Robotics

Final Project: Complete design of a real-world robot

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Abstract

A novel approach is presented to our four-link industrial robot that has been designed to develop the industry 4.0 workers. The dynamic behavior and performance of our 4-link industrial robots play a vital role for industry development. In this approach, 4 joint actuators are treated as forward and inverse kinematics with the help of four slider gains that gain is 50.4. The industrial robot could not be possible to control without sensors and actuators. Our proposed dynamic industrial robot will be able to work 0 to 360 degrees at their working environment. The last joint link especially helps to make different holes and shapes on the working surface. We also analyze that joint link is equal to the actuator for designing a multi-link robot.

Introduction

Historically, the concept of robots has started in the ancient world. This concept is found in Greek mythology, ancient Egypt, early China, India and Europe, where it was used to develop art, stories, toy22s, and sculptures. The concept turned into what is known as Automata, a mechanical device that imitates humans, and later turned into industrial and mobile robots. Industrial robots execute multiple tasks such as picking and placing objects. These types of movements are implemented based on the tasks that are usually handled by a biological human arm. These robotic arms are referred to as robotic manipulators. They were primarily designed to deal with bio-hazardous or radioactive substances, but now we use them for medical operations, such as performing remote surgeries, and in manufacturing, such as welding, material handling, spraying, and drilling.

A manipulator is built with links connected by joints. It has one fixed end and one free end to execute a task, for example, moving a box. The joints and manipulators are considered as dynamic components, which gives them required motion between the links. In addition, there are two linear joints to this manipulator which guarantees that non-rotational motion between the links exists, and three rotary type joints that guarantees the required rotational motion between the links. The manipulator consists of two parts, arm and body and wrist. The arm and body are three joints connected by big links. They are utilized to move and place objects or tools in a workspace. However, the wrist fixes the objects or tools at a given workspace. From a structural characteristic perspective, the wrist consists of two or three compact joints. Motion planning, Remote handling, teleoperation, and Humanoid robots are a few of the applications of the robot manipulator.

The robot chosen is the KUKA manipulator. KUKA stands for Keller Und Knappich Augsburg and it is a German manufacturer of both industrial solutions and robots. It has 25 subsidiaries, including Japan, Mexico, Russia, Canada and several countries within Europe. In addition, KUKA Manipulators are utilized by several automotive manufacturers including BMW and Volvo, as well as manufacturers from other industrial sectors such as Siemens, Airbus and others.

In this project, we will walk through the design of this robot manipulator, including the material used to build it, the structure and components, including the sensors, motors or actuators, controller. We will proceed to discuss the main functions of the robot, the environmental requirement for its operation. And finally, we will share the main design, our analysis and simulation.

Design Requirements

Main Design Requirements

As in any robot design, the main goal of an industrial robot design is to develop optimal results based on the function of the robot specifications. The robot design is dependent on three important factors: intermediate result, robot design activity and design phase.

The intermediate result depends on the product idea, functional specification, system concept, technical, prototype, per-series product and series product. Moreover, the robot design activity also depends on the market and product research, product planning, conceptual design, critical function, concept evaluation and detailing, designing hardware, software, manufacturing and integration, redesign, and large-scale trials. Therefore, the design phase also depends on the product planning, system analysis, and system design.

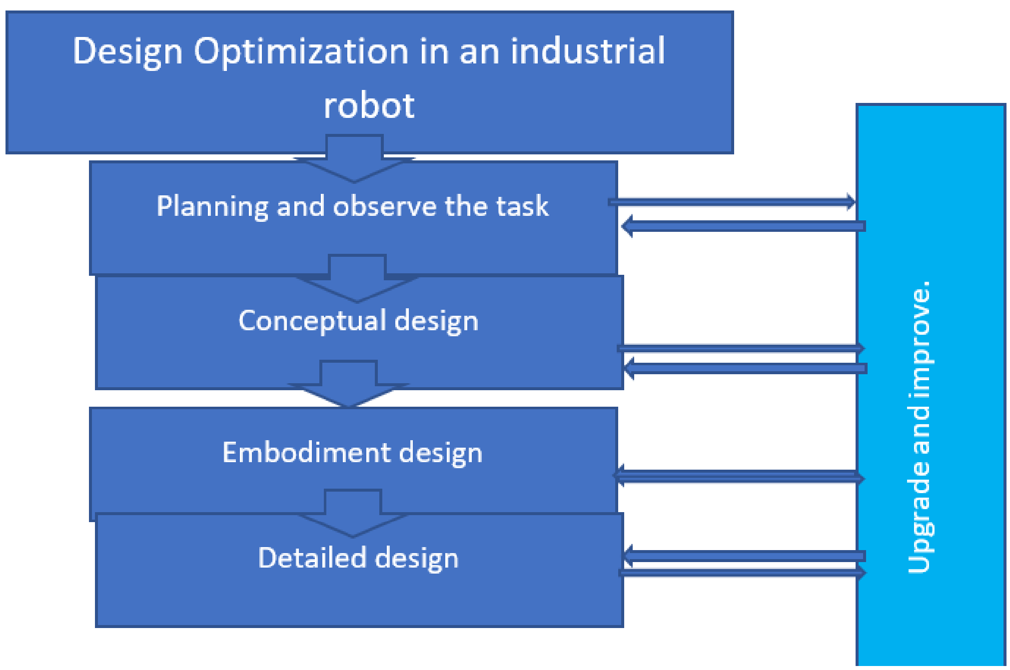


Figure 1: Industrial robot design flow-chart

We also follow the above flowchart to design our 4-link industrial robot. Planning and observation, Detailed design, Embodiment design, Conceptual design are very important things to design that could enlarge our knowledge.

For design an industrial robot we must follow few designing conditions as follows:

- Rigid body dynamics
- Actuators and sensors
- Control system
- Forward and inverse kinematics
- Hardware prototyping

The robot consists of a fixed base, series of links connected by joints and a free end carrying the tool or end effector.

Material:

Robots are mostly built of common materials. Some specialized robots for clean room applications, the space program, or other "high tech" projects may use titanium metal and structural composites of carbon fibers. The operating environment and strength required are major factors in material selection. There are a wide variety of metals and composites available in the market these days. The selection of material is a very deep process.

Steel, cast iron, and aluminum are the most often used materials for the arms and bases of robots. Aluminum is a softer material and therefore easy to work with. But steel is several times stronger. We chose to design the parts with aluminum. It has not been a direct selection. The shoulder has a choice to have more weight when compared to other parts. The remaining parts are not grounded and needed to carry some weight of other arms and end effector also the sheet in this case. So, they cannot be heavier than the base.

Aluminum is a very light metal and the strength of the metal can be increased by adding small quantities of other metals (alloys). The low weight reduces energy consumption related to transportation, and hence also emissions of greenhouse gases and other pollutants. The material also offers high ductility, high resistance to corrosion, good electrical conductivity and is generally considered non-combustible.

KUKA robot of this type comprises the following components:

- Manipulator
- GUI/ SmartPAD
- Motors/Actuators
- Sensors
- Power supply units/ Batteries
  Electrical supply voltage 200-230 V AC, 65-60 HZ
- PLC / Microprocessor and operating software

Sensors:

KUKA robot sensor interface supports simple and flexible interfacing with sensors in the KR C4. It is also possible to integrate a number of channels with real-time requirements.

Camera: The basic requirement for the control system is to keep the tool at a defined distance to the tracking point, and with a defined orientation to the surface vicinity of the tracking point. Since the shape of the workpiece is unknown, a sensor system was built to provide distance measurements around the tool center point. The distance is measured by laser triangulation. An Ethernet camera and four lasers are mounted on the tool-holder to measure the distances. The camera used in the sensor system is a GC1350 Gigabit Ethernet Camera with a maximal resolution of 1360x1024 and a frame rate of 20 fps at this resolution. It is mounted on the tool flange, together with laser LEDs.

Temperature sensors: Temperature sensors are a form of electrical transducer that converts a temperature reading into an electrical output that becomes a proxy for the level of temperature. The use of temperature sensors is widespread in both industrial applications as well as in commercial and consumer products. There are several common forms of temperature sensors available, among them thermocouples, thermistors, RTD's (resistance temperature detectors), infrared sensors, and most recognizably, thermometers.

Potentiometer: The Potentiometer is used to measure the angular position of the axle or shaft passed through its center. The Potentiometer can be attached to the robot using the mounting arcs surrounding the center of the sensor. The arcs provide flexibility for the orientation of the Potentiometer, allowing the full range of motion to be utilized more easily. When mounted on the rotating shaft of a moving portion of the robot, such as an arm or gripper, the Potentiometer provides precise feedback regarding its angular position. This sensor data can then be used for accurate control of the robot.

Motors/Actuators

We will use servo motors for our manipulator. Since there are two joints in our robot, we would need two servo motors to move each robot joint. A servomotor with a closed-loop mechanism will use position feedback to control its motion.

Controller:

The KUKA robot is equipped with a Kuka KRC-4 controller and robot control software.

The KR C4 controller integrates Robot Control, PLC control, Motion Control and Safety Control. All controllers share a database and infrastructure. It understands KRL and the PLC and CNC languages (G-code).

Control software supports every aspect of the robot system, such as motion control, development and execution of application programs, communication etc.

Kuka KR C4 is powerful, safe, flexible, and intelligent. It has a flexible configuration and expansion capability. The number of hardware components, cables and connectors has been significantly reduced and replaced by software-based solutions. The controller is designed for low maintenance.

The controller comes with a KUKA SmartPAD which has an integrated USB port which can be connected and disconnected at any time. It has intuitive operator control with eight jog keys for direct control of eight axes/external axes.

Main Functions of your selected robot

Main function of a KUKA robot are

- Material handling
- Packaging
- Assembly
- Coating
- Cutting

Operational Environment requirements

Ambient temperature:

Manipulator during operation: +5°C to +45°C and No condensation permissible.

Complete robot during transportation and storage: - 25°C to + 55°C

At low environmental temperature, as with any other machine, a warm-up phase is recommended to be run with the robot. Otherwise there is a risk that the robot stops or runs with lower performance due to temperature dependent oil- and grease viscosity.

Relative humidity:

Relative air humidity ≤ 90% at constant temperature during robot operation, transportation and storage.

Altitude:

- Up to 1000 m above mean sea level with no reduction in power
- 1000 m ... 4000 m above mean sea level with a reduction in power of 5%/1000 m

Handling capacity:

Rated payload: 3Kg and max. Payload: 6kg

Noise level:

<70 dB (A) outside the working envelope (acc. to Machinery directive 2006/42/EG)

Safety:

Safety standards valid for complete robot, manipulator and controller, with protection type IP54.

Maintenance:

The robot requires only minimum maintenance during operation. It has been designed to make it as easy to service as possible.

Mounting:

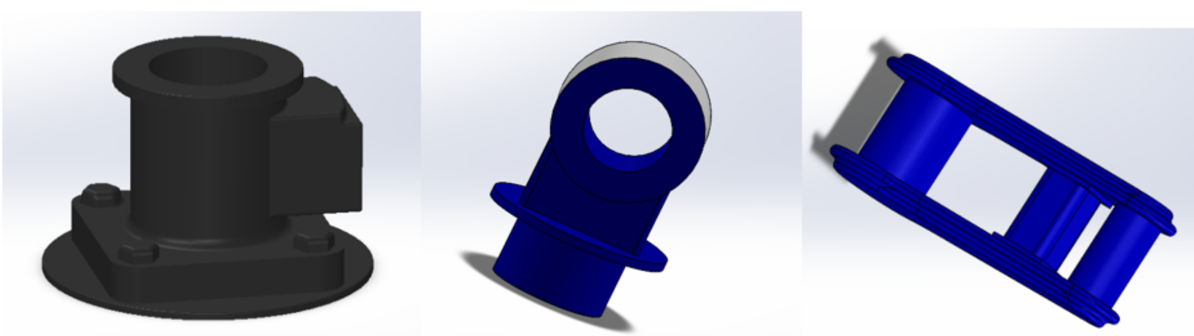
KUKA robot can be mounted on the floor, shelf, inverted or tilted

Explosive environments: The robot must not be located or operated in an explosive environment.

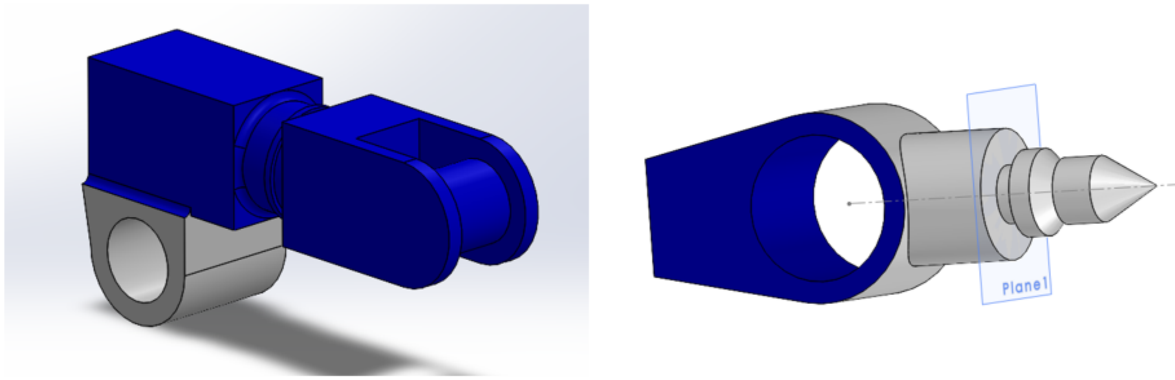
Main Design and Analysis, Simulation - with Graphs, Tables, Equations and Diagrams

i) Free body diagram of the robot

We designed a 4-link industrial robot by using solid work 2021 software. Also, a 4-link industrial robot has four different shapes of the manipulator with a strong base that could be helped to hold all the joint links. Therefore, a 4-link manipulator moves freely 0 to 360 degrees in their working environments as follows as the position and direction.



(a) Base **(b) First joint link** **(c) Second joint link**



(d) Third Joint link **(e) Four joint link**

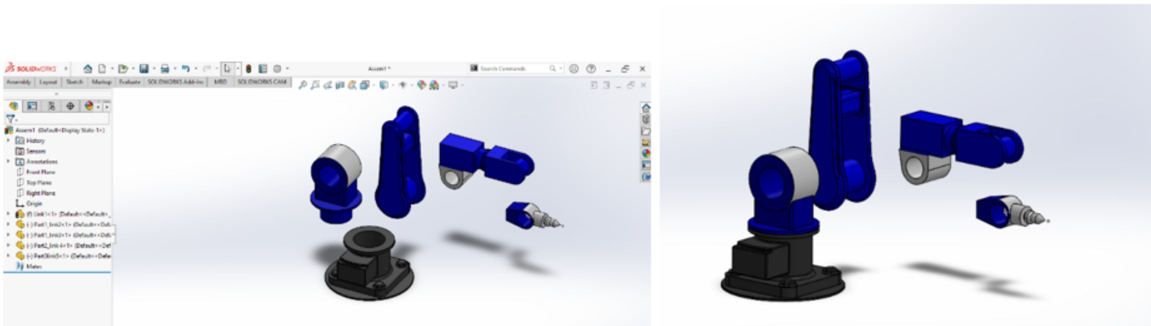
Figure 2: All jointing parts of the 4-link industrial robot.

- The 4-link industrial robot designed to follow the kinematics and dynamics equations (shown below in next sections) will help for finding the velocities, angular position, acceleration, force and torque experience. Moreover, all those factors could be helping to move different industrial working positions. In the above figure (2), the base is shown in fig.(a) that is also black color. The base is very important for holding all joints. That is why we designed it this way with four locking points that also help to fit the base strongly with the surface. The first, second and third joint will be rotated 0 to 360 degrees as following their working principle. The Actuators and sensors could be assisted to find out their location, position with respect to their commands.

- In the figure (2), we have designed this link to make the different shapes and holes which is very essential for industrial cases.

- As per customers' orders, we will be able to design a gripper in the last joint that could be helped to hold the surface of the object or working tools.

Assembly the 4-link industrial robot:



(a) All of the link with base (b) First joint mate with base

Figure 3: Assembly 4-link joint in a single phase.

After designing all joint links with base, we must assemble all parts as follows as figure (3). In this case, we used the mate function from the solid work toolboxes. We selected first base face and link 2 inner faces then chose the mate function that could be helped to join each other. In this way, we assembled all joint links on a single base. After completing all assembly, we reset the coordinator as follows our 4-link surface otherwise it will not move 360 degrees. We used four controlling systems on our 4-link surface.

After assembly, we redesigned our 4-link industrial robot with a controlling system.

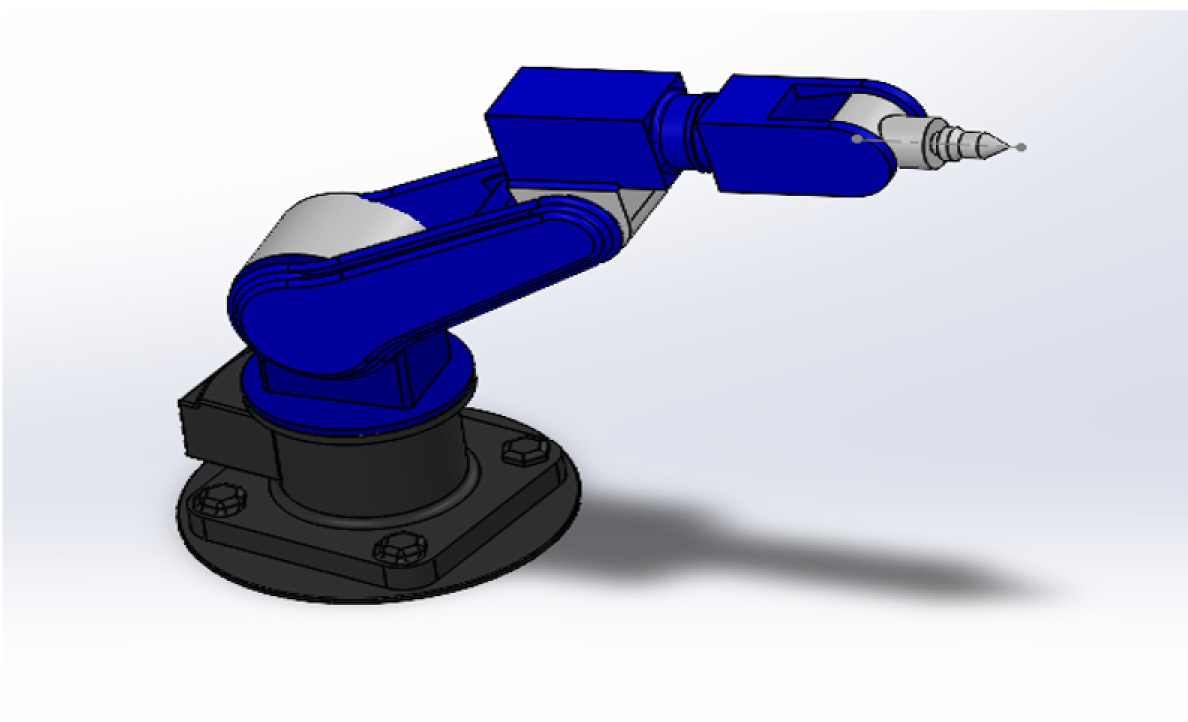


Figure 4: Fully designing 4-Link industrial robot.

ii) Axis labelling and DH parameters

When we use the matlab program a1=486; a2=500; a3=420.17; a4=160, then we will get this forward kinematic for X,Y,Z direction and a 4- link robot also working this position.

Forward Kinematic	
BASE	54
Shoulder	-14.4
Elbow	-21.60
Wrist	-50.40

Position		
X	Y	Z
490.36	674.93	-34.99

Table 1: Moving a 4-link robot to its working positions.

iii) Kinematics

Kinematics is a very important key factor for designing an industrial robot that must be calculated from position, velocity, acceleration of the end effector and the joint also [1]. Besides, which also deals with respect to speed without regard to the force or torques. The inverse kinematics is obtained from a possible set of the correct joint variable and their relative time derivatives which also helps to find out the end-effector as following their set position [1], [2]. Moreover, the end-effector position, orientation and their corresponding time derivative must be helped to find out the forward kinematics. The velocity kinematics can be written as following as [3]:

$$X = [v\ w]^T = J(q_1) + q_2 \quad \text{...(1)}$$

where as,

X= **The linear and angular velocities of the end-effector with respect to the robot base.**

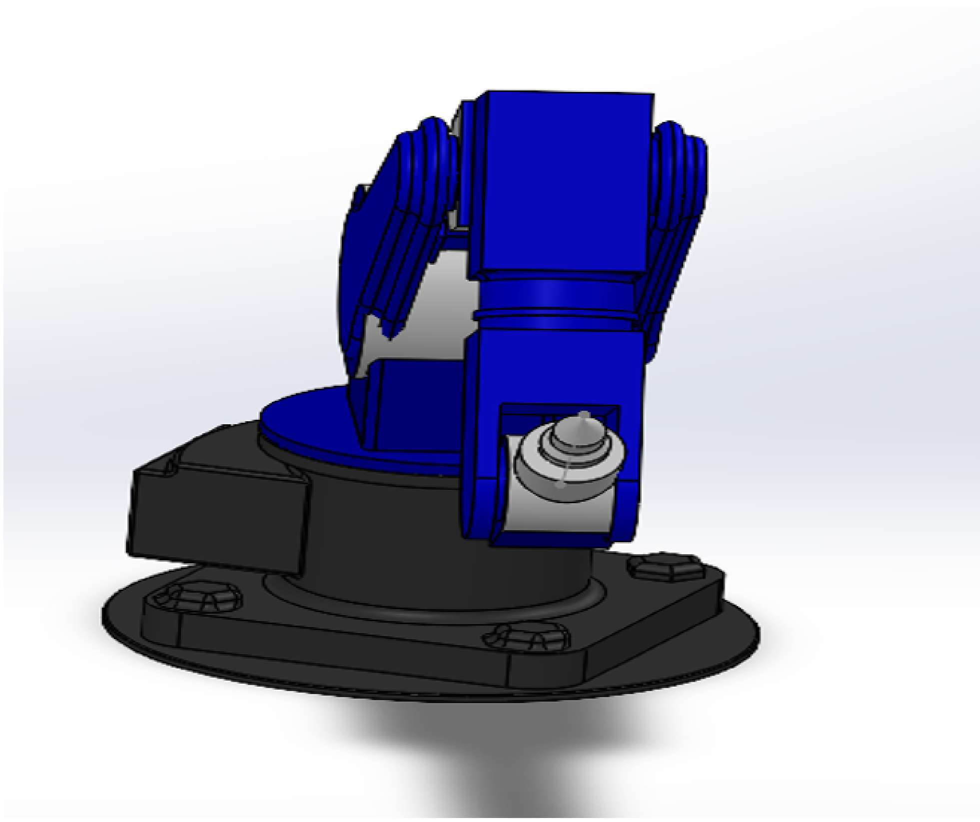


Figure 9: Industrial working position our 4-link robot.

When we move our robot then we will get the inverse and forward kinematic for X, Y and Z position.

Forward Kinematic		Inverse Kinematic	
BASE	152	Px	-122.4

Shoulder	-144.35	Py	64
Elbow	120.60	Pz	36
Wrist	23.40		

Position		
X	Y	Z
-122.4	64.4	36

Table 2: Moving the 4-link robot to its working positions.

iv) Torque Requirements at Joints

$J(q_1)$ = Manipulator of Jacobian.

q_2= Vector joint positions and velocities.

The dynamics are based on the forces and torques due to which the robot gets the motion. Also, the Lagrangian function depends on the kinetic and potential energy of the mechanical system. Therefore, designing an industrial robot requires the Lagrangian equation. We can be also written as following as [3]:

$L=K-U$…………………………….(2)

The torque experience will be found from the formation of the Lagrangian function that also depends on the kinetic and potential energy. We can be driven the Lagrangian function for getting the robot joint torque experience [3],

$d/dt(dL/dq_i)-dL/dq_i=\tau_i$ ………………(3)

where i=1,2, 3………………..α

Let each of the link lengths be represented as ‘l’ and mass as ‘m’.

The actuating torque is
$\tau actuator = \tau inertia + \tau coupling + \tau Coriolis + \tau centrifugal + \tau gravity + \tau friction$

Let us assume that our manipulator is acting in a horizontal plane and gravitational torque is zero.
The actuation torque required at joint 2 is
$\tau 2 = Inertia\, \ddot{\theta}_2 + Coupling\, \ddot{\theta}_1 + Centrifugal\, (\dot{\theta}_1)^2 + \tau friction$

where
$Inertia$ = 0.3342 ml^2
$Coupling$ = $(0.3342 + C_2/2)ml^2$
$Centrifugal$ = $(ml^2/2)\, S_2$

$Inertia$ is constant, hence the proportional plus velocity join controller is critically damped in all configurations.
The $Coupling$ and $Centrifugal$ torques vary with the configuration. The effect of these torques on trajectory tracking depends on how much $friction$ torque will be needed.

The actuation torque required for joint 1 is

$\tau 1 = Inertia\, \ddot{\theta}_1 + Coupling\, \ddot{\theta}_2 + Coriolis\, \theta_1\theta_2 + Centrifugal\, (\dot{\theta}_2)^2 + \tau friction$

where
$Inertia$ = $(1.6683 + C_2)ml^2$
$Coupling$ = $(0.3342 + C_2/2)ml^2$
$Coriolis$= $ml^2\, S_2$
$Centrifugal$ = $-\, (ml^2/2)\, S_2$

For both joints, the magnitudes of $Coupling$ and $Centrifugal$ force constants are the same. The first joint has a $Coriolis$ torque whereas the second does not.

The other difference is that the $Inertia$ at the first joint varies with the configuration of the second link. Thus the damping of the proportional plus velocity controller for the first joint changes with configuration. The $Inertia$ varies upto 37.5% below the maximum as the configuration changes.

The impact of the second link on the dynamics of the first joint can be reduced either by mechanical design or control system design. Mechanically, the impact is reduced by reducing the mass (m) or the length (l) of the second link.

v) Workspace and effectiveness of optimal path

Optimal path planning is about finding collision free motion from one position to another in such a way that it minimizes/maximizes at least one of the following objective functions.

1. Minimize execution time, respectively maximizing the robot productivity, considering that the relative speeds of the actuators elements are limited constructively.
2. Minimize energy consumption or mechanical work necessary for execution, leading to a reduction of the mechanical stresses in actuators and on the robot structure and obtaining smooth trajectories, easy to follow.
3. Minimize maximum power required for operating a robot.
4. Minimize maximum actuation forces.

vi) Actuators/motors

The measured position from the potentiometer is compared with the final position and the difference (or error) is used to rotate the motor in either direction. As this measured position becomes equal to the final position, this difference becomes zero and the motor stops.

The KUKA Servo Motor also has a servo drive.The servo drive translates low power command signals from the controller into high power voltage and current to the motor.

A motor based on calculated torque from the attached **'KUKA motor data.pdf'** document.

vii) Sensors

The KUKA RobotSensorInterface (RSI) is an add-on technology package to enable communication between the robot controller and external system of sensors. Cyclical data transmission from the robot controller and external sensors takes place in parallel to the execution of the KUKA Robot Language (KRL) program. Using RSI makes it possible to influence robot motion or the execution of the KRL program by processing external data.

We use the below external sensors for our application.

1) Camera -
   GC1350 Gigabit Ethernet Camera with
   a) Maximum resolution of 1360x1024 and a frame rate of 20 fps at this resolution.
   b) High quality monochrome and color image quality.
   c) Power consumption at 12 V = 3W

   Datasheet -
   https://www.rmaelectronics.com/content/AVT-Cameras/Prosilica%20GC_DataSheet_1350_v2.0.2_en.pdf

2) Temperature sensors-

   Our manipulator operates in temperature range +5°C to +45°C. We use a solid state temperature sensor 837T-D3x from Rockwell Automation. It can operate from -20 to + 80°C. Operates on a power supply of 15V DC and current consumption 20mA analog signal. The sensor has an accuracy of <=0.5% of span.

   Datasheet - [*https://literature.rockwellautomation.com/idc/groups/literature/documents/um/837t-um001_-en-p.pdf*](https://literature.rockwellautomation.com/idc/groups/literature/documents/um/837t-um001_-en-p.pdf)

3) Potentiometer -

   We use ST-15 360º potentiometer from Piher Sensing Systems to measure the angular position of each joint. This potentiometer can measure a maximum 360º mechanical rotation angle and is suitable for automotive control applications

   Datasheet - [*https://www.piher.net/pdf/ST-15.pdf*](https://www.piher.net/pdf/ST-15.pdf)

viii) Control model for the manipulator

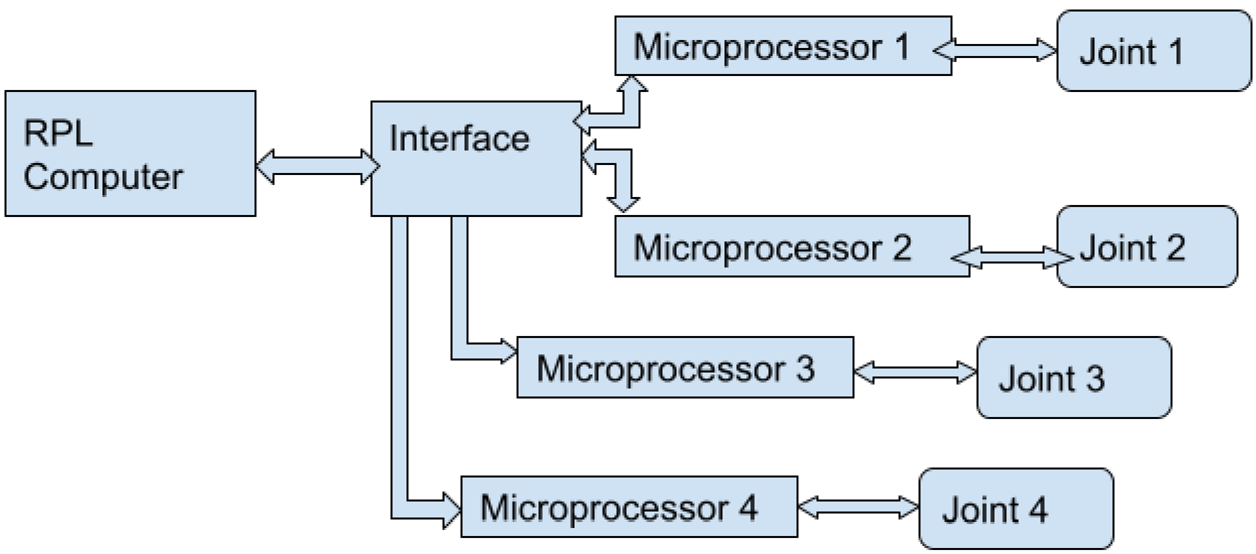
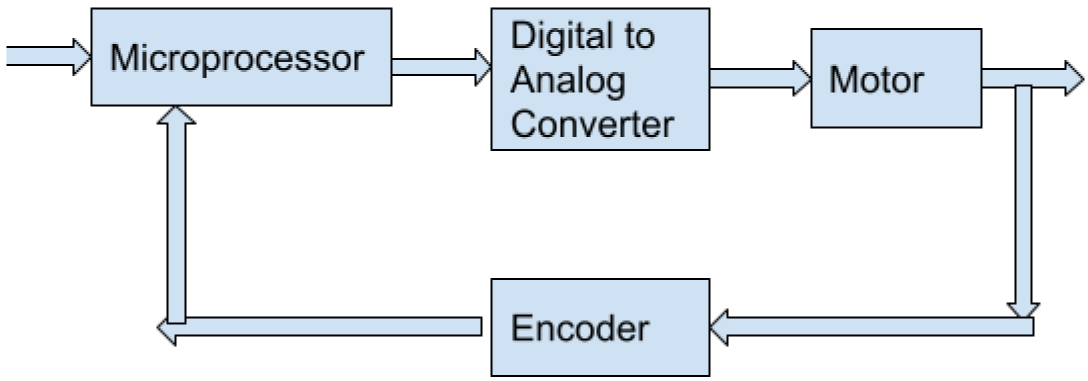


Figure - Computer Architecture of the 4-link robot-control system

Since there are four joints in our manipulator we would need four of below functional blocks for the joint-control.

θd

$\theta(t)$



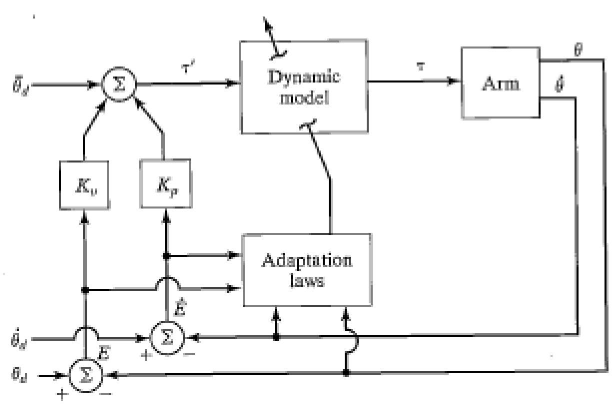
θ

Figure - Functional blocks of a joint-control system of the manipulator

The controller used will depend on the significance of the dynamic terms at normal operating velocities, the accuracy with which the dynamic parameters can be modelled, and the available computing power. For our KUKA robot, we choose an adaptive controller KR C4 as mentioned in the design requirement part.

From the control system's point of view, one of the 'PID control', 'Vision based control', 'Force control' or 'Adaptive control' can be used.

The schematic diagram of adaptive control is shown below



Often the parameters of a model do not match the parameters of a real device resulting in servo errors. These servo errors could be used to drive some adaptation scheme such that attempts to update the value of model parameters until the errors disappear. A system like this would 'learn' its own dynamic properties.

In one such scheme, an adaptive control system adjusts the gains of the control loops in order to maintain critical damping over a range of operating velocities and a range of manipulator configurations. Adaptive control can be used with nonlinear compensation to achieve a good tracking over a wide range of operating conditions. Adaptive systems can improve the performance with poor models.

The closed loop transfer function$T(s)$ for the proportional plus velocity position controller is

$$T(s) = \frac{(g_1 K_a / J R_a)(R_a F + K\square^2)}{S^2 + (S / JR_a)\,[K\square + g_3\, Kfw\, K_a\,(R_a F + K\square^2)] + (g_1 K_a / J R_a)(R_a F + K\square^2)}$$

where
g_1 = proportional gain of the controller
K_a= amplifier voltage gain of the motor
J = motor armature inertia
R_a= motor armature resistance
F= Force due to load
$K\square$= back electromotive force constant of the motor
S= transfer function variable
g_3= velocity (or the derivative) gain of the controller
Kfw= velocity feedback constant

The parameter in the transfer function which changes with configuration is inertia. To maintain critical damping over a range of configurations, the gains have to be adjusted to keep the roots of the characteristic equation in the denominator constant.

ix) Matlab program for design analysis and simulations

After completing the path joint assembly, we link up solid work 2021 to MATLAB 2021b for the Simulink analysis.

Controlling system

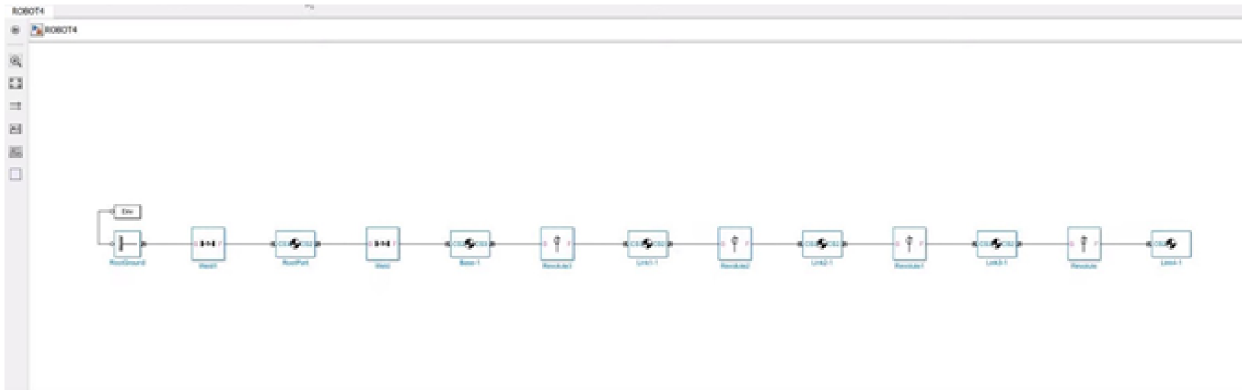


Figure 5 : First controlling block diagram

When the solid work software links up with the matlab by using the robot controlling code then the matlab will automatically generate this block diagram. If we have designed four link robots that is why we also get the 4-Revolute with root ground, weld 1 root part, weld, base-1, and 4 joint links, all of those are series connected to each other.

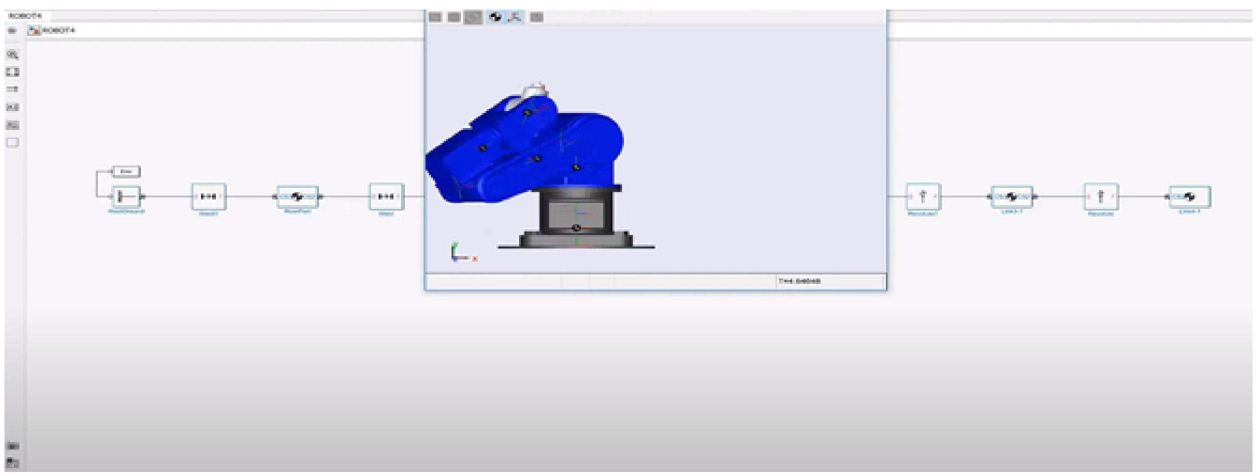


Figure 6: Without actuator and sensor Simulink outcomes.

From fig. (6), the most interesting thing is that if we do not add the actuator and sensor with 4-joint link, all arms will move randomly, and which would not be able to control for any working position.

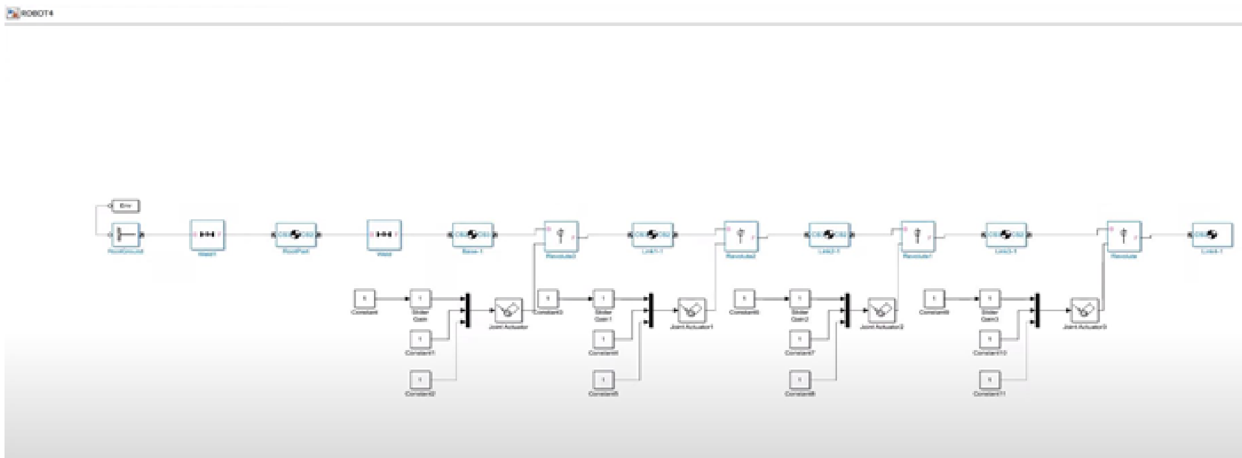


Figure (7): Completing controlling block diagram for 4-link robot.

For controlling the 4-link industrial robot, we redesigned our block diagram and we also fixed the joint actuator, constant input with slider gain. In this case, one constant input is series connected with slider gain 50.4 and this path and another two constant inputs will be parallel connected with a joint actuator that could be controlled by each joint. We have designed a 4-link robot that is why the same controlling model will relate to another three-joint link in which will be helped for moving 0 to 360 degrees in the 3D working environment.

Summary and further recommendation

Discussion and Result analysis

- From figure (1), For designing any kind of industrial robot we must follow all the steps that could be helped to design any industrial robot for their working place.

- From figure (2), (3), (4), we have designed, assembly our proposed 4-link industrial robot. Shape is very important for designing any robot otherwise that could not be filtered and contour properly. When we design any kind of robot then the inner and outer shape are very important things otherwise the robot could not fit properly. And if the design has some problem, the solid work will not link up with MATLAB for Simulink results at forward and inverse kinematic.

- We must need proper knowledge about equation (1), (2) & (3) for designing or calculating joint velocities, angular moment, direction, phase analysis, forces and torque. Therefore, we could not understand the joint velocities and which velocities work with joint links for any industrial robot.

- From figure (5), (6), (7), we have investigated that there is no industrial robot that could not work their working environment without sensors and actuators. For tracking and controlling their own position, we need good sensors and actuators.

- From figure (8) & (9), we observed that the sensors could be helped too much to find out their working direction. For different angles and positions, we will get different forward and inverse kinematics.

- To design a proper industrial robot, we must consider the working safety and security otherwise the worker will face a huge problem. Also, an industrial robot must be costly, if there is no security, that could be damaged.

Conclusion

In conclusion, we discussed in this paper the design of the KUKA robot manipulator, including the material used to build it, the structure and components, including the sensors, motors or actuators, controller. We later proceeded to discuss the main functions of the robot, the environmental requirement for its operation. And finally, we shared the main design, our analysis and simulation.

We designed a 4-link industrial robot that could assist an industry's 4.0 workers. It will also be 360 degrees as their working environment. We also observed at the designing time that there is no robot that will be worked properly without sensors and actuators. The last joint link must be helped to industrial people for making holes and different shapes of the surface tools.

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8. ‘Introduction to Robotics’ book by PJ McKerrow

Contribution by each participants

1. Introduction - Patricia
2. Design Requirements - Siba
3. Free diagram for our robot - Shaikh
4. Axis labelling and DH parameters - Shaikh
5. Kinematics - Shaikh
6. Torque Requirements at Joints - Shaikh + Jaya
7. Workspace and effectiveness of optimal path - Shaikh + Jaya
8. Actuators/Motors - Jaya
9. Sensors - Jaya
10. Control model with diagrams and equations - Jaya
11. Summary and further recommendation - Shaikh + Patricia
12. Report compilation - All members
13. Coordinator - Jaya