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Methodology for performance assessment of industrial robots

Daouda CAMARA [1, 2, *], Fadaba DANIOKO [1, 2], Bourama COULIBALY [3] and Mamadou DANSOKO [1]

[1] *Computing and Modeling Center, Faculty of Sciences and Techniques of Bamako, University of Sciences, Techniques and Technologies of Bamako (USTTB), Bamako, Mali.*
[2] *Artificial Intelligence and Robotics Center in Mali (AIRC-Mali).*
[3] *Electrical Engineering Department, Normal School of Technical and Vocational Education, Bamako, Mali.*

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Abstract

The study of industrial robots is particularly interesting in view of the many advantages that these robots offer in the production line. This paper aims to study manipulator arms in order to better understand the performance of manipulator arms. The recurring issue for the manipulator arms remains the analysis of their operating path patterns in a well-defined working space. We propose a methodology based, on the one hand, on the definition of the functional specifications of manipulator arms necessary for design and on the other hand, on the geometric modelling and control of these manipulator arms in Matlab/Simulink. The model thus constructed is capable of reproducing different trajectory configurations depending on the joint variables in a well-defined working space. The results of our model are consistent with those provided by the mathematical model using the Denavit-Hartenberg convention. According to two scenarios, the analysis of the trajectories of the manipulator arms's end effector is carried out and especially on the SCARA, cartesian and spherical robots. This analysis generally reveals elliptic trajectories or lines described by the end effector of robots in relation to the plane linked to their base.

Keywords: Geometric modeling; Performance; Trajectory; Workspace; Simulation

1. Introduction

The history of the industry has seen many changes: from handicrafts requiring enormous effort by workers with high risks of injury or death, to continuous work in a semi-automatic or automatic mode of operation requiring more complex machines and a fairly rigorous control procedure. By pushing this automation to have an increasingly higher productivity, the manufacturers have finally moved towards robotization of certain parts of their installations that require monitoring and precision.

Indeed, people is by nature weak in terms of strength and sorely lacking in precision when performing repetitive tasks. The advent of industrial robots in the industrial chain has remedied both these gaps in human.

However, the deployment of industrial robots to ensure industrial activity requires a better knowledge of the robot's architecture, control and mastery of motion paths and task planning in the dedicated workspace. To do this, an important step for the study and the understanding of robots is the modeling. Among the types of modeling, we will use geometric modeling (direct and indirect) capable of providing in real time the positions of the end effector as a function of joint variables and vice versa.

* Corresponding author: Daouda CAMARA

On the one hand, it is a question of developing the functional specification to validate the design study and on the other hand with different configurations of paths, how to control and evaluate the position of the end effector in the dedicated workspace?

Indeed, Robotic manipulators are complex systems made up of rigid links connected by joints and designed to operate like a human arm, but with increased strength and payload capacity [1].

Currently, the growing demand for complex manipulations and the evolution of devices such as multi-finger effectors and multi-foot platforms has generated a wide field of research in the study of robotic systems. However, the centerpiece of these systems is the robot manipulator.

Indeed, understanding the complexity of robots and their applications requires knowledge in mechanical engineering, electrical engineering, systems and industrial engineering, computer science, economics, and mathematics [2]. Thus, in the literature, we can group the work into seven points:

The first point deals with the modeling and control of manipulator arms with an identification and control approach [3,4,5,6], or the modeling and design of the robot components (for example, the gripper) [7,8,9,10] or the study and realization of the arms [11,12].

The second point concerns the analysis of mobile robot movements, whether in terms of the computer vision [13,14], or the robot movement performance (detection, obstacle avoidance, moving speed) [15,16].

The third point is based on the study of robot design approaches according to the choice of materials, the synthesis of control laws for the generation of mobile trajectory and the regulation of this trajectory, the control of the speed of the driving wheels [17,18].

The fourth point concerns the practical implementation of mobile robots via a practical realization of mobile robots [19,20,21,22,23].

The fifth point assesses the performance of robot manipulators in terms of accuracy. Among performance indicators such as accuracy, payload, etc., repeatability is the most widely discussed, due to its simplicity [24,25,26,27,28].

The sixth point addresses the control of remote manipulator arms, via IP networks, by algorithms [29,30,31,32,33].

There are, of course, some works that are closer to our study of manipulator modeling, notably those by [34] , but which used the finite element method, based on the theory of bending beams. We note that not all these works deal with performance evaluation in terms of positioning and orientation of the end effector in the workspace, by identifying the robot's trajectory configurations. The remainder of this paper is organized as follows: the second section deals with our proposed approach, the third section deals with the results from our approach and validation discussions, and the final section provides the conclusion and perspectives to this work

2. Material and methods

We propose an approach based on a general study of the mathematical modeling of industrial robots and a definition of the rules for transition to modeling in Matlab/Simulink, in order to dynamically understand the robot's behavior in the dedicated workspace. A detailed analysis of robot motion will be carried out according to the scenarios, to identify the configurations of paths respecting the singularities.

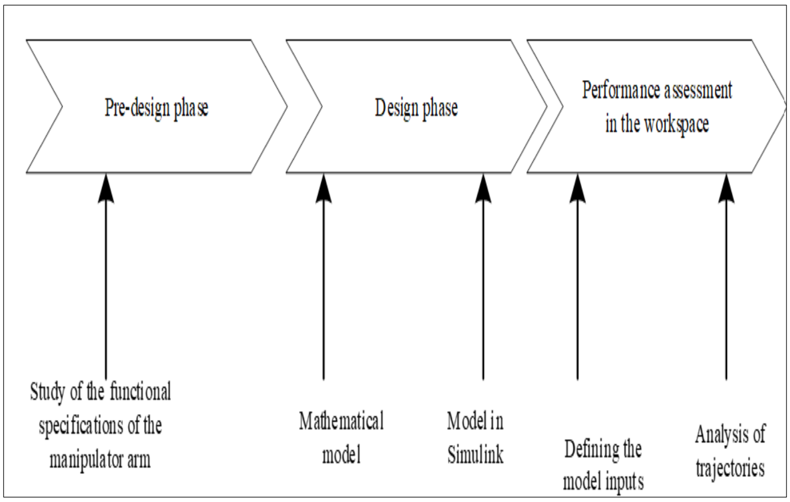


Figure 1 Overview of our approach

2.1. Study of the functional specifications of the industrial robot

We're going to carry out a general functional analysis of the use of industrial robots. To do this, we use the APTE method (figure 2), the Octopus diagram (figure 3) and the FAST diagram (figure 4).

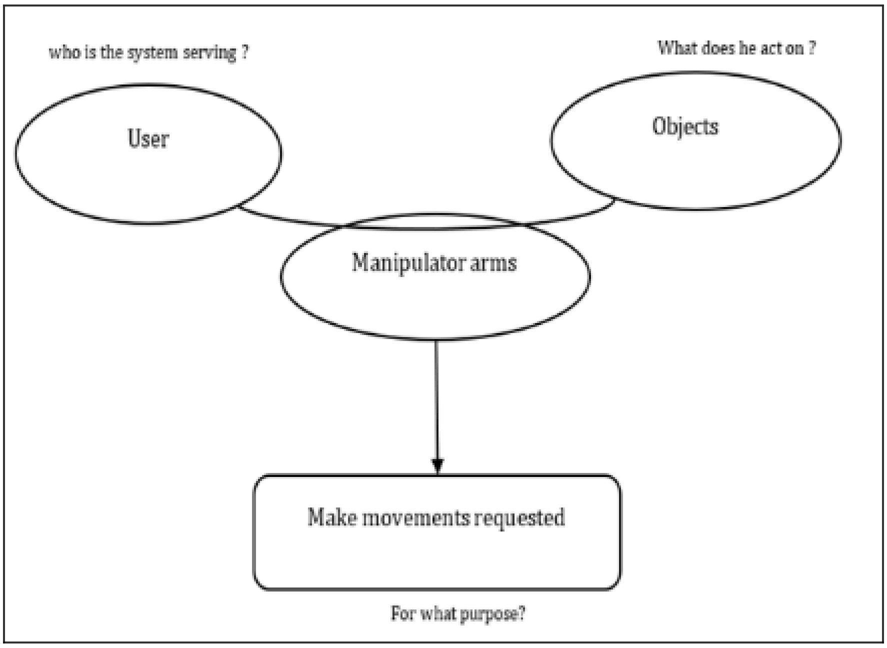


Figure 2 Horned beast diagram

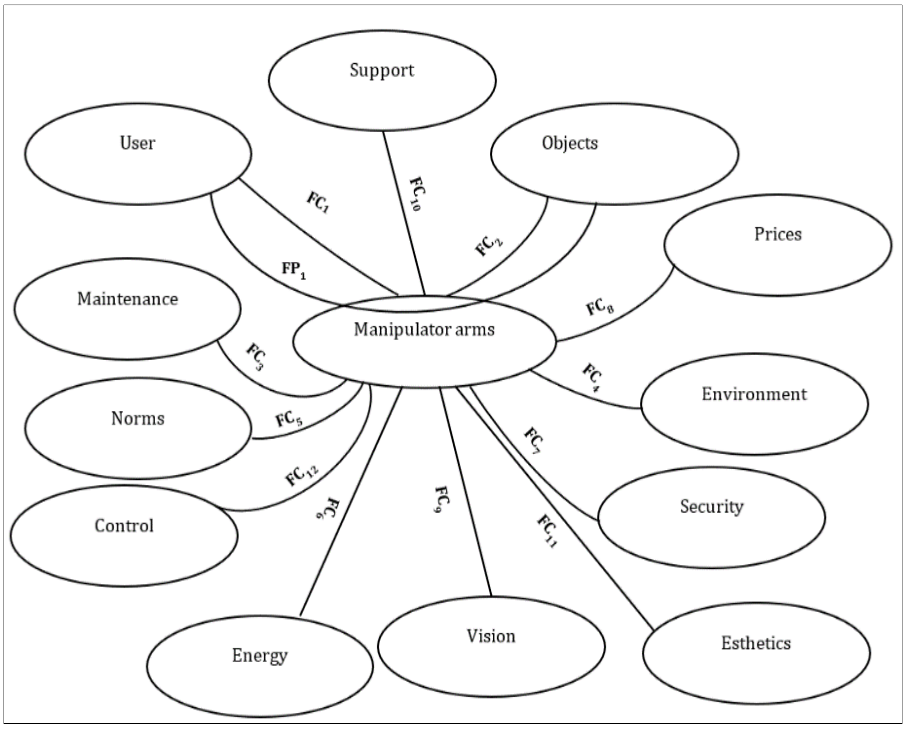


Figure 3 Octopus diagram in the project design phase

Service functions are classified into main functions (MF) and constraint functions (CF). The table below lists the service functions identified for the manipulator arm to be studied.

Table 1 Octopus diagram function

Service functions	Criteria	Levels
FP1: Move an object	Work envelope	700mmx700mmx450mm
	Maximum acceleration	5 m/s^2
	Velocity maximum	0.6 m/s
	Accuracy	∓ 0.5 mm
FC1: Being able to manipulate from a distance	Putting the robot into service	Manual, automatic
FC2: Carrying Mass items	Weight of the object	≤ 3 Kg
FC3: Facilitate maintenance operations	Curative and preventive maintenance	Easy assembly and disassembly
FC4: Respect for the environment	Recyclage	Use of recyclable materials
FC5: Respect the standards	Safety standards	ISO and AFNOR
FC6: Have autonomy in electrical energy	Type of generator	12V electrical energy
	Type of technology	Any technology that can provide power
FC7: Do not deform the object	Security of the object	No fingerprints on the object
FC8: Sell at an affordable price	Total price of the robot	Reasonable cost
FC9: Identify the positions of objects in space	Position sensors	Automatic
FC10: Fix to a support	Method of attachment of the object	Minimum: one side

FC11: Be aesthetic	Overall dimensions (shape)	Dimensions compatibles
	Colour	Must be attractive to be marketed
FC12: Control the system	Steering the robot	Simple control with motion display

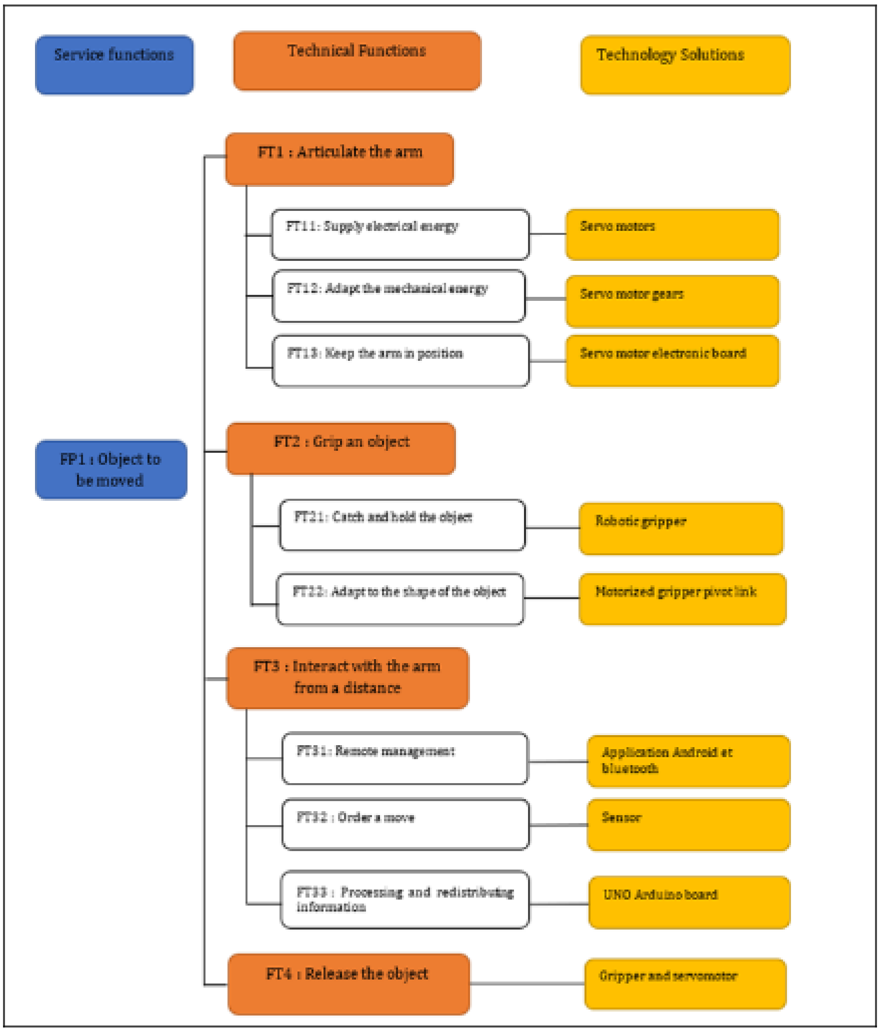
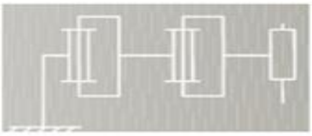
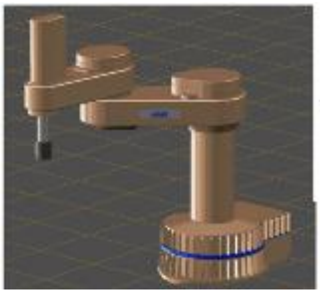
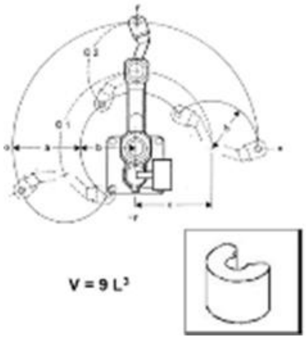
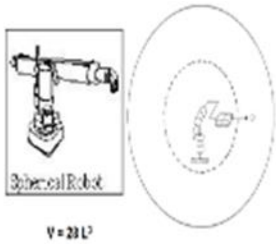
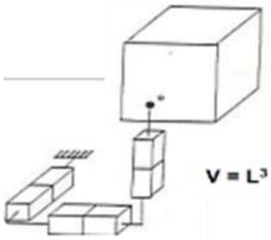


Figure 4 FAST diagram

2.2. Modeling and control of manipulator arms

Robot performance assessment in the context of our study here is based on (a) the classification of industrial robots, in particular manipulator arms, according to the number of joints, number of degrees of freedom, payload, accuracy and simplified kinematic diagram (table 2); (b) the geometric configurations of the end-effector trajectory in the workspace.

Table 2 Classification of industrial robots studied

SCARA Robot : Selective Complice Articulated Robot for Assembly Three(03) axes, series, RRP,3ddl ; Cylindrical workspace ; Accurate, very fast	 	
Spherical robot :: Three-axis, serial, RRP, 3 ddl; Spherical workspace; Large payload	  	
Cartesian robot: Three axes perpendicular two by two, serial, PPP, 3 ddl; Perfect accuracy; Slow.	 	

In order to control or simulate a robot in a well-defined workspace with the desired performance, a mathematical model is needed to give the designer a better understanding of the robot's behavior. Several types of mathematical modeling (geometric, kinematic and dynamic models) are applicable, depending on the objectives, the constraints of task and the performance sought.

In our study, we will restrict ourselves to the geometric model (direct and indirect) to determine the position of the end effector as a function of our robot's joint variables.

Then, in the geometric model, the position and orientation (laying) of the end effector are linked to the variables joints $q = (q_1,\ q_2, \ldots,\ q_n)$ the mechanical structure in relation to a reference frame (usually one of the two ends: the base or the end effector).

Joint variables can also be expressed as a function of end effector position

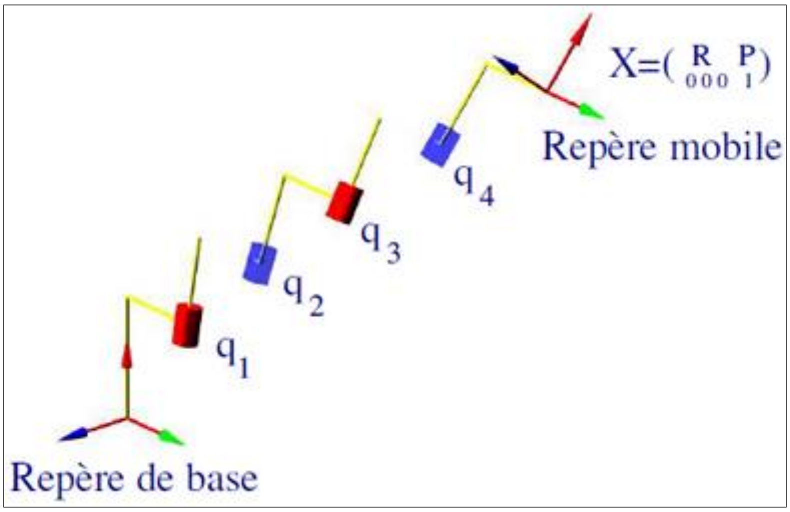


Figure 5 Direct geometric model representation [34]

Direct Geometric Modeling (DGM)

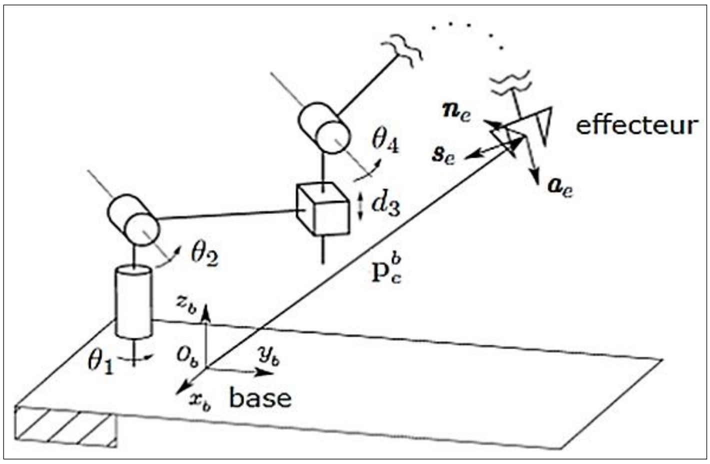


Figure 6 Example of a robot representation with n joint variables

With respect to the reference frame O_b, x_b, y_b, z_b , the direct geometric model is expressed by the matrix of homogeneous transformation:

$$T_e^b(q) = \begin{bmatrix} n_e^b(q) & s_e^b(q) & a_e^b(q) & p_e^b(q) \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{.....................(1)}$$

n_e^b, s_e^b, q_e^b : Unit vectors of the reference frame exprimed with respect to the base.

p_e^b : vector describing the origin of the end effector relative to frame of reference the base

$q \in \mathbb{R}^n$: vector of the variable

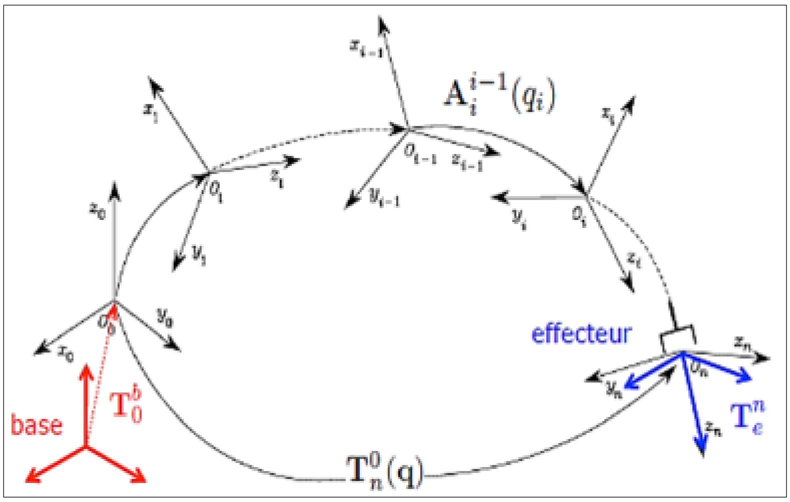


Figure 7 Association of frames with articular variables

$$T_n^0(q) = A_1^0(q_1) \times A_2^1(q_1) \ldots A_n^{n-1}(q_n) \quad \ldots\ldots\ldots\ldots(2)$$

In general terms, the effective coordinate transformation that describes the laying of the end-effector with respect to the base is given by :

$$T_n^0(q) = T_0^b \times T_n^0(q) T_e^n \quad \ldots\ldots\ldots\ldots\ldots(3)$$

T_0^b : Transformation matrix (constant) describing the position of the 0 frame relative to the base

T_e^n : Transformation matrix (constant) describing the position of the end-effector frame.

The product of the matrices leads to the following expression for the transformation ${}^{i-1}T_i$ expressed in the reference frame R_{i-1} :

$$ {}^{i-1}T_i = \begin{bmatrix} C\theta_i & -S\theta_i C\alpha_i & S\theta_i S\alpha_i & a_i C\theta_i \\ S\theta_i & C\theta_i C\alpha_i & -C\theta_i S\alpha_i & a_i S\theta_i \\ 0 & 0 & C\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} {}^{i-1}R_i & {}^{i-1}O_i \\ 0^T & 1 \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots(4)$$

The sub-matrix (3×3) supérieure gauche est la rotation ${}^{i-1}R_i$.

The last column (first 3 components) is the translation vector between the origins: ${}^{i-1}O_i = \overrightarrow{O_{i-1}O_i}$ Inverse Geometric Modeling.

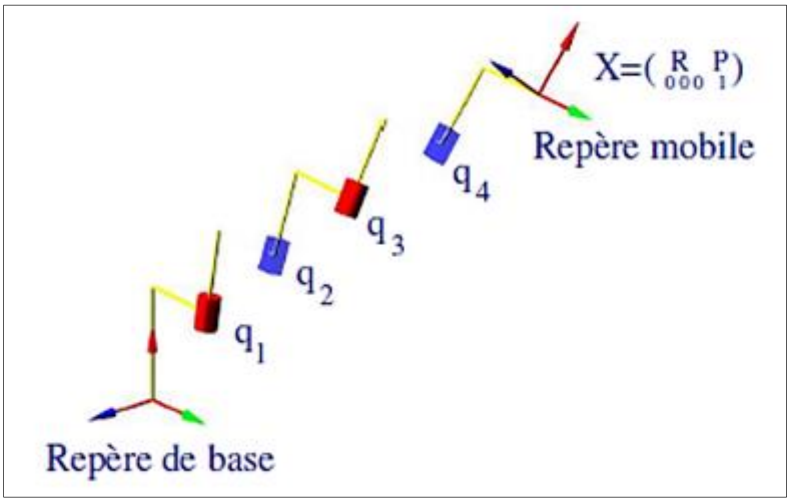


Figure 8 Representation of the inverse geometric model [34]

Determine: $\left[q_1, q_2, \ldots, q_n\right] = F_{MGI}\left(X, \zeta\right)$ with ζ the geometric parameters (parameters that define the series robot geometry).

The MGI calculates joint coordinates based on operational coordinates, and is written as:

$$q = f^{-1}\left(X\right) = g\left(X\right) \quad \ldots\ldots\ldots\ldots\ldots (5)$$

3. Results and discussion

3.1. Matlab/Simulink modeling and control of arms (SCARA, Cartesian robot, spherical robot)

In this section, we will validate the analytical results obtained from the mathematical model with the model designed in the SIMULINK environment.

To do this, we define the input data for our model, which are the number of joint variables, the values of rotation angles and/or translation (displacement) of each joint variable, and the length of segments (arms). The model's output should provide different configurations of paths depending on the variation of the joint variables, and vice versa.

After the input data is provided to the model, it will be transcribed into Matlab code. This transcription into code will allow us to automate and simulate the output data. The approach will be applied to application cases, in particular SCARA, spherical, Cartesian robots because of their specificities and practical interests. The geometric model of these robots are based on the formalism of Denavit-Hartenberg

Finally, an analysis of the trajectories will be made to assess the performance of these robots and to identify similarities in behaviour. So, several scenarios were made by fixing a joint variable and varying the other variables in each of the planes of space.

3.2. Analysis of results

To better evaluate the robot trajectories, we run several scenarios:

- Scenario1: a progressive variation at constant step of one of the articulars and fixing the other nulles ;
- Scenario2: a simultaneous variation of all joint variables.

To do this, a database on the position and orientation of the terminal organ is extracted from the Matlab simulation environment by varying the joint variables as described in the previous scenarios.

An analysis of this database according to the XY plane associated with the robot base allows us to understand the nature of the trajectories of the terminal organ following this plane.

3.3. Case studies

3.3.1. Case 1: SCARA robot

For the SCARA model, the input data are segment (body) dimensions, joint variables:
$q_1 = \pm 180, q_2 = \pm 180, d_3 = 100, q_4 = \pm 180$

The program associated with this Matlab model is described as follows :

```
% D-H parameters :

%theta i

theta1=180;

theta2=180;

theta3=0;

theta4=0;

%di

d1=363;

d2=0;

d3=100;

d4=0;

%ai

a1=300;

a2=260;

a3=0;

a4=0;

%alpha

alpha1=0;

alpha2=180;

alpha3=0;

alpha4=0;

L1=Link([theta1,d1,a1,alpha1,0]);

L2=Link([theta2,d2,a2,alpha2,0]);
```

```
L3=Link([theta3,d3,a3,alpha3,1]);

L3.qlim=[0 d3];

L4=Link([theta4,d4,a4,alpha4,0]);

scara=SerialLink([L1 L2 L3 L4], 'name', 'SCARA');

scara.plot([0 0 0 0])

scara.teach
```

The parameters are listed in the following table.

Table 3 Denavit Hartenberg parameters for the SCARA robot

SCARA 4 axis, RRPR, stdDH, slowRNE					
J	**theta**	**d**	**a**	**alpha**	**offset**
1	q1	363	300	0	0
2	q2	0	260	180	0
3	0	q3	0	0	0
4	q4	0	0	0	0

With the input data supplied to the model, the implementation of the program gives us the following figure, which describes the position and orientation of the end effector in the defined workspace according to the values of the joint variables.

By varying the joint variables, you can simulate different robot trajectory configurations with their positions and orientations.

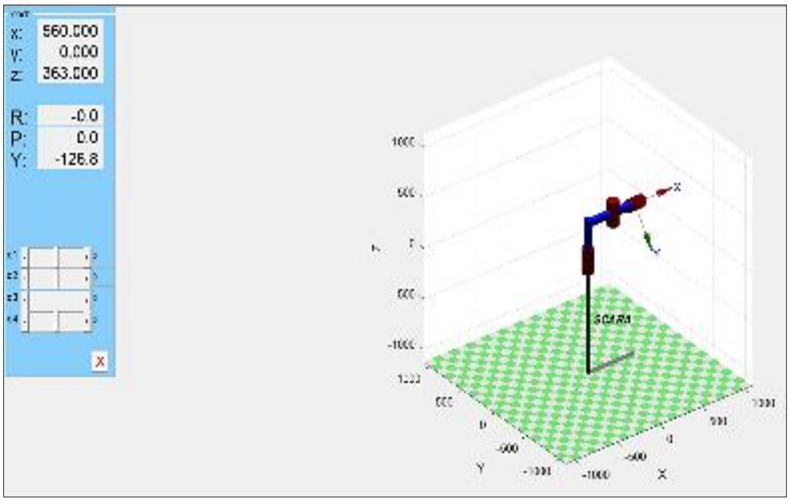


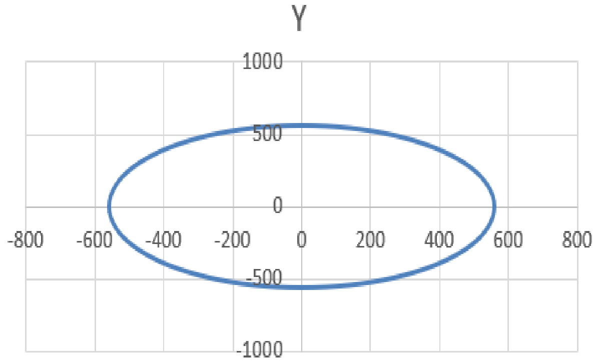
Figure 9 SCARA robot trajectory in Simulink

The results of the trajectory analysis in the XY plane give the following recommendations:

Concerning the position of the end effector: Scenario1 generally gives an elliptical trajectory, a straight line and a point; Scenario2 gives any movement.

As for the orientation of the end effector, we have either sinusoidal movements, straight lines or none at all.

Table 4 Position in XY plane

<table>
<tr>
<td>Avec $q_2= q_3=q_4=0$, q_1=vary

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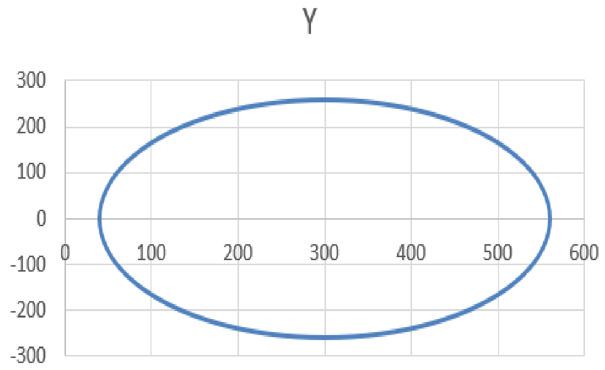
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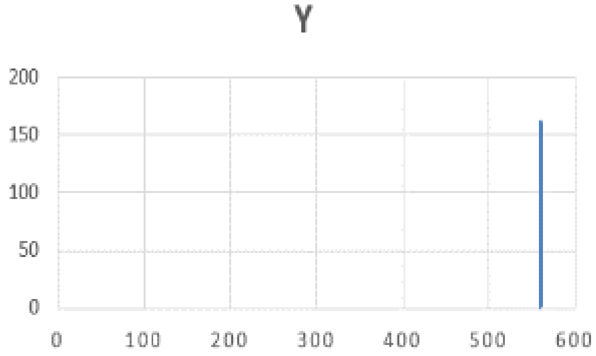
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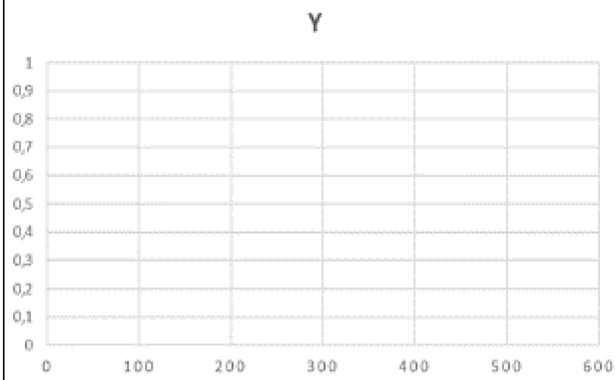
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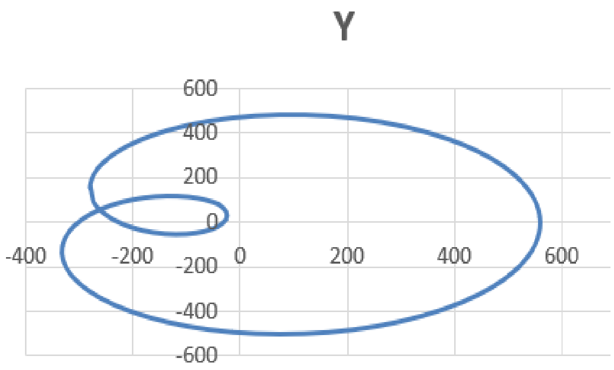
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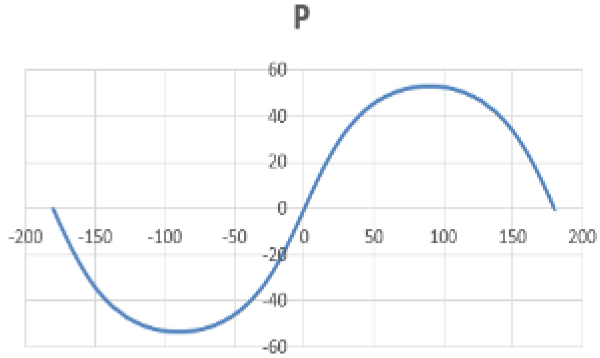
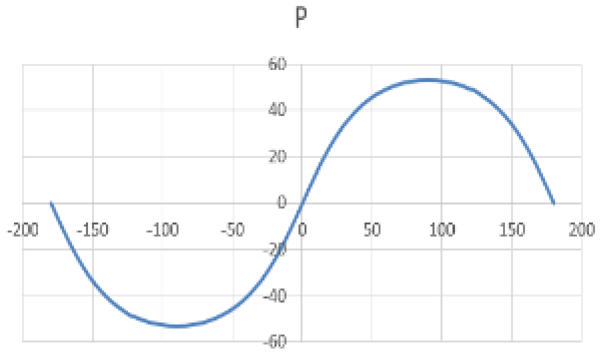
Table 5 Orientation in the RP plane

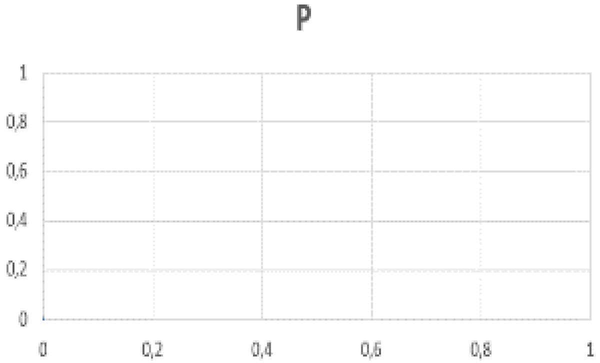
Avec q2= q3=q4=0, q1=vary



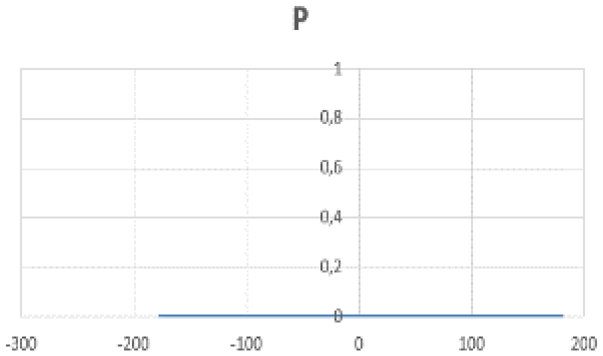
Avec q1=q2= q3= 0, q2=vary



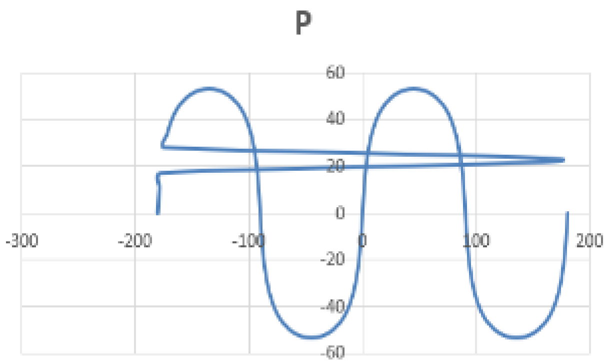
Avec q2= q1=q4=0, q3=vary



Avec q2= q3= q1=0, q4=vary



Avec q2, q3, q1, q4 ,vary



3.3.2. Case2: Cartésien robot

For the cartesian model, the input data are the dimensions of the segments (body), joint variables: $d_1 = 500, d_2 = 400, d_3 = 300, q_4 = \pm 180$

The program associated with this Matlab model is described as follows:

Parameter D-H:

%thetai

```
theta1=0;
theta2=0;
theta3=0;
theta4=180;
%di
d1=500;
d2=400;
d3=300;
d4=0;
%ai
a1=300;
a2=260;
a3=200;
a4=0;
%alpha
alpha1=0;
alpha2=180;
alpha3=0;
alpha4=0;
L1=Link([theta1,d1,a1,alpha1,1]);
L1.qlim=[0 d1];
L2=Link([theta2,d2,a2,alpha2,1]);
L2.qlim=[0 d2];
L3=Link([theta3,d3,a3,alpha3,1]);
L3.qlim=[0 d3];
L4=Link([theta4,d4,a4,alpha4,0]);
cartesien=SerialLink([L1 L2 L3 L4], 'name', 'CARTESIEN') ;
cartesien.plot([0 0 0 0])
cartesien.teach
```

The Denavit-Hartenberg parameters are listed in the following table.

Table 6 Denavit Hartenberg parameters for the Cartesian robot

Cartesian: 4 axis, PPPR, stdDH, slowRNE					
J	**theta**	**d**	**a**	**alpha**	**offset**
1	0	q1	300	0	0
2	0	q2	260	180	0
3	0	q3	200	0	0
4	q4	0	0	0	0

With the input data supplied to the model, the implementation of the program gives us the following figure, which describes the position and orientation of the end effector in the workspace defined as a function of the values of the joint variables.

By varying the joint variables, you can simulate different robot trajectory configurations with their positions and orientations.

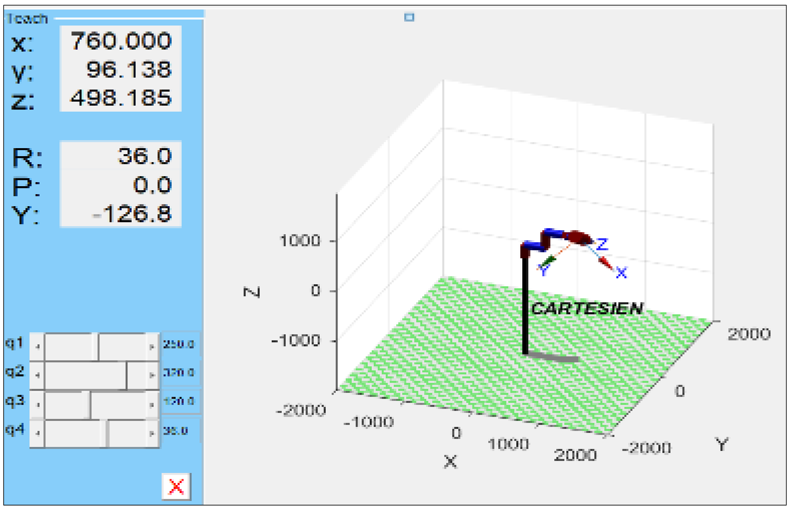


Figure 10 Cartesian robot trajectory in Simulink

The results of the trajectory analysis give the following recommendations: regarding the position of the end effector

- In the XY plane, which in this case is the horizontal plane on the robot's base: Scenario1 generally gives a straight line and a point; scenario2 gives a straight line.
- In the YZ plane (robot's the frontal plane): scenario1 gives a straight line, any movement, a point; scenario2 gives any movement.
- In the XZ plane (the robot's profile plane): scenario1 gives a straight line and a point, and scenario2 gives a straight line.

For the orientation of the end effector, we have either straight lines or points.

Table 7 Position in XY plane

<table>
<tr>
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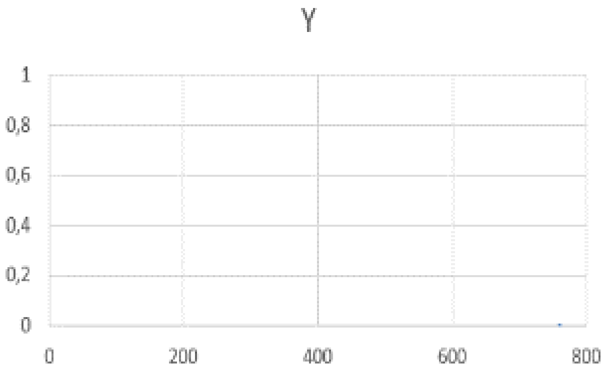
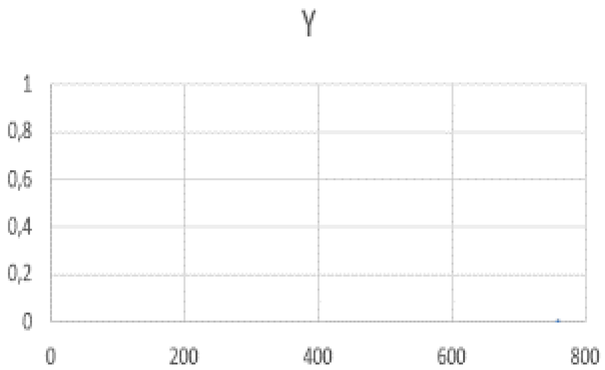

</td>
<td>Avec $q_1=q_2= q_3= 0$, q_2=vary

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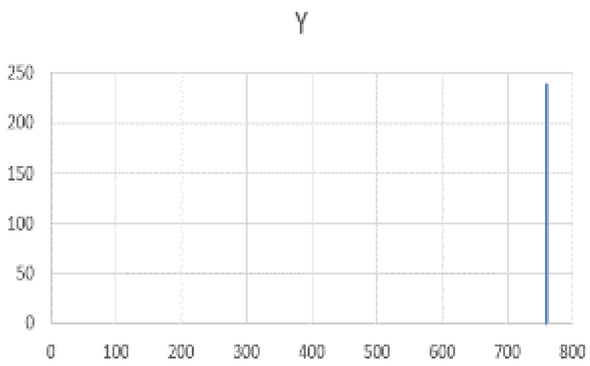
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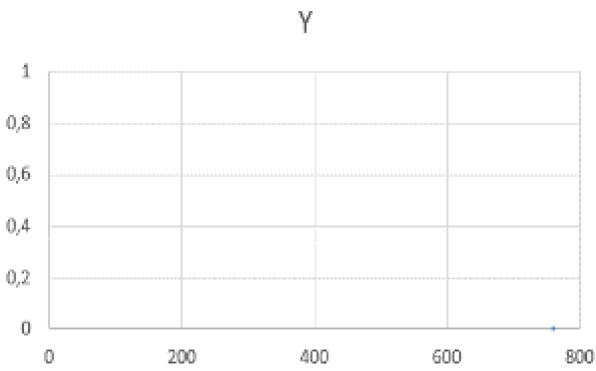
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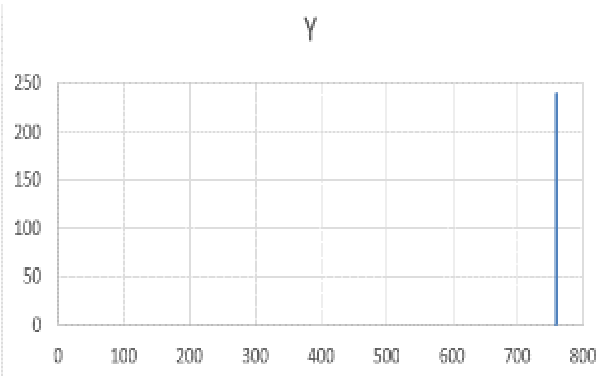
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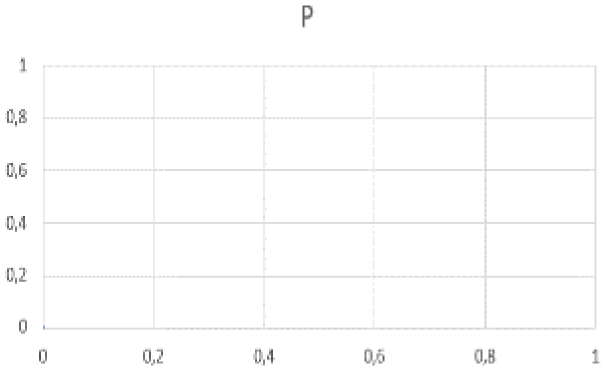
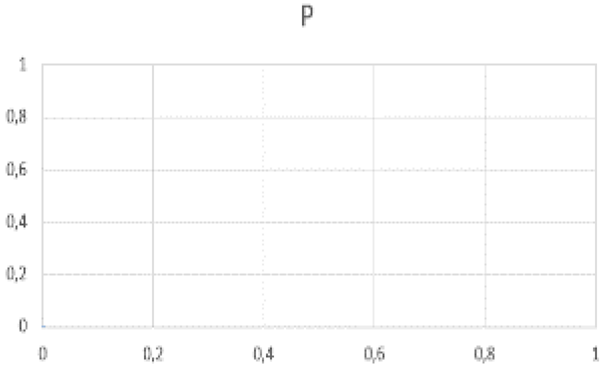
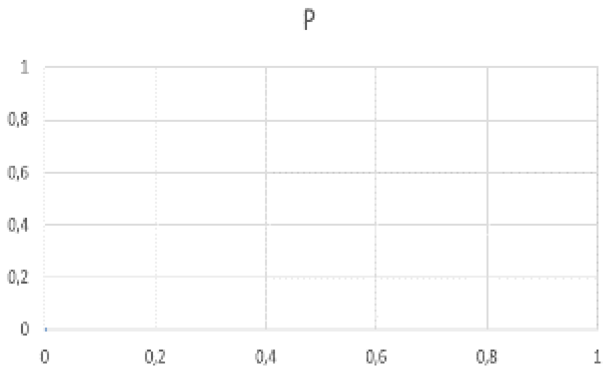
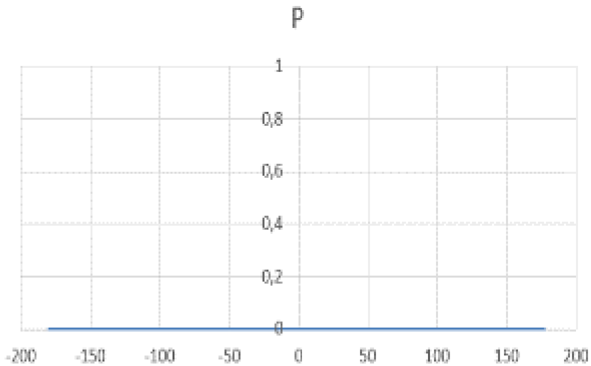
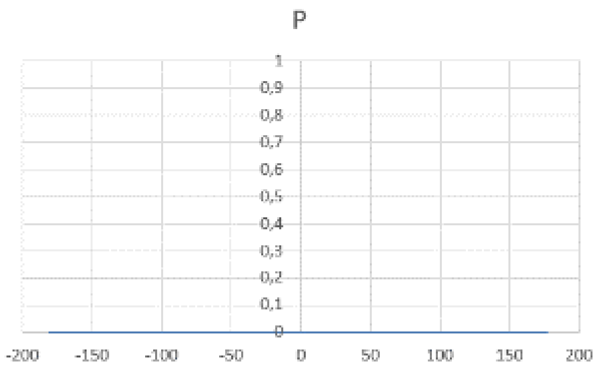
Table 8 Orientation in the RP plane

Avec q_2= q_3=q_4=0, q_1=vary 	Avec q_1=q_2= q_3= 0, q_2=vary 
Avec q_2= q_1=q_4=0, q_3=vary 	Avec q_2= q_3= q_1=0, q_4=vary 
Avec q_2, q_3, q_1, q_4 , vary 	

3.3.3. Case 3 : Spherical robot

For the spherical model, the input data are the dimensions of the segments (bodies), the variables joints: $q_1 = \pm 180, q_2 = \pm 180, d_3 = 300, q_4 = \pm 180$

The program associated with this Matlab model is described as follows:

%Parameter D-H:

```
%thetai
theta1=180;
theta2=180;
theta3=0;
theta4=180;
%di
d1=0;
d2=400;
d3=300;
d4=0;
%ai
a1=0;
a2=0;
a3=0;
a4=0;
%alpha
alpha1=-90;
alpha2=90;
alpha3=0;
alpha4=-90;
L1=Link([theta1,d1,a1,alpha1,0]);
L2=Link([theta2,d2,a2,alpha2,0]);
L3=Link([theta3,d3,a3,alpha3,1]);
L3.qlim=[0 d3];
L4=Link([theta4,d4,a4,alpha4,0]);
spherique=SerialLink([L1 L2 L3 L4], 'name','SPHERIQUE')
spherique.plot([0 0 0 0])
spherique.teach
```

The geometric model of this robot is based on the Denavit-Hartenberg formalism, and its parameters are listed in the following table.

Table 9 Denavit Hartenberg parameters for the spherical robot

Spherical: 4 axis, RRPR, stdDH, slowRNE					
J	theta	d	a	alpha	offset
1	q1	0	0	-90	0
2	q2	400	0	90	0
3	0	q3	0	0	0
4	q4	0	0	-90	0

With the input data supplied to the model, the implementation of the program gives us the following figure, which describes the position and orientation of the end effector in the workspace defined according to the values of the joint variables.

By varying the joint variables, you can simulate different robot trajectory configurations with their positions and orientations

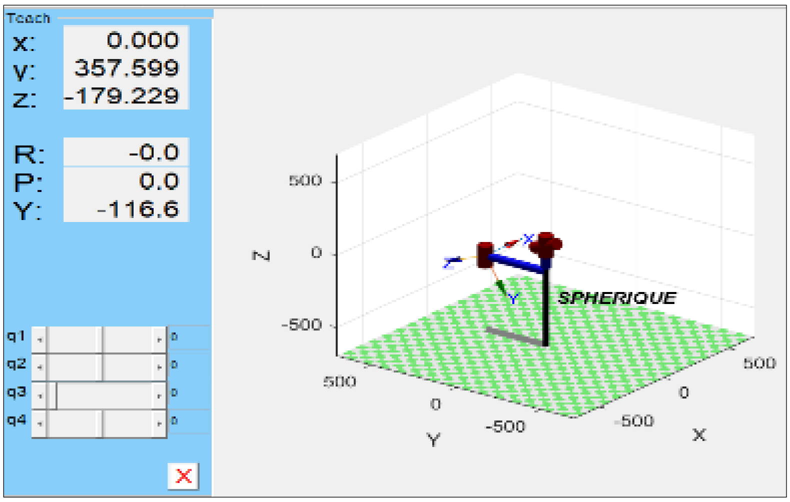


Figure 11 Spherical robot trajectory in Simulink

The results of the trajectory analysis give the following recommendations: regarding the position of the end effector

- In the XY plane, which here is the horizontal plane on the robot's base: Scenario1 generally gives an elliptical trajectory, a straight line and a point; scenario2 gives any movement
- In the YZ plane (the robot's frontal plane) : scenario1 gives a straight line and a point ; scenario2 gives any movement (arc).
- In the XZ plane (the robot's profile plane) : scenario1 gives a straight line (rectilinear movement) and a point ; scenario2 gives any movement, which is a source of imprecision

Regarding the orientation of the end effector, we have sinusoidal movements, straight lines, points and any movements.

Table 10 Position in XY plane

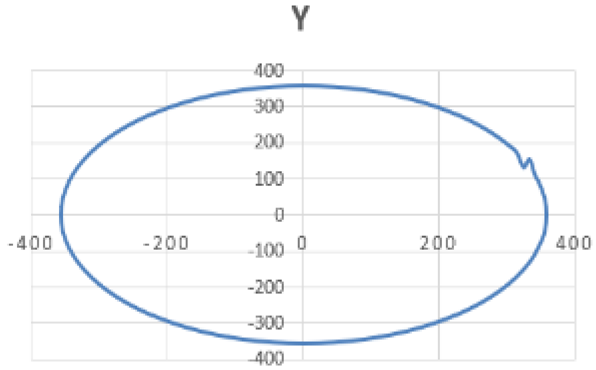
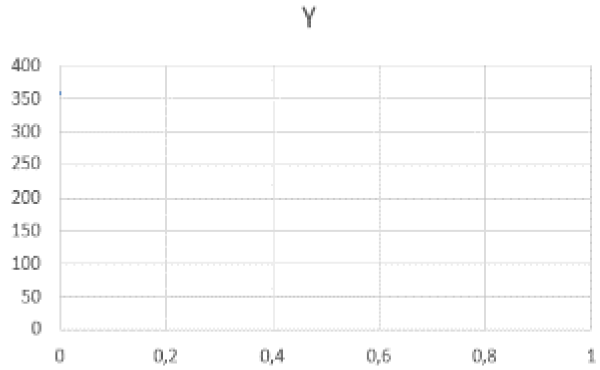
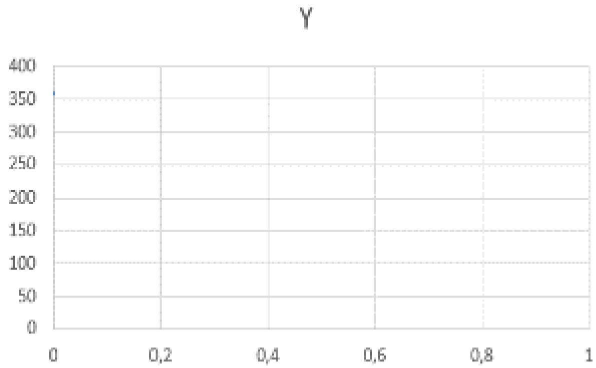
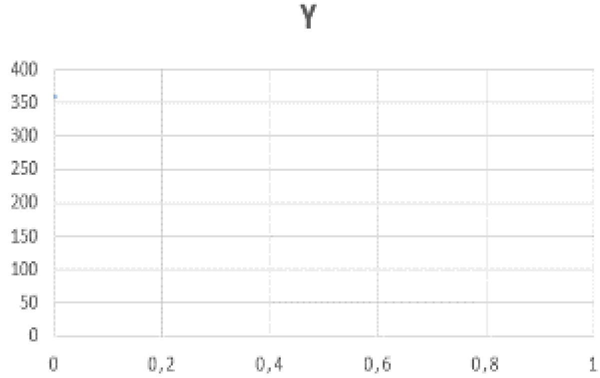
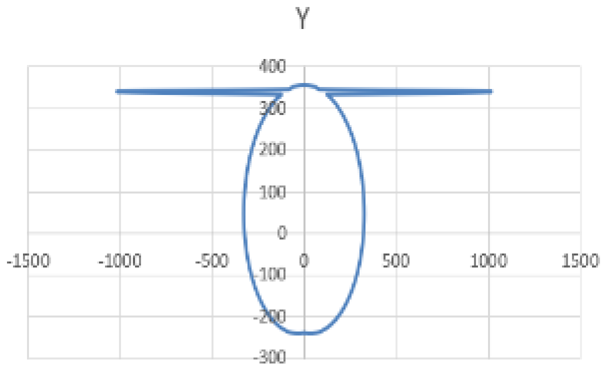
Avec $q_2 = q_3 = q_4 = 0$, q_1=vary 	Avec $q_1 = q_2 = q_3 = 0$, q_2=vary 
Avec $q_2 = q_1 = q_4 = 0$, q_3=vary 	Avec $q_2 = q_3 = q_1 = 0$, q_4=vary 
Avec q_2, q_3, q_1, q_4, vary 	

Table 11 Orientation in the RP plane

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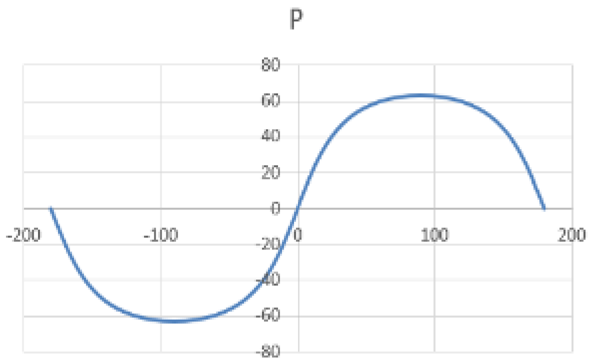
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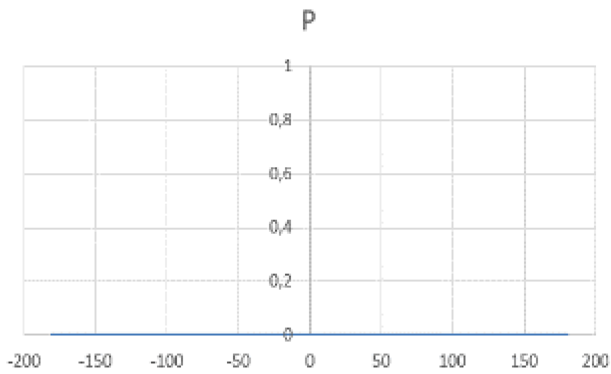
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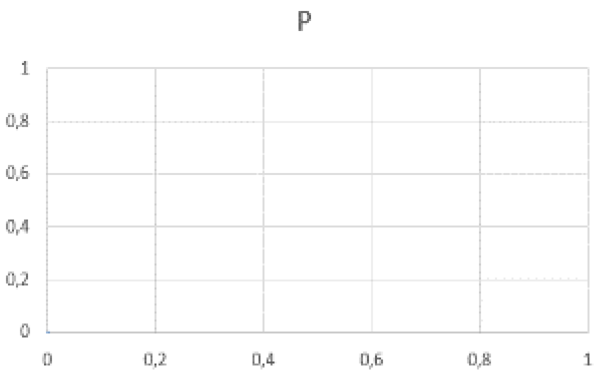
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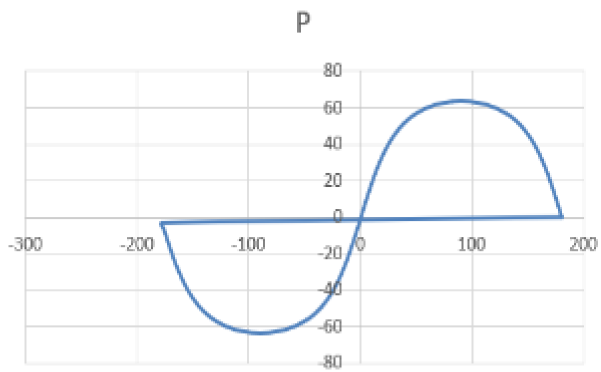
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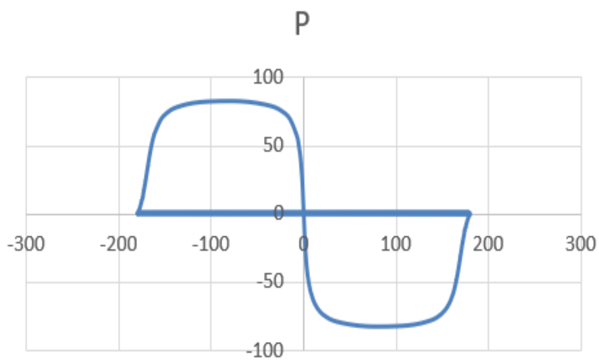
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4. Conclusion

This paper has enabled us to propose a structured approach to modeling and evaluating the performance of manipulator arms in a dedicated workspace. Indeed, we have (a) reviewed the literature on manipulator arms in terms of modeling and performance, (b) carried out a functional specification study based on the APTE method and the Octopus diagram to validate their design, (c) established a mathematical model followed by the construction of a geometric model in Simulink. This model, based on well-defined inputs, is capable of simulating different trajectory configurations in a defined workspace. The results of our model are in line with those predicted by the mathematical model using Denavit-Hartenberg parameters. An analysis of these trajectory configurations in relation to the plane linked to the robot base is carried out according to several scenarios in order to better understand the behavior of manipulator arms, in particular SCARA, Cartesian and spherical robots. The first scenario considers the variation of one of the joint variables, while the second simultaneously varies all the variables. In future work, a manipulator arm singularity study and actuator dimensioning will be required to validate the performance and stability studies of these robots.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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