ECOLE CENTRALE DE NANTES LS2N, Nantes

SUMMER INTERNSHIP REPORT

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Presented by

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Design of modular 3-D printable 3R robot

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THANK YOU

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1 Introduction

This is a summer internship project to explore & learn the fundamentals of kinematics and robot design. The concepts of 3-D printable & modular designs are also learnt and implemented.

1.1 Problem Statement

A physical nR serial mechanism to demonstrate the concept of cuspidality in robots with non-standard alpha values (D-H parameter) i.e., not 90 or 180, with interchangeable/reusable parts and be easily producible.
To design and prototype a 3R arm which is modular and 3D printable. The designing is mainly done in CATIA with additional creative designs in Inventor. The CAD software should be able to give the final design based on the DH Parameters provided to it in the form of an excel table. This is achieved by smart parametrization of the design wherein just the input DH parameters will be able to control the final output.

1.2 Modular

The manipulator should be designed in accordance to the concept of interchangeable and reusable parts where, for example, a single joint alpha parameter needs to be changed or a link length impacting the d-parameter needs to be varied, then the whole mechanism need not be printed instead just print only the part affected with the changes. This level of modularity facilitates for further development of this work from a 3R mechanism to an nR serial robot with the basic links and joints being the same modular ones.

1.3 3-D Printable

Since, we are utilizing the 3D printing technology for rapid prototyping, the design should be made with full compliance to the technology's limitations all the while leveraging its benefits. The parts are designed for efficient material consumption. Designs which require additional support structures for printing are avoided where possible to save both resource and process time.

1.4 Parametric

Each part is designed and constrained in such a manner that the input DH parameters are the sole requirement for the final geometric design. For example, whenever a specific alpha-parameter is changed the corresponding joint angle will be modified.

2 3R positioning serial chain

General visualization of a robot tends to be similar to the modern Humanoid robot or a mechanical arm/manipulator. While Humanoid robots have a wide range of functions including path planning, learning from the environment, etc, mechanical arms perform actions similar to human arms. These arms are made of a fixed base and a series of links connected by joints. They also have an end-effector that performs the operations. Rotational, prismatic and spherical joints are common types of joints. The relative motion between two links connected by a rotational joint is angular/rotational. In 3R manipulators, three links are connected to the fixed base by a series of three rotational joints. They do not consist of loops like parallel manipulators.

Joint angles at the three rotational joints may be varied to change the position of the end-effector. Forward kinematics refers to the manipulation of the position and orientation of the end-effector by controlling the joint angles, and Inverse kinematics refers to the manipulation of the joint angles by controlling the position and orientation of the end-effector. The following figures illustrate 3R manipulators.

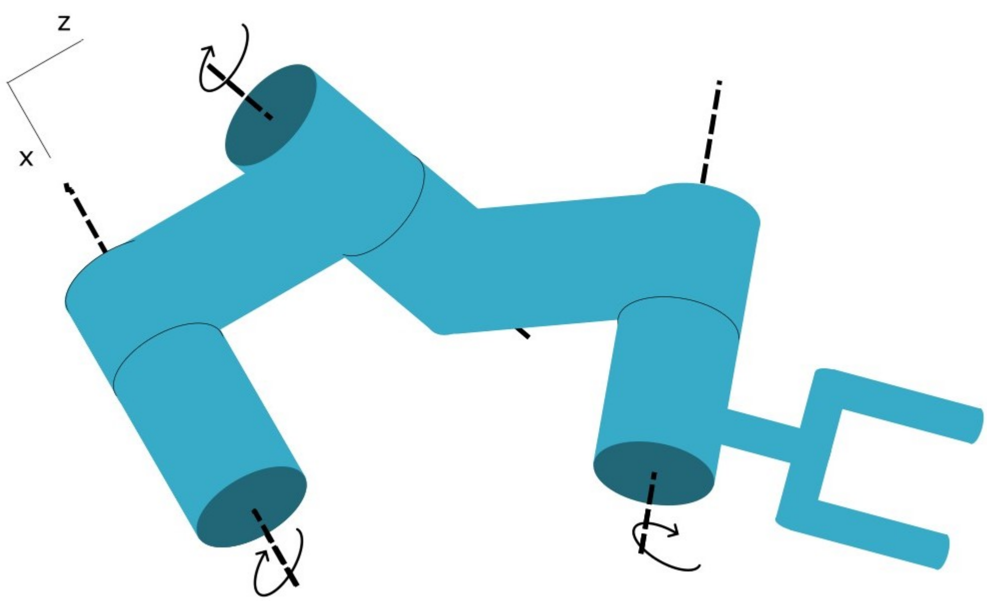

Figure 1: General 3R manipulator

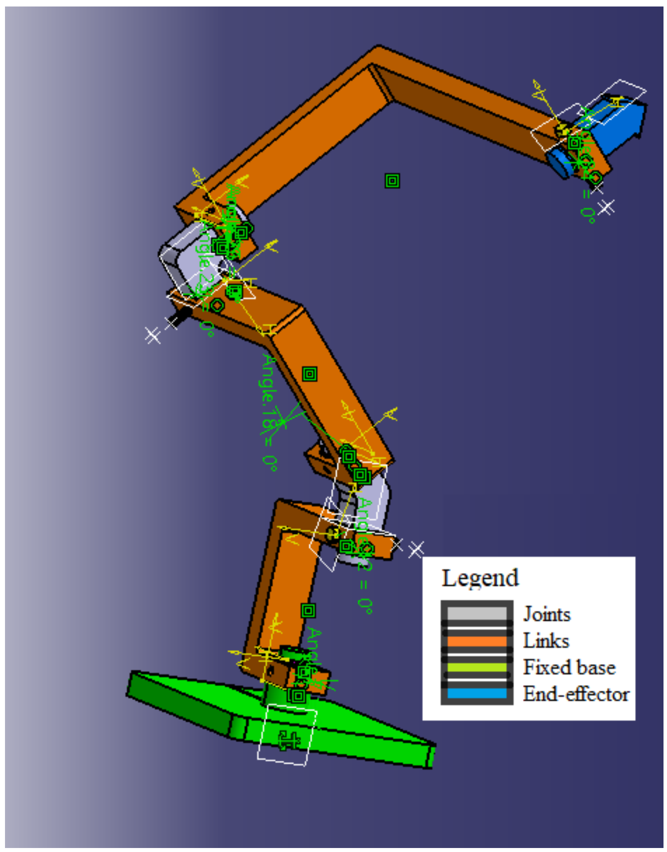

Figure 2: Design of 3R manipulator in home position

3 D-H parameters

As mentioned earlier, a serial arm consists of a sequence of links connected by joints. A rigid body in space can be described by six parameters, three of which are it's position coordinates and other three are it's orientation angles. It is also known that when the orientation of two axes of the body, say X and Z, are known, the orientation of Y is evident. A method exists to define links in space connected by rotational or prismatic joints using only four parameters. This was accomplished by Denavit and Hartenberg. Hence, the four parameters are called Denavit-Hartenberg parameters or D-H parameters. As shown in the figure below, the parameters d_i, a_i, θ_i and α_i are the four D-H parameters. Using these four parameters the frame $i+1$ may be described with respect to the frame i. For achieving frame $i+1$, we translate d_i along Z_i, rotate θ_i about Z_i, translate a_i along X_{i+1}, and rotate α_i about X_{i+1}.

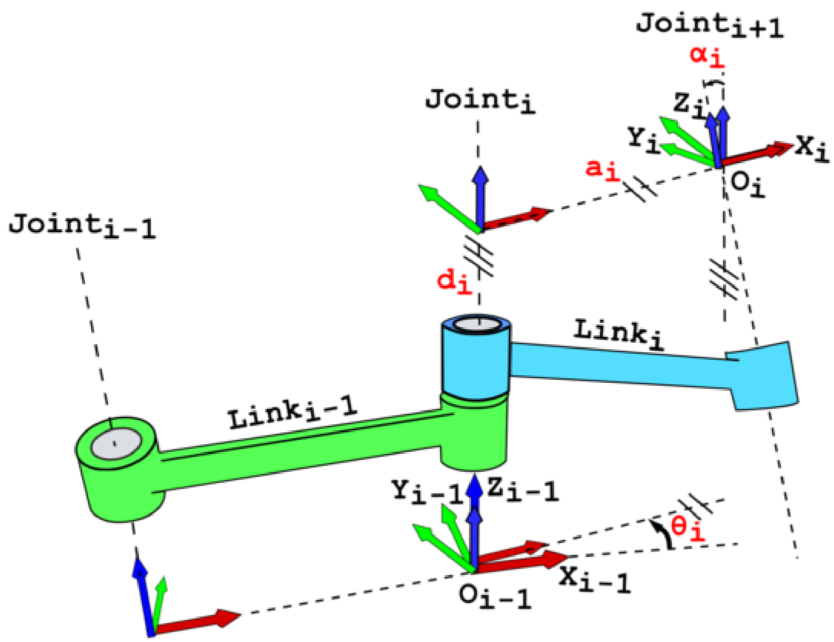

Figure 3: Representation of D-H parameters

Having the D-H parameters is not sufficient. To transform from $i+1$ frame to i frame we need perform matrix operations. Each of the D-H parameters represent a transformation matrix. The angles represent rotational matrices, and the translation distances represent translational matrices. R_z and T_z represent rotational and translational tansformations about and along the Z_i axis. R_x and T_x represent the same about and along the X_{i+1} axis. The following equations represent the transformation matrices.

$$R_z = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_x = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha & 0 \\ 0 & \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$t_z = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$t_x = \begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

To get the final transformation matrix, we multiply the above matrices in an order.

$$^{i+1}T_i = R_z t_z R_x t_x$$

The matrix obtained $^{i+1}T_i$ helps us transform space from frame $i+1$ to frame i. The final transformation matrix is obtained from classical D-H parameters. If modified D-H parameters were used, the final transformation matrix would be obtained as follows. Classical D-H parameters have been used in our study.

$$^{i+1}T_i = R_x t_x R_z t_z$$

For example, in the below equation, the transformation matrix helps us change perspective from frame $i+1$ to frame i:

$$^{i}P_{i+1} =^{i} T_{i+1} P_{i+1}$$

where P_{i+1} is a vector pointing to co-ordinates $P_{(i+1)x}, P_{(i+1)y}, P_{(i+1)z}$ in frame $i+1$

The inverse can also be performed, that is change perspective from frame i to frame $i+1$. This can be done with the help of the inverse of the transformation matrix. The transformation matrix is a 4x4 matrix, that consists of a 3x3 rotation matrix and a 1x3 translation vector. It may be thought of as follows:

$$T = \begin{bmatrix} R & t \\ 0 & 1 \end{bmatrix}$$

where R is a 3x3 rotation matrix and t is the translation vector.

The inverse of the translation matrix can be calculated as follows:

$$T^{-1} = \begin{bmatrix} R^{-1} & -R^{-1}t \\ 0 & 1 \end{bmatrix}$$

4 Proposed Design

As mentioned earlier, the robot design is required to be modular and 3-D printable. To approach modularity, the robot as a whole is divided into six parts namely, base, links, joints end-effector, circlips and bolts, all with simple designs. The links and joints are designed keeping in mind that any two links may be joined by any joint. The ends of the links and the joints are designed to accommodate both circlips (which enable free rotation with respect to the previous link) and bolts (which fix the current link with the previous link).

The 3-R arm is designed to adapt to the set of D-H parameters provided. To accomplish this, the D-H parameters have been infused into the design of the links and joints. When the d and r parameters are changed the length of the links along appropriate directions change. As the α values are varied the angles that the joints represent change.

Lego sets are the best examples of modularity. They consist of a few standard parts that may be fixed be with any other part. A similar ideology has been adopted for the design of joints. Joints with certain standard α angles (Ex: 90°, 135°, 120°, etc) are to be designed and printed. 3-R arms with these standard joint α angles may be constructed. Similar standardization may also be followed with the length d of the links. Following are the designs of standard links and joints.

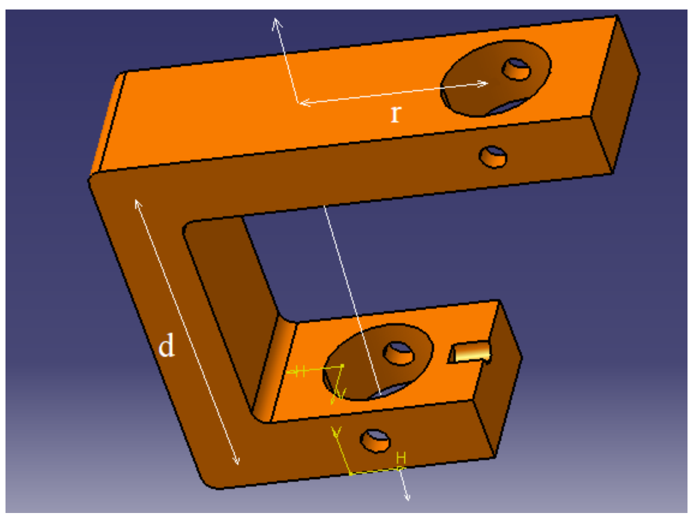

Figure 4: Design of standard link, d=60mm, r=30mm

Since all the parts have to be 3-D printed, minimal usage of circular cross-sections has been utilized. Filleting the parts only on those sides that conform to 3-D printing has also been implemented.

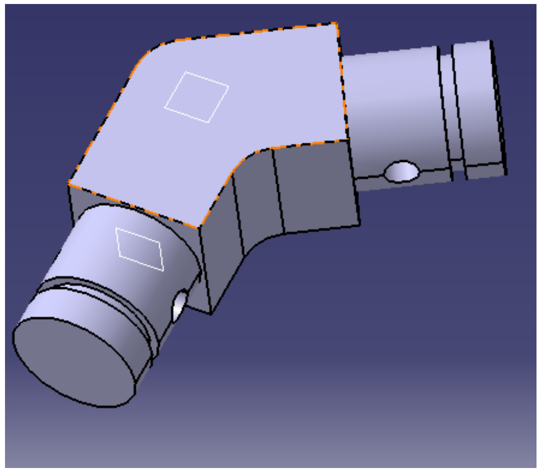

Figure 5: Design of standard α=120°joint

Tolerances are also provided so that the joints and links have free relative movement when required. However, in case of bolts and their respective holes, the holes have a slightly smaller diameter. This has been implemented to enable the bolts to be screwed into the holes, to ensure that they don't fall off. This design also eliminates the requirement of a nut. Standard M4 bolts and circlips that are available in the market may be used.
A particular limitation of the proposed design is that kinematic and dynamic analysis of the design has not been completed. Balance and part strength may pose problems in the practical product

4.1 Limitations

The following are the limitations of the design:

- Kinematic and dynamic analysis of the design has not been completed. Balance and part strength may pose problems in the practical product.
- The d value of the links i.e. the link length cannot be made zero.
- Values of a, $alpha$ and d must be within practical limits, as follows:

  $$\alpha \in [80°, 179°] \cup [-80°; -179°]$$

  The design of the joints are only feasible within these limits

  $$d \in [10, 100]$$

  $$r \in [0, 40]$$

- Joints with only standard α values are initially 3-D printed. For particular requirements new parts with required specifications must be designed and printed.

5 Concepts learnt

This summer internship experience provided an opportunity to learn a lot of things, they may be listed as follows:

- D-H parameters: The concepts of D-H parameters and that of transformation matrices has been thoroughly inculcated.
- Part and assembly design in CATIA: Through this internship, we have learnt to use CATIA well. Not only part and assembly design, but also the methods of parameterization and the methods to control the parameters from an excel sheet has also been learnt.
- Modular and 3-D printable design: Given that our design has to be both Modular and 3-D printable, we have learnt how produce such a design and also few ways to get around the challenges that come in the way.
- LaTeX: As we write this report, we have thoroughly learnt how to use LaTeX, and also the importance of using LaTeX for documentation purposes
- Zotero: Zotero is an application that can be used to organize the literature review that is done before any research.

6 Conclusion

This summer internship provided us with an immense amount of research experience and also helped us learn a lot of things that we are sure will be useful in the future. Once the parts are printed and assembled we shall have in our hand a 3R arm with modular variable parts. It is also evident that the experience that we have with LaTeX will also prove to be useful in the future.
This work can be further utilized for testing cuspidality and other such concepts in an nR Serial Mechanism.