International Journal of Engineering Research and Technology.
ISSN 0974-3154 Volume 11, Number 12 (2018), pp. 2135-2158

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Investigation of Inverse Kinematics Software Program of KUKA Manipulator Robot and Creation of Optimal Trajectory Control for Quality Evaluation within Chemical Production Lines

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Abstract

The objective of this research is to compute the inverse kinematics and control of a trajectory for a robotic arm, which is using in chemical industries such as plastic, polymer, pharmaceuticals and chemistry production. Workers in chemical factories sometimes causing some errors during the packaging process, as well as high production costs and time spent on implementation, therefore, it is better to replace this human work with programmable robotic arms that can be implemented with maximum precision, and also reduce the cost of these operations from the previous one. In addition, the main advantage of using these manipulators is automating control without losing working time or boredom and quality evaluation within chemical production lines. This study was done by using a new developed geometrical approach method to compute inverse kinematics problems with a highly accurate result, saving a long time in mathematical calculations, easier and comfort in using for mechatronics and robotics designers and engineers. The advantages of this research, first is to design and study an inverse kinematics of Four Degree of Freedom as Revolute-Revolute- Revolute- Revolute joints 4-DOF (RRRR)

Manipulator robot (such as exist in KUKA 4R Robot), second is to control of end-effector trajectory, finding of all possible solutions with selection the optimal trajectory. An investigation of inverse kinematics software program of KUKA manipulator robot was developed to save time and cost with regards to reprogramming efforts. Obtained results can be implemented in food and biotechnology industry, cryogenics and other industries.

Keywords: LabVIEW; SolidWorks; Trajectory Control; Chemical Industry; KUKA Robot; Optimal Design; Inverse Kinematics; Motion; Mechatronics.

INTRODUCTION

The control of robot manipulators has been a research area for years and has developed various control strategies [1, 2, 3]. More and more tasks in various sectors, as in chemical industrial applications, are assisted by or completely transferred to robotic manipulators. Robots are also planned to be used in the future in the construction industry, where more goals that are complex should be accomplished, such as cooperative tasks. Moreover, it is mainly designed for interactions with humans, and is therefore equipped with movement of each actuated joint, which allows for cooperative interaction control. In order to develop model-based controllers for a robotic manipulator, its kinematic model is needed. Furthermore, if robotic arms tasks are considered, it is valuable to do kinematic simulations of the robots' motions and interactions. In order to obtain reliable simulation results and selection the optimal trajectory of the end-effector manipulators. The chemical industry is a challenging yet changing market. Flexibility within this industry is the most sought after property in the modern day production line system. This industry is a rapidly versatile industry driven by customer quality needs and the ability to respond to changes swiftly in the shortest time, at the lowest cost [4]. Flexibility can be seen as the capacity of a system to change and assume different positions or states in response to changing requirements with little penalty in time, effort, cost, or performance [5]. Introducing an automated adapting system that is flexible, enough to adapt its programming methods automatically seems like in order to satisfy quality requirements. We need to investigate which type of automated system to implement that can adapt on the control production system. Using the current conventional methods can be restrictive when new products are introduced on current assembly systems [6, 7]. Using the KUKA Robot to detect and move items without pre-required programming on the KUKA Robot Language (KRL) platform; this could benefit the assembly process through real-time manipulation [8, 9].

In this study, the design of an adaptive trajectory-tracking controller based on an inverse kinematics program and LabVIEW using NI-SoftMotion module as a controller is developed on a KUKA robot. This controller is designed based on connection between LabVIEW and Solidwork programs, where NI-SoftMotion module works to send and receive the data and information of inverse kinematic problem.

INVERSE KINEMATICS OF KUKA 4R MANIPULATOR ROBOT

A. Kinematics Models

Nowadays, after decades of progress, there are various approaches to the robotic manipulator control. The methods range from the classical independent joint PID control to more advanced model-based methods [10-13]. Taking into account the dynamic model of the manipulator should improve the performance in the position-tracking task. An example is [14] where the adaptive control of manipulators subject to motion constraints is proposed. Kinematics studies the motion of bodies without consideration of the forces or moments that cause the motion. Robot kinematics refers the analytical study of the motion of a robot manipulator with formulating the suitable kinematics models for a manipulator robot is very important for analyzing the behavior of industrial manipulators. There are mainly two different spaces used in kinematics modelling of manipulators namely, Cartesian space and Quaternion space.

The transformation between two Cartesian coordinate systems can be analyzed into a rotation and a translation [15]. Denavit-Hartenberg (1955) method that uses four parameters is the most common method for describing the robot kinematics. Denavit & Hartenberg showed that a general transformation between two joints requires four parameters. These parameters known as the Denavit-Hartenberg (DH) parameters have become the standard for describing robot kinematics [16].

B. The main advantages of proposed control program

The proposal of an inverse kinematics program and LabVIEW using NI-SoftMotion module as a controller has the following advantages:

1. This control technique can be applied to an inverse kinematic problem, which is the case of the KUKA robot manipulator and can be applied for other manipulators.
2. The complete analysis was done in a New Geometrical Developed Approach method.

3. It can control most of the robot manipulator systems with knowing their possible solution, which can be found.
4. The main advantage of this method is that it does not require previous knowledge of the robot dynamics.
5. The proposed control program gives to mechatronics and mechanical design engineers all possible trajectory and can select the suitable trace and can be saved a power of manipulator actuators by select a short path.

Different between new developed geometrical approach method and conventional mathematical method is as shown below table

Comparisons	**New Developed Geometrical Approach Method (2-Dimensional Problem)**	**Conventional Mathematical Method The Denavit–Hartenberg (DH) method (3-Dimensional Problem)**
Mathematical Requirements	Not require high level of mathematical background because don't using matrices and dealing with simple equations	Using 4x4 homogenous matrices with a specific structure (John J. Craig, 2005)
Software Programming	Easy to programmed with any software (LabVIEW Program)	Need high-level mathematical background in deal with matrices processing
Accuracy	High precision results get from calculations	Calculations are not carried out with infinite precision (Taylor, 1979)
Singularity	Using to represents positions and orientations, which provides robot kinematics avoiding singularities	Singularity and nonlinear expressions of joint relations are major problem in the homogenous matrices method (Aydin and Kucuk, 2006)

C. The parts of the block diagram are mentioned as follows

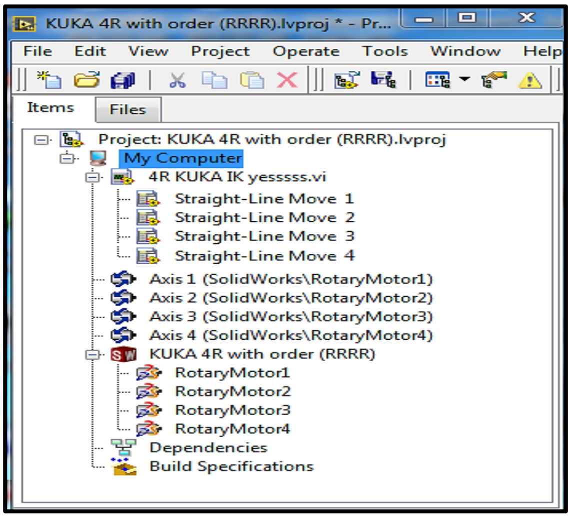
Input Parameters – includes two types: the first is constant as manipulator dimensions (El, Wr and Gr), and the second is variables as Cartesian Coordinates of end-effector/ tool (x, y and z).

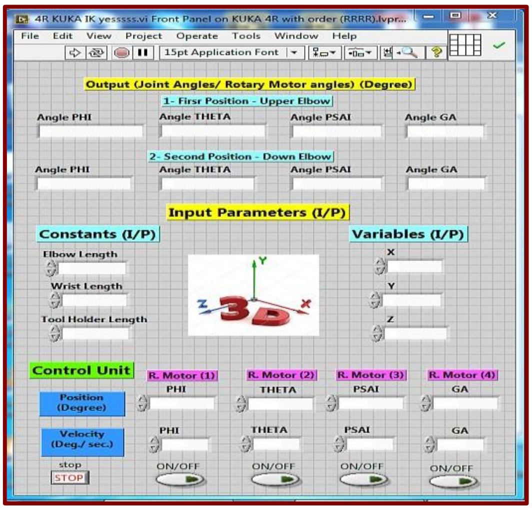
Output Parameters – includes the rotational joint angles (φ, θ, ψ and γ).

ON/OFF – Controls for the Move Function input of motors.

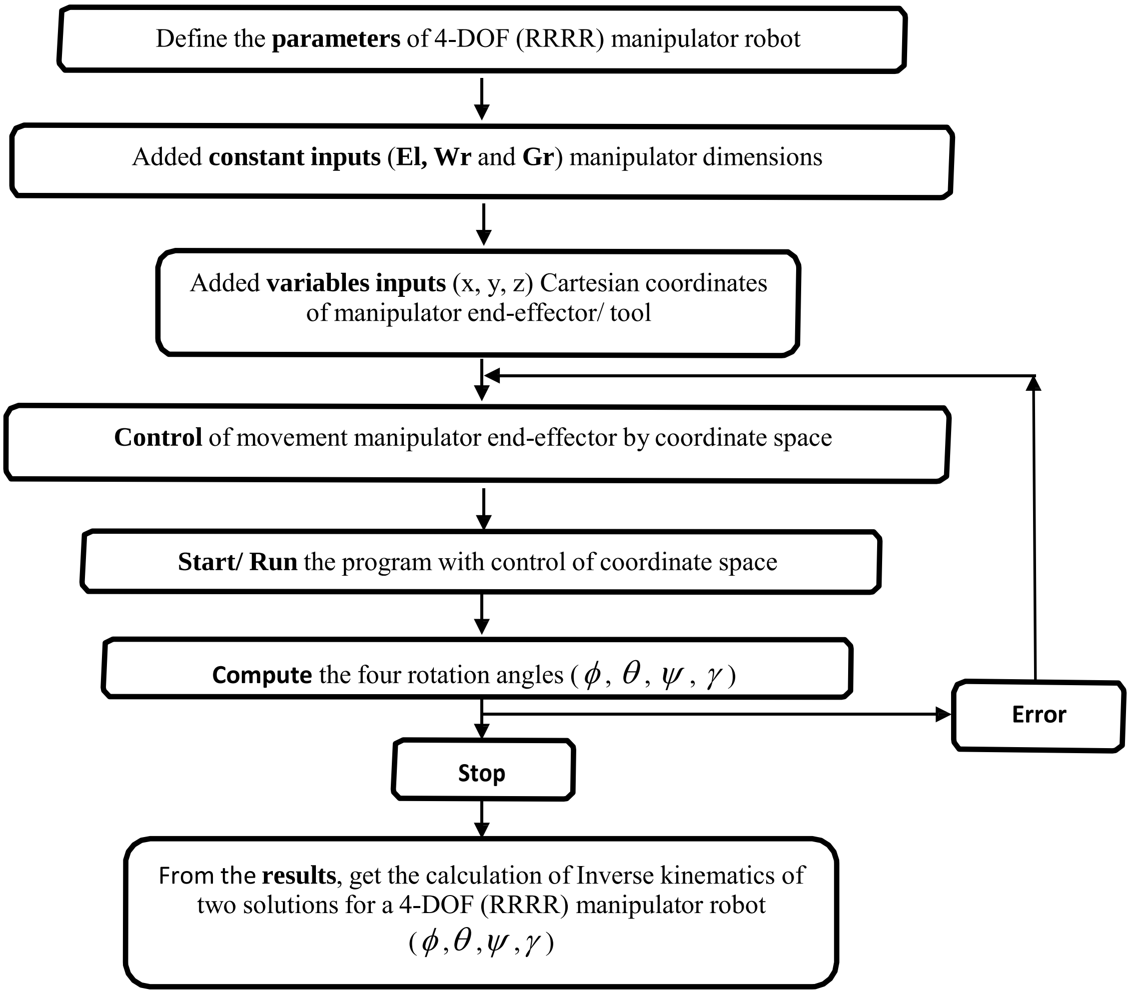
Stop – To exit the loop and stop motion control.

Interface programs LabVIEW and SolidWorks of inverse kinematics and trajectory control of KUKA 4R robot is as shown below.





Algorithm of Inverse Kinematics Programming Design and Control of 4-DOF (RRRR) Manipulator robot Using LabVIEW and SolidWorks is as shown below.



Applications of manipulators in chemical production lines

Manipulator robots can be used in the work of chemical industries applications such as plastic, polymer, pharmaceuticals and chemistry production:

A-**Applications of manipulators in plastic and polymer production**

Many applications in this field as: robotic injection-Molding, robotic pick and place, and robotic assembly.

Automatic control of robotic arms and improve plastic and polymer production

1- Manipulators increase safety in plastic and polymer production

Robotic arms can be used across all areas of plastic and polymer production, including injection-molding, loading and unloading, and pick and place projects.

2- Protect workers to higher-value tasks

Dangerous, repetitive tasks in plastics and polymer manufacturing are no longer a challenge. Robot arms can take over dirty, dangerous, and dull jobs to reduce repetitive strain and accidental injuries, while freeing up human operators for higher-value tasks.

3- Manipulators are ideal for flexible plastics manufacturing processes

Flexibility is key in automating plastic and polymer manufacturing, since different materials require specific processing setups and temperature ranges. It is fast and easy to move the robot to a new process, giving you the agility to automate almost any task, including those with small batches or fast change-overs in plastic and polymer production and can increase or decrease production without having to adjust staffing levels.

Advantages of using manipulators in the plastics and polymer industry:

- Eliminate machine and worker idle time during injection molding processes.
- Increase output with consistent, ongoing processing.
- Easily reprogram and redeploy robot arm to other operations as needed.
- Improve quality and reduce waste.

B-**Applications of manipulators in pharmaceuticals and chemistry production**

Many applications in this field as robotic packaging and palletizing.

Maintain high quality with robot arms in pharmaceuticals and chemistry production

1- Robots take on a range of healthcare-related applications

Robotics in the pharmaceutical and chemistry industries are performing a wide range of tasks. Robot arms can be used for mixing, counting, dispensing, inspection, and packaging to deliver consistent results. For these critical applications, robots can eliminate human error and possibility of contamination, and increase output and consistent quality.

2- Meet stringent healthcare industry specifications

Robots are designed to meet the healthcare industry's stringent requirements for accuracy, precision, and hygiene. Manipulators are provided with a smooth outer housing, which collects almost no dust or deposits.

3- Easy manipulators redeployment for varied processes

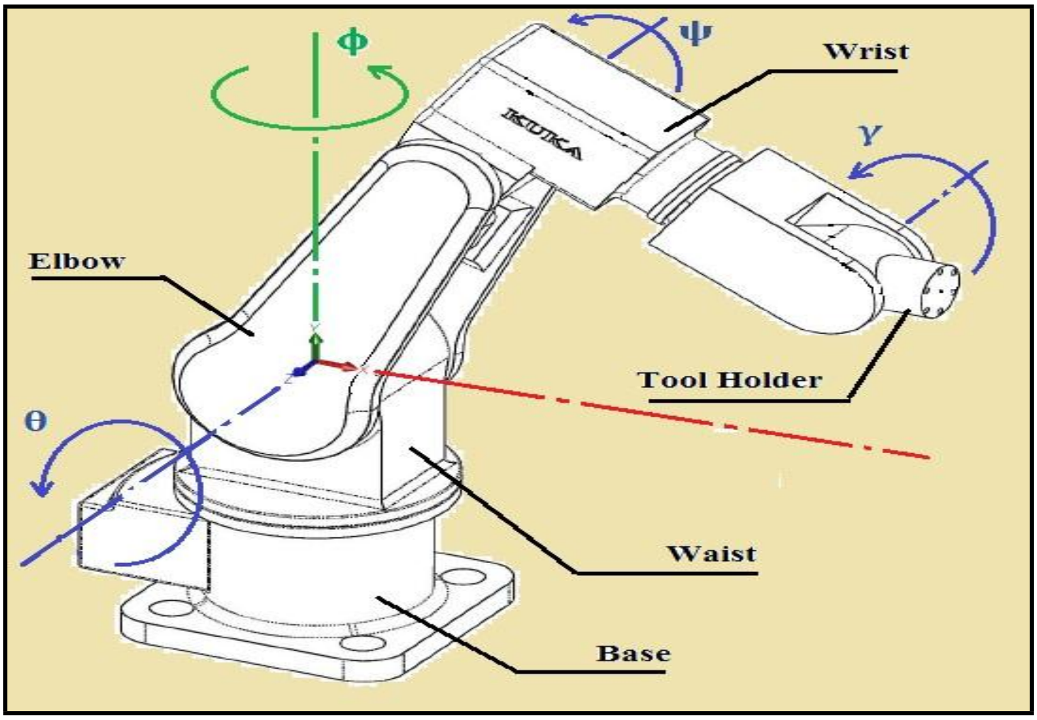
Robotic arms are small enough to fit in nearly any pharmaceutical or chemistry process. Simple programming allows them to be used for a wide range of applications, and programs can be reused for recurrent processes.

Advantages of manipulators in the pharmaceuticals and chemistry industry:

- Hermetically sealed for use in hygienic environments.
- Specifically designed outer casing to reduce accumulation of dust and debris.
- Improve consistency while reducing waste.

KUKA 4R Manipulator robot

The isometric of 4-DOF (RRRR) manipulator robot with three moving axes (such as exist in KUKA Robot) is as shown below.



In this study, we defined the 4-DOF (RRRR) KUKA manipulator robot parameters as the following:

x: a displacement of end-effector manipulator along x-axis from the rotation point.

y: a displacement of end-effector manipulator along y-axis from the rotation point.

z: a displacement of end-effector manipulator along z-axis from the rotation point.

x_1: a displacement of tool holder axis along x-axis from the rotation point.

y_1: a displacement of tool holder axis along y-axis from the rotation point.

z_1: a displacement of tool holder axis along z-axis from the rotation point.

El: an elbow manipulator length.

Wr: a wrist manipulator length.

Gr: a tool holder manipulator length.

L1: a distance between the reference point (0, 0, 0) and tool holder axis (x_1, y_1, z_1), which measured from the top plane of a manipulator.

M: a distance between the reference point (0, 0, 0) and tool holder axis (x_1, y_1, z_1), which measured from the front plane of a manipulator.

L2: a total length of M and Gr.

L_3: a distance between the axis of elbow and the axis of tool holder.

N: a projected length of M in the top plane of a manipulator.

ϕ_1: an angle between Gr and x-axis, which measured from top plane of a manipulator.

ϕ_2: an angle between L_1 and x-axis, which measured from top plane of a manipulator.

θ_1: a slope of the M in the xy-plane.

θ_2: a slope of the tool holder in the xy-plane.

θ_3: a slope of the end-effector in the xy-plane.

β: a slope of the wrist in the xy-plane.

α: an angle between M and Wr, which measured from front plane of a manipulator.

ϕ : the rotation angle of the waist of a manipulator.

θ: the rotation angle of the elbow of a manipulator.

ψ: the rotation angle of the wrist of a manipulator.

γ: the rotation angle of the tool holder of a manipulator.

Manipulator Robot Parameters Constraints:

1- $El > 0$;

2- $Wr > 0$;

3- $Gr > 0$;

4- $El > Wr > Gr$.

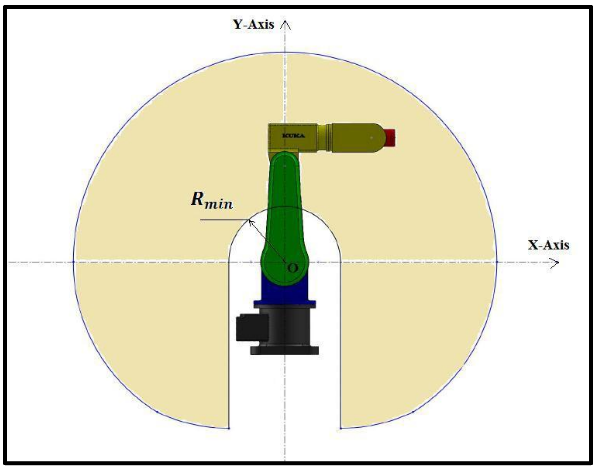
Manipulator Robot WorkSpace Constraints:

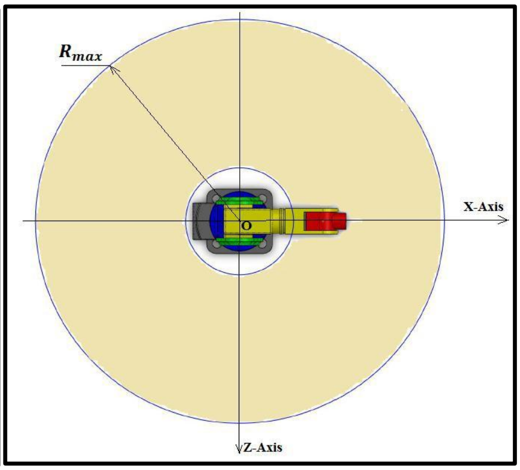
1- $\sqrt{x^2 + y^2 + z^2} \geq (Wr + Gr - El)$;

2- $\sqrt{x^2 + y^2 + z^2} \leq (El + Wr + Gr)$.

The 4-DOF (RRRR) robotic arm's manipulator Workspace

In performing tasks, a manipulator has to reach a number of workpieces or fixtures. In some cases, these can be positioned as needed to suit the workspace of the manipulator. In other cases, a robot can be installed in a fixed environment with rigid workspace requirements [1]. Workspace is also sometimes called work volume or work envelope is as front and plane views shown below.





What are the limits for the 4-DOF (RRRR) robotic arm's manipulator?

The achievable working space looks like a hollow sphere, where:

1- The maximum outer diameter will be:

$$2(El + Wr + Gr).$$

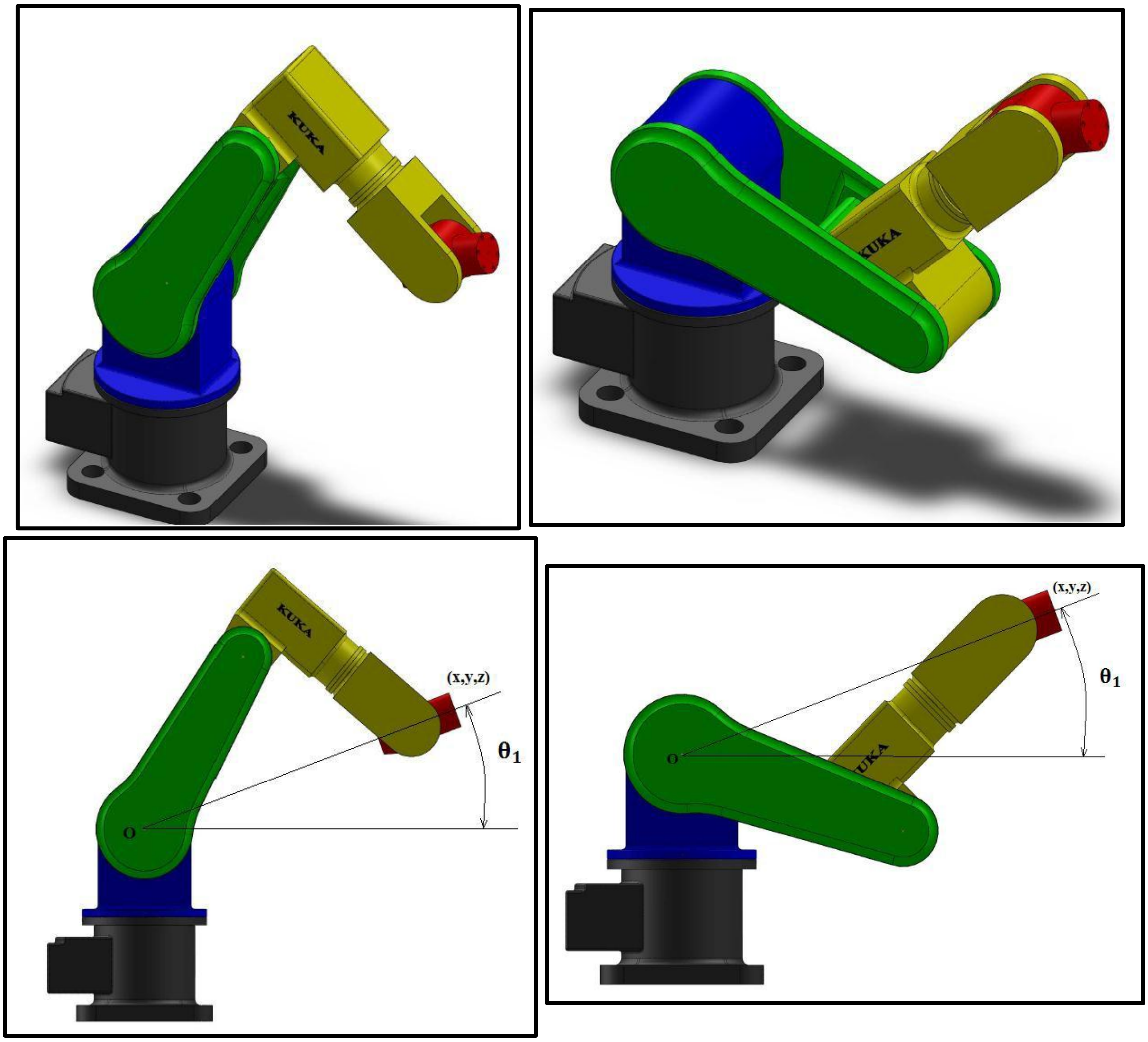
2- The minimum inner diameter will be:

$$2(Wr + Gr - El).$$

Possible Solutions for an Inverse Kinematics of 4-DOF (RRRR) KUKA Manipulator Robot

The two possible position solutions of 4-DOF (RRRR) manipulator robot at the same slope of tool holder on xy-plane is as shown below:

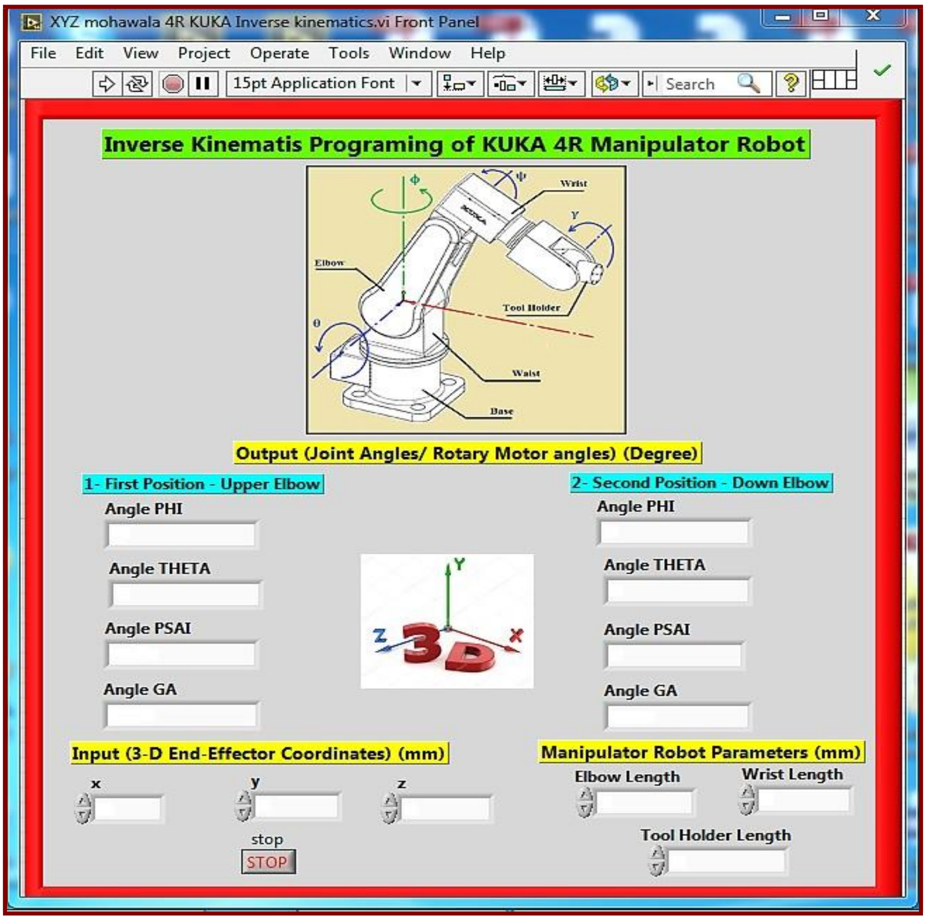
i- First Position – Upper Elbow. 2- Second Position – Down Elbow.



- There are two possible solutions to reach the manipulator end-effector/ tool to the purposed point in (x, y, z), if this point was located inside the manipulator workspace (inside the hollow sphere).
- There are no possible solution, if a purposed point in (x, y, z) was located outside of the manipulator workspace (outside the hollow sphere).
- Both forward and inverse kinematics models are derived for the KUKA robot

with a new geometrical approach method is realized in LabVIEW program.

In the designed interface, required parameters are determined and calculated for each joint. Interface program of forward and inverse kinematics KUKA robot are shown here.



Mathematical KUKA Robot Model Programming by a New Geometrical Developed Approach of an Inverse Kinematics Study (IK)

Define the Parameters

$$L_2 = \sqrt{x^2 + z^2 + y^2}\,, \quad \theta_1 = \tan^{-1}\left(\frac{y}{\sqrt{x^2 + z^2}}\right), \quad M = L_2 - Gr\,, \quad y_1 = M \times \sin(\theta_1),$$

$$\phi_1 = \tan^{-1}\left(\frac{z}{x}\right), \quad N = M \times \cos(\theta_1), \quad x_1 = N \times \cos(\phi_1), \quad z_1 = N \times \sin(\phi_1)$$

When (x ≤ 0) && (z > 0), then:

$$x_1 = -N \times \cos(\phi_1), \quad z_1 = -N \times \sin(\phi_1)$$

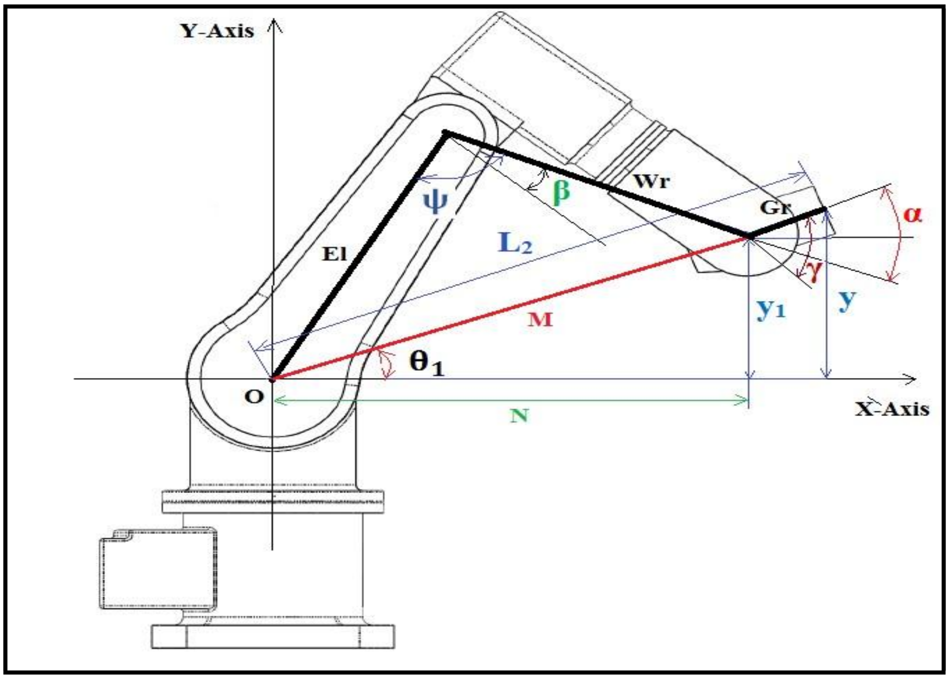
When (x ≤ 0) && (z < 0), then:

$$x_1 = -N \times \cos(\phi_1), \quad z_1 = -N \times \sin(\phi_1)$$

$L_1 = \sqrt{{x_1}^2 + {z_1}^2}$, $\alpha = \cos^{-1}\left(\dfrac{Wr^2 + \sqrt{x_1^2 + z_1^2 + y_1^2} - El^2}{2 \times Wr \times \sqrt{x_1^2 + z_1^2 + y_1^2}}\right)$, $\phi_2 = \tan^{-1}\left(\dfrac{z_1}{x_1}\right)$, $L_3 = \sqrt{{L_1}^2 + {y_1}^2}$

$\theta_2 = \tan^{-1}\left(\dfrac{y_1}{L_1}\right)$, $\theta_3 = \cos^{-1}\left(\dfrac{{L_3}^2 + El^2 - Wr^2}{2 \times L_3 \times El}\right)$

Front view of upper elbow for a 4-DOF (RRRR) Manipulator robot is as shown below.



$$\theta = (\theta_2 + \theta_3) - 90, \quad \psi = \cos^{-1}\left(\frac{Wr^2 + El^2 - {L_3}^2}{2 \times Wr \times El}\right) - (90 + \beta), \quad \gamma = (\alpha + \beta)$$

i- First Position: Upper Elbow (UE)

1- When ($x_1 > 0$) and ($z_1 \geq 0$), then:

$\phi = -\phi_2$

2- When ($x_1 \geq 0$) and ($z_1 < 0$), then:

$\phi_2 = \cos^{-1}\left(\dfrac{x_1}{L_1}\right)$, $\phi = \phi_2$

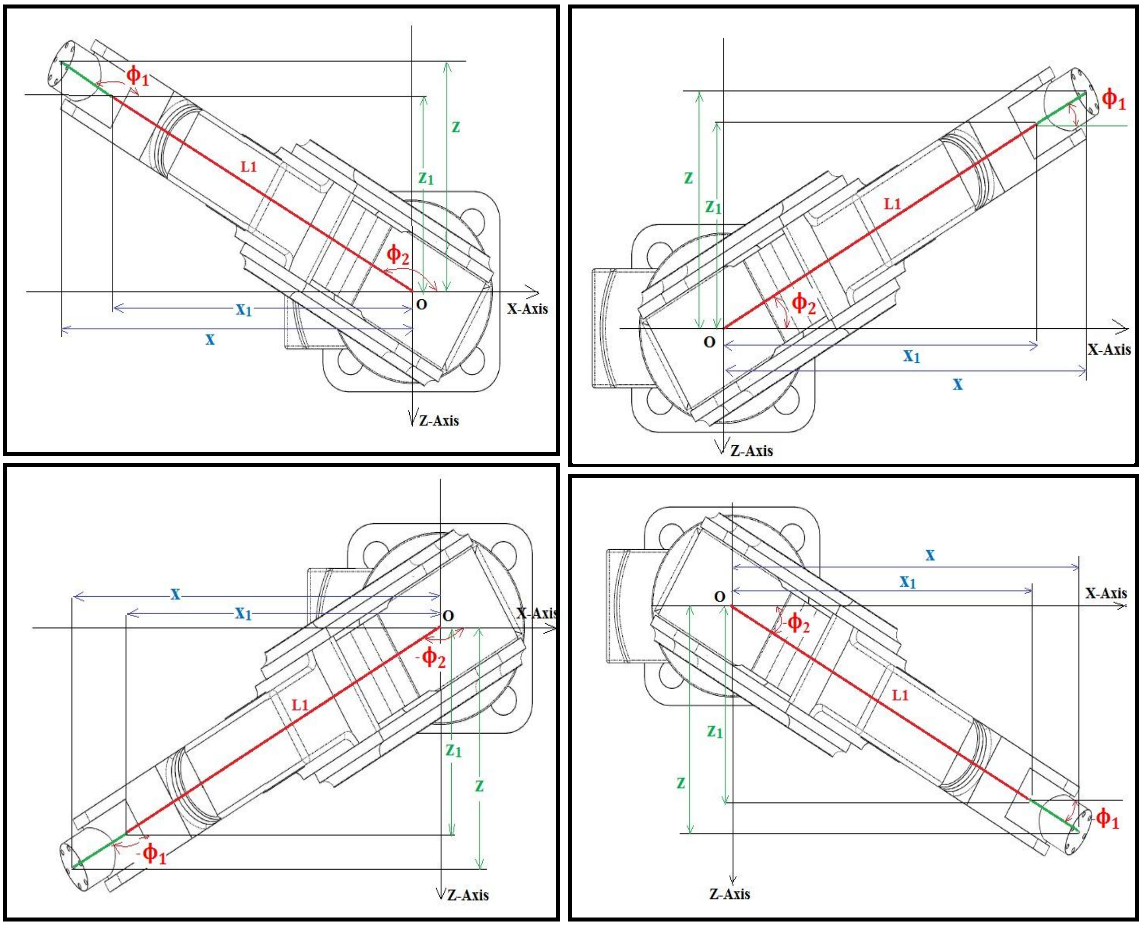
3- When ($x_1 < 0$) and ($z_1 \leq 0$), then:

$\phi = 180 - \phi_2$

4- When ($x_1 \leq 0$) and ($z_1 > 0$), then:

$\phi_2 = \sin^{-1}\left(\frac{z_1}{L_1}\right), \quad \phi = 180 + \phi_2$

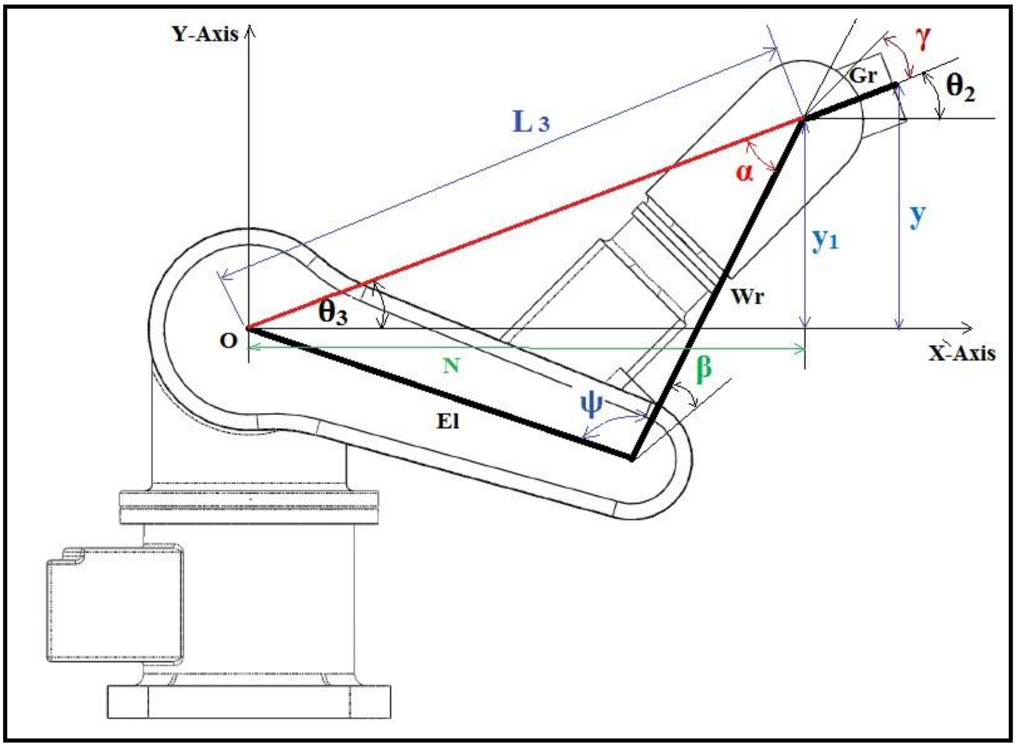
Top views of upper and down elbow when (x > 0), (z ≥ 0) && (x ≥ 0), (z < 0) && (x < 0), (z ≤ 0) and (x ≤ 0), (z > 0) is as shown below.



ii- Second Position: Down Elbow (DE)

$$\theta = (\theta_2 - \theta_3) - 90, \quad \psi = 270 - \left(\cos^{-1}\left(\frac{Wr^2 + El^2 - L_3{}^2}{2 \times Wr \times El}\right) + \beta\right), \quad \gamma = (\beta - \alpha)$$

Front view of Down elbow for a 4-DOF (RRRR) is as shown below.



1- When ($x_1 > 0$) and ($z_1 \geq 0$), then: $\phi = -\phi_2$.

2- When ($x_1 \geq 0$) and ($z_1 < 0$), then: $\phi_2 = \cos^{-1}\left(\frac{x_1}{L_1}\right)$, $\phi = \phi_2$.

3- When ($x_1 < 0$) and ($z_1 \leq 0$), then: $\phi = 180 - \phi_2$.

4- When ($x_1 \leq 0$) and ($z_1 > 0$), then: $\phi_2 = \sin^{-1}\left(\frac{z_1}{L_1}\right)$, $\phi = 180 + \phi_2$.

Trajectory Control of an End-Effector KUKA robot

We can get different trajectories for reaching to the same point, which is demanded, by control with order arrangement of motors rotation first, second, etc. and this has been done according to which a trajectory is suitable with different specific applications to avoid a contact and stick with anybody exist in a manipulator workspace. Therefore, this makes a designer has alternative and accessible solutions to reach the best possible motion path (trajectory). All possible trajectory control of KUKA end-effector robot is presented in Table 1.

Table 1: All possible trajectory control of KUKA end-effector robot.

O/P position of end-effector	Order of rotary motor (Φ)	Order of rotary motor (θ)	Order of rotary motor (ψ)	Order of rotary motor (γ)
First Position – Upper Elbow	(2) + ϕ	(1) + θ	(3) + ψ	(4) + γ
	(2) + ϕ	(4) + θ	(1) + ψ	(3) + γ
	(3) + ϕ	(1) + θ	(4) + ψ	(2) + γ
	(3) + ϕ	(4) + θ	(2) + ψ	(1) + γ
	(2) + ϕ -360	(1) + θ	(3) + ψ	(4) + γ
	(2) + ϕ -360	(4) + θ	(1) + ψ	(3) + γ
	(3) + ϕ -360	(1) + θ	(4) + ψ	(2) + γ
	(3) + ϕ -360	(4) + θ	(2) + ψ	(1) + γ
Second Position – Down Elbow	(2) + ϕ	(1) + θ	(3) + ψ	(4) + γ
	(2) + ϕ	(4) + θ	(1) + ψ	(3) + γ
	(3) + ϕ	(1) + θ	(4) + ψ	(2) + γ
	(3) + ϕ	(4) + θ	(2) + ψ	(1) + γ
	(2) + ϕ -360	(1) + θ	(3) + ψ	(4) + γ
	(2) + ϕ -360	(4) + θ	(1) + ψ	(3) + γ
	(3) + ϕ -360	(1) + θ	(4) + ψ	(2) + γ
	(3) + ϕ -360	(4) + θ	(2) + ψ	(1) + γ

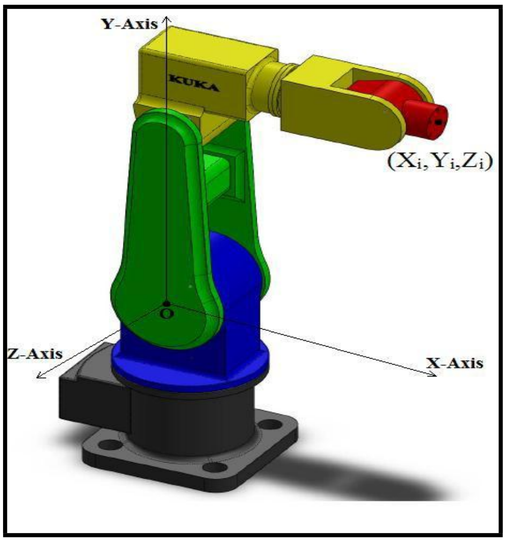
Case Study

In this study, we used the 4-DOF rotational manipulator robot input parameters as in the following table.

Table 2: Input parameters of KUKA Robot inverse kinematics and control program.

Manipulator Dimensions (mm)	**X**	**Y**	**Z**
Elbow = 500 Wrist = 468.03 Tool Holder = 122.5	$X_i = 567.5$	$Y_i = 645$	$Z_i = 0$
	$X_f = -600$	$Y_f = 300$	$Z_f = 700$

Initial position of KUKA 4R is as shown below.

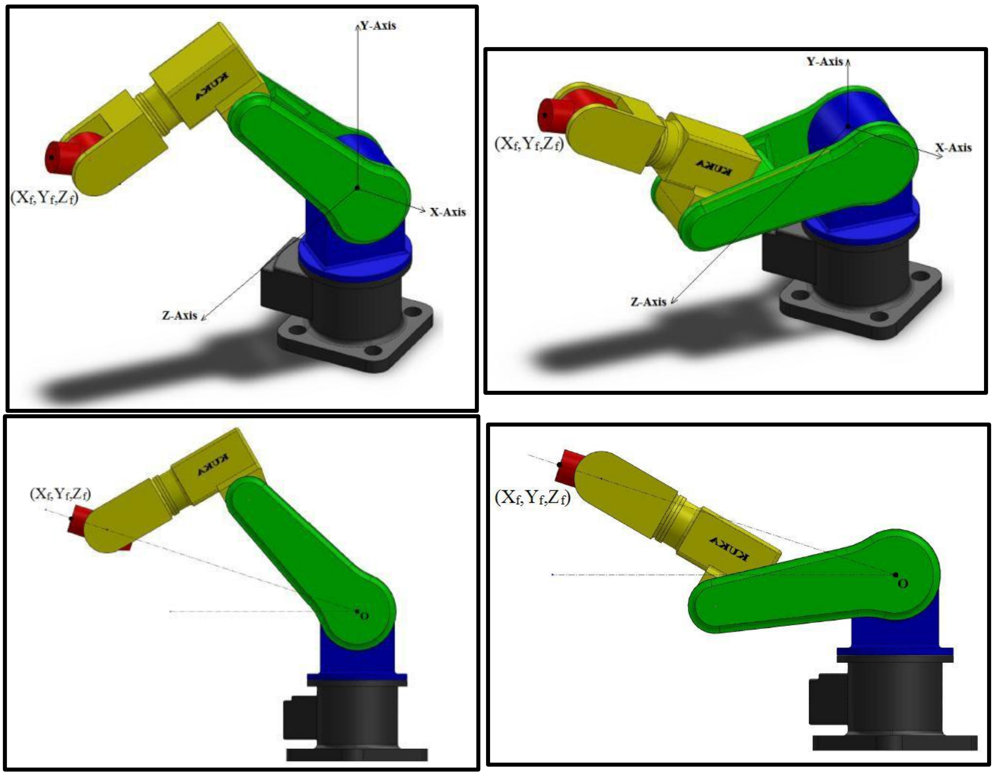


Results of a program with the input data table 2 presented in the table 3.

Table 3: Output results of KUKA Robot inverse kinematics and control program.

O/P position of end-effector	Trajectory Graph Number	Order of (Φ) degree	Order of (θ) degree	Order of rotary motor (ψ)	Order of rotary motor (γ)	Trajectory Length (mm)
First Position – Upper Elbow	6	(2) 229.4	(1) -44.1	(3) 14	(4) 48.1	4347.0
	9	(2) 229.4	(4) -44.1	(1) 14	(3) 48.1	4729.1
	2	(3) 229.4	(1) -44.1	(4) 14	(2) 48.1	4529.8
	13	(3) 229.4	(4) -44.1	(2) 14	(1) 48.1	4871.8
	5	(2) -130.6	(1) -44.1	(3) 14	(4) 48.1	2865.5
	15	(2) -130.6	(4) -44.1	(1) 14	(3) 48.1	3119.7
	7	(3) -130.6	(1) -44.1	(4) 14	(2) 48.1	2968.7
	10	(3) -130.6	(4) -44.1	(2) 14	(1) 48.1	3200.0
Second Position – Down Elbow	1	(2) 229.4	(1) -99.9	(3) 129.9	(4) -12	6291.2
	12	(2) 229.4	(4) -99.9	(1) 129.9	(3) -12	6916.4
	3	(3) 229.4	(1) -99.9	(4) 129.9	(2) -12	6189.4
	11	(3) 229.4	(4) -99.9	(2) 129.9	(1) -12	6906.7
	8	(2) -130.6	(1) -99.9	(3) 129.9	(4) -12	4809.8
	16	(2) -130.6	(4) -99.9	(1) 129.9	(3) -12	5248.6
	4	(3) -130.6	(1) -99.9	(4) 129.9	(2) -12	4743.7
	14	(3) -130.6	(4) -99.9	(2) 129.9	(1) -12	5234.9

Final position of upper and down elbow with the same slope of isometric and front views for KUKA 4R is as shown below.



RESULTS AND DISCUSSION

By using the inverse kinematics and control program of KUKA robot, we can control of the order and arrangement of rotary motors. Therefore, we get 16- possible trajectory path of the end effector when moving from point to another as the following drawings (1-16) in the last pages. We can choose the optimal path of them by select the minimum value of criterion (trajectory length, working time, used energy). For our criterion – trajectory length – we found:

1- The first optimal trajectory is number 5 with path length of 2865.5 mm.

2- The second optimal trajectory is number 7 with path length of 2968.7 mm.

CONCLUSION

This This program interface of inverse kinematics can be used for any Four Degree of Freedom as Revolute-Revolute-Revolute-Revolute joints 4-DOF (RRRR) Manipulator robot (such as exist in KUKA 4R Robot), with any dimension lengths.

Manipulator trajectory can be controlled by order arrangement of motors rotation to avoid a contact and collision with anybody exist in a manipulator workspace.

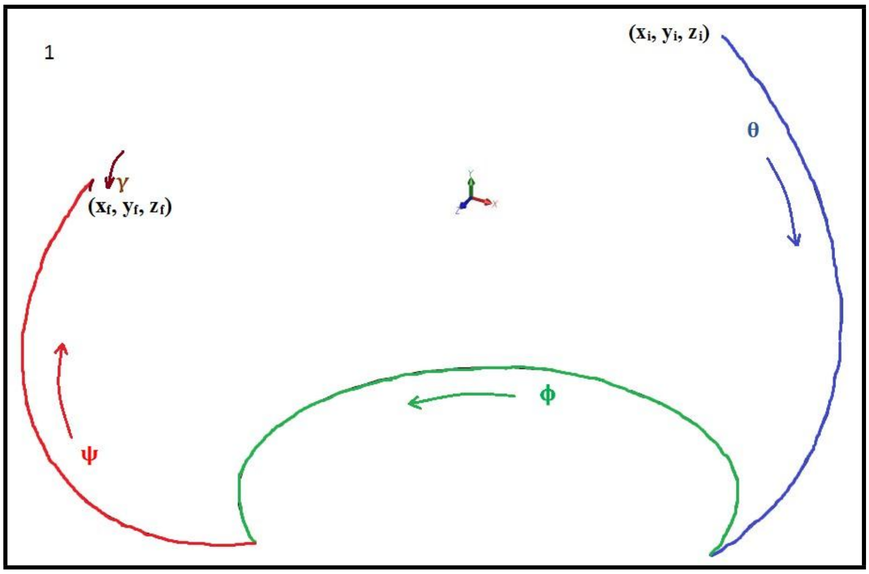
The results of the research can be used in such industries as chemical, plastic, pharmaceuticals, cryogenic and other as a software package to:

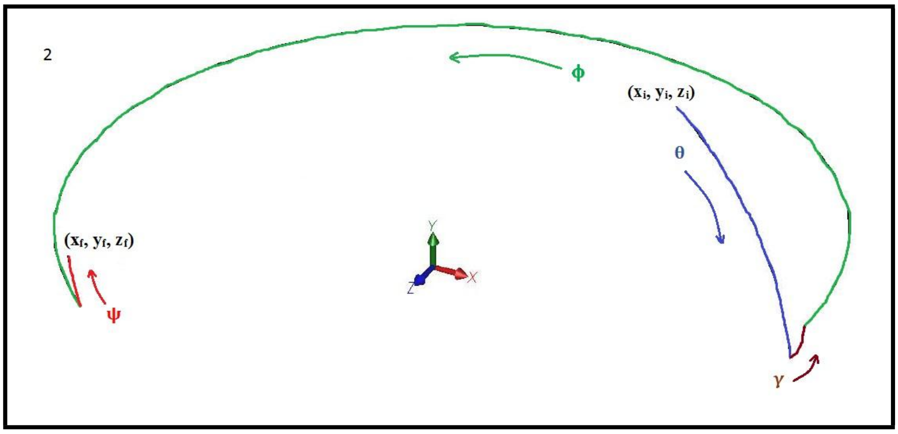
1- Minimizing an account number of labors by using the automating robotic system;
2- Improvement of the production line productivity;
3- Reaching to the increasing of efficiency and accuracy by choosing the optimal path, which achieve the saving in working time and energy using.

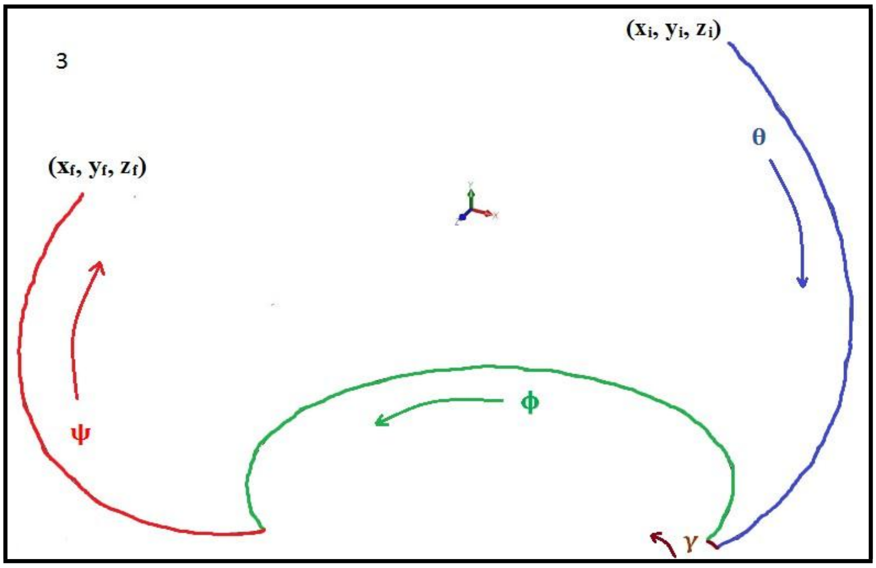
Finally, this program saves a lot of time in calculation with respect to another calculations method and can be implemented in mobile devices.

FUNDING

The work is executed at support of the project 15.8792.2017/8.9 "Development of optical methods for monitoring the status of biotech facilities and the creation of the basis of their automation systems".



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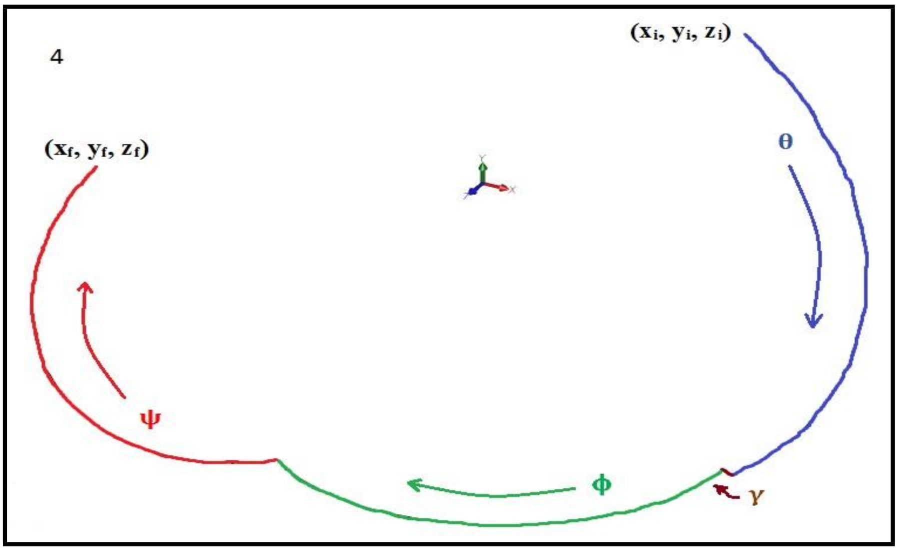
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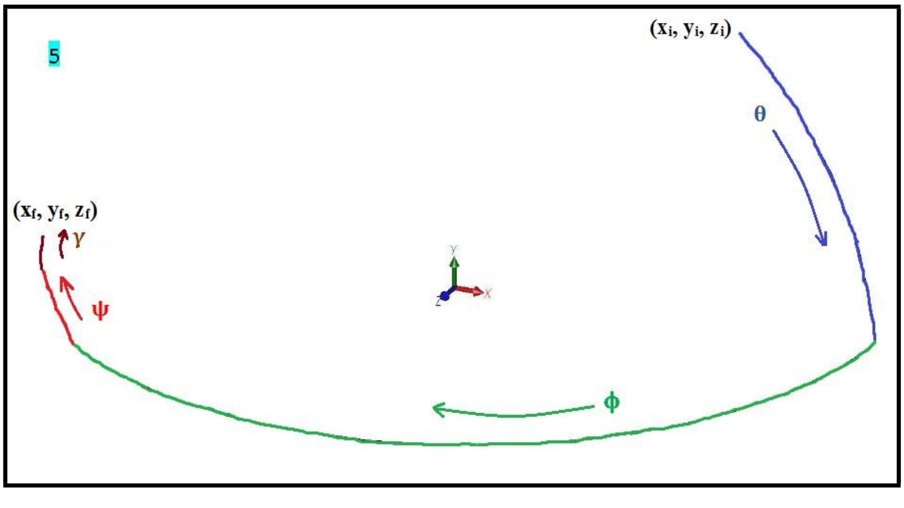
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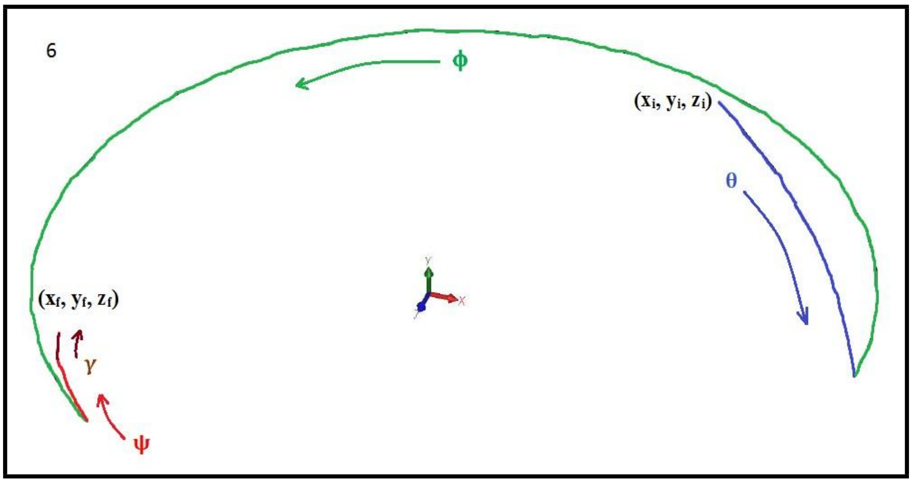
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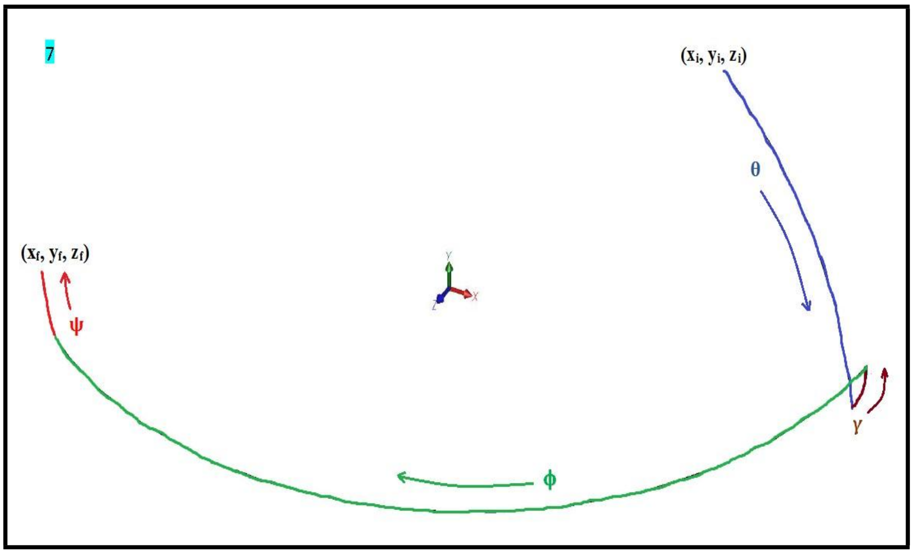
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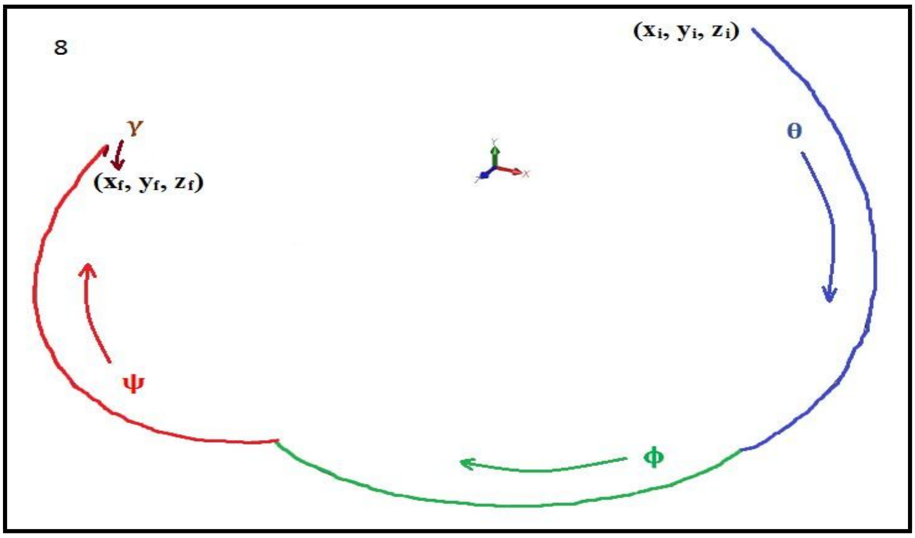
γ
ϕ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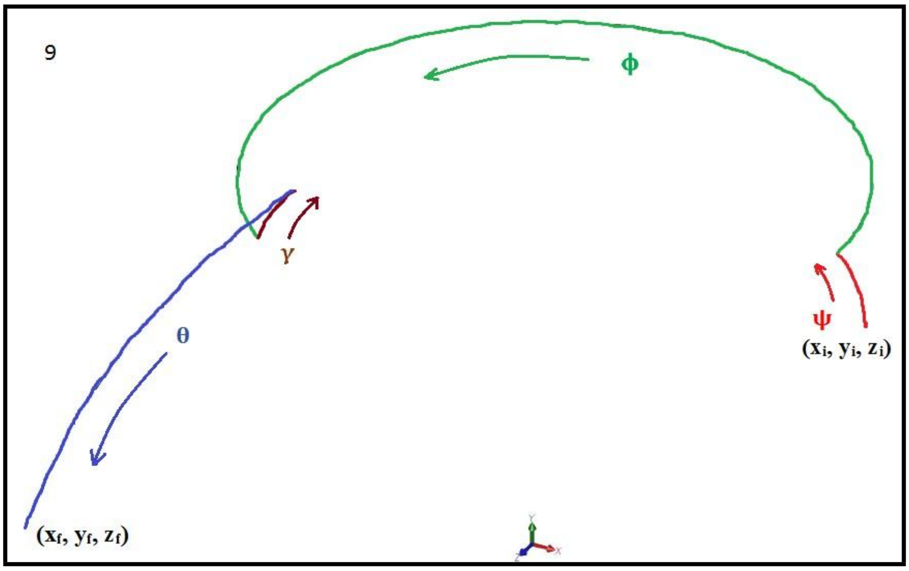
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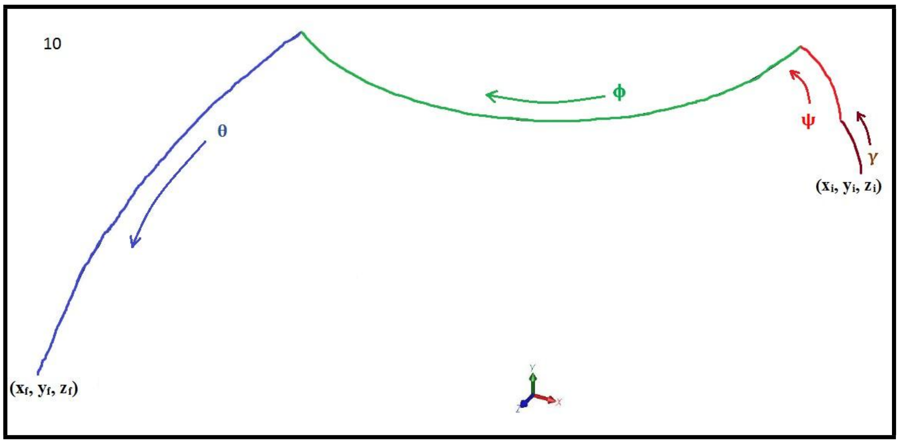
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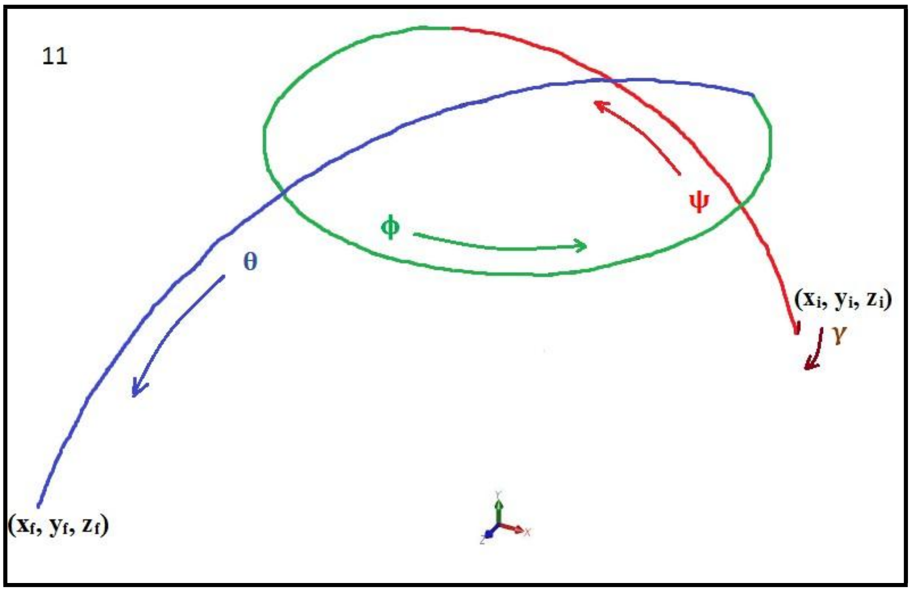
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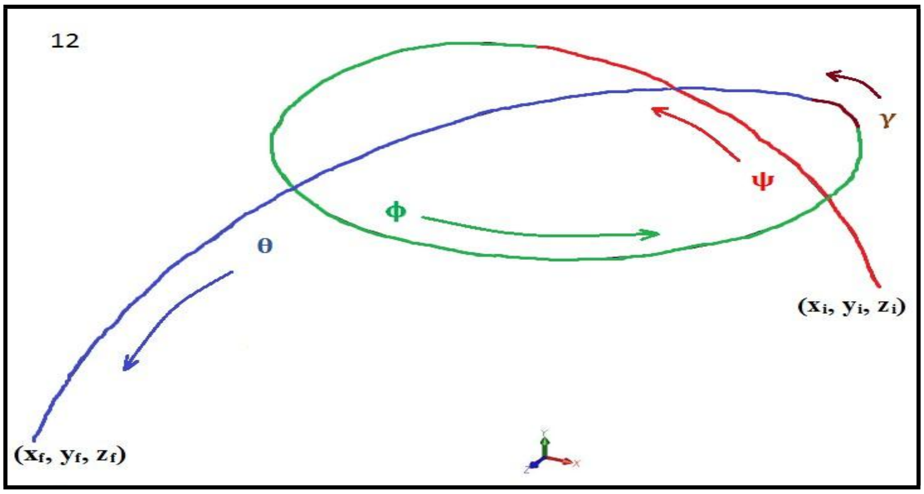
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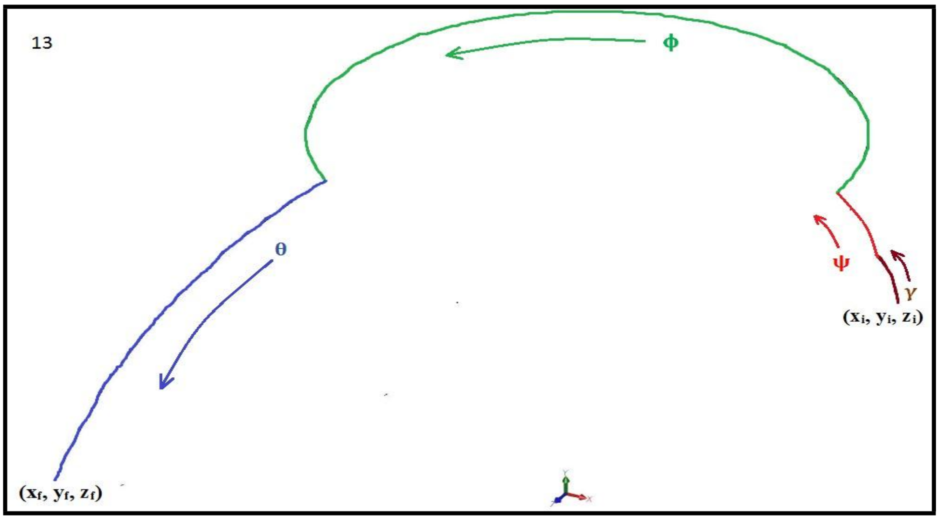
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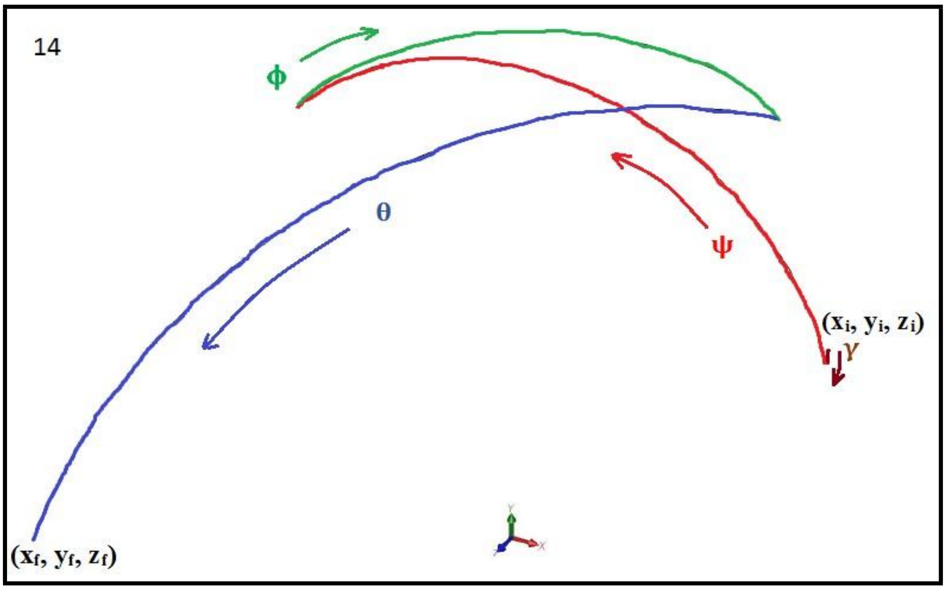
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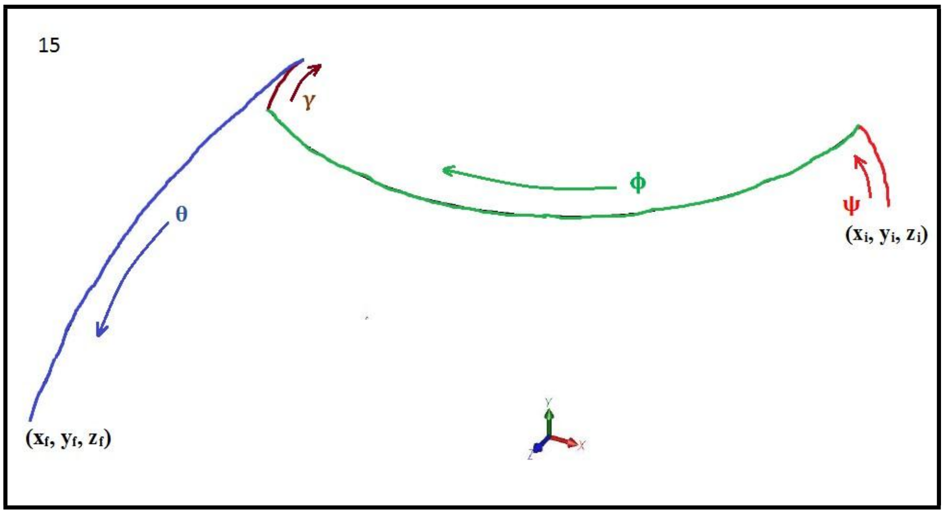

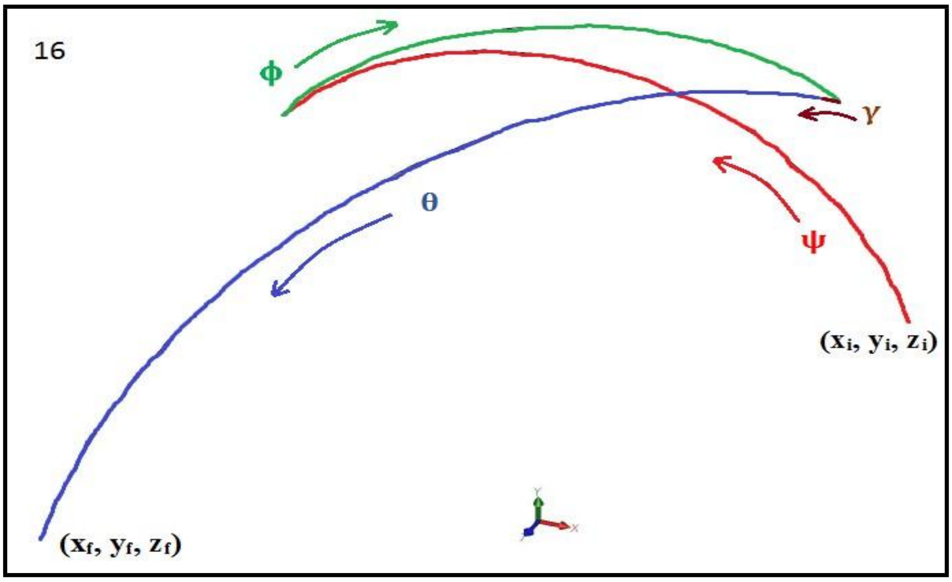

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