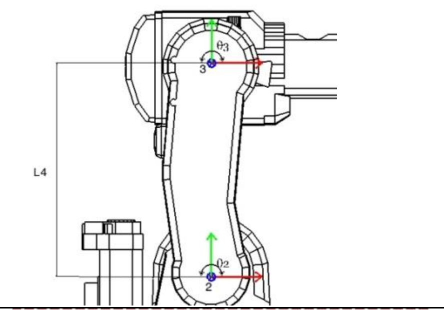
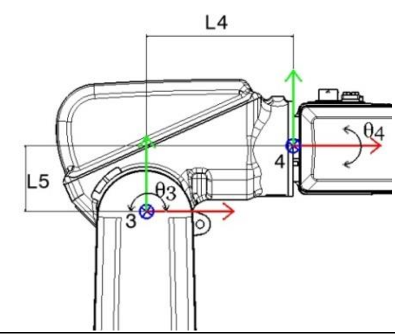
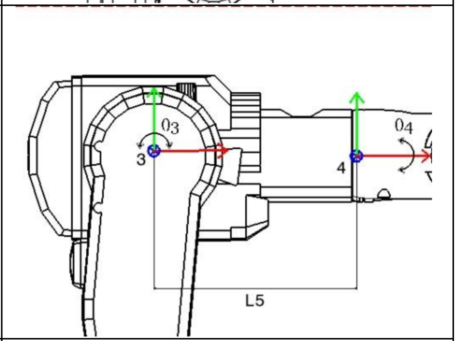
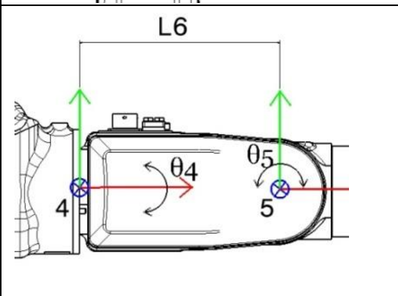
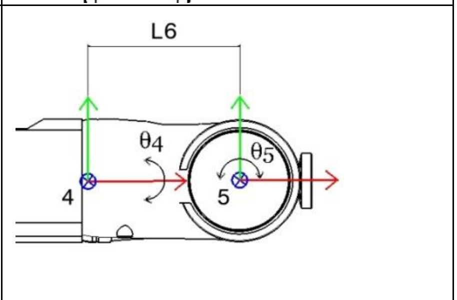
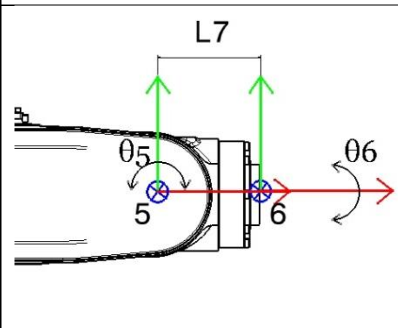
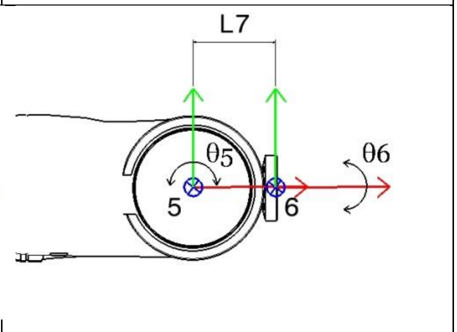


</td></tr>
</table>

18 ***ABB Product specification IRB120; Document ID: 3HAC035960-001; Copyright 2010-2017 ABB; www.abb.com/robotics; ***ABB Product specification IRB140; Document ID: 3HAC041346-001; Copyright 2010-2017 ABB; www.abb.com/robotics

T12(IRB 120) $\begin{pmatrix} cos\theta 2 & 0 & sin\theta 2 & 0 \\ 0 & 1 & 0 & 0 \\ -sin\theta 2 & 0 & cos\theta 2 & L2 \\ 0 & 0 & 0 & 1 \end{pmatrix}$ (3) T12(IRB 140) $\begin{pmatrix} cos\theta 2 & 0 & sin\theta 2 & L2 \\ 0 & 1 & 0 & 0 \\ -sin\theta 2 & 0 & cos\theta 2 & L3 \\ 0 & 0 & 0 & 1 \end{pmatrix}$ (4)		
T23(IRB 120) $\begin{pmatrix} cos\theta 3 & 0 & sin\theta 3 & 0 \\ 0 & 1 & 0 & 0 \\ -sin\theta 3 & 0 & cos\theta 3 & L3 \\ 0 & 0 & 0 & 1 \end{pmatrix}$ (5) T23(IRB 140) $\begin{pmatrix} cos\theta 3 & 0 & sin\theta 3 & 0 \\ 0 & 1 & 0 & 0 \\ -sin\theta 3 & 0 & cos\theta 3 & L4 \\ 0 & 0 & 0 & 1 \end{pmatrix}$ (6)		
T34(IRB 120) $\begin{pmatrix} 1 & 0 & 0 & L4 \\ 0 & cos\theta 4 & -sin\theta 4 & 0 \\ 0 & sin\theta 4 & cos\theta 4 & L5 \\ 0 & 0 & 0 & 1 \end{pmatrix}$ (7) T34(IRB 140) $\begin{pmatrix} 1 & 0 & 0 & L5 \\ 0 & cos\theta 4 & -sin\theta 4 & 0 \\ 0 & sin\theta 4 & cos\theta 4 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$ (8)		
T45 (IRB 120) $\begin{pmatrix} cos\theta 5 & 0 & sin\theta 5 & L6 \\ 0 & 1 & 0 & 0 \\ -sin\theta 5 & 0 & cos\theta 5 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$ (9) T45 (IRB 140) $\begin{pmatrix} cos\theta 5 & 0 & sin\theta 5 & L6 \\ 0 & 1 & 0 & 0 \\ -sin\theta 5 & 0 & cos\theta 5 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$ (10)		
T56 (IRB 120) $\begin{pmatrix} 1 & 0 & 0 & L7 \\ 0 & cos\theta 6 & -sin\theta 6 & 0 \\ 0 & sin\theta 6 & cos\theta 6 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$ (11) T56 (IRB 140) $\begin{pmatrix} 1 & 0 & 0 & L7 \\ 0 & cos\theta 6 & -sin\theta 6 & 0 \\ 0 & sin\theta 6 & cos\theta 6 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$ (12)		

In order to prove the compatibility of the new approach with the classic DH approach, for the moment a simplified model will be elaborated and used without taking into account the full set of geometric parameters. For robot models ABB IRB 120 and ABB IRB 140 the modeling is very similar, differences occurring at the lengths of the elements. Further will be presented the steps for developing the kinematic scheme with positioning of the reference frames and mathematical formalization for ABB robots IRB 120 and IRB 140.

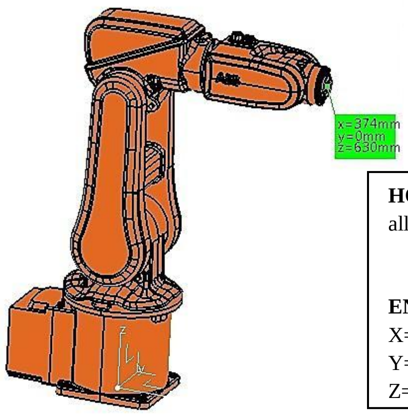
By multiplication of the frame transformation matrices of each joint (equation 13), the solution of forward kinematics is obtained (position and orientation of the robot's end effector) relative to base reference system.

$$T_{base\text{-}effector}=T_{01}*\ T_{12}*\ T_{23}*\ T_{34}*\ T_{45}*\ T_{56}=\begin{pmatrix} R11 & R12 & R13 & Px \\ R21 & R22 & R23 & Py \\ R31 & R32 & R33 & Pz \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad (13)$$

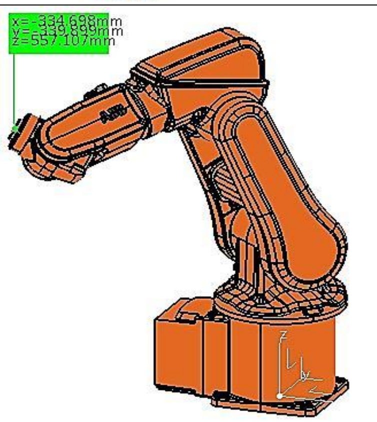
VALIDATION WITH 3D CAD MODEL

For almost each robot model manufactured by ABB Robotics, the virtual model of the robot is available on the manufacturer's website in order to be able to use them with the specialized programming and off-line simulating software. Virtual models for the robots studied in this paper were imported in the design and simulation software, CATIA V5. "DMU Kinematics" workbench from CATIA V5 allows loading the virtual model, creating geometric constraints between robot elements, changing joint parameters and monitoring of those in the virtual 3D space. In the following table (table 4), results of end-effectors position for different robot poses are presented.

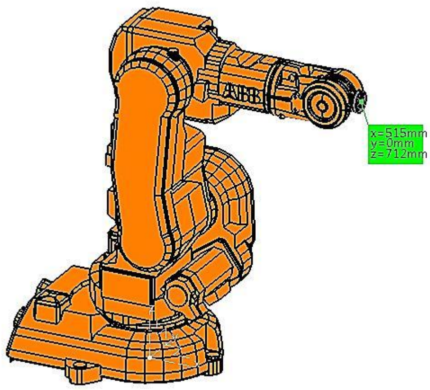
Table 4: Comparison between DH, new approach and virtual model

<table>
<tr><th>Virtual Model (CATIA V5)
ACTIVE JOINTS PARAMETERS</th><th>NEW APROACH JOINT PARAMETERS AND END EFFECTOR POSITION RESULT</th></tr>
<tr><td colspan="2">IRB 120</td></tr>
<tr><td>

HOME POSE:
all joints at 0 ^o

END EFFECTOR:
X=374;
Y=0;
Z=630:</td>
<td>NEW APPROACH
<table>
<tr><td>Θ_0</td><td>0</td><td colspan="4">T06 = T01*T12*T23*T34*T45*T56</td></tr>
<tr><td>Θ_1</td><td>0</td><td>1</td><td>0</td><td>0</td><td>374</td></tr>
<tr><td>Θ_2</td><td>0</td><td>0</td><td>1</td><td>0</td><td>0</td></tr>
<tr><td>Θ_3</td><td>0</td><td>0</td><td>0</td><td>1</td><td>630</td></tr>
<tr><td>Θ_4</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td></tr>
<tr><td>Θ_5</td><td>0</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Θ_6</td><td>0</td><td></td><td></td><td></td><td></td></tr>
</table>
DH
<table>
<tr><td colspan="5">T06 = T01*T12*T23*T34*T45*T56</td></tr>
<tr><td>-6.12574E-17</td><td>-6.12574E-17</td><td>1</td><td>374.000</td><td>X</td></tr>
<tr><td>-6.12574E-17</td><td>1</td><td>6.126E-17</td><td>0.000</td><td>Y</td></tr>
<tr><td>-1</td><td>-6.12574E-17</td><td>-6.13E-17</td><td>630.000</td><td>Z</td></tr>
<tr><td>0</td><td>0</td><td>0</td><td>1</td><td></td></tr>
</table></td></tr>
<tr><td>

RANDOM POSE:
J1= -130 ^o
J2= 25 ^o
J3= -10 ^o
J4=40 ^o
J5=-55 ^o
J6=-5 ^o
END EFFECTOR:
X=-334.698;
Y=-339.899;
Z=557.107;</td>
<td>NEW APPROACH
<table>
<tr><td>Θ_0</td><td>0</td><td colspan="4">T06 = T01*T12*T23*T34*T45*T56</td></tr>
<tr><td>Θ_1</td><td>-130</td><td>-0.86387</td><td>0.464719</td><td>0.194312</td><td>-334.698</td></tr>
<tr><td>Θ_2</td><td>25</td><td>-0.21037</td><td>-0.68338</td><td>0.699097</td><td>-339.899</td></tr>
<tr><td>Θ_3</td><td>-10</td><td>0.457673</td><td>0.563054</td><td>0.688117</td><td>557.107</td></tr>
<tr><td>Θ_4</td><td>40</td><td>0</td><td>0</td><td>0</td><td>1</td></tr>
<tr><td>Θ_5</td><td>-55</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Θ_6</td><td>-5</td><td></td><td></td><td></td><td></td></tr>
</table>
DH
<table>
<tr><td colspan="5">T06 = T01*T12*T23*T34*T45*T56</td></tr>
<tr><td>-0.194311863</td><td>0.464719297</td><td>-0.863874</td><td>-334.698</td><td>X</td></tr>
<tr><td>-0.699097496</td><td>-0.6833782</td><td>-0.210373</td><td>-339.899</td><td>Y</td></tr>
<tr><td>-0.688117425</td><td>0.56305436</td><td>0.4576727</td><td>557.107</td><td>Z</td></tr>
<tr><td>0</td><td>0</td><td>0</td><td>1</td><td></td></tr>
</table></td></tr>
<tr><td colspan="2">IRB 140</td></tr>
</table>



HOME POSE:
all joints at 0^{o}

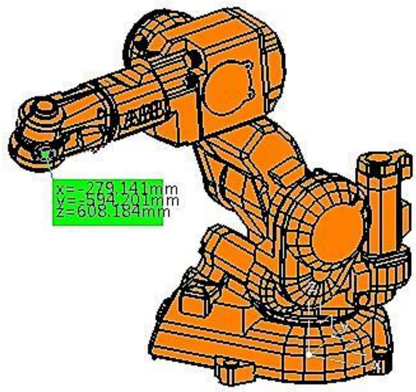
END EFFECTOR:
X=515;
Y=0;
Z=712;

NEW APPROACH

		T06 = T01*T12*T23*T34*T45*T56			
Θ_0	0				
Θ_1	0	1	0	0	515
Θ_2	0	0	1	0	0
Θ_3	0	0	0	1	712
Θ_4	0	0	0	0	1
Θ_5	0				
Θ_6	0				

DH

T06 = T01*T12*T23*T34*T45*T56				
6.126E-17	-6.12574E-17	1	515.000	X
-1	0	6.1E-17	0.000	Y
0	-1	-6E-17	712.000	Z
0	0	0	1	



RANDOM POSE:
J1= -120^{o}
J2= 30^{o}
J3= -25^{o}
J4=70^{o}
J5=65^{o}
J6=15^{o}
END EFFECTOR:
X=-279.141;
Y=-594.201;
Z=608.184;

NEW APPROACH

		T06 = T01*T12*T23*T34*T45*T56			
Θ_0	0				
Θ_1	-120	0.540554	0.039068	-0.8404	-279.141
Θ_2	30	-0.76703	-0.38749	-0.51138	-594.201
Θ_3	-25	-0.34563	0.921044	-0.1795	608.184
Θ_4	70	0	0	0	1
Θ_5	65				
Θ_6	15				

DH

T06 = T01*T12*T23*T34*T45*T56				
-0.039068	0.84040161	0.54055	-279.141	X
0.3874949	0.511376949	-0.767	-594.201	Y
-0.921044	0.179495819	-0.3456	608.184	Z
0	0	0	1	

In above pictures and tables are compared the results obtained from the conventional DH modeling, new approach modeling and 3D CAD virtual modeling, showing a perfect correspondence. For the new approach and for the DH formalization, parameters and transformation matrices were implemented in excel files in order to be easily computed.

CONCLUSIONS

In this paper, a new approach for forward modeling of IR kinematic was presented. For the two studied robots (ABB IRB 120 and IRB 140) the mathematical modeling results using the new approach and the results from the classic DH formalism are proving the compatibility of the new approach with the D-H one. Also, the correctness of the new approach was also confirmed by comparison and validation with the results from the robot virtual model using CATIA V5 CAD environment. Among the major benefits of applying the new approach first of all we can mention eliminating the ambiguities introduced by DH modeling with regard to the development of kinematic schemas and the assignment of reference systems. The fact that the coordinate systems now have the same orientation facilitates the elaboration of correct cinematic schemas in particular if it is desired to take into account of the real robot geometric parameters. This way it is very easy to introduce parameters regarding to joint distances and displacement of the elements as simple translation parameters in the same directions X, Y, Z. Therefore, first step presented in chapter 3 is complete. Further, the focus will be to prove the compatibility of the new approach with the robots including closed kinematic chain (mathematical model and validation being also done for ABB IRB460 and presented in another paper) and to develop mathematical model by taking into account full set of real constructive and functional and error parameters.

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