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STUDY REGARDING INDUSTRIAL ROBOTS DIGITAL TWIN DESIGN IN CAD-CAM SOFTWARE

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Rezumat. *Noile tehnologii de digitalizarea a entităţilor economice specifice conceptului de industrie 4.0 nu pot fi transpuse în practică fără utilizarea echipamentelor comandate numeric. Roboţii Industriali (RI) reprezintă echipamentele prin acţiunea programată în mediul virtual este realizată în mediul real. În acest caz, acurateţea modelului virtual al unui sistem de producţie este esenţială. Practic, trebuie recreat „geamănul digital" al fiecărui echipament real, implicit a RI. Lucrarea de faţă îşi propune să prezinte metodologia de implementare a RI în medii CAD-CAM şi utilizarea în aplicaţii de modelare a sistemelor de producţie. O implementare corectă a unui robot industrial într-un mediu virtual CAD-CAM implică modelarea atât a arhitecturii RI, a cinematicii acestuia, dar şi a echipamentului de comandă.*

Abstract. *New technologies, for digitizing economic entities, specific to the concept of Industry 4.0 cannot be put into practice without the use of numerically controlled equipment. Industrial Robots (IR) represent the equipment through the action programmed in the virtual environment is transferred in the real environment. In this case, the accuracy of the virtual model of a production system is essential. Practically, the "digital twin" of each real equipment, implicitly of RI, must be recreated. This paper aims to present the methodology for implementing IR in a CAD-CAM environments and its use in production system modeling applications. A digital twin IR definition consist in a correct modeling of robot features like architecture, controller, and kinematics.*

Keywords: CAD-CAM, Industrial Robots, Digital Twin, Kinematics

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1. Introduction

The current industrial systems can no longer perform in a dynamic market without an intensive digitization of each phase of production, administration, management, and marketing. Practically today we are talking about the evolution of production systems both from a real point and a virtual point of view. The real systems develop their digital twin in the same time with the transformations imposed by necessity of communication between the two environments: real-virtual.

A current industrial system must be able to download information from a CAD-CAM software (which defines the virtual environment) but also to upload data from the real environment to virtual environment [1].

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The data transfer to virtual environment it can be made with the help of different types of sensors as well as with the help of human operators, which effectively enters the data manually into specialized software.

Reversely, the things are a little more complicated, the data transfer from the digital environment to the real environment in industrial system of production is done by using numerically controlled equipment's that can act on the environment [2].

Thus, for the effective manufacturing phases, in digital era, the classical conventional machines and equipment are being replaced with numerically controlled equipment and machines, practically, almost all the manufacturing technologies (metal cutting, EDM, laser processing, plasma processing, water jet processing, plastic deformation, stamping etc).

For the serving of numerically controlled equipment in a mixed system real-digital industrial robot are used. There are different types of industrial robots architectures, the most common being the articulated arm robot with open or closed kinematic chains as well as the SCARA robots (Selective Compliance Assembly Robot Arm) (fig.1)

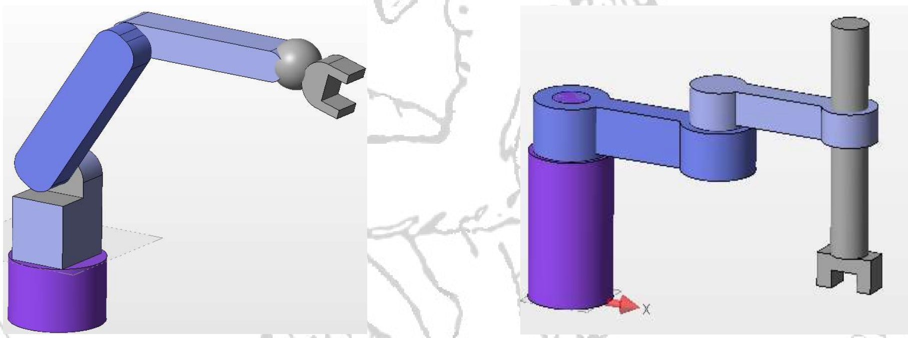

Fig. 1. Industrial Robots architecture

a. Articulated arm **b.** SCARA

The design of digital equipment's identical with the real ones represents the basis from where starts the digital twin industrial production system [5][6].

From the point of view of robotics, the creation of industrial robots under digital form in different CAD-CAM programming environments represents the basis from which to start the definition of industrial systems 4.0.

The high-level CAD-CAM software used for the creation of production systems (ex. Delmia, NX) as well as the dedicated ones developed by the production of industrial robots companies (ex. ABB Robot Studio) or independent (Ex. RoboDk) provide for the users databases with virtual models of industrial robots and peripherals equipment's, but also the possibility to implement CAD models and controllers for industrial robots defined by the users [7].

In this paper we aim to present the methodology for implementing an industrial robot architecture in a CAD-CAM software, namely DELMIA V5 as well as the mathematical knowledge and software required[6], [8].

2. The methodology for implementing industrial robot in CAD-CAM software.

The correct implementation of an industrial robot architecture in a dedicated CAD-CAM software involves a certain way of CAD modeling of the structural elements of the industrial robot (but not of the kinematic chains) as well as a certain way of defining the rotation and translation joints specific to the robot construction.

The knowledge of the software possibilities that is being used represents a major request for the correct implementation.

Also, the engineer must know the mathematical model for direct and inverse kinematics as well as the profile for accelerations and speeds specific to the industrial robot architecture addressed.

The general method of implementing industrial robot in CAD-CAM software can be described in the following steps:

Step 1. CAD modeling of the industrial robot assembly.

Step 1.1 The alignment of all the CAD components of the industrial robot according to the global reference system through translation and rotation operations. It is recommended that the reference system of each robot component to coincide with the global reference system.

Step 1.2 The simplification of the CAD model. It is recommended: the elimination of the internal components belong to industrial robot, the elimination of duplicate elements, embedding of the visible elements in a single 3D body for each of the industrial robot segment through Boolean operations. The results will be a file with relatively small dimensions and lower complexity which will allow a high quality animated simulation.

Step 2. Defining the rotation and translation joints in successive order starting from the universal coordinate system of RI (usually at the base) to the end-effector of RI. The RI tool-tip it is specified at the robot flange.

Step3. Modeling the kinematics of RI by implementing the specific mathematical model for the direct and inverse kinematics in a CAD-CAM software. In general, in high level CAD-CAM software (ex. DELMIA), for the classical architectures of RI there are databases with mathematical models already implemented. In the same time it is allowed the introduction of a new model. (see chapter 3)

Step 4. Defining the limits on each type of joint, maximum speeds and accelerations.

*Step 5.*Defining the profiles for the speed and acceleration.

3. The mathematical model, theoretical aspects

To position the industrial robot end-effector in the workspace it is necessary to describe the position in relation to a reference system [9]. The unanimously reference system used is the orthogonal cartesian system.

For noting a reference system$AX_AY_AZ_A$it will be used the notation$\{A\}$. The position of a point in relation to the reference system $\{A\}$it is localized through the position vector $\overline{{}^{A}P}$, respectively through the three cartesian coordinatesp_x, p_y, p_z.

The matrix can be written:

$$ {}^{A}P \Rightarrow \left[p_x; p_y; p_z\right]^T \tag{1} $$

For positioning a rigid solid relative to a reference system$\{A\}$, it is attached to the rigid (tool) a reference system$\{B\}$, invariably related to it (fig. 2). The determination of the rigid position in relation to the system$\{A\}$return to the accuracy of the system position$\{B\}$in relation to the reference system$\{A\}$.The system$\{B\}$it is completely localized in relation to the system$\{A\}$if it is known the position of the origin B given by the vector$\overline{AP}_{Boxg}$and the orientation of the axes$\bar{\imath}_B, \bar{\jmath}_B, \bar{k}_B$.

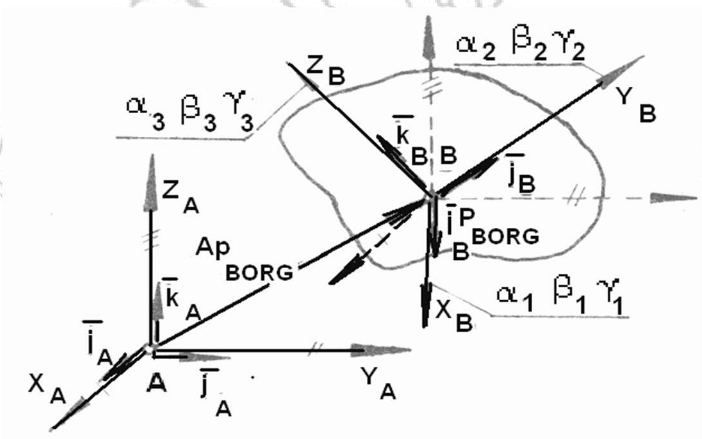

Fig.2 The positioning in relation to a reference system

Under matrix form the orientation is :

$$ {}_B^A[R]=\begin{bmatrix} \overline{i_B}\cdot\overline{i_A} & \overline{j_B}\cdot\overline{i_A} & \overline{k_B}\cdot\overline{i_A} \\ \overline{i_B}\cdot\overline{j_A} & \overline{j_B}\cdot\overline{j_A} & \overline{k_B}\cdot\overline{j_A} \\ \overline{i_B}\cdot\overline{k_A} & \overline{j_B}\cdot\overline{k_A} & \overline{k_B}\cdot\overline{k_A} \end{bmatrix} \tag{2} $$

Where:

${}_B^A[R]$ - it is the matrix that gives the orientation of the system$\{B\}$in relation to the system$\{A\}$.

The elements of the last matrix are the guiding cosines of the axes system$\{B\}$in relation to system$\{A\}$which according to figure 3.1 it can be written:

$$ {}_B^A[R]=\begin{bmatrix} \alpha_1 & \alpha_2 & \alpha_3 \\ \beta_1 & \beta_2 & \beta_3 \\ \gamma_1 & \gamma_2 & \gamma_3 \end{bmatrix} \tag{3} $$

Noting that:

$$ \alpha_i\alpha_j+\beta_i\beta_j+\gamma_i\gamma_j=\delta_{ij};\ \delta_{ij}=\begin{cases} 0 & \mathrm{i}\neq j \\ 1 & \mathrm{i}=j \end{cases} \tag{4} $$

The properties of matrix3allow the writing of the following relations:

$$ {}_B^A[R]^T={}_A^B[R];\quad {}_B^A[R]^T\cdot{}_A^B[R]=[I_3]; \tag{5} $$

$$ {}_B^A[R]={}_A^B[R]^{-1}={}_A^B[R]^T \tag{6} $$

Where:

${}_B^A[R]^T$ is the matrix transposed ${}_B^A[R]$;

$[I_3]$is the unit matrix 3x3

${}_A^B[R]^{-1}$ is the matrix reverse ${}_A^B[R]$

Restricted, the position of a system$\{B\}$in relation to the system$\{A\}$it is written:

$$ \{B\}=\left\{{}_B^A[R],\ A_{[P]\mathrm{BORG}}\right\} \tag{7} $$

3.1The transformation of the reference system

Translation

Let$\{A\}$ and$\{B\}$ be two reference systems having parallel axes. The position of a point P in relation with the two systems it is given by the vectors $\overline{^{B}P}$and$\overline{^{A}P}$. Between those two vectors there is the dependency relation:

$$\overline{^{A}P} = \overline{^{B}P} + \overline{^{A}P}_{BORG} \tag{8}$$

Rotation

Two reference systems are considered$\{A\}$and $\{B\}$having the same originand the position vector$\overline{^{B}P}$ of the point P (fig.3) registered in relation to the reference system$\{A\}$. Let$^{A}_{B}[R]$ be the transition matrix from the system $\{B\}$to the system$\{A\}$.

The position of the point P in relation to the system$\{A\}$it is given by the position vector

$$^{A}[P]=^{A}_{B}[R]^{B}[P] \tag{9}$$

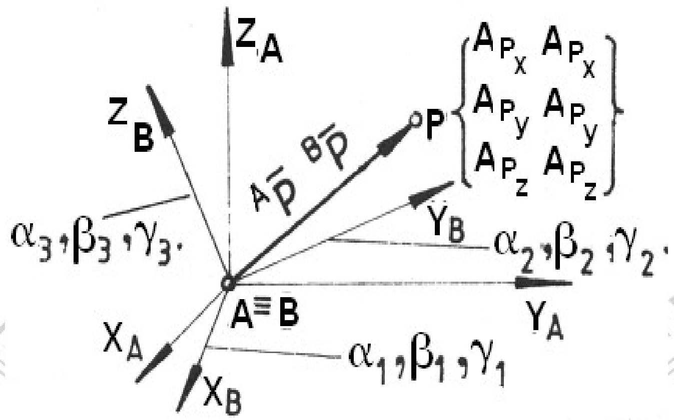

Fig.3 Rotation in relation to a reference system

$$\begin{pmatrix} ^{A}P_x \\ ^{A}P_y \\ ^{A}P_z \end{pmatrix} = \begin{pmatrix} \alpha_1 & \alpha_2 & \alpha_3 \\ \beta_1 & \beta_2 & \beta_3 \\ \gamma_1 & \gamma_2 & \gamma_3 \end{pmatrix} \cdot \begin{pmatrix} ^{B}P_x \\ ^{B}P_y \\ ^{B}P_z \end{pmatrix} \tag{10}$$

Where:

${}^{A}P_x$, ${}^{A}P_y$, ${}^{A}P_z$represents the projections of the position vector $\overline{{}^{A}P}$ (the coordinates of the point P) in relation to the system$\{A\}$;

${}^{B}P_x$, ${}^{B}P_y$, ${}^{B}P_z$are the projections of the position vector $\overline{{}^{B}P}$ (the coordinates of the point P) in relation to the system$\{B\}$;

α_i, β_i, θ_i (i=1..3) the guiding cosines of the system's axes$\{B\}$in relation to$\{A\}$.

The general transformation of the reference systems

Let point P be positioned in relation to the system $\{B\}$through the vector $\overline{{}^{B}P}$. It is required the position of the point in relation to the system$\{A\}$, ($\overline{{}^{A}P}$), knowing the position of the system$\{B\}$in relation to the system$\{A\}$. (fig. 4).

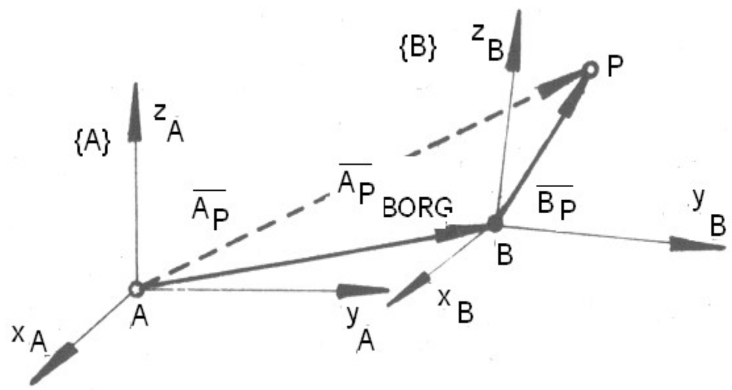

Fig.4 The general transformation of a reference system

Solving the problem is reduced at two changes (transformations) of the reference system.$\{B\}$. It is considered at the beginning that the two reference systems$\{A\}$and$\{B\}$have the same origin but they are rotated relative to each other, the rotation matrix being ${}^{A}_{B}[R]$.

According to relation (10)the position of point P in the system$\{A\}$will be given by the vector $\overline{{}^{A}P}$.

$$\overline{{}^{A}P'} \Rightarrow {}^{A}_{B}[R] \cdot {}^{B}[P] \tag{11}$$

It is translated then the reference system$\{A\}$in the position given by the vector $\overline{{}^{A}P}_{BORG}$, in relation to point A. The position vector of point P in relation to system$\{A\}$, it is:

$$\overline{{}^{A}P} = \overline{{}^{A}P'} + \overline{{}^{A}P}_{BORG} \tag{12}$$

Depending on the relations(11) and(12)it can be written the matrix relation:

$$\begin{pmatrix} {}^{A}P_x \\ {}^{A}P_y \\ {}^{A}P_z \end{pmatrix} = \begin{pmatrix} \alpha_1 & \alpha_2 & \alpha_3 \\ \beta_1 & \beta_2 & \beta_3 \\ \gamma_1 & \gamma_2 & \gamma_3 \end{pmatrix} \cdot \begin{pmatrix} {}^{B}P_x \\ {}^{B}P_y \\ {}^{B}P_z \end{pmatrix} + \begin{pmatrix} {}^{A}X_B \\ {}^{A}Y_B \\ {}^{A}Z_B \end{pmatrix} \tag{13}$$

By using homogeneous coordinates to express a vector (x,y.z,1), respectively homogeneous transformations, the matrix expression (13) it can be written in the form:

$$\begin{pmatrix} {}^{A}[P] \\ \\ -- \\ 1 \end{pmatrix} = \begin{pmatrix} {}^{A}_{B}[P] & & ! & {}^{A}[P] \\ & & ! & \\ -- & -- & -- & -- \\ 0 & 0 & 0\,! & 1 \end{pmatrix} \tag{14}$$

Developing the relation (14)it is obtained:

$$\begin{pmatrix} {}^{A}P_x \\ {}^{A}P_y \\ {}^{A}P_z \\ -- \\ 1 \end{pmatrix} = \begin{pmatrix} \alpha_1 & \alpha_2 & \alpha_3 & {}^{A}x_B \\ \beta_1 & \beta_2 & \beta_3 & {}^{A}x_B \\ \gamma_1 & \gamma_2 & \gamma_3 & {}^{A}x_B \\ -- & -- & -- & -- \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} {}^{B}P_x \\ {}^{B}P_y \\ {}^{B}P_z \\ -- \\ 1 \end{pmatrix} \tag{15}$$

Where:

${}^{A}x_B$, ${}^{A}y_B$, ${}^{A}z_B$represent the coordinates of the system's origin$\{B\}$in relation to the system$\{A\}$.

${}^{B}P_x$, ${}^{B}P_y$, ${}^{B}P_z$are the coordinates of the point P in relation to the system$\{B\}$.

The matrix

$$\begin{pmatrix} \alpha_1 & \alpha_2 & \alpha_3 & {}^{A}x_B \\ \beta_1 & \beta_2 & \beta_3 & {}^{A}x_B \\ \gamma_1 & \gamma_2 & \gamma_3 & {}^{A}x_B \\ & & & \\ 0 & 0 & 0 & 1 \end{pmatrix} = {}^{A}_{B}[T] \tag{16}$$

It is an operator that corresponds to the general transformation from the system$\{B\}$to the system$\{A\}$.

3.2Homogeneous simple operators for transformations

Translation operators

The general operator [29] the case of some translations related to the cartesian system's axes has the form:

$$\text{Translation along Ax axis}\begin{pmatrix} 1 & 0 & 0 & {}^{A}x_B \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{18}$$

$$\text{Translation along Ay axis}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & {}^{A}y_B \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{19}$$

$$\text{Translation along Az axis}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & {}^{A}z_B \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{20}$$

Rotation operators

$$\text{Rotation around Ax axis}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c\theta & -s\theta & 0 \\ 0 & s\theta & c\theta & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{21}$$

$$\text{Rotation around Ay axis}\begin{pmatrix} c\theta & 0 & s\theta & 0 \\ 0 & 1 & 0 & 0 \\ -s\theta & 0 & c\theta & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{22}$$

$$\text{Rotation around Az axis}\begin{pmatrix} c\theta & -s\theta & 0 & 0 \\ s\theta & c\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad (23)$$

Where $c\theta = \cos(\theta)$ and $s\theta = \sin(\theta)$

4. Mathematical model for the SCARA architecture

One method of approaching the indutrial robots kinematics is the matrix method.To use this method it is necessary to know the Denavit-Hartenberg parameteres, associated with the attaching of a coordinate system to each kinematic joint of an industrial robot. The arrangement of the axes that belong to the coordinate system is made with the following particularities: the z_i axis is always oriented on the direction of the respective joint, the x_i axis is always oriented from the z_{i-1} axis to the z_i axis, being in the extension of the common perpendicular between the two axes and the y_{i-1} is chosen according to the rule of the right hand.

The coordinate system i-1 it can be related to the coordinate system i with the help of the following conditions:

1. It rotates the system i-1 around z_{i-1}axiswith the angle$\theta_i$until the x_{i-1}axis becomes parallel with the x_i axis;
2. It translates the system rotated around the z_{i-1}axis with the lengthuntil the x_{i-1} si x_i axisit is places on the same line;
3. It translates along $x_i$axis with the length $a_i$until the coordinate axis coincide;
4. It rotates around x_i axiswith the angle α_i until it overlaps z_{i-1}axiscu z_i axis.

The use of the matrix method and implicitly the Denavit-Hartenberg algorithm involves the analysis of 4 parameters that determine the transformations between the reference systems : the distance between the origin of the previous coordinate system and the origin of the new coordinate system, along the z axis (d_i), the angle of rotation around the z axis to align the x_{i-1} axis with the $x_i$axis (θ_i), the distance between the origin of the previous coordinate system and the distantce of the new coordinate system along the x axis (l_i), the rotation angle around x axisfor align $z_{i-1}$and z_i axis (fig.5).

If $z_{i-1}$and z_i axis are parallel they have an infinte number of common normals, thus the distance (d_i) between the origin of the previous coordinate system and the origin of the new coordinate system, along the z axis is a free parameter and you can choose any convenient d_i.

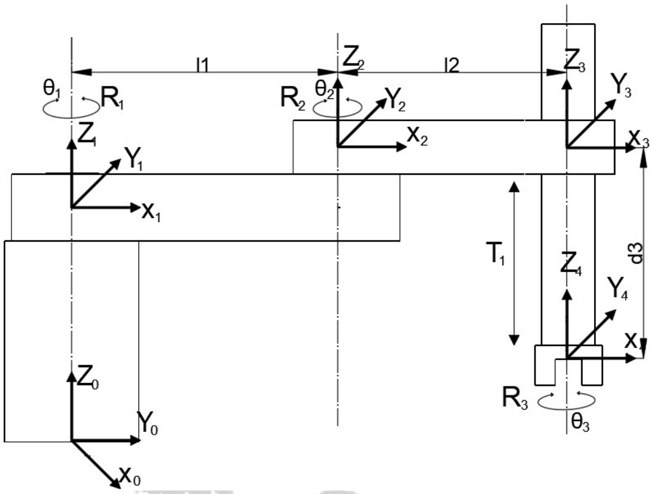

Fig. 5 The coordinate system chosen for SCARA arhitecture

The calculations of the kinematics necessary for modeling the behaviour of the RI are performed regarding the mathematical model presented previously and applied to the specific kinematics of RI(SCARA) using the notations from fig. 5. The matrices corresponding to the alignment of the coordinate system axes attached to each joint of the industrial robot are:

$$ {}_1^0[T] * {}_2^1[T] * {}_3^2[T] * {}_4^3[T] = $$

$$\begin{bmatrix} c\theta_1 & -s\theta_1 & 0 & 0 \\ s\theta_1 & c\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} c\theta_2 & -s\theta_2 & 0 & l_1 \\ s\theta_2 & c\theta_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & l_2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c\theta_4 & -s\theta_4 & 0 & 0 \\ s\theta_4 & c\theta_4 & 0 & 0 \\ 0 & 0 & 1 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} =$$

$$\begin{bmatrix} c\theta_{124} & -s\theta_{124} & 0 & l_1c_1 + l_2c_{12} \\ s\theta_{124} & c\theta_{124} & 0 & l_1s_1 + l_2s_{12} \\ 0 & 0 & 1 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (24)$$

5. Case study of industrial robot SCARA-DUARO1 implementation in DELMIA

5.1 Technical specifications DUARO

The DUARO industrial robot enables humans and robots to work together in the same workspace.With it’s two co-axial arms, DUARO cand fit into a single-person space and provides a wide collaborative working range. The wheeled base that accommodates the arms and controller enables the user to move the robot to any location. In the event of a collision with the worker, the collision detection function will stop the DUARO safely. In adition, the soft materials on the arm surfaces also reduces shocks.

Table 1 shows the technical specifications of the DUARO1 industrial robot.

Table 1

Arm	Joint	Travel	Speed	Acceleration
1	Arm rotation(JT1)	-170° ~ +170°	420 °/s	3.665 rad/s^2
	Arm rotation(JT2)	-140° ~ +140°	780 °/s	3.665 rad/s^2
	Arm up-down(JT3)	0mm ~ +150 mm	1.2m/s	3.3 m/s^2
	Wrist swivel(JT4)	-360°~ +360°	3000 °/s	3.665 rad/s^2
2	Arm rotation(JT1)	-140°~ +500°	420 °/s	3.665 rad/s^2
	Arm rotation(JT2)	-140°~ +140°	780 °/s	3.665 rad/s^2
	Arm up-down(JT3)	0mm ~ +150 mm	1.2 m/s	3.3 m/s^2
	Wrist swivel(JT4)	-360°~ +360°	3000 °/s	3.665 rad/s^2

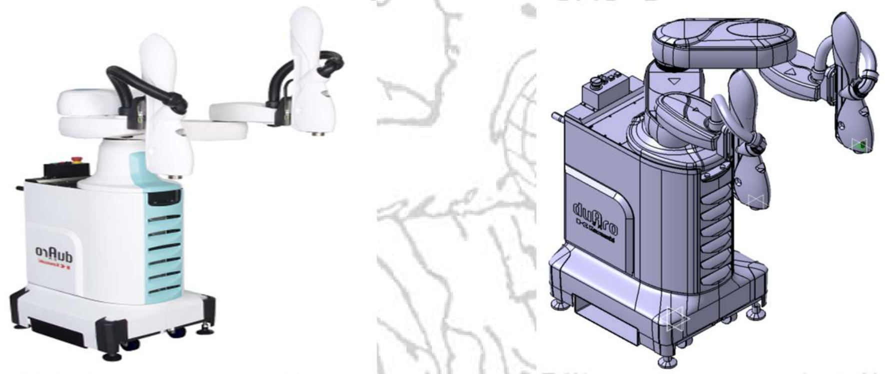

Fig.6 DUARO1 robot [4].
a-model RI b-CAD model of RI

5.2 The modelling of the digital twin DUARO1

For the CAD modelling of the DUARO1 industrial robot (fig. 6), all its components were aligned according to the global reference system through specific rotation and translation techniques. Thus, every reference system of each component should coincide with theglobal system of the assembly, except for the output flange of the orientation system of industrial robot.

For the implementation in DELMIA in order to simulate and program the DUARO1 robot, it was necessary to introduce a new model, as it does not exist in the program library. The DUARO1 robot was divided in 2 parts: arm1 and arm2.

In this sense, the following steps were performed:

1. Creating a new product and introducing the components related to a single arm of the robot.
2. Creating a new mechanism and defining the rotation and translation joints (fig. 7).

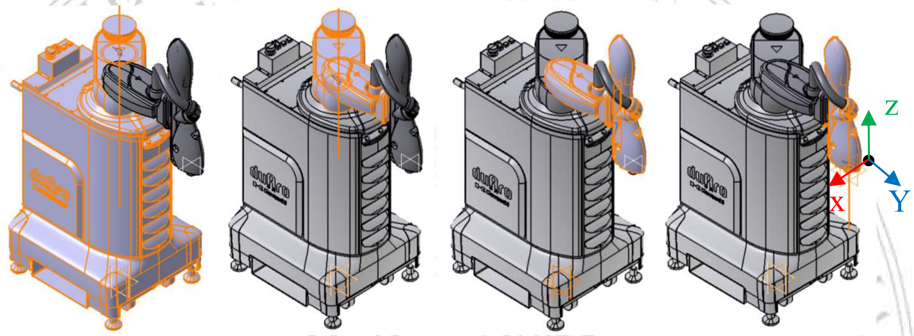

Fig. 7 Defining the translation and rotation joints

3. Defining the limits on each joint to avoid colisions an speed and acceleration on each joint (fig.8).

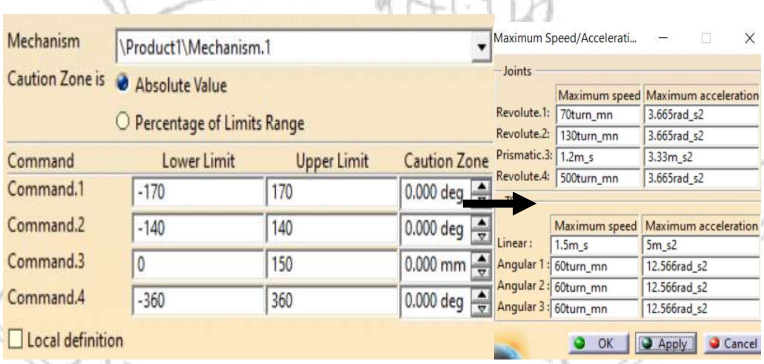

Fig. 8 Defining the limits on each joint

4. Setting the atributes for reverse kinematics.

To set the attributes, choose the robot flange for the „Mount Part” and the tool-tip for the Mount offset” and the base of the robot as „Reference Part”, respectively „Base Part”, then chosen solver type being „Numeric inverse”(fig. 9).

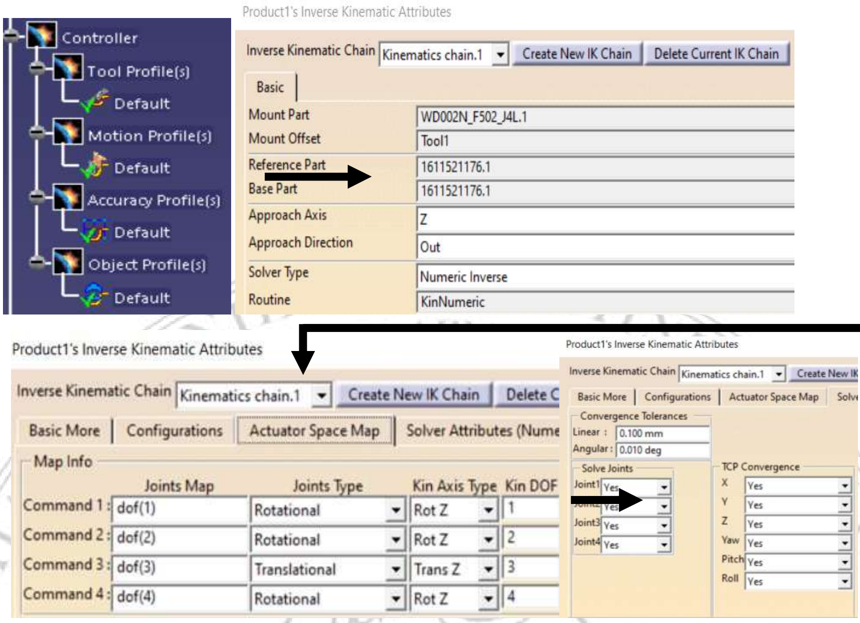

Fig. 9 Setting the atributes for inverse kinematics

5.4 Simulation and programmingof DUARO1

To simulate and program the industrial robot (fig.10), choose from the „Device Task Definition" window, in which was introduced the robot implemented previously, the „Teach a device" option and then „Create a new task". Further, different points are inserted by moving the robot, thus being created a work cycle.

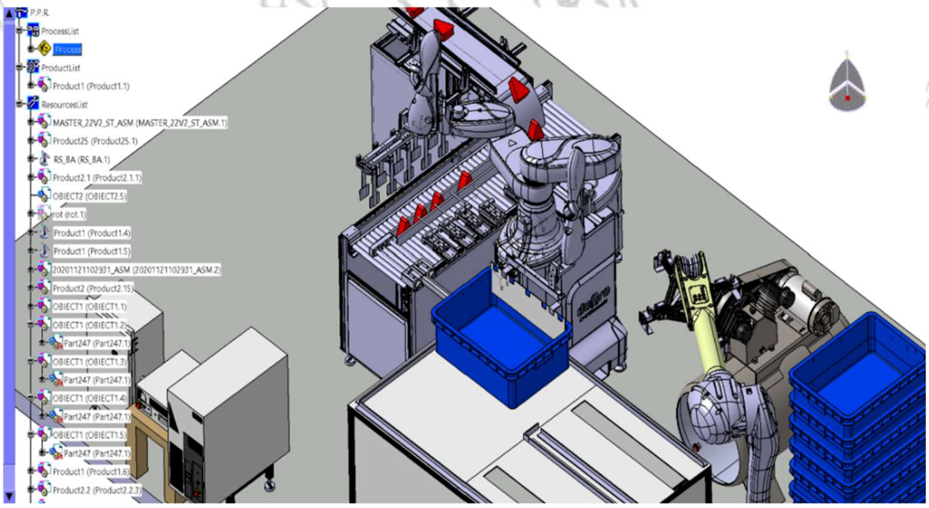

Fig. 10 The steps for creating a work cycle

Conclusions

The digitalization of manufacturing process is the first step to maximize the efficiency of a production system, but this involves a lot of resources.

CAD-CAM software's has evolved to allow the end-user to digitize their activities in production chain starting from scratch. An application in this area involves: CAM technologies and a standard workflow, develop a digital twin machines and robots with flexible and adaptive postprocessors, a DNC (direct NC communication), MDC (manufacturing data collection) and PDM (product data management) software solution.

The study case presented in this paper show a methodology for Industrial Robot digitization in an advanced CAD-CAM software used in top industry field.

Basic math knowledge is necessary for kinematic profile of robot emulation for accurate simulation and postprocessor development.

Using a digital twin production system in a virtual environment allows checking different scenario flow by simulation, validate the optimum workflows and automatically generate the system programs.

Notations and/or **Abbreviations**

$\{A\}$ reference system$AX_AY_AZ_A$;
$\{B\}$ reference system.
$\overline{^AP}$ position vector.
p_x, p_y, p_z cartesian coordinates.
$\bar{i}_B, \bar{j}_B, \bar{k}_B$ vectors for the orientation of the axes.
${}^A_B[R]$ the matrix which gives the orientation of the system$\{B\}$in relation to the system$\{A\}$;
$\alpha_i, \beta_i, \gamma_i$ the guiding cosines of the system axes$\{B\}$in relation to the system.
${}^A_B[R]^T$ the transpose of the matrix ${}^A_B[R]$;
$[I_3]$ unit matric 3x3;
${}^B_A[R]^{-1}$ the reverse of the matrix ${}^B_A[R]$;
$\overline{^BP}$ position vector of the point P in relation to the reference system$\{A\}$;
${}^AP_x$, ${}^AP_y$, ${}^AP_z$the projections of the position vector $\overline{^AP}$ (coordinates of the point P) in relation to the system$\{A\}$;

${}^{B}P_x$, ${}^{B}P_y$, ${}^{B}P_z$projections of the position vector $\overline{{}^{B}P}$ (coordinates of the point P) in relation to the system$\{B\}$;

α_i, β_i, θ_i (i=1..3) the guiding cosines of the system axes $\{B\}$in relation to the system$\{A\}$;

${}^{A}x_B$, ${}^{A}y_B$, ${}^{A}z_B$represent the coordinates of the system's origin$\{B\}$in relation to the system$\{A\}$;

${}^{B}P_x$, ${}^{B}P_y$, ${}^{B}P_z$ coordinates of the pointin relation to the system$\{B\}$;

$c\theta$ $\cos(\theta)$;

$s\theta$ $\sin(\theta)$;

$v\phi$ $1 - \cos\phi$;

γ rotation angle around$x_A$axis;

β rotation angle around y_A fixed axis;

α rotation angle around z_A fixed axis;

ψ precession angle;

θ nutated angle;

ϕ own rotation angle;

l_1, l_2 length between the origin of the previous coordinate system and the distance of the new coordinate system along the x axis;

d_3 length between the origin of the previous coordinate system and the origin of the new coordinate system, along the z axis.

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