DESIGN, FABRICATION AND KINEMATIC ANALYSIS OF KLANN MECHANISM

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BACHELOR OF TECHNOLOGY

IN

MECHANICAL ENGINEERING

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ABSTRACT

Legged locomotion systems have been effective in numerous robotic missions, and such locomotion is especially useful for providing better mobility over irregular landscapes. Klann mechanism is one such legged locomotion linkage in research. In this project work firstly, kinematic analysis is performed using complex algebraic method, which is easy to understand and for the scope of easy manipulation. The use of complex numbers provides consideration of vectors apart from angles and displacements for the analytical expression of arbitrary motion of points in a plane. The present work represents the design of a 4-legged walking mechanism based on Klann linkage and also the kinematic analysis (i.e. position, angular velocity and angular acceleration of every link) of a single leg of Klann mechanism using complex algebraic method. Further a 4-legged walking mechanism is fabricated using 3d printed technology.

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CHAPTER 1

1. INTRODUCTION

1.1 Mechanism History

Mechanism is the belief that natural wholes (principally living things) are like complicated machines or artifacts, composed of parts lacking any intrinsic relationship to each other. Thus, the source of an apparent thing's activities is not the whole itself, but its parts or an external influence on the parts.

The doctrine of mechanism in philosophy comes in two different flavours. They are both doctrines of metaphysics, but they are different in scope and ambitions: the first is a global doctrine about nature; the second is a local doctrine about humans and their minds, which is hotly contested. For clarity, we might distinguish these two doctrines as **universal mechanism** and **anthropic mechanism**.

There is no constant meaning in the history of philosophy for the word Mechanism. Originally, the term meant that cosmological theory which ascribes the motion and changes of the world to some external force. In this view material things are purely passive, while according to the opposite theory (i.e., Dynamism), they possess certain internal sources of energy which account for the activity of each and for its influence on the course of events. These meanings, however, soon underwent modification. The question as to whether motion is an inherent property of bodies, or has been communicated to them by some external agency, was very often ignored. With a large number of cosmologists the essential feature of Mechanism is the attempt to reduce all the qualities and activities of bodies to quantitative realities, i.e., to mass and motion. But a further modification soon followed. Living bodies, as is well known, present at first sight certain characteristic properties which have no counterpart in lifeless matter. Mechanism aims to go beyond these appearances. It seeks to explain all "vital" phenomena as physical and chemical facts; whether or not these facts are in turn reducible to mass and motion becomes a secondary question, although Mechanists are generally inclined to favour such reduction. The theory opposed to this biological mechanism is no longer Dynamism, but Vitalism or Neo-vitalism, which maintains that vital activities cannot be explained, and never will be explained, by the laws which govern lifeless matter.

1.2 Definition

A **mechanism** is a device designed to transform input forces and movement into a desired set of output forces and movement. Mechanisms generally consist of moving components belt and chain such as gears and gear trains, drives, cam and follower mechanisms, and linkages as well as friction devices such as brakes and clutches, and structural components such as the frame, fasteners, bearings, springs, lubricants and seals, as well as a variety of specialized machine elements such as splines, pins and keys.

The German scientist Reuleaux provides the definition "a machine is a combination of resistant bodies so arranged that by their means the mechanical forces of nature can be compelled to do work accompanied by certain determinate motion." In this context, his use of machine is generally interpreted to mean mechanism.

The combination of force and movement defines power, and a mechanism is designed to manage power in order to achieve a desired set of forces and movement.

A mechanism is usually a piece of a larger process or mechanical system. Sometimes an entire machine may be referred to as a mechanism. Examples are the steering mechanism in a car, or the winding mechanism of a wristwatch. Multiple mechanisms are machines.

1.3 Types of Mechanisms

- 1.3.1 Kinematic pairs
- 1.3.2 Planar mechanism
- 1.3.3 Spherical mechanism
- 1.3.4 Spatial mechanism
- 1.3.5 Gears and gear trains
- 1.3.6 Cam and follower mechanisms
- 1.3.7 Linkages
- 1.3.8 Flexure mechanisms

From the time of Archimedes through the Renaissance, mechanisms were considered to be constructed from simple machines, such as the lever, pulley, screw, wheel and axle, wedge and inclined plane. It was Reuleaux who focused on bodies, called links, and the connections between these bodies called kinematic pairs, or joints.

In order to use geometry to study the movement of a mechanism, its links are modeled as rigid bodies. This means distances between points in a link are assumed to be unchanged as the mechanism moves,that are the link does not flex. Thus, the relative movement between points in two connected links is considered to result from the kinematic pair that joins them.

Kinematic pairs, or joints, are considered to provide ideal constraints between two links, such as the constraint of a single point for pure rotation, or the constraint of a line for pure sliding, as well as pure rolling without slipping and point contact with slipping. A mechanism is modeled as an assembly of rigid links and kinematic pairs.

1.3.1 Kinematic pairs

Reuleaux called the ideal connections between links kinematic pairs. He distinguished between higher pairs which were said to have line contact between the two links and lower pairs that have area contact between the links. J. Phillips shows that there are many ways to construct pairs that do not fit this simple model.

Lower pair: A lower pair is an ideal joint that has surface contact between the pair of elements. We have the following cases:

- A revolute pair, or hinged joint, requires a line in the moving body to remain co-linear with a line in the fixed body, and a plane perpendicular to this line in the moving body maintain contact with a similar perpendicular plane in the fixed body. This imposes five constraints on the relative movement of the links, which therefore has one degree of freedom.
- A prismatic joint, or slider, requires that a line in the moving body remain co-linear with a line in the fixed body, and a plane parallel to this line in the moving body maintain contact with a similar parallel plane in the fixed body. This imposes five constraints on the relative movement of the links, which therefore has one degree of freedom.
- A cylindrical joint requires that a line in the moving body remain co-linear with a line in the fixed body. It is a combination of a revolute joint and a sliding joint. This joint has two degrees of freedom.

- A spherical joint, or ball joint, requires that a point in the moving body maintain contact with a point in the fixed body. This joint has three degrees of freedom.
- A planar joint requires that a plane in the moving body maintain contact with a plane in fixed body. This joint has three degrees of freedom.
- A screw joint, or helical joint, has only one degree of freedom because the sliding and rotational motions are related by the helix angle of the thread.

Higher pairs: Generally, a higher pair is a constraint that requires a line or point contact between the elemental surfaces. For example, the contact between a cam and its follower is a higher pair called a cam joint. Similarly, the contact between the involute curves that form the meshing teeth of two gears are cam joints.

1.3.2 Planar mechanism

A planar mechanism is a mechanical system that is constrained so the trajectories of points in all the bodies of the system lie on planes parallel to a ground plane. The rotational axes of hinged joints that connect the bodies in the system are perpendicular to this ground plane.

1.3.3 Spherical mechanism

A **spherical mechanism** is a mechanical system in which the bodies move in a way that the trajectories of points in the system lie on concentric spheres. The rotational axes of hinged joints that connect the bodies in the system pass through the center of these circles.

1.3.4 Spatial mechanism

A spatial mechanism is a mechanical system that has at least one body that moves in a way that its point trajectories are general space curves. The rotational axes of hinged joints that connect the bodies in the system form lines in space that do not intersect and have distinct common normal.

1.3.5 Gears and gear trains

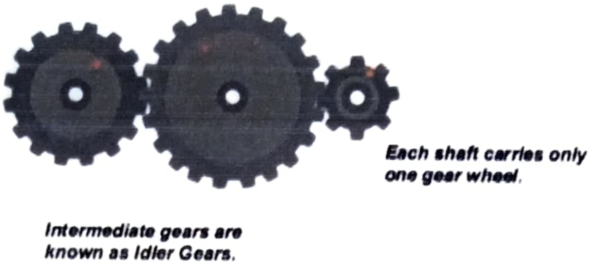

Figure 1.1 Gear mechanism

The transmission of rotation between contacting toothed wheels can be traced back to the Antikythera mechanism of Greece and the south-pointing chariot of China. Illustrations by the renaissance scientist Georgius Agricola show gear trains with cylindrical teeth. The implementation of the involute tooth yielded a standard gear design that provides a constant speed ratio. Some important features of gears and gear trains are:

- The ratio of the pitch circles of mating gears defines the speed ratio and the mechanical advantage of the gear set.
- A planetary gear train provides high gear reduction in a compact package.
- It is possible to design gear teeth for gears that are non-circular, yet still transmit torque smoothly.
- The speed ratios of chain and belt drives are computed in the same way as gear ratios. See bicycle gearing.

1.3.6 Cam and follower mechanisms

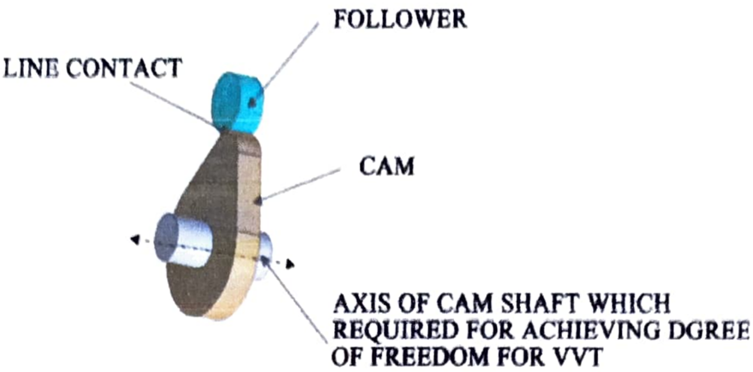

Figure 1.2 Cam and Follower mechanism

A cam and follower is formed by the direct contact of two specially shaped links. The driving link is called the cam (also see cam shaft) and the link that is driven through the direct contact of their surfaces is called the follower. The shape of the contacting surfaces of the cam and follower determines the movement of the mechanism. In general a cam follower mechanism's energy is transferred from cam to follower. The cam shaft is rotated and, according to the cam profile, the follower moves up and down. Now slightly different types of eccentric cam followers are also available in which energy is transferred from the follower to the cam. The main benefit of this type of cam follower mechanism is that the follower moves a little bit and helps to rotate the cam 6 times more circumference length with 70% force.

1.3.7 Linkages

A linkage is a collection of links connected by joints. Generally, the links are the structural elements and the joints allow movement. Perhaps the single most useful example is the planar four-bar linkage. However, there are many more special linkages:

- Watt's linkage is a four-bar linkage that generates an approximate straight line. It was critical to the operation of his design for the steam engine. This linkage also appears in vehicle suspensions to prevent side-to-side movement of the body relative to the wheels. Also see the article Parallel motion.
- The success of Watt's linkage leads to the design of similar approximate straight line linkages, such as Hoeken's linkage and Chebyshev's linkage.
- The Peaucellier linkage generates a true straight-line output from a rotary input.

- The Sarrus linkage is a spatial linkage that generates straight-line movement from a rotary input.
- The Klann linkage and the Jansen linkage are recent inventions that provide interesting walking movements. They are respectively a six-bar and an eight-bar linkage.

1.3.8 Flexure mechanisms

A flexure mechanism consisted of a series of rigid bodies connected by compliant elements (flexure bearings also known as flexure joints) that is designed to produce a geometrically well-defined motion upon application of a force.

1.4 Complex mechanisms

The Jansen's linkage is a leg mechanism designed by the kinetic sculptor Theo Jansen to simulate a smooth walking motion. Jansen has used his mechanism in a variety of kinetic sculptures which are known as Strandbeests. Jansen's linkage bears artistic as well as mechanical merit for its simulation of organic walking motion using a simple rotary input.

Figure 1.3 Jansen mechanism

The Geneva drive is also called a "Maltese cross mechanism" due to the visual resemblance when the rotating wheel has four spokes, since they can be made small, and are able to withstand substantial mechanical stress. These mechanisms are frequently used in mechanical watches. One application of the Geneva drive is in movie projectors.

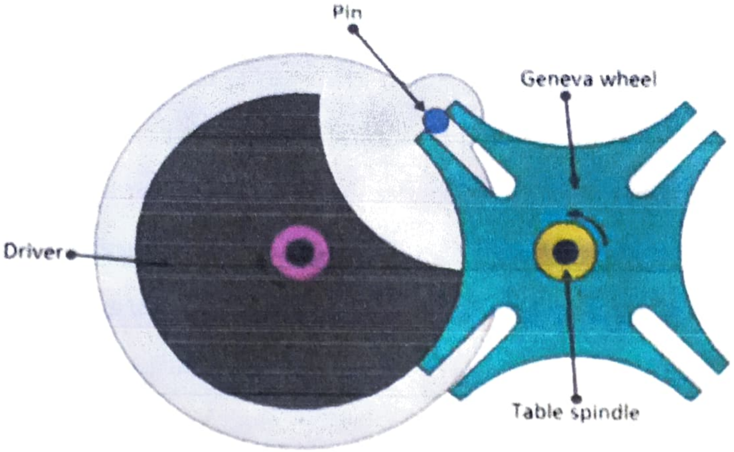

Figure 1.4 Geneva drive

The **Klann linkage** is a planar mechanism designed to simulate the gait of legged animal and function as a wheel replacement. The linkage consists of the frame, a crank, two grounded rockers, and two couplers all connected by pivot joints. It was developed by Joe Klann in 1994 as an expansion of Burmester curves which are used to develop four-bar double-rocker linkages such as harbor crane booms. It is categorized as a modified Stephenson type III kinematic chain.

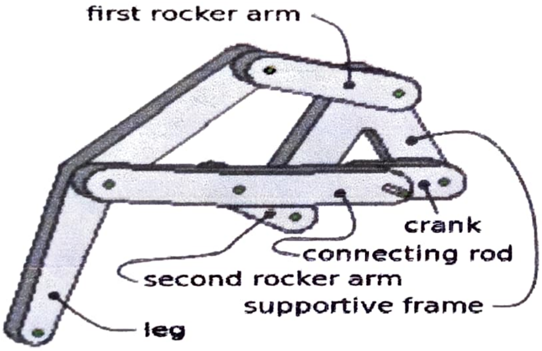

Figure 1.5 Klann mechanism

The proportions of each of the links in the mechanism are defined to optimize the linearity of the foot for one-half of the rotation of the crank. The remaining rotation of the crank allows the foot to be raised to a predetermined height before returning to the starting position and repeating the cycle. Two of these linkages coupled together at the crank and one-half cycle out of phase with each other will allow the frame of a vehicle to travel parallel to the ground.

The **Klann linkage** provides many of the benefits of more advanced walking vehicles without some of their limitations. It can step over curbs, climb stairs, or travel into areas that are currently not accessible with wheels but do not require microprocessor control or multitudes of actuator mechanisms. It fits into the technological space between these walking devices and axle-driven wheels.

The **Klann mechanism** uses six links per leg, whereas the Jansen's linkage developed by Theo Jansen uses eight links per leg, with one degree of freedom. It can walk only on even surfaces and terrain. The number of links in the Jansen mechanism is greater than in the Klann mechanism, and is more costly.

The **Klann linkage** can walk on non-planar roads and hill areas, and on uneven surfaces and terrain. The design of the Klann mechanism is portable with less linkage for movement. Friction is required for motion between the legs and surface so it can hold, otherwise it will slip.

The **Chebyshev's Lambda Mechanism** is a four-bar mechanism that converts rotational motion to approximate straight-line motion with approximate constant velocity. The precise design trades off straightness, lack of acceleration, and what proportion of the driving rotation is spent in the linear portion of the full curve. The example to the right spends over half of the cycle in the near straight portion. The Chebyshev's Lambda Mechanism is a cognate linkage of the Chebyshev linkage. The linkage was first shown in Paris on the Exposition Universelle (1878) as "The Plantigrade Machine". The Chebyshev's Lambda Mechanism looks like the Greek letter lambda, therefore the linkage is also known as Lambda Mechanism.

The **Hoeckens linkage** is a four-bar mechanism that converts rotational motion to approximate straight-line motion. It is named after Karl Hoecken (1874—1962). The example to the right spends over half of the cycle in the near straight portion. The Hoeckens linkage is a cognate linkage of the linkage. The linkage was first published in 1926.

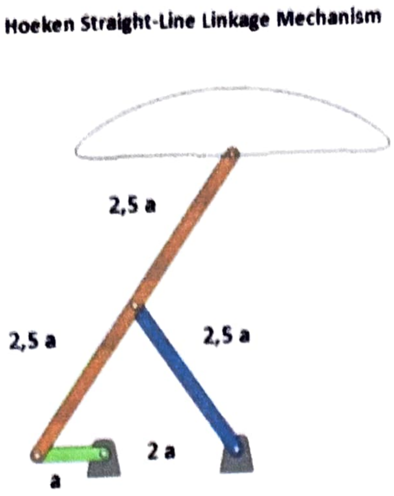

Figure 1.6 Hoeckens linkage

1.5 Analysis and Synthesis of Mechanisms

Analysis is consisted of techniques of determining the positions, velocities and accelerations of certain points on the members of mechanisms. The angular positions, velocities and accelerations of the members of mechanisms are also determined during analysis of mechanisms. By analysis of mechanisms the trajectory of particular points and the orientation of the members at particular points of time are obtained.

If the desired set of positions/angular positions, velocities/angular velocities and acceleration/angular acceleration at definite points of time are stipulated. Then the synthesis of mechanisms comprises of mathematically determining the geometry of members of mechanisms such as to produce the desired results. When that mechanism is operated it will pass through the stipulated points with the required velocity and acceleration, and the members will have the desired orientation.

Synthesis of mechanisms as per the requirement can be achieved through two ways. First Rational Synthesis, which consists of standard synthesis techniques developed by kinematicians. Being systematic these techniques can be automated using computer programs. Limitation of rational synthesis technique is that it is applicable only to some specific types of mechanisms.

Second technique commonly used by design engineers is Informal Synthesis. This design procedure involves first a guess of dimensions of members of mechanisms and then checking the resultant performance by analysis. The dimensions are modified based on previous performance and adjusted such that to obtain results close to desired. In this way the process of iterative synthesis and analysis is repeated to obtain acceptable design.

1.6 Introduction to Solidworks

1.6.1 What is Solidworks?

SolidWorks is a solid modeling computer-aided design (CAD) and computer-aided engineering (CAE) computer program that runs on Microsoft Windows. SolidWorks is published by Dassault Systems.

Solidworks Corporation was founded in December 1993 by Massachusetts Institute of Technology graduate Jon Hirschtick. SolidWorks released its first product Solidworks 95 in November 1995. In 1997 Dassault, best known for its CATIA CAD software, acquired SolidWorks for $310 million in stock.

SolidWorks currently markets several versions of the SolidWorks CAD software in addition to eDrawings, a collaboration tool, and DraftSight, a 2D CAD product.

The SOLIDWORKS CAD software is a mechanical design automation application that lets designers quickly sketch out ideas, experiment with features and dimensions, and produce models and detailed drawings.

A SOLIDWORKS model consists of 3D geometry that defines its edges, faces, and surfaces. The SOLIDWORKS software lets to design models quickly and precisely. SOLIDWORKS models are:

- Defined by 3D design
- Based on components

1.6.2 3D Design

SOLIDWORKS uses a 3D design approach. As to design a part, from the initial sketch to the final result, to create a 3D model. From this model, to create 2D drawings or mate components consisting of parts or subassemblies to create 3D assemblies. We can also create 2D drawings of 3D assemblies. When designing a model using

SOLIDWORKS, to visualize it in three dimensions, the way the model exists once it is manufactured.

This document discusses concepts and terminology used throughout the SOLIDWORKS application. It familiarizes with the commonly used functions of SOLIDWORKS.

Parts are the basic building blocks in the SOLIDWORKS software. Assemblies contain parts or other assemblies, called subassemblies.

Figure 1.7 Solidworks 3d assembly

Figure 1.9 Solidworks 3d part

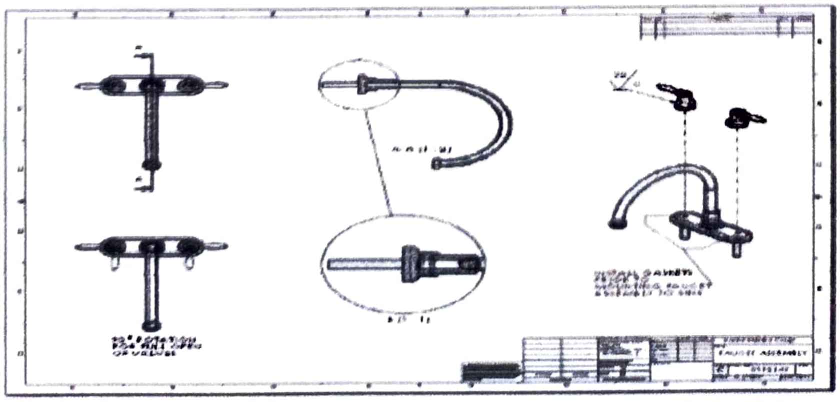

Figure 1.8 Solidworks 2d drawing generated from 3d model

Component Based

One of the most powerful features in the SOLIDWORKS application is that any change to make to a part is reflected in all associated drawings or assemblies.

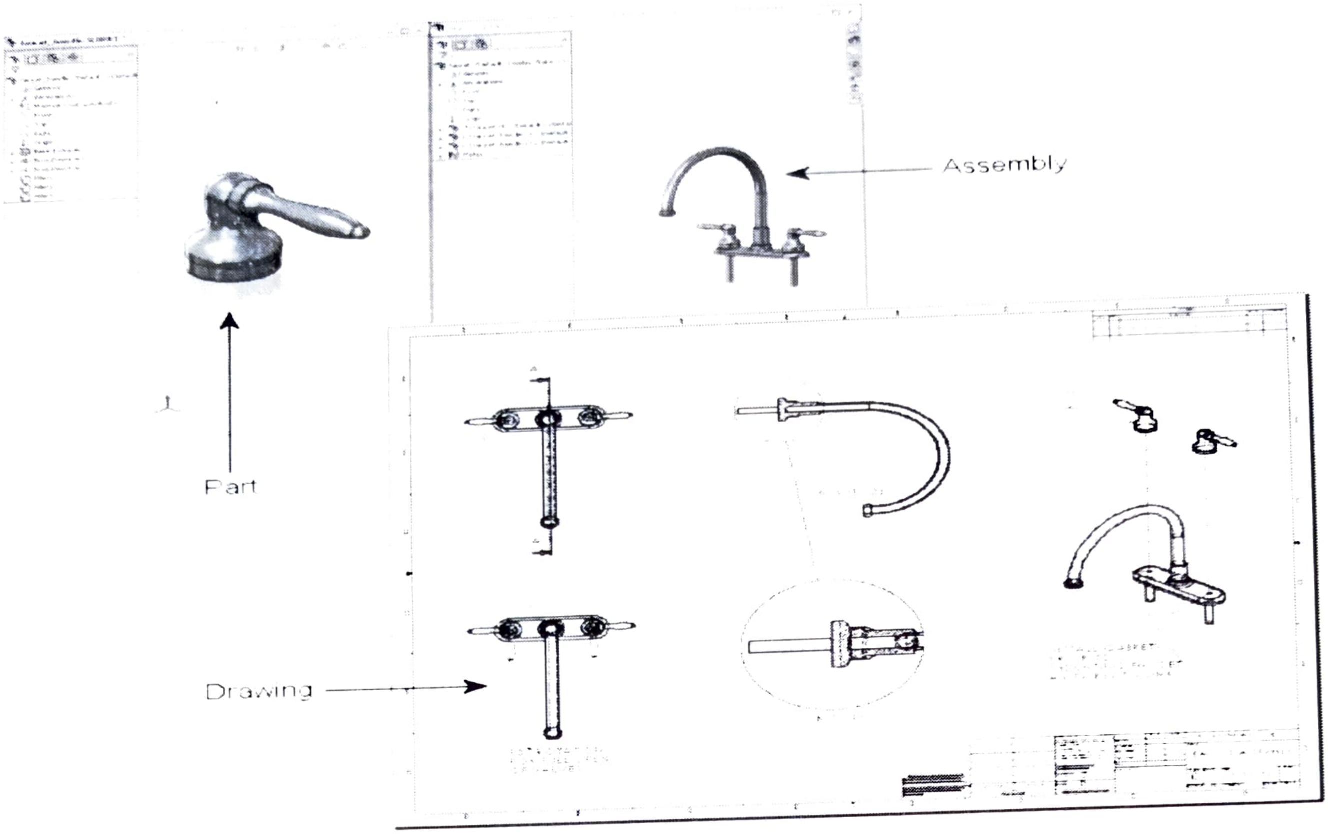

Figure 1.10 Drawing sheet in SOLIDWORKS

This section uses the following terminology for the models:

1.6.3 Terminology

These terms appear throughout the SOLIDWORKS software and documentation.

Origin: Appears as two blue arrows and represents the (0,0,0) coordinate of the model. When a sketch is active, a sketch origin appears in red and represents the (0,0,0) coordinate of the sketch. To can add dimensions and relations to a model origin, but not to a sketch origin.

Plane: Flat construction geometry. To use planes for adding a 2D sketch, section view of a model , or a neutral plane in a draft feature, for example.

Axis: Straight line used to create model geometry, features or patterns. To create an axis in different ways , including intersecting two planes. The SOLIDWORKS application creates temporary axes implicity for every conical or cylindrical face in a model.

Face: boundaries that help define the shape of a model or a surface. A face is a selectable area of a model or surface. For example, a rectangular solid has six faces.

Edge: Location where two or more faces intersect and are joined together. To select edges for sketching and dimensioning, for example.

Vertex: Point at which two or more lines or edges intersect. To select vertices for sketching and dimensioning , for example.

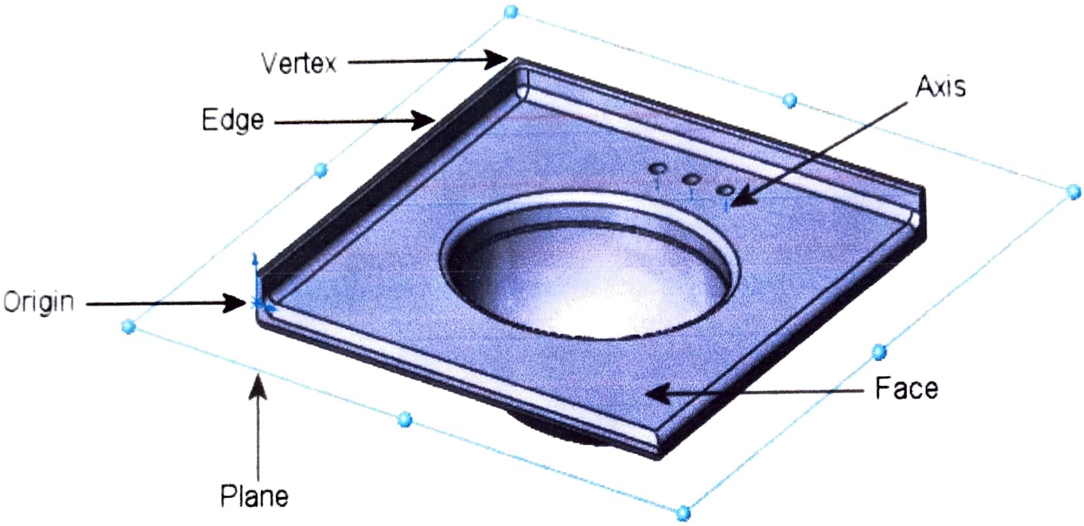

Figure 1.11 Terminology

1.6.4 Design Process

The design process usually involves the following steps:

- Identify the model requirements.
- Conceptualize the model based on the identified needs.
- Develop the model based on the concepts.
- Analyze the model.
- Prototype the model.
- Construct the model.
- Edit the model, if needed.

1.6.5 Design Intent

Design intent determines how you want your model to react as a result of the changes you need to make to the model. Design intent is primarily about planning. How to create the model determines how changes affect it. The closer the design implementation is to design intent, the greater the integrity of the model.

Various factors contribute to the design process, including:

Current needs: Understand the purpose of the model to design it efficiently.

Future considerations: Anticipate potential requirements to minimize redesign efforts.

1.6.6 Design Method

Before actually designing the model, it is helpful to plan out a method of how to create the model.

After identifying needs and isolating the appropriate concepts, model can be developed:

Sketches: Create the sketches and decide how to dimension and where to apply relations.

Features: Select the appropriate features, such as extrudes and fillets, determine the best features to apply, and decide in what order to apply those features.

Assemblies: Select the components to mate and types of mate to apply.

1.7 Introduction to 3D-Printing

1.7.1 What is 3D-Printing?

3D printing is any of various processes in which material is joined or solidified under **computer control** to create a **three-dimensional** object, with material being added together (such as liquid molecules or powder grains being fused together), typically layer by layer. In the 1990s, 3D printing techniques were considered suitable only for the production of functional or aesthetical prototypes and a more appropriate term was **rapid prototyping**. Today, the precision, repeatability and material range have increased to the point that 3D printing is considered as an industrial production technology, with the name of **additive manufacturing**. 3D printed objects can have a very complex shape or geometry and are always produced starting from a digital **3D model** or a **CAD** file. There are many different **3D printing processes**, that can be grouped into seven categories:

- Stereolithography
- Material jetting
- Binder jetting
- Powder bed fusion
- Material Extrusion
- Directed energy deposition
- Selective Deposition lamination

It is widely believed that 3D printing or additive manufacturing (AM) has the vast potential. 3D printing has now been covered across many television channels, in mainstream newspapers and across online resources.

3D printing is a radically different manufacturing method based on advanced technology that builds up parts, additively, in layers at the sub mm scale. 3D printing is a process for creating objects directly, by adding material layer by layer in a variety of ways, depending on the technology used. Simplifying the ideology behind 3D printing, for anyone that is still trying to understand the concept (and there are many), it could be likened to the process of building something with Lego blocks automatically.

3D printing is an enabling technology that encourages and drives innovation with unprecedented design freedom while being a tool-less process that reduces prohibitive costs and lead times. Components can be designed specifically to avoid assembly requirements with intricate geometry and complex features created at no extra cost. 3D printing is also emerging as an energy-efficient technology that can provide environmental efficiencies in terms of both the manufacturing process itself, utilising up to 90% of standard materials, and throughout the product's operating life, through lighter and stronger design.

In recent years, 3D printing has gone beyond being an industrial prototyping and manufacturing process as the technology has become more accessible to small companies and even individuals. Once the domain of huge, multi-national corporations due to the scale and economics of owning a 3D printer, smaller (less capable) 3D printers can now be acquired for under $1000.

This has opened up the technology to a much wider audience, and as the exponential adoption rate continues apace on all fronts, more and more systems, materials, applications, services and ancillaries are emerging.

1.7.2 3D-Printing Technology

The starting point for any 3D printing process is a 3D digital model, which can be created using a variety of 3D software programmes and in industry this is 3D CAD, for Makers and Consumers there are simpler, more accessible programmes available or scanned with a 3D scanner. The model is then 'sliced' into layers, thereby converting the design into a file readable by the 3D printer. The material processed by the 3D printer is then layered according to the design and the process. As stated, there are a number of different types of **3D-Printing Technologies**, which process different materials in different ways to create the final object. Functional plastics, metals, ceramics and sand are, now, all routinely used for industrial prototyping and production applications. Research is also being conducted for 3D printing bio materials and different types of food. Generally speaking though, at the entry level of the market, materials are much more limited. Plastic is currently the only widely used material- usually ABS or PLA, but there are a growing number of alternatives, including Nylon. There is also a growing number of entry level machines that have been adapted for foodstuffs, such as sugar and chocolate.

The different types of 3D printers each employ a different technology that processes different materials in different ways. For example some 3D printers process powdered materials (nylon, plastic, ceramic, metal), which utilize a light/heat source to sinter/melt/fuse layers of the powder together in the defined shape. Others process polymer resin materials and again utilize a light/laser to solidify the resin in ultra thin layers. Jetting of fine droplets is another 3D printing process, reminiscent of 2D inkjet printing, but with superior materials to ink and a binder to fix the layers. Perhaps the most common and easily recognized process is deposition, and this is the process employed by the majority of entry-level 3D printers. This process extrudes plastics, commonly PLA or ABS, in filament form through a heated extruder to form layers and create the predetermined shape. Because parts can be printed directly, it is possible to produce very detailed and intricate objects, often with functionality built in and negating the need for assembly.

However, another important point to stress is that none of the 3D printing processes come as plug and play options as of today. There are many steps prior to pressing print and more once the part comes off the printer these are often overlooked. Apart from the realities of designing for 3D printing, which can be demanding, file preparation and conversion can also prove time-consuming and complicated, particularly for parts that demand intricate supports during the build process. However there are continual updates and upgrades of software for these functions and the situation is improving. Furthermore, once off the printer, many parts will need to undergo finishing operations. Support removal is an obvious one for processes that demand support, but others include sanding, lacquer, paint or other types of traditional finishing touches, which all typically need to be done by hand and require skill and/or time and patience.

1.7.3 3D-Printing Processes

1.7.3.1 Stereolithography

Because of the nature of the SL process, it requires support structures for some parts, specifically those with overhangs or undercuts. These structures need to be manually removed.

In terms of other post processing steps, many objects 3D printed using SL need to be cleaned and cured. Curing involves subjecting the part to intense light in an oven-like machine to fully harden the resin.

Stereolithography is generally accepted as being one of the most accurate 3D printing processes with excellent surface finish. However limiting factors include the post-processing steps required and the stability of the materials over time, which can become more brittle.

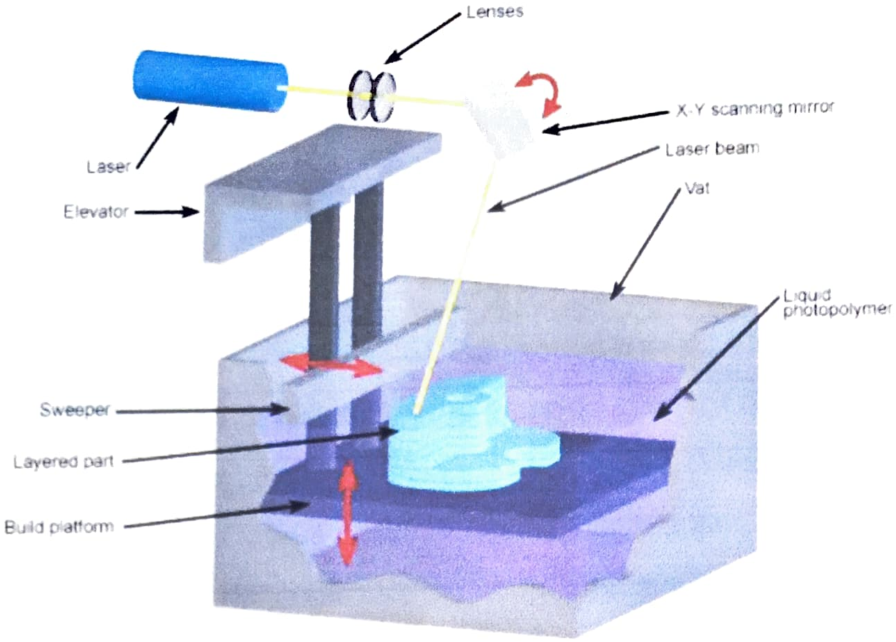

Figure 1.12 Stereolithography

It is a form of 3D printing technology used for creating models, prototypes, patterns, and production parts in a layer by layer fashion using photochemical processes by which light causes chemical monomers to link together to form polymers. Those polymers then make up the body of a three-dimensional solid. Stereolithography can be used to create prototypes for products in development, medical models, and computer hardware, as well as in many other applications. While stereolithography is fast and can produce almost any design, it can be expensive.

Stereolithography is an additive manufacturing process that, in its most common form, works by focusing an ultraviolet (UV) laser on to a vat of photopolymer resin. With the help of computer aided manufacturing or computer-aided design (CAM/CAD) software, the UV laser is used to draw a pre-programmed design or shape on to the surface of the photopolymer vat. Photopolymers are sensitive to ultraviolet light, so the resin is photochemically solidified and forms a single layer of the desired 3D object. Then, the build platform lowers one layer and a blade recoats the top of the tank with resin. This process is repeated for each layer of the design until the 3D object is complete. Completed parts must be washed with a solvent to clean wet resin off their surfaces.

1.7.3.2 Material Extrusion

3D printing utilizing the extrusion of thermoplastic material is easily the most common and recognizable 3DP process. The most popular name for the process is Fused Deposition Modelling (FDM). Sometimes also called filament freeform fabrication is a 3D printing process that uses a continuous filament of a thermoplastic material. Filament is fed from a large coil through a moving, heated printer extruder head, and is deposited on the growing work. The print head is moved under computer control to define the printed shape. Usually the head moves in two dimensions to deposit one horizontal plane, or layer, at a time; the work or the print head is then moved vertically by a small amount to begin a new layer. The speed of the extruder head may also be controlled to stop and start deposition and form an interrupted plane without stringing or dribbling between sections.

In terms of models produced, the FDM process is an accurate and reliable process. The process can be slow for some part geometries and layer-to-layer adhesion can be a problem, resulting in parts that are not watertight. Again, post-processing using Acetone can resolve these issues.

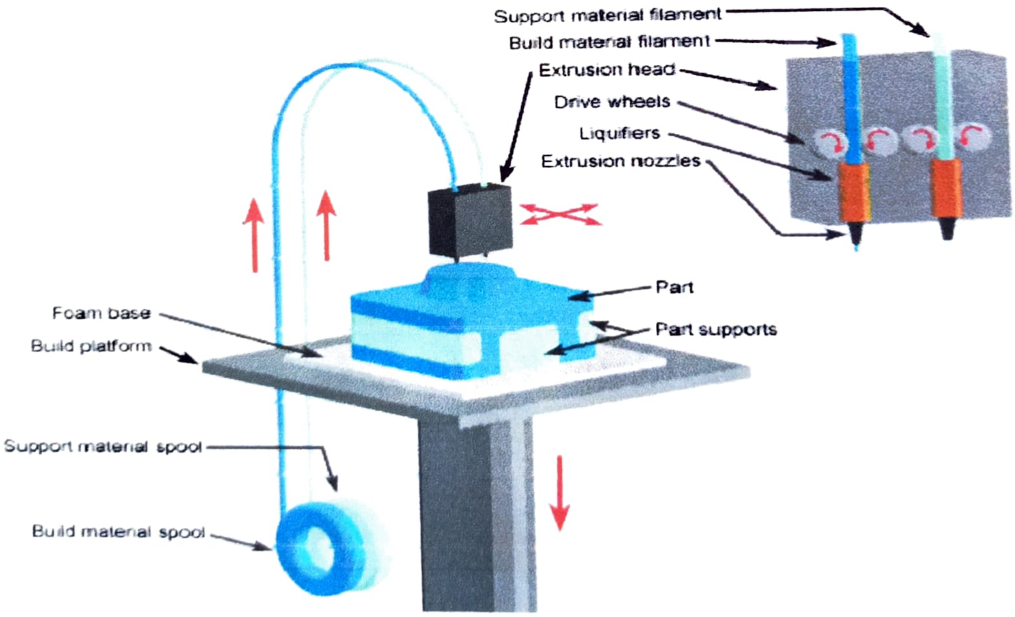

Figure 1.13 Material extrusion

1.7.3.3 Binder Jetting

In this the material being jetted is a binder, and is selectively sprayed into a powder bed of the part material to fuse it a layer at a time to create/print the required part. As is the case with other powder bed systems, once a layer is completed, the powder bed drops incrementally and a roller or blade smoothes the powder over the surface of the bed, prior to the next pass of the jet heads, with the binder for the subsequent layer to be formed and fused with the previous layer.

Advantages of this process, like with SLS, include the fact that the need for supports is negated because the powder bed itself provides this functionality. Furthermore, a range of different materials can be used, including ceramics and food. A further distinctive advantage of the process is the ability to easily add a full colour palette which can be added to the binder. The parts resulting directly from the machine, however, are not as strong as with the sintering process and require post-processing to ensure durability.

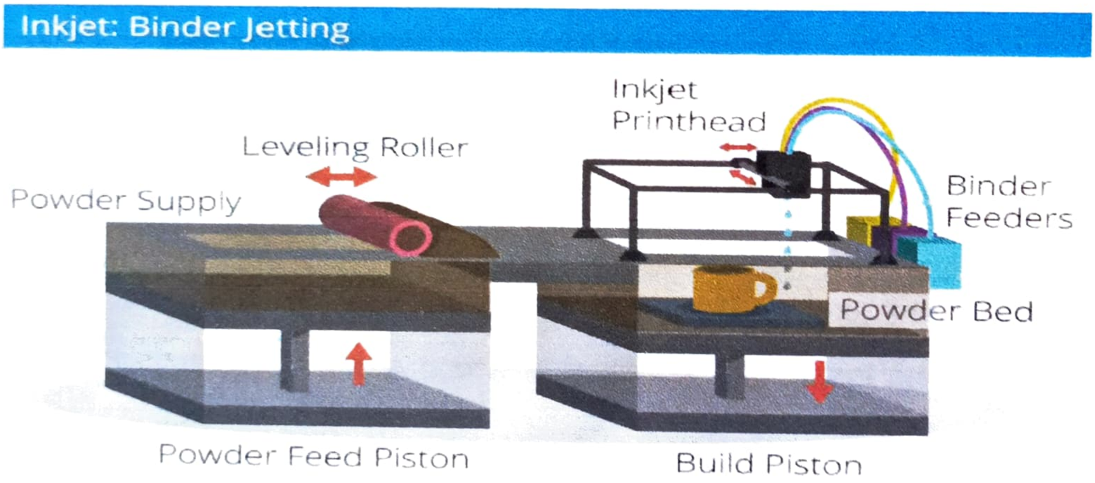

Figure 1.14 Binder jetting

1.7.3.4 Material Jetting

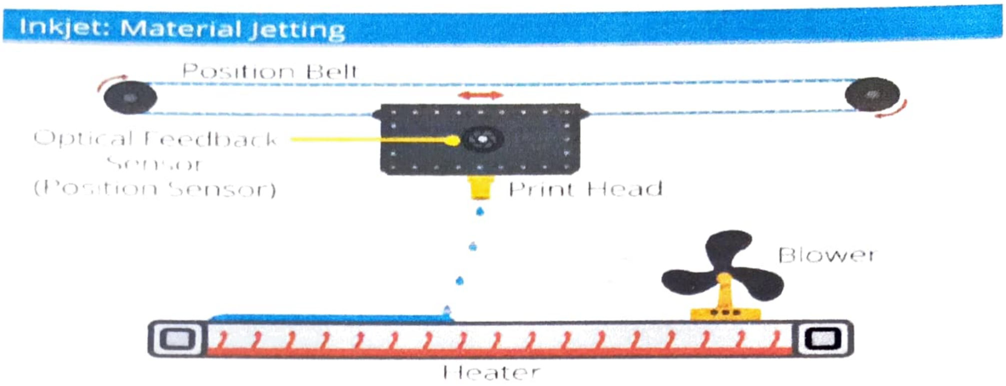

Figure 1.15 Material Jetting

A 3D printing process whereby the actual build materials (in liquid or molten state) are selectively jetted through multiple jet heads (with others simultaneously jetting support materials). However, the materials tend to be liquid photopolymers, which are cured with a pass of UV light as each layer is deposited.

The nature of this product allows for the simultaneous deposition of a range of materials, which means that a single part can be produced from multiple materials with different characteristics and properties. Material jetting is a very precise 3D printing method, producing accurate parts with a very smooth finish.

1.7.4 3D Printing Materials

The materials available for 3D printing have come a long way since the early days of the technology. There is now a wide variety of different material types, that are supplied in different states (powder, filament, pellets, granules, resin etc).

Plastics

It is naturally white in colour but it can be coloured. This material can also be combined with powdered aluminium to produce another common material for sintering. ABS is another common plastic used for 3D printing, and is widely used on the entry-level FDM 3D printers in filament form. It is a particularly strong plastic and comes in a wide range of colours. ABS can be bought in filament form from a number of non-propreitary sources, which is another reason why it is so popular.

PLA is a bio-degradable plastic material that has gained traction with 3D printing for this very reason. It can be utilized in resin format for DLP/SL processes as well as in filament form for the FDM process. It is offered in a variety of colours, including transparent, which has proven to be a useful option for some applications of 3D printing. However it is not as durable or as flexible as ABS.

LayWood is a specially developed 3D printing material for entry-level extrusion 3D printers. It comes in filament form and is a wood/polymer composite (also referred to as WPC).

Metals

A growing number of metals and metal composites are used for industrial grade 3D printing. Two of the most common are aluminium and cobalt derivatives

Figure 1.16 Aluminum

One of the strongest and therefore most commonly used metals for 3D printing is Stainless Steel in powder form for the sintering/ melting/EBM processes. It is naturally silver, but can be plated with other materials to give a gold or bronze effect.

In the last couple of years Gold and Silver have been added to the range of metal materials that can be 3D printed directly, with obvious applications across the jewellery sector. These are both very strong materials and are processed in powder form.

Titanium is one of the strongest possible metal materials and has been used for 3D printing industrial applications for some time. Supplied in powder form, it can be used for the sintering/melting/ EBM processes.

Ceramics

Ceramics are a relatively new group of materials that can be used for 3D printing with various levels of success. The particular thing to note with these materials is that, post printing, the ceramic parts need to undergo the same processes as any ceramic part made using traditional methods of production namely firing and glazing.

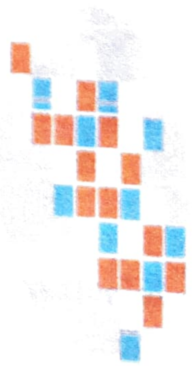

Figure 1.17 Ceramics

Paper

Standard A4 copier paper is a 3D printing material employed by the proprietary SDL process supplied by Mcor Technologies. The company operates anotably different business model to other 3D printing vendors, whereby the capital outlay for the machine is in the mid-range, but the emphasis is very much on an easily obtainable, cost-effective material supply, that can be bought locally. 3D printed models made with paper are safe, environmentally friendly, easily recyclable and require no post-processing.

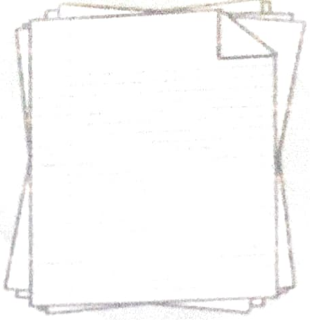

Figure 1.18 Paper

Bio Materials

There is a huge amount of research being conducted into the potential of 3D printing bio materials for a host of medical (and other) applications. Living tissue is being investigated at a number of leading institutions with a view to developing applications that include printing human organs for transplant, as well as external tissues for replacement body parts.

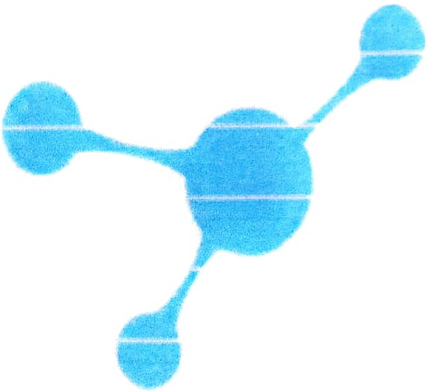

Figure 1.19 Bio materials

Food

Experiments with extruders for 3D printing food substances has increased dramatically over the last couple of years. Chocolate is the most common (and desirable). There are also printers that work with sugar and some experiments with pasta and meat. Looking to the future, research is being undertaken, to utilize 3D printing technology to produce finely balanced whole meals.

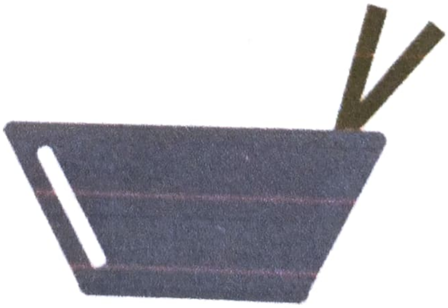

Figure 1.20 Food materials

CHAPTER 2

2. MECHANISM SYNTHESIS

2.1 Introduction to Klann mechanism

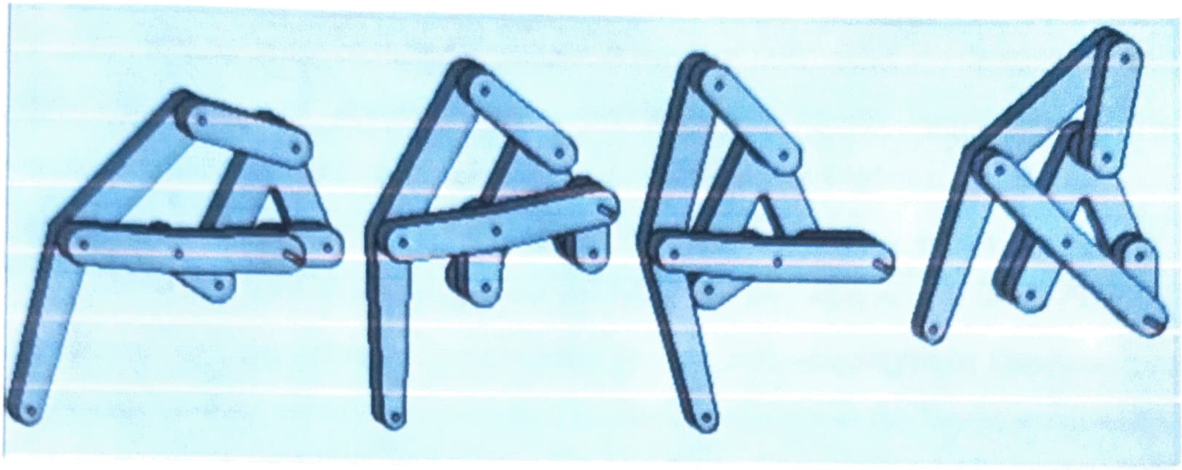

Figure 2.1 Klann mechanism

The **Klann linkage** is a planar mechanism designed to simulate the gait of legged animal and function as a wheel replacement. The linkage consists of the frame, a crank, two grounded rockers, and two couplers all connected by pivot joints. It was developed by Joe Klann in 1994 as an expansion of Burmester curves which are used to develop four-bar double-rocker linkages such as harbor crane booms. It is categorized as a modified Stephenson type III kinematic chain.

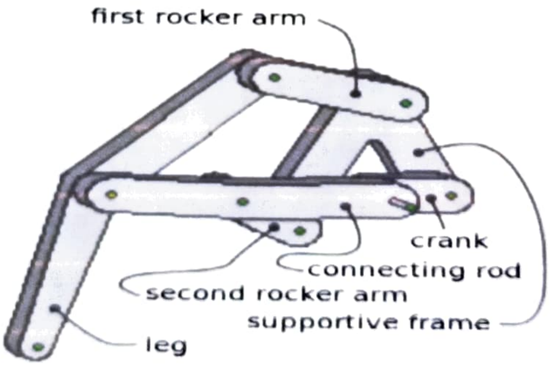

Figure 2.2 Leg of Klann mechanism

The proportions of each of the links in the mechanism are defined to optimize the linearity of the foot for one-half of the rotation of the crank. The remaining rotation of the crank allows the foot to be raised to a predetermined height before returning to the starting position and repeating the cycle. Two of these linkages coupled together at the crank and one-half cycle out of phase with each other will allow the frame of a vehicle to travel parallel to the ground.

The **Klann linkage** provides many of the benefits of more advanced walking vehicles without some of their limitations. It can step over curbs, climb stairs, or travel into areas that are currently not accessible with wheels but do not require microprocessor control or multitudes of actuator mechanisms. It fits into the technological space between these walking devices and axle-driven wheels.

The **Klann mechanism** uses six links per leg, whereas the Jansen's linkage developed by Theo Jansen uses eight links per leg, with one degree of freedom. It can walk only on even surfaces and terrain. The number of links in the Jansen mechanism is greater than in the Klann mechanism, and is more costly.

The **Klann linkage** can walk on non-planar roads and hill areas, and on uneven surfaces and terrain. The design of the Klann mechanism is portable with less linkage for movement.

2.2 Degrees of freedom

$F=3(n-1)-2j-h$

Where n=number of links

j=number of binary joints

h=number of higher pairs

$F=3(6-1)-2*7-0$

$F=1$

2.3 Advantages and Disadvantages

2.3.1 Advantages

1. Contact with the ground at discrete points:

The rims of wheels have continuous contact with the ground over which they travel. Walking machines place their feet and once placed, frictional force prevents further movement of the foot and movement if confined within the linkage system of the leg. The dynamics of the vehicle body is determined by the leg kinematics alone,where as in wheeled vehicles, the body position is continuously affected by the contour of the road surface. Vehicle suspension mitigates this effect on modern vehicles, but it is entirely eliminated in walking mechanisms.

2.Elimination of roads:

Although heavy usage would lead to tracks forming, as found when animals move along the same path regularly, walking machines do not require roads or other prepared surface to walk on. With light traffic, a legged vehicle should leave only a series of discrete footprints.

3.Minimal contact area with ground:

In number of footprints per distance travelled. This is considerably less than the area moved over by a wheeled or tracked vehicle, which is the width of tyre or track times the distance travelled. For example, in an area of land where land mines have been randomly deployed. The continuous track of a wheeled vehicle increases the chance of a land mine being trigged. Whereas a walker touches a much smaller area of the land over which it travels, and there would be reduced risk of triggering mines, walking machines, the total ground area touched is the area of each footprint times the number of legs.

4.Reduced ground pressure:

As a walking machine may carry a foot of practically any size, the average ground pressure it exerts can be very small. In wheeled vehicles the diameter of the wheels places a physical limit on the length of the footprint. Although tyres can be made wide, the maximum contact patch size is limited, and ground pressure cannot easily be reduced below a certain value. Tracked vehicles can have a large contact area, and hence are preferred where low ground pressure is advantageous, for example vehicles that operate in snow or swamps. A walking machine could be competitive with a tracked vehicle in these conditions, although this still depends on the reduced body weight that could result from improved design of walkers.

5.Vehicle height:

If a walking machine has a mammalian type body plan, with the legs attached underneath its body, then the body is carried higher off the ground than the body of a conventional wheeled or tracked vehicle would be. This body position may be advantageous where the vehicle is intended as a moveable vantage point, for example in game viewing applications. Greater vehicle height would also enhance wading abilities.

6.Increased traction:

Wheeled vehicles are subject to slip, especially when applying high tractive effort on loose slippery or wet surfaces. A suitable walking machine, with sharp feet to increase ground pressure, and hence penetration, could apply more tractive effort than a wheeled vehicle. It may not be able to compete with a tracked vehicle however other types of feet that firmly attach to the walking surface could also be employed to allow increased traction

7.Amphibious potential:

With a suitable leg arrangement carrying a set of floats or pontoons, a walking machine could be made an effective amphibious vehicle. If the area of float can be made large enough, then vertical displacement of the weight carrying floats can be less than the foot lift of the returning leg. This means the vehicle could walk on the surface of water, as returning floats would be lifted clear of the water surface, and placed forward of the current float. Such a vehicle should also walk on land, with extremely low ground pressure.

8.Climbing abilities:

With the addition of suitable foot attachment devices, such as electromagnets for steel surfaces or suction devices for smooth surfaces, such as glass, it should be possible to make a walking machine travel vertically or even upside down. The foot attachment mechanism would need to have grip control, releasing grip to allow the leg to be lifted on the return stroke and acquiring it when the leg is on its duty cycle.

2.3.2 Disadvantages

The fact that vehicles that use wheels or tracks are the only types of vehicles currently being constructed in any significant numbers, and given that many attempts have been made to create walking machines, there must be severe disadvantages to using walking machines for transportation. These include:

1.Complication:

Wheels are extremely simple, in the simplest form, a circular plate with a central hole. The wheel is widely considered one of human kind's greatest inventions. It is probably the simplest device that can be used for land transportation. Walking vehicles are generally orders of magnitude more complex. There are many joints, kinematic links, sensors, software, multiple actuators, difficult manoeuvrability issues and stability issues that all make most current walking machines more complex.

2.Inefficiency:

Walking machines are not fuel-efficient, especially considering the slow speeds at which they travel. Wheels running on a good road surface are the most efficient way to travel on land. Tracks are considerably less efficient than wheels. This is primarily due to the energy required to move the track itself. The large number of revolute joints connecting the track sections, with their associated friction, means that simply turning a track absorbs considerable power.

Although it is hard to accumulate data or find a means of comparing tracks to legs in terms of transport efficiency, a brief consideration would indicate that walking machines could be made to be similar in efficiency to tracked vehicles.

3.Cost:

The cost of construction will generally be related to its complexity. Given the complexity of most current walkers it is not surprising that none has entered production, as presumably they could not be sold at a reasonable price. However, tracked vehicles are also extremely costly in relation to wheeled ones. Even specialist wheeled vehicles command a premium price. If a sufficiently simple hence cheap walking machine could be constructed, and located in specific marketing and operational niches, it may be possible to sell these at a competitive price.

2.4 Applications of Klann linkage

1. The final design of this new walking machine is intended for transport service across rough terrain. It should be large enough to carry a significant payload, of some tons. It should be capable of operating without roads, and should be self-sufficient with respect to motive power. The envisaged operating environment would be somewhat flat land, such as open bush country, or light forest. It should be capable of ascending and

descending slopes of up to 40̊ and should be sufficiently manoeuvrable to avoid large obstacles. It should be able to move at reasonable walking speeds, up to 50 kilometres per hour and have a useable range of several hundred kilometres before refuelling. It should be robust, simple and easy to maintain. Complex parts that cannot be repaired in the field should be minimized.

2. The two legs in Klann linkage coupled together at the crank can act as a wheel replacement and provide vehicles with greater ability to handle obstacles and travel across uneven terrain while providing a smooth ride.

3. This linkage could be utilized almost anywhere a wheel is employed from small wind-up toys to large vehicles capable of transporting people.

4. Initially the linkage was called spider bike but applications for this linkage have expanded well beyond the initial design purpose of a human-powered walking machine.

5. Other practical applications could include:

    1. Forestry applications
    2. Land mine clearing
    3. Game viewing
    4. Off-road use in areas where roads are undesirable e.g. in game parks
    5. Transportation across snow or ice
    6. Travel in swampy areas, and
    7. Travel on beaches or sandy areas.

CHAPTER 3

3. LITERATURE REVIEW

1. **Shunsuke Nansaia , Mohan Rajesh et al** [1] presented dynamic analysis of a four legged Theo Jansen link mechanism using projection method that resulted in constraint force and equivalent Lagrange's equation of motion necessary for any meaningful extension and/or optimization of this niche mechanism. Numerical simulations using MaTX was presented in conjunction with the dynamic analysis. This research did set a theoretical basis for future investigation into Theo Jansen mechanism.

2. **V. V. Pharate , S. M. Patil et al** [2]developed and designed three planar straight line mechanisms using type , number and dimension synthesis. Calculations of their kinematics are done by vector loop equations and Freudenstein's equations. Spread sheets are developed for the relation between input and output angles, and the travel distance for corresponding input. Selection of one mechanism which proves to be the best for given problem statement is done using relative point method. This method takes into consideration all the parameters necessary for the application.

3. **Kim, Hyun-Gyu;Jung, Min-Suck et al** [3]suggested Klann-linkage as a walking mechanism for a water-running robot and was optimized using level average analysis. The structure of the Klann-linkage was introduced first and design variables for the Klann-linkage are identified considering the kinematic task of the walking mechanism. Next, the design problem was formulated as a path generation optimization problem. Specifically, the desired path for the foot-pad was defined and the objective function was defined as the structural error between the desired and the generated paths. A process for solving the optimization problem was suggested utilizing the sensitivity analysis of the design variables. As a result, optimized lengths of Klann-linkage are obtained and the optimum trajectory is obtained. It was found that the optimized trajectory improves the cost function by about 62% from the initial one. It is expected that the results from this research can be used as a good example

for designing legged robots.

4. **Jaichandar Kulandaidaasan Sheba_; Edgar Martínez-García et al** [4] discussed about design, integration and functional evaluation of reconfigurable Klann based four legged robot platform. Here a four legged platform generating six useful gaits was implemented. The design process, mechanical assembly, electronic control and transformation mechanism for various scenarios was reported. The designed platform was able to control servo motors to generate various gaits of interest in an efficient manner. By adopting Klann mechanism and extending reconfiguration in the designed platform several bio inspired gaits resembling natural system has been envisaged.

5. **Dileep kumar P** [5] performed Kinematic and Dynamic analysis of Theo jansen mechanism using complex algebraic method. Only one leg of the mechanism was considered for the analysis. It laid a platform for further research and discussion on legged mechanisms.

CHAPTER 4

4. KINEMATIC ANAYSIS OF KLANN MECHANISM

4.1 Kinematic analysis of first loop

4.1.1 Displacement analysis

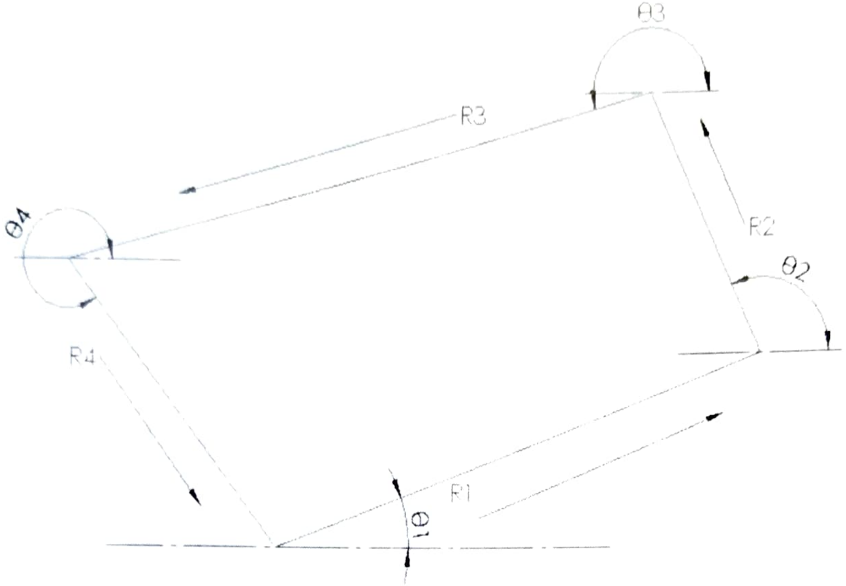

Figure 4.1 Loop 1

The vector loop $R_1+R_2+R_3+R_4=0$
$ae^{i\theta_1}+be^{i\theta_2}+ce^{i\theta_3}+de^{i\theta_4}=0$………. (4.1)

Separating the real and imaginary parts in eq (4.1), the real part is

$a\cos\theta_1+b\cos\theta_2+c\cos\theta_3+d\cos\theta_4=0$………. (4.2)

The imaginary part is

$a\sin\theta_1+b\sin\theta_2+c\sin\theta_3+d\sin\theta_4=0$………. (4.3)

$k1=a\cos\theta_1+b\cos\theta_2$

$k2=a\sin\theta_1+b\sin\theta_2$

$k1+c\cos\theta_3+d\cos\theta_4=0$……………………………….(4.4)

$k2+c\sin\theta_3+d\sin\theta_4=0$………………………………….(4.5)

eliminating θ_4From the above equations (4.4) & (4.5) we get

$-d\cos\theta_4=k_1+c\cos\theta_3$………. (4.6)

$-d\sin\theta_4=k_2+c\sin\theta_3$………. (4.7)

Squaring and adding the above equations (4.6) & (4.7)

$d^2=k_1^2+k_2^2+c^2+2c(k_1\cos\theta_3+k_2\sin\theta_3)$

$k_1 \cos\theta_3 + k_2 \sin\theta_3 = \dfrac{d^2 - k_1^2 - k_2^2 - c^2}{2c}$

$k_3 = \dfrac{d^2 - k_1^2 - k_2^2 - c^2}{2c}$

$k_3 = k_1 \cos\theta_3 + k_2 \sin\theta_3$ .... (4.8)

By substituting $\cos\theta_3 = \dfrac{1 - tan^2\left(\frac{\theta_3}{2}\right)}{1 + tan^2\left(\frac{\theta_3}{2}\right)}$,

$\sin\theta_3 = \dfrac{2tan\left(\frac{\theta_3}{2}\right)}{1 + tan^2\left(\frac{\theta_3}{2}\right)}$

We get. $A \tan^2\left(\frac{\theta_3}{2}\right) + B \tan^2\left(\frac{\theta_3}{2}\right) + C = 0$..........(4.9)

A=-k1-k3

B=2k2

C=k1-k3

By solving the above quadratic equation (4.9), we get

$\theta_3 = 2tan^{-1}\left(\dfrac{-B \pm \sqrt{B^2 - 4AC}}{2A}\right)$.......... (4.10)

Similarly for θ_4. we get

$\theta_4 = 2tan^{-1}\left(\dfrac{-E \pm \sqrt{E^2 - 4DF}}{2D}\right)$.......... (4.11)

4.1.2 Velocity analysis

Differentiating position equation (4.1) of second loop to get the velocity expression

$a\omega_1 ie^{i\theta_1} + b\omega_2 ie^{i\theta_2} + c\omega_3 ie^{i\theta_3} + d\omega_4 ie^{i\theta_4} = 0$.......... (4.12)

Separating the real and imaginary parts in eq (4.12), the real part is

$a\omega_1 \cos\theta_1 + b\omega_2 \cos\theta_2 + c\omega_3 \cos\theta_3 + d\omega_4 \cos\theta_4 = 0$.......... (4.13)

The imaginary part

$a\omega_1 \sin\theta_1 + b\omega_2 \sin\theta_2 + c\omega_3 \sin\theta_3 + d\omega_4 \sin\theta_4 = 0$.......... (4.14)

Multiplying eq (4.13) with $\sin\theta_4$+ and eq (4.14) with $\cos\theta_4$ we get

$a\omega_1 \sin\theta_4 \cos\theta_1 + b\omega_2 \sin\theta_4 \cos\theta_2 + c\omega_3 \sin\theta_4 \cos\theta_3 + d\omega_4 \sin\theta_4 \cos\theta_4 = 0$.... (4.15)

$a\omega_1 \sin\theta_1 \cos\theta_4 + b\omega_2 \sin\theta_2 \cos\theta_4 + c\omega_3 \sin\theta_3 \cos\theta_4 + d\omega_4 \sin\theta_4 \cos\theta_4 = 0$.... (4.16)

Subtracting the above equations, we get

$b\omega_2(\sin\theta_2 \cos\theta_4 - \cos\theta_4 \sin\theta_2) + c\omega_3(\sin\theta_3 \cos\theta_4 - \cos\theta_3 \sin\theta_4) = 0$.........(4.17)

$b\omega_2 \sin(\theta_4 - \theta_3) + c\omega_3 \sin(\theta_3 - \theta_4) = 0$.........(4.18)

By solving above equation (4.18), we get

$$\omega_3 = \frac{b\omega_2 \sin(\theta_2 - \theta_4)}{c \sin(\theta_3 - \theta_4)} \quad \text{..........} \ (4.19)$$

Similarly for ω_4,

$$\omega_4 = \frac{b\omega_2 \sin(\theta_3 - \theta_2)}{d \sin(\theta_4 - \theta_3)} \quad \text{..........} \ (4.20)$$

4.1.3 Acceleration analysis

Differentiating the angular velocity equation (4.12) of second loop

$b e^{i\theta_2}(i\alpha_2 - \omega_2^2) + c e^{i\theta_3}(i\alpha_3 - \omega_3^2) + d e^{i\theta_4}(i\alpha_4 - \omega_4^2) = 0$.........(4.21)

$$e^{i\theta_3} = \cos\theta_3 + i \sin\theta_3$$

$$e^{i\theta_4} = \cos\theta_4 + i \sin\theta_4$$

$$e^{i\theta_2} = \cos\theta_2 + i \sin\theta_2$$

Separating the real and imaginary parts of eq (4.21), we get real part

$b\alpha_2 \sin\theta_2 + b\omega_2^2 \cos\theta_2 + c\alpha_3 \sin\theta_3 + c\omega_3^2 \cos\theta_3 + d\alpha_4 \sin\theta_4 + d\omega_4^2 \cos\theta_4 = 0$

Imaginary part

$b\alpha_2 \cos\theta_2 - b\omega_2^2 \sin\theta_2 + c\alpha_3 \cos\theta_3 - c\omega_3^2 \sin\theta_3 + d\alpha_4 \cos\theta_4 - d\omega_4^2 \sin\theta_4 = 0$

$Y_1 = -c\omega_3^2 \sin\theta_3 - d\omega_4^2 \sin\theta_4 + d\alpha_4 \cos\theta_4 - b\omega_2^2 \sin\theta_2 = 0$

$Y_1 + c\alpha_3 \cos\theta_3 + d\alpha_4 \cos\theta_4 = 0$..................(4.22)

$Y_2 = c\omega_3^2 \cos\theta_3 + b\alpha_2 \sin\theta_2 + b\omega_2^2 \cos\theta_2 + d\alpha_4 \sin\theta_4 + d\omega_4^2 \cos\theta_4 = 0$

$Y2 + c\alpha_3 \sin\theta_3 + d\alpha_4 \sin\theta_4 = 0$....................(4.23)

Multiplying the eq (4.22) with $\sin\theta_7$ and eq (4.23) with $\cos\theta_7$,we get

By solving the above equations we get

$Y_1 \sin\theta_4 - Y2 \cos\theta_4 = c\alpha_3(\sin(\theta_3 - \theta_4))$................(4.24)

$$\alpha_3 = \frac{Y_2 cos\theta_4 - Y_1\ sin\theta_4}{csin(\theta_4 - \theta_3)} \text{............(4.25)}$$

Similarly for α_4 ,

$$\alpha_4 = \frac{Y_2 cos\theta_3 - Y_1\ sin\theta_3}{dsin(\theta_3 - \theta_4)} \text{............(4.26)}$$

4.2 Kinematic analysis of second loop

4.2.1 Displacement analysis

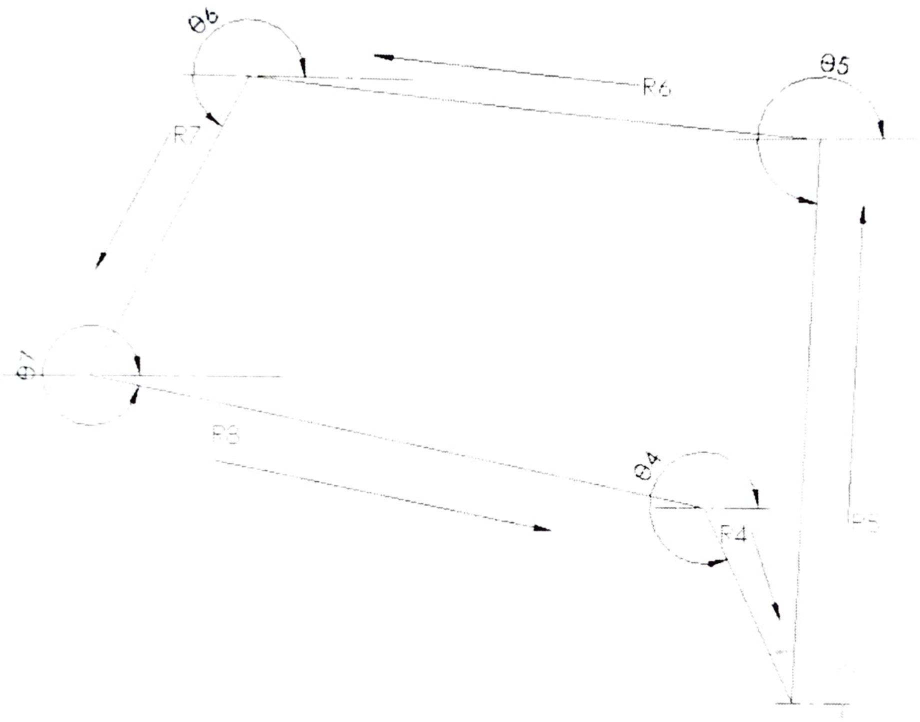

Figure 4.2 Loop 2

The vector loop $R_4+R_5+R_6+R_7+R_8=0$

$\alpha = \cos^{-1}((i^2+a^2-e^2)/2ei)$

$\theta_4=\alpha + 15$

$\Upsilon = \sin^{-1}((c\sin(\theta_3 - 180)/2ei)$

$de^{i\theta_4}+ie^{i\theta_c}+fe^{i\theta_5}+ge^{i\theta_6} + he^{i\theta_7}=0$.......... (4.27)

Separating the real and imaginary parts in eq (4.27), the real part is

$d\cos\theta_4+i\cos\theta_c+f\cos\theta_5+g\cos\theta_6 + h\cos\theta_7=0$.......... (4.28)

The imaginary part is

$d\sin\theta_4+i\sin\theta_c+f\sin\theta_5+g\sin\theta_6 + h\sin\theta_7=0$.......... (4.29)

$k7=d\cos\theta_4+ i\cos\theta_c+h\cos\theta_7$

k8= d sin θ_4+ i sin θ_c+h sin θ_7

k9=$\dfrac{f^2 - g_1^2 - k_7^2 - k8 \quad ^2}{2g}$

G=k9+1

H=2

I=k9-1

We get, G $\tan^2\left(\frac{\theta_6}{2}\right)$+H $\tan^2\left(\frac{\theta_6}{2}\right)$+I=0……….(4.30)

By solving the above quadratic equation (4.9), we get

$$\theta_3 = 2tan^{-1}\left(\frac{-H \pm \sqrt{H^2-4GI}}{2G}\right) \ldots\ldots\ldots (4.31)$$

Similarly forθ_4, we get

$$\theta_4 = 2tan^{-1}\left(\frac{-K \pm \sqrt{K^2-4JL}}{2J}\right) \ldots\ldots\ldots (4.32)$$

Where

k_{10}=$\dfrac{g^2 - f^2 - k_7^2 - k8c^2}{2f}$

J=k_{10} +1

K=2

L=k_{10}-1

4.2.2 Velocity analysis

Differentiating position equation (4.27) of second loop to get the velocity expression dω_4i$e^{i\theta_4}$+f$\omega_5 ie^{i\theta_5}$+g$\omega_6 ie^{i\theta_6}$+h$\omega_7 ie^{i\theta_7}$=0……….. (4.33)
Separating the real and imaginary parts in eq (4.33), the real part is

dω_4 cos θ_4+fω_5 cos θ_5+gω_6 cos θ_6+hω_7 cos θ_7=0……….. (4.34)

The imaginary part

dω_4 sin θ_4+fω_5 sin θ_5+gω_6 sin θ_6+hω_7 sin θ_7=0……….. (4.35)

Multiplying eq (4.34) with sin θ_5+ and eq (4.35) with cos θ_5 and solving we get

dω_4(sin θ_5 cos θ_4 – cos θ_5 sinθ_4)+ gω_6 (sin θ_5 cos θ_6 – cos θ_6 sinθ_5) +

hω_7 (sin θ_5 cos θ_7 – cos θ_7 sinθ_5)=0………(4.36)

d$\omega_4$sin (θ_5 – θ_4)+g$\omega_6$sin (θ_5 – θ_6) + h$\omega_7$sin (θ_7 – θ_3) =0……….(4.37)

By solving above equation (4.37), we get

$$\omega_6 = \frac{d\omega_4 \sin(\theta_5-\theta_4)+h\omega_7 \sin(\theta_5-\theta_7)}{g\sin(\theta_6-\theta_5)} \text{..........} (4.38)$$

Similarly for ω_4,

$$\omega_5 = \frac{d\omega_4 \sin(\theta_6-\theta_4)+h\omega_7 \sin(\theta_6-\theta_7)}{f\sin(\theta_5-\theta_6)} \text{.......... ....} (4.39)$$

4.2.3 Acceleration analysis

Differentiating the angular velocity equation (4.33) of second loop

$$de^{i\theta_4}(i\alpha_4 - \omega_4^2) + fe^{i\theta_5}(i\alpha_5 - \omega_5^2) + ge^{i\theta_6}(i\alpha_6 - \omega_6^2) + he^{i\theta_7}(i\alpha_7 - \omega_7^2) = 0 \text{.........} (4.40)$$

Separating the real and imaginary parts of eq (4.40), we get real part

$$d\alpha_4 \, sin\theta_4 + d\omega_4^2 \, cos\theta_4 + f\alpha_5 \, sin\theta_5 + f\omega_5^2 \, cos\theta_5 + g\alpha_6 \, sin\theta_6 + g\omega_6^2 \, cos\theta_6 +$$

$$h\alpha_7 \, sin\theta_7 + h\omega_6^2 \, cos\theta_7 = 0$$

Imaginary part

$$d\alpha_4 \, cos\theta_4 - d\omega_4^2 \, sin\theta_4 + f\alpha_5 \, cos\theta_5 - f\omega_5^2 \, sin\theta_5 + g\alpha_6 \, cos\theta_6 - g\omega_6^2 \, sin\theta_6 +$$

$$h\alpha_7 \, cos\theta_7 - h\omega_6^2 \, sin\theta_7 = 0$$

$$X_1 = d\alpha_4 \, sin\theta_4 + d\omega_4^2 \, cos\theta_4 + f\omega_5^2 \, cos\theta_5 + g\omega_6^2 \, cos\theta_6 + h\omega_6^2 \, cos\theta_7 = 0$$

$$X_1 + f\alpha_5 \, sin\theta_5 + g\alpha_6 \, sin\theta_6 + h\alpha_7 \, sin\theta_7 = 0 \text{..................} (4.41)$$

$$X_2 = d\alpha_4 \, cos\theta_4 - d\omega_4^2 \, sin\theta_4 - f\omega_5^2 \, sin\theta_5 - g\omega_6^2 \, sin\theta_6 - h\omega_6^2 \, sin\theta_7$$

$$X2 + f\alpha_5 \, cos\theta_5 + g\alpha_6 \, cos\theta_6 + h\alpha_7 \, cos\theta_7 = 0 \text{....................} (4.42)$$

Multiplying the eq (4.41) with $\cos\theta_5$ and eq (4.42) with $\sin\theta_5$, we get

By solving the above equations we get

$$X_1 \, cos\theta_5 - X2 \, sin\theta_5 = g\alpha_6(\, sin(\theta_6 - \theta_5) + h\alpha_7(\, sin(\theta_7 - \theta_5) \text{................} (4.43)$$

$$\alpha_6 = \frac{X_1 cos\theta_5 - X_2 \, sin\theta_5}{h_{\alpha_7} sin(\theta_7 - \theta_5)} \text{..........} (4.44)$$

Similarly for α_5 ,

By solving above equation (4.37), we get

$$\omega_6 = \frac{d\omega_4\sin(\theta_5-\theta_4)+h\omega_7\sin(\theta_5-\theta_7)}{g\sin(\theta_6-\theta_5)} \text{..........} (4.38)$$

Similarly for ω_4,

$$\omega_5 = \frac{d\omega_4\sin(\theta_6-\theta_4)+h\omega_7\sin(\theta_6-\theta_7)}{f\sin(\theta_5-\theta_6)} \text{.....................} (4.39)$$

4.2.3 Acceleration analysis

Differentiating the angular velocity equation (4.33) of second loop

$de^{i\theta_4}(i\alpha_4-\omega_4^2) + fe^{i\theta_5}(i\alpha_5-\omega_5^2)+ge^{i\theta_6}(i\alpha_6-\omega_6^2)+ he^{i\theta_7}(i\alpha_7-\omega_7^2)=0$.........(4.40)

Separating the real and imaginary parts of eq (4.40), we get real part

$d\alpha_4\sin\theta_4 + d\omega_4^2\cos\theta_4 + f\alpha_5\sin\theta_5 + f\omega_5^2\cos\theta_5+g\alpha_6\sin\theta_6+g\omega_6^2\cos\theta_6 +$

$h\alpha_7\sin\theta_7 + h\omega_6^2\cos\theta_7 = 0$

Imaginary part

$d\alpha_4\cos\theta_4 - d\omega_4^2\sin\theta_4 + f\alpha_5\cos\theta_5 - f\omega_5^2\sin\theta_5+g\alpha_6\cos\theta_6-g\omega_6^2\sin\theta_6 +$

$h\alpha_7\cos\theta_7 - h\omega_6^2\sin\theta_7 = 0$

$X_1= d\alpha_4\sin\theta_4 + d\omega_4^2\cos\theta_4 + f\omega_5^2\cos\theta_5+g\omega_6^2\cos\theta_6 + h\omega_6^2\cos\theta_7 = 0$

$X_1+f\alpha_5\sin\theta_5+g\alpha_6\sin\theta_6+h\alpha_7\sin\theta_7 =0$..................(4.41)

$X_2= d\alpha_4\cos\theta_4 - d\omega_4^2\sin\theta_4 - f\omega_5^2\sin\theta_5-g\omega_6^2\sin\theta_6 - h\omega_6^2\sin\theta_7$

$X2+ f\alpha_5\cos\theta_5+g\alpha_6\cos\theta_6+h\alpha_7\cos\theta_7=0$....................(4.42)

Multiplying the eq (4.41) with $\cos\theta_5$ and eq (4.42) with $\sin\theta_5$,we get

By solving the above equations we get

$X_1\cos\theta_5 - X2\sin\theta_5= g\alpha_6(\sin(\theta_6-\theta_5) + h\alpha_7(\sin(\theta_7-\theta_5)$................(4.43)

$$\alpha_6=\frac{X_1\cos\theta_5-X_2\sin\theta_5}{h_{\alpha_7}\sin(\theta_7-\theta_5)} \text{............} (4.44)$$

Similarly for α_5 ,

$$\alpha_5 = \frac{X_1 cos\theta_6 - X_2\ sin\theta_6}{h_{\alpha_7} sin(\theta_7 - \theta_6)} \text{............}(4.45)$$

CHAPTER 5

5. DESIGN AND FABRICATION

5.1 Description of Klann mechanism parts

1. Each leg of a Klann linkage consists of the frame, a crank, two grounded rockers, and two couplers all connected by pivot joints that converts rotating motion into linear motion.
2. Each leg of a Klann linkage includes a frame which supports a walking assembly composed of a cooperative arrangement of linkages axially connected together so as to provide a walking assembly which simulates the walking gait of an animal.
3. The linkages are approximately linked together by axial linking means for axially connecting the linkages together and to the frame.
4. The linkages include a pair of rocker arms (upper and lower) axially mounted to a frame, a connecting arm or rod, a reciprocating leg and a cranking link.
5. The pair of rocker arms includes a first rocker arm(upper) and a second rocker arm(lower) respectively axially anchored at one of their respective rocker arm ends to the frame and to different linkages at an opposite rocker arm end.

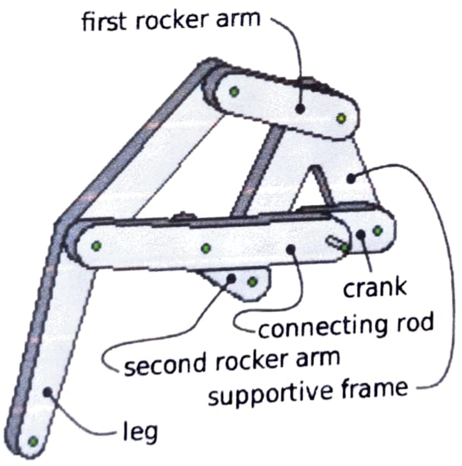

Figure 5.1 Leg of Klann mechanism

5.2 Design of parts using Solidworks software

The individual parts of the Klann mechanism are designed using Solidworks software and further assembled together.

So the individual parts to be designed in Solidworks are as follows.

1. Fixed frame
2. Connecting rod or power link
3. Top and bottom rocker arms
4. Crank
5. Leg of the mechanism

The lengths of the Klann mechanism considered for the

1. Crank = 20 mm
2. Top rocker = 40 mm
3. Bottom rocker = 30 mm
4. Connecting rod consists of two different lengths included by an angle of 165°. The two lengths are 40 mm and 50 mm

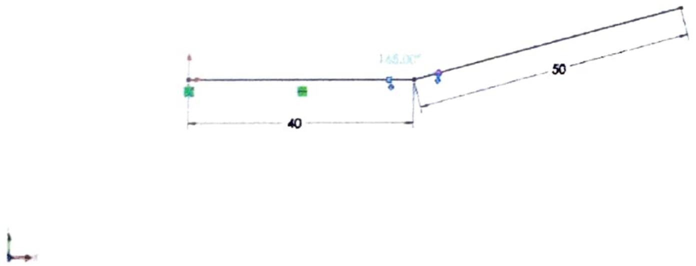

Figure 5.2 Connecting rod line diagram

5. Leg consists of two lengths with an included angle of 150°. The two lengths are 70 mm each

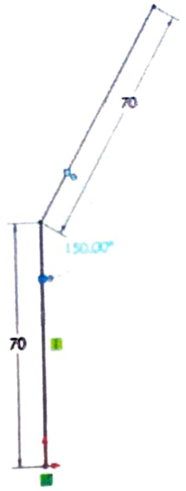

Figure 5.3 Leg line diagram

6. The fixed frame is considered as a triangular shaped member whose dimensions are as shown below

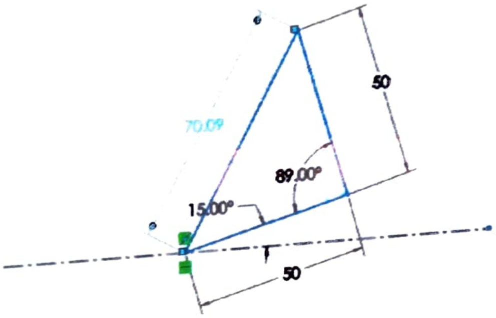

Figure 5.4 Frame line diagram

The basic line diagram of a single leg of Klann mechanism is as shown below. This figure depicts the entire components of the klann mechanism (i.e crank, connecting rod, top and bottom rockers, fixed frame and leg) joined together in the form of a basic line diagram.

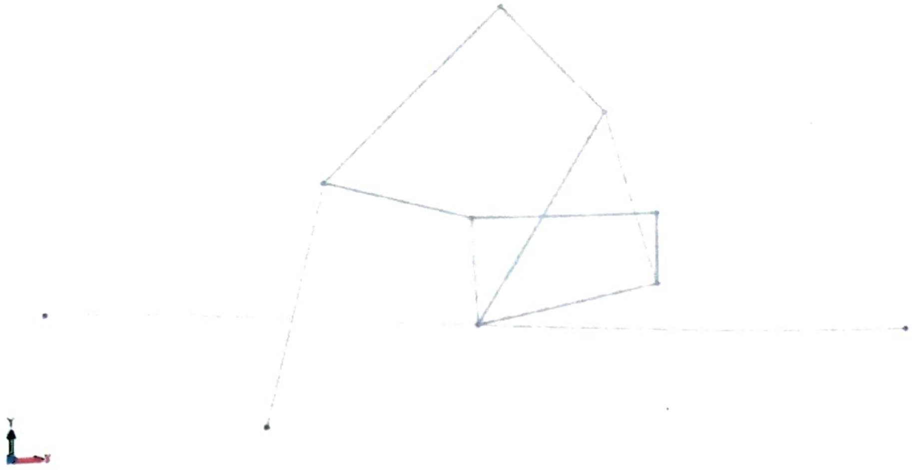

Figure 5.5 Line diagram of Klann mechanism

The same is depicted below with a clear view of dimensions of the linkage used.

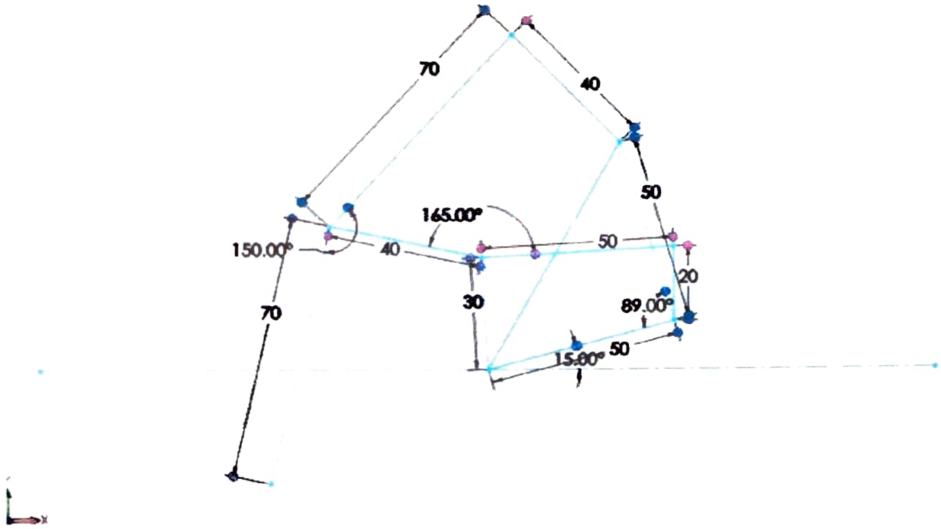

Figure 5.6 Line diagram with dimensions

This forms the basic blueprint of design of Klann mechanism. Further keeping this as basis, a complete assembly of the linkage has been designed using Solidworks. In order to design the individual parts , the process began with creating a platform which has to carry the entire 4 legs of the mechanism.

In the considered design process a platform supported by two linkge frames. The linkage frames are the components designed which are 2 in number which are attached to either side of the platform. There is a centre spur gear designed which is directly connected to the motor. The centre spur gear is in turn connected to two cranks (designed as spur gears) which rotate the front and back leg. There are two linkage connectors which are designed for the convenience of attaching the side linkage frames on either side of the platform. The designed parts are shown below.

5.2.1 Design of Linkage frame

The linkage frame is one the main components of the mechanism as the centre spur gear and also the cranks of both the front and back legs of the moving mechanism are mounted on it.

Thus it is initially carried out by sketching in front plane in solid works. The initial sketch is as shown below.

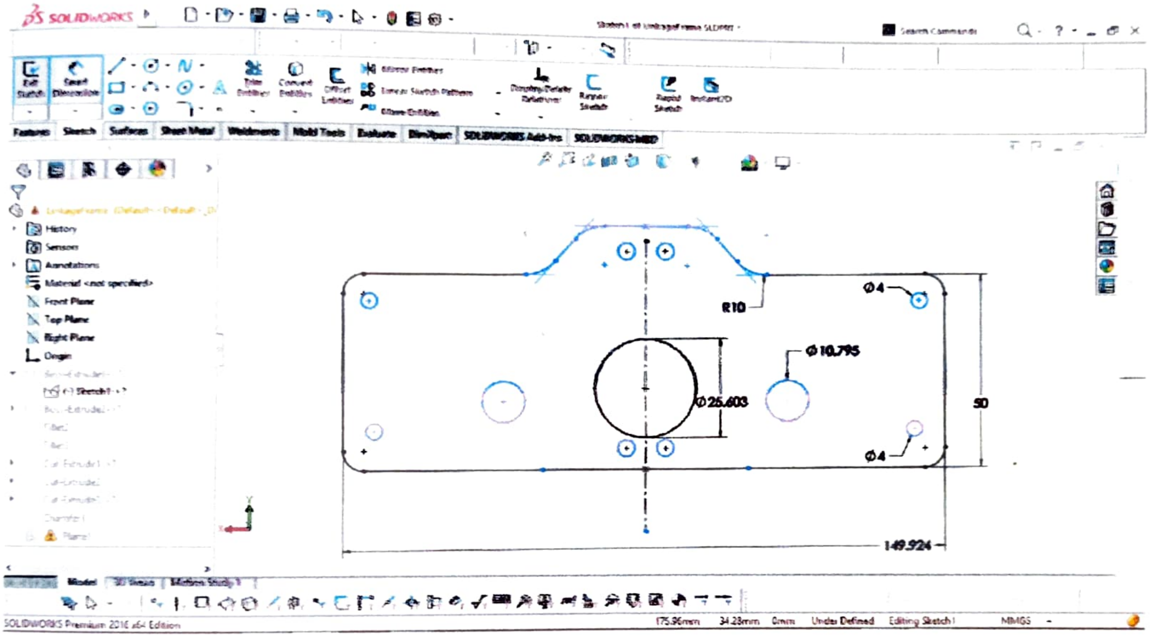

Figure 5.7 Sketch of linkage frame

The dimensions are taken so as to accomodate the required links of the mechanism. Circular cut outs are left at every corner as well as at required other spaces for accommodating a fit of M3 bolt and nut. Thus 1 mm of allowance is given to the holes so as to allow the free movement of links without any obstruction. Thus the circular holes have a diameter of 4 mm as shown in figure.

After the completion of basic sketch the part id extruded by a distance of 4 mm. all the components are extruded by an amount of 4mm. After extrusion the component is as shown below.

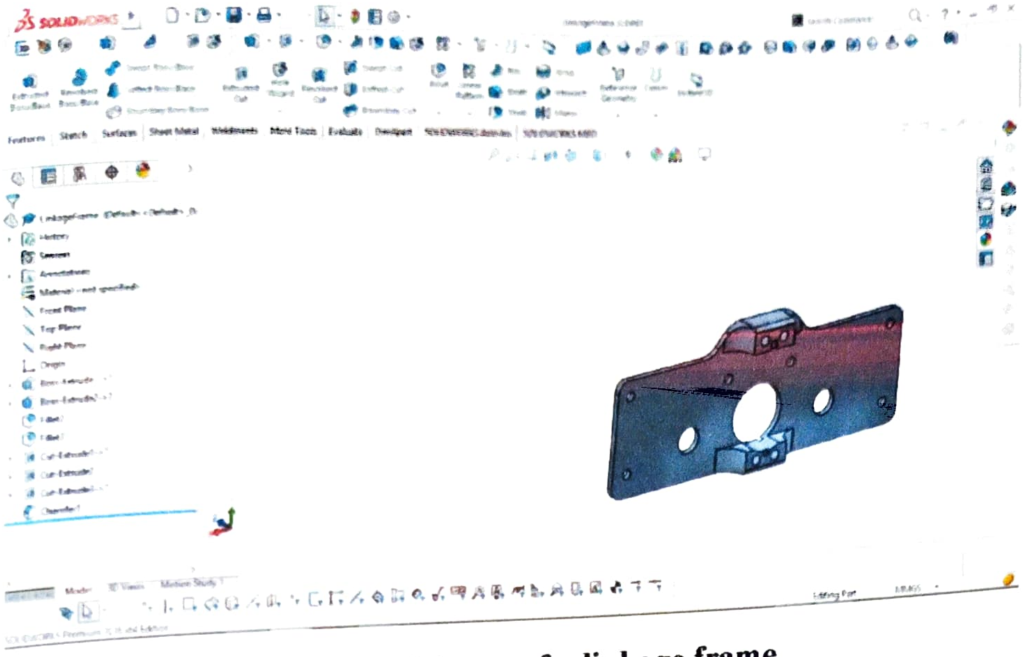

Figure 5.8 3d part of a linkage frame

The projected space on the side of the linkage frame shown in the figure is designed to fit a stepper motor in it. The middle circle on the side of the frame is given for the attachment of the centre spur gear. The right and left cutouts are given for the attachment of cranks of front and back legs of the moving klann mechanism.

5.2.2 Design of connecting rod

Connecting rod is one of the main components of the Klann mechanism. It is the component which connects the crank to the bottom rocker and also to the leg. It is not a straight link. It consists of two lengths included by an angle of 165°. The two lengths of link members are 20 mm and 25 mm. The part is first designed as a line diagram. Keeping this as basis, the the part is constructed as a 2d digram.

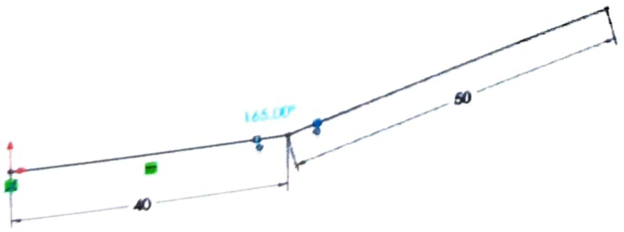

Figure 5.9 Line diagram of connecting rod

The then designed part in Solidworks is as shown below.

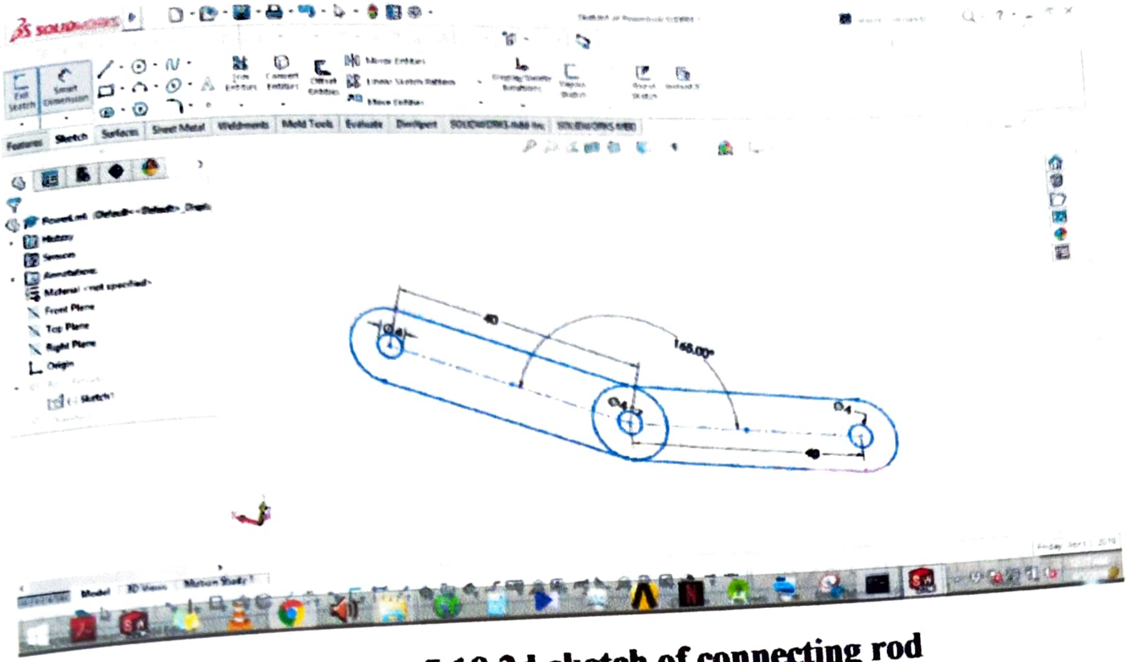

Figure 5.10 2d sketch of connecting rod

5.2.3 Design of leg of the mechanism

Design of leg is most crucial because the entire mechanism is based on the 4 legs on the floor in this case. There will be 4 legs in the considered design on the mechanism as there are 4 legs. The leg of the Klann mechanism is connected to bothe the connecting rod or powerlink and also to the to rocker.

The basic line diagram initially designed is as shown.

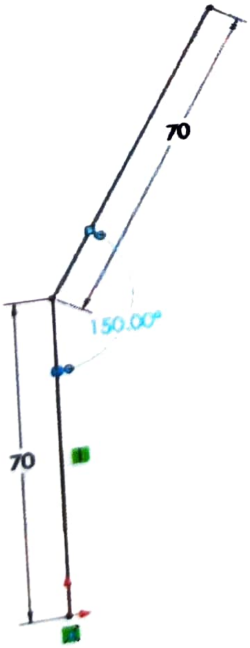

Figure 5.11 Line diagram of leg

Keeping this as basis a 2d sketch of the part is made using Solidworks as shown

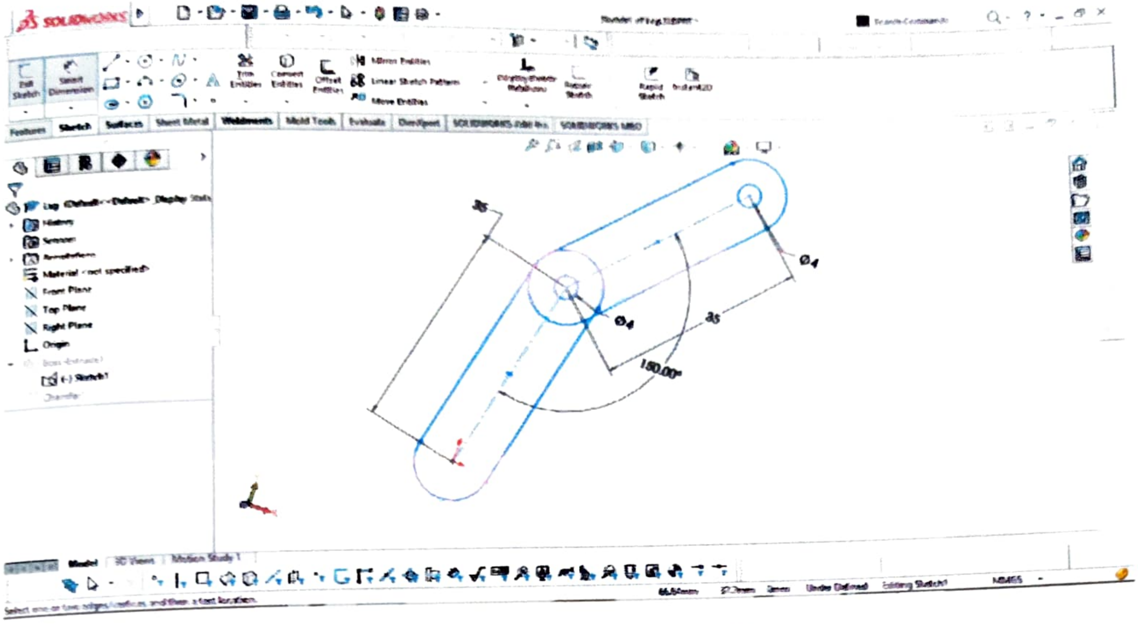

Figure 5.12 2d sketch of leg

The sketched part is then extruded by 4mm by using the extrude feature in solidworks which convert the 2d sketch into a 3d component. After extruding the part diagram by 4 mm the obtained part diagram in 3d is as shown in figure.

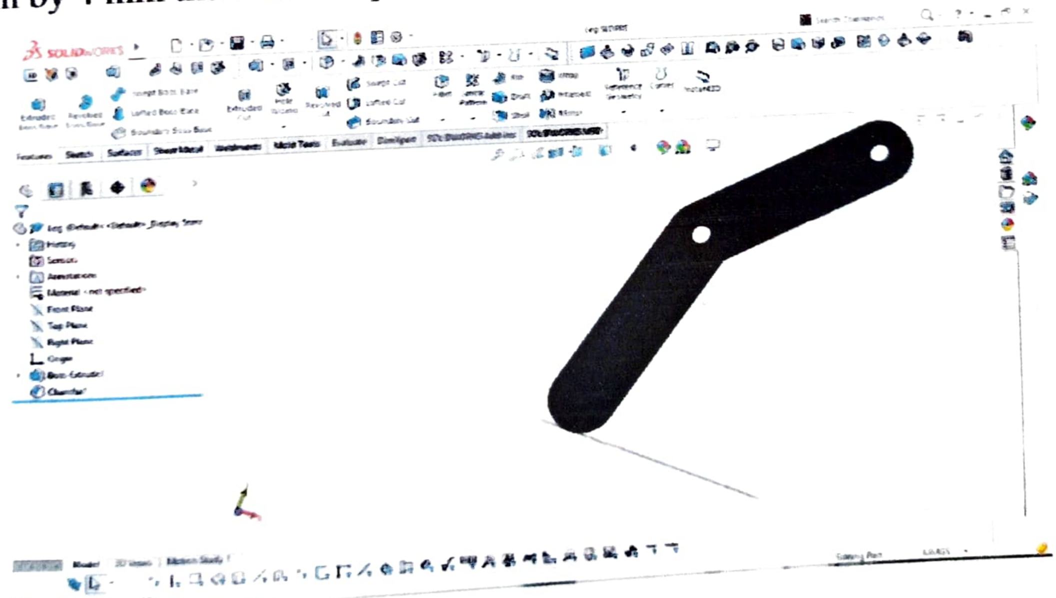

Figure 5.13 3d part of leg

5.2.4 Design of crank of a single leg

Crank is by far the most important component designed for the mechanism considered. In the design considered a stepper motor is connected to the inner side of the linkage frame. The spindle of the stepper motor is projected out from centre circular cutout of the linkage frame. The motor on one side of the considered design is connected two cranks of a side (i.e the front and back legs of a single side of the moving mechanism). Thus the crank is also designed so as to be a spur gear so that it draws power from the centre gear.

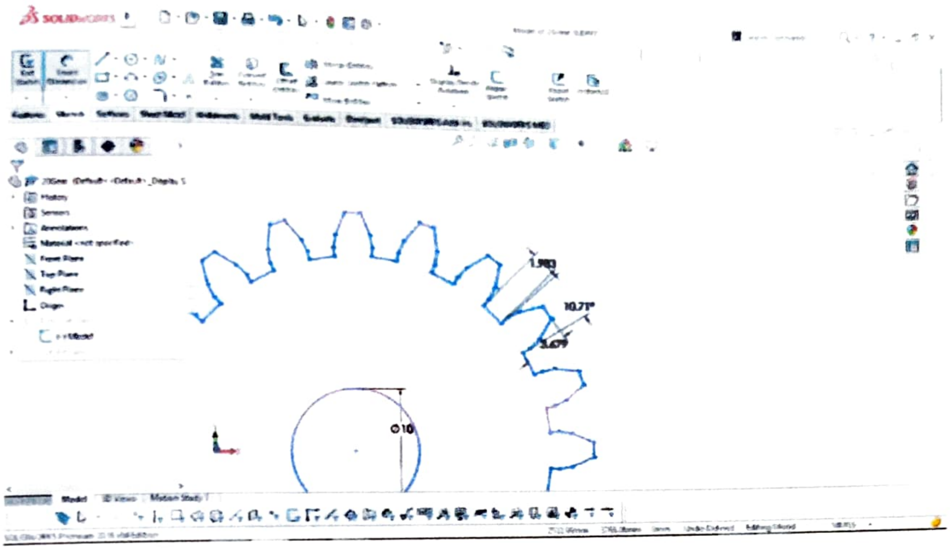

Figure 5.14 Sketch of crank

5.2.5 Design of top and bottom rockers

There are two rockers in the design of Klann mechanism. They are present at the top and bottom left of the triangular frame respectively. These play a very important role in converting the rotary motion of the crank into walking motion of the leg. The top rocker is connected to the frame on one side and the leg on it's other side. The bottom rocker on the other side is connected to the frame on one side and the other side of the bottom rocker is connected to the connecting rod. The parts after extruding from basic 2d sketch by an amount of 4 mm look like the images shown below.

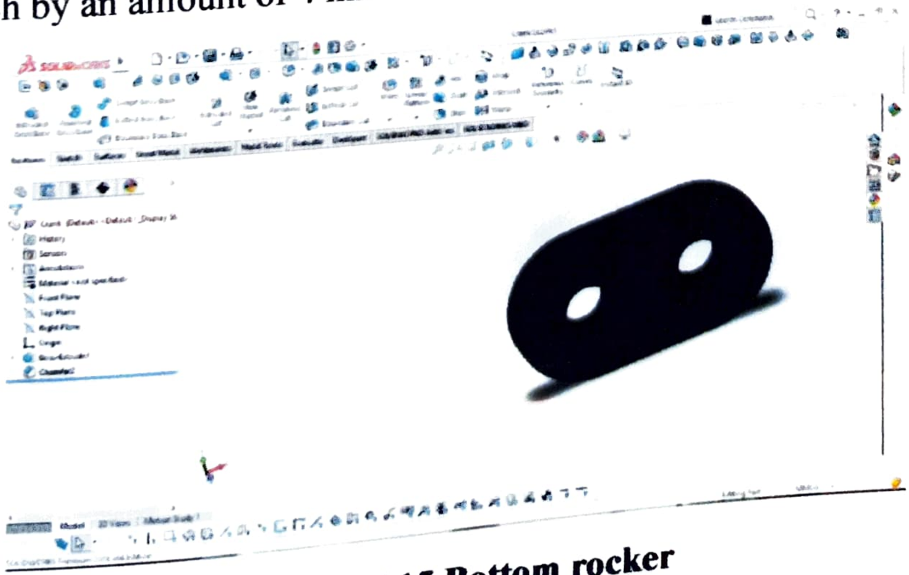

Figure 5.15 Bottom rocker

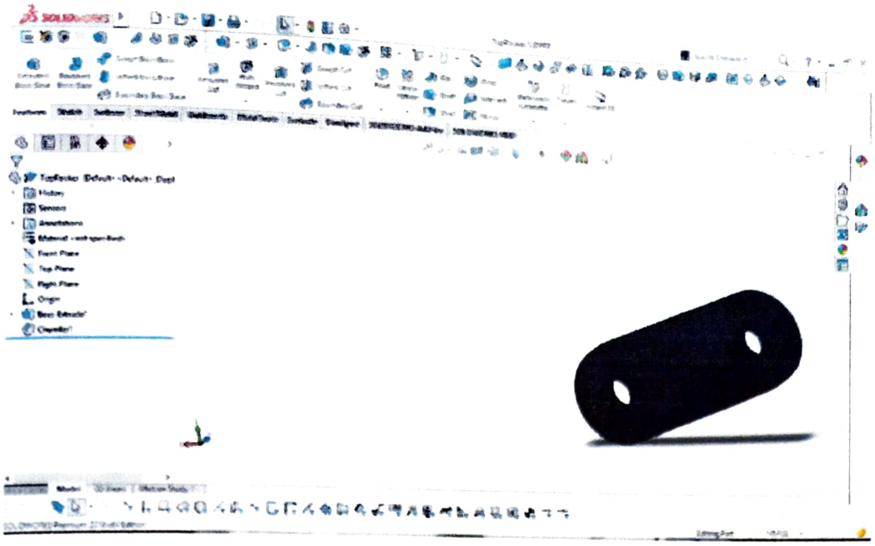

Figure 5.16 Top rocker

5.2.6 Assembly of the parts of Klann mechanism

Assembly is a difficult and crucial task in designing of any mechanism or machine which includes numerous parts. The Klann mechanism consists of 6 links for a single leg including the fixed frame. For the considered design there are 4 legs connected to two linkage frames. The assembly is very complex because at first all the individual links of a single leg are to be assembled perfectly and further 4 such legs are to be assembled to linkage frames.

The linkage frames are then supported by the platform. Further the centre spur gear and cranks have to perfectly align with each other. Amidst all this complexity involved, the design assembly of the of the Klann mechanism is done by using the assembly of parts function available in Solidworks.

The final assembly of the walking mechanism using Klann linkage is as shown below.

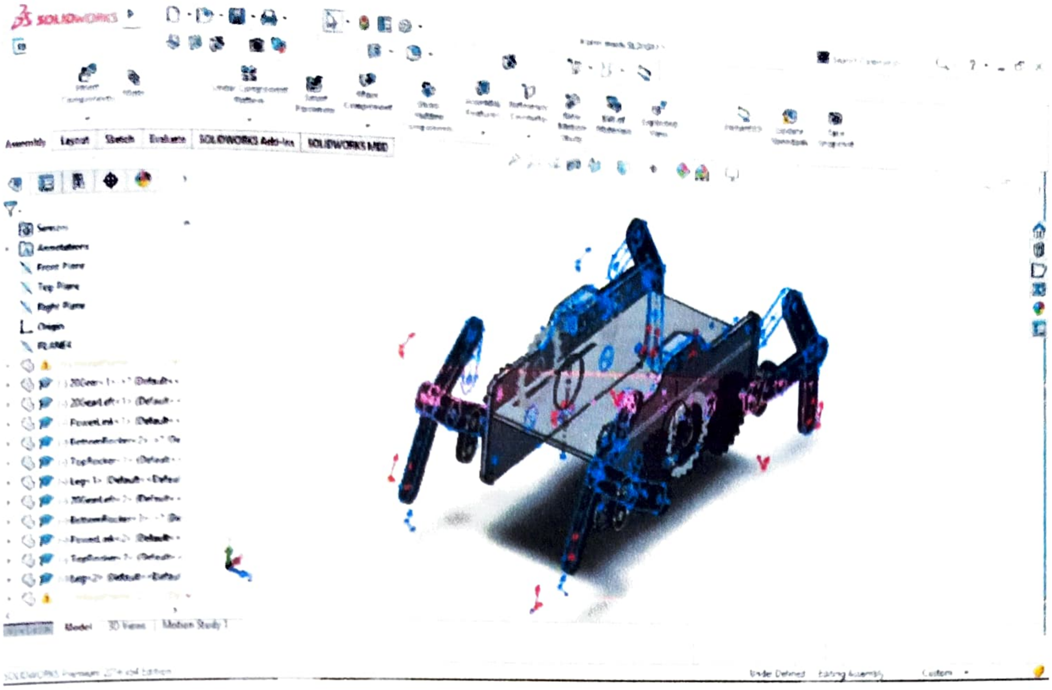

Figure 5.17 Assembly 1

Figure 5.18 Assembly 2

5.3 Fabrication of walking mechanism using 3D printing

3d printing is one the major leading technological processes right now in the world. It is an additive manufacturing process which heats a material,melts it and thereby arranges the melt of the material over a flat platform so as to obtain any required object or shape with high accuracy and repeatability. The object which has to be printed has to be initially generated using a computer software and further coded into the 3d printing machine.

The applications of 3d printing are increasing day by day due to its simplicity in manufacturing complex parts or shapes. Klann mechanism as discussed in previous chapters consists of 6 links per leg including the frame. Out of these 6 links two links namely the leg and connecting rod are not straight links but consist a fixed included angle. This angle has a major role to play because any change in the angle varies the gait pattern and the path traced by that link leg. Thus in order to get 4 legs of similar shape and size with minimum error error possible, 3d printing is an apt manufacturing process.

The designed solidworks parts are initially saved in a common folder by varying the extension of the files. The extension of the parts are changed to " .stl". the saved parts are then inserted into a pendrive and coded to the 3d-printing machine.

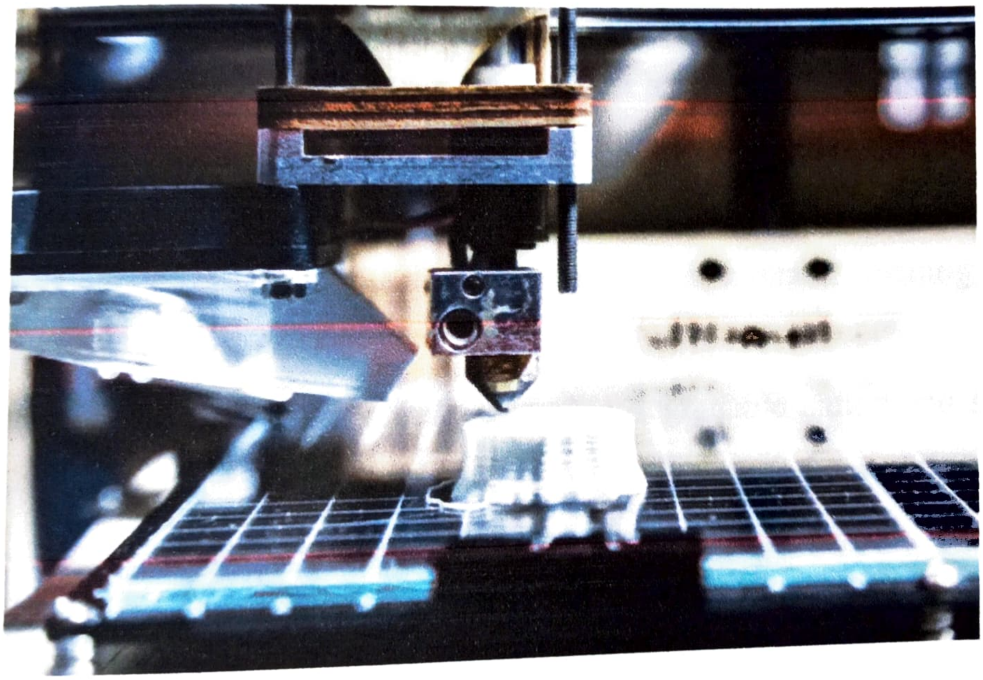

Figure 5.19 3d printing

The different materials available for 3d-printing are as follows:

1. ABS
2. PLA
3. PVA
4. NYLON
5. Wood filament
6. Metal filament

Out of all these materials available PLA is selected for 3d-printing. Polylactic acid (PLA) is a polymer plastic, made from biological materials like corn starch or sugarcane. It is similar to the material used in biodegradable plastic packaging and melts at between 180 and 200 degrees C, depending on other materials that are added for colour and texture. PLA is a tough, resilient material with a matte, opaque quality, but it is not as tolerant of heat as ABS is. PLA begins to deform at temperatures above 60 degrees C, and it is not water or chemical resistant. There is a slight smell when it is heated, rather like microwave popcorn, but no toxic odors or vapor.

PLA is generally the preferred option for low-cost 3D printers, because it is easier to print with than ABS, as it is stickier. It will stick well to aprint base covered in white glue or blue painter's tape, which means that a heated print bed is not needed. The material is also biodegradable; like other corn- or sugar-based materials, it is slowly consumed by many common bacteria. It will last a long time in normal conditions, though. It's only when buried that it breaks down. That said, PLA is not food safe and somewhat brittle, making prints prone to shattering under stress. However, chemicals can be added that make it less brittle and more heat-tolerant, creating what some manufacturers call tough PLA.

Thus due to the following reasons i.e the bio degradable nature and simplicity in manufacturing PLA material is selected for manufacturing the walking mechanism using klann linkage by the application of 3d-printing.

The parts obtained after the 3d-printing process are as follows:

1. Crank
2. Leg
3. Connecting rod
4. Top and bottom rockers
5. Linkage frame
6. Linkage connectors
7. Spacers
8. Centre spur gear

Figure 5.20 Fabricated 3d parts

5.4 Assembly of fabricated parts

The assembly took place in the following order.

1. First the leg and the connecting rod are joined with the help of m30 bolt
2. Next top rocker is connected to the top point of leg and bottom rocker is connected to the middle point for the 4 legs.
3. To the platform, the linkage connector and linkage frame are joined.
4. Then to the linkage frames the legs are connected by using the m30 bolts.
5. Now the centre spur gear is attached on both the sides and the gear is properly aligned to the cranks on either sides.
6. The motor is then attached on both the sides and and the two cranks on the front are kept at 180° out of phase.
7. The required electronics are performed and the fabrication is completed

CHAPTER 6

6. RESULTS AND DISCUSSIONS

6.1 Kinematic Analysis

6.1.1 Results of Angular Positions analysis

Table 6.1 Angular position analysis

SL NO	CRANK ANGLE	Link 3 (deg)	Link4 (deg)	Link5 (deg)	link 6 (deg)	Link 7 (deg)	Link8 (deg)
1	0	146.5847	-101.12	-78.8803	33.41526	101.367	138.6562
2	10	148.7262	-98.7243	-76.9349	35.61454	103.3099	141.0552
3	20	150.784	-95.9097	-75.4678	37.83847	104.7698	143.8803
4	30	152.7384	-92.7101	-74.5057	40.04583	105.7213	147.0959
5	40	154.5747	-89.1636	-74.0751	42.18652	106.139	150.6625
6	50	156.282	-85.3125	-74.2047	44.20078	105.9958	154.5363
7	60	157.8519	-81.2034	-74.9262	46.01847	105.261	158.6695
8	70	159.2763	-76.8882	-76.2772	47.55831	103.8981	163.0094
9	80	160.5464	-72.4251	-78.3011	48.72744	101.8642	167.4974
10	90	161.6502	-67.8808	-81.0473	49.4217	99.11014	172.0668
11	100	162.5696	-63.3345	-84.5683	49.52761	95.58416	176.6386
12	110	163.2771	-58.8837	-88.9112	48.92794	91.23942	-178.884
13	120	163.7308	-54.6535	-94.1021	47.51355	86.05058	-174.625
14	130	163.867	-50.8106	-100.117	45.20573	80.04294	-170.75
15	140	163.5912	-47.5824	-106.834	41.9927	73.33892	-167.486
16	150	162.7696	-45.2773	-113.973	37.97964	66.21951	-165.14
17	160	161.2309	-44.2901	-121.042	33.43681	59.17762	-164.107
18	170	158.8028	-45.0493	-127.345	28.80328	52.90158	-164.827
19	180	155.4092	-47.8555	-132.144	24.59075	48.11356	-167.616
20	190	151.1967	-52.6553	-134.951	21.19723	45.29553	-172.433

21	200	146.5632	-58.9578	-135.71	18.76912	44.50993	-178.775
22	210	142.0204	-66.0266	-134.723	17.23039	45.47026	174.1112
23	220	138.0073	-73.1663	-132.418	16.40877	47.75499	166.9299
24	230	134.7943	-79.8834	-129.189	16.13297	50.97018	160.1768
25	240	132.4865	-85.8979	-125.346	16.26916	54.8062	154.1306
26	250	131.0721	-91.0888	-121.116	16.72288	59.03437	148.9111
27	260	130.4724	-95.4317	-116.665	17.43045	63.48699	144.5415
28	270	130.5783	-98.9527	-112.119	18.34984	68.03828	140.9949
29	280	131.2726	-101.699	-107.575	19.45358	72.5903	138.2235
30	290	132.4417	-103.723	-103.112	20.72372	77.06351	136.1748
31	300	133.9815	-105.074	-98.7966	22.14814	81.39068	134.7992
32	310	135.7992	-105.795	-94.6875	23.71795	85.51299	134.0535
33	320	137.8135	-105.925	-90.8364	25.4253	89.37774	133.9013
34	330	139.9542	-105.494	-87.2899	27.26161	92.93707	134.3117
35	340	142.1615	-104.532	-84.0903	29.21598	96.14735	135.2578
36	350	144.3855	-103.065	-81.2757	31.27377	98.9691	136.7144
37	360	146.5847	-101.12	-78.8803	33.41526	101.367	138.6562

6.1.2 Results of Angular Velocity Analysis

Table 6.2 Angular velocity analysis

SL NO	CRANK ANGLE	Link 3 (rad/s)	Link 4 (rad/s)	link 5 (rad/s)	Link 6 (rad/s)	Link 7 (rad/s)	Link 8 (rad/s)
1	0	6.525822	6.525822	6.525822	6.525822	6.525822	6.525822
2	10	6.310215	7.831239	5.132296	6.65332	5.117425	7.852798
3	20	6.026708	9.039326	3.657079	6.669697	3.629663	9.07983
4	30	5.692273	10.13911	2.102629	6.549462	2.06655	10.19423
5	40	5.3202	11.11857	0.466455	6.264823	0.426057	11.18353
6	50	4.919673	11.96486	-1.25948	5.785712	-1.30027	12.03552
7	60	4.49535	12.66379	-3.08864	5.079794	-3.12678	12.73717
8	70	4.046858	13.19849	-5.03884	4.1128	-5.07213	13.2729
9	80	3.568034	13.54713	-7.12927	2.849825	-7.15619	13.62204
10	90	3.045643	13.67923	-9.37485	1.258737	-9.39418	13.75507
11	100	2.457213	13.55014	-11.7754	-0.68243	-11.7859	13.62821
12	110	1.767533	13.09285	-14.2966	-2.97127	-14.2966	13.17526
13	120	0.923402	12.20605	-16.8389	-5.55625	-16.8261	12.29582
14	130	-0.15301	10.73877	-19.1909	-8.29915	-19.1618	10.83979
15	140	-1.5686	8.476884	-20.9746	-10.9292	-20.925	8.593171
16	150	-3.44833	5.15404	-21.6171	-13.0147	-21.5449	5.286131
17	160	-5.87518	0.546654	-20.4398	-14.018	-20.3542	0.681036
18	170	-8.73894	-5.26509	-16.9906	-13.5168	-16.9254	-5.17084
19	180	-11.5512	-11.5512	-11.5512	-11.5512	-11.5512	-11.5512
20	190	-13.5168	-16.9906	-5.26509	-8.73894	-5.33034	-17.0849
21	200	-14.018	-20.4398	0.546654	-5.87518	0.461023	-20.5742
22	210	-13.0147	-21.6171	5.15404	-3.44833	5.081815	-21.7492
23	220	-10.9292	-20.9746	8.476884	-1.5686	8.427217	-21.0909
24	230	-8.29915	-19.1909	10.73877	-0.15301	10.70962	-19.2919
25	240	-5.55625	-16.8389	12.20605	0.923402	12.19324	-16.9287
26	250	-2.97127	-14.2966	13.09285	1.767533	13.09291	-14.379
27	260	-0.68243	-11.7754	13.55014	2.457213	13.56066	-11.8534
28	270	1.258737	-9.37485	13.67923	3.045643	13.69856	-9.45069
29	280	2.849825	-7.12927	13.54713	3.568034	13.57405	-7.20418
30	290	4.1128	-5.03884	13.19849	4.046858	13.23179	-5.11324
31	300	5.079794	-3.08864	12.66379	4.49535	12.70193	-3.16202
32	310	5.785712	-1.25948	11.96486	4.919673	12.00566	-1.33014
33	320	6.264823	0.466455	11.11857	5.3202	11.15897	0.401489
34	330	6.549462	2.102629	10.13911	5.692273	10.17518	2.047509
35	340	6.669697	3.657079	9.039326	6.026708	9.066741	3.616575

36	350	6.65332	5.132296	7.831239	6.310215	7.84611	5.110737
37	360	6.525822	6.525822	6.525822	6.525822	6.525822	6.525822

6.1.3 Results of Angular Acceleration Analysis

Table 6.3 Angular acceleration analysis

SL.NO	CRANK ANGLE	link3 (rad/s^2)	link4 (rad/s^2)	link5 (rad/s^2)	link6 (rad/s^2)	link7 (rad/s^2)	link8 (rad/s^2)
1	0	-30.109	232.1877	-232.188	30.10904	-234.816	235.9742
2	10	-43.4308	216.3144	-246.684	13.06143	-249.099	219.8616
3	20	-53.5443	198.6785	-260.385	-8.16224	-262.237	201.594
4	30	-61.0442	179.0532	-274.065	-33.9677	-275.179	181.1504
5	40	-66.6008	157.2946	-288.641	-64.7452	-289.025	158.6014
6	50	-70.9554	133.2366	-305.08	-100.888	-304.859	133.9222
7	60	-74.9248	106.5606	-324.259	-142.774	-323.591	106.847
8	70	-79.4284	76.64184	-346.734	-190.663	-345.755	76.74292
9	80	-85.5523	42.35366	-372.362	-244.456	-371.158	42.45191
10	90	-94.6666	1.801347	-399.656	-303.189	-398.253	2.050234
11	100	-108.614	-48.0642	-424.687	-364.137	-423.047	-47.5241
12	110	-129.984	-111.998	-439.325	-421.338	-437.347	-111.02
13	120	-162.419	-197.14	-428.773	-463.494	-426.294	-195.563
14	130	-210.704	-313.415	-369.084	-471.795	-365.919	-311.114
15	140	-279.669	-472.023	-227.507	-419.861	-223.663	-469.154
16	150	-369.349	-677.441	27.02321	-281.068	30.63982	-675.251
17	160	-462.452	-905.388	392.3599	-50.5756	392.5821	-907.696
18	170	-507.982	-1071.72	785.9999	222.2593	778.2369	-1083.79
19	180	-434.362	-1048.79	1048.79	434.3621	1035.637	-1067.3
20	190	-222.259	-786	1071.723	507.9822	1063.96	-798.07
21	200	50.57563	-392.36	905.3876	462.4521	905.6098	-394.669
22	210	281.0683	-27.0232	677.4411	369.3495	681.0577	-24.8327
23	220	419.8612	227.5073	472.0226	279.6687	475.8665	230.3756
24	230	471.7949	369.0839	313.4152	210.7042	316.5802	371.3851
25	240	463.4935	428.7728	197.1399	162.4192	199.6191	430.3495
26	250	421.3383	439.3246	111.9979	129.9841	113.9755	440.3027
27	260	364.1371	424.6873	48.06421	108.6144	49.70412	425.2274
28	270	303.1885	399.6565	-1.80135	94.66655	-0.39796	399.9053
29	280	244.4558	372.3618	-42.3537	85.5523	-41.1501	372.46
30	290	190.6634	346.7337	-76.6418	79.4284	-75.6635	346.8347
31	300	142.7737	324.2591	-106.561	74.92476	-105.893	324.5454
32	310	100.8881	305.08	-133.237	70.95535	-133.015	305.7656
33	320	64.74515	288.6405	-157.295	66.60077	-157.679	289.9473
34	330	33.96768	274.065	-179.053	61.04418	-180.167	276.1622

35	340	8.162237	260.3851	-198.679	53.54429	-200.53	263.3005
36	350	-13.0614	246.6838	-216.314	43.43081	-218.73	250.231
37	360	-30.109	232.1877	-232.188	30.10904	-234.816	235.9742

6.2 C Code

6.2.1 C code for displacement

```
#include<stdio.h>
#include<conio.h>
#include<math.h>
void main()
{
float
a=50,c=50,d=30,e=50,i=70,j=70,g=70,k,rad,deg,beta,k7,k8,k9,k10,thetakh,theta7,thetac
;
float
k1,k2,k3,A,B,C,G,H,I,J,K,L,theta3,theta31,theta32,k4,k5,k6,D,E,F,theta4,theta41,theta
42,theta51,theta52,theta5,theta61,theta62,theta6,thetaai;
rad=(4*atan(1))/180;
deg=180/(4*atan(1));
int b=20,f=40,h=40,theta1,theta2,o,m,n;
k=sqrt(h*h+d*d-2*h*d*cos(165));
//DISPLACEMENT ANALYSIS
theta1=15;
//theta2= 0:10:360;
for(o=0;o<36;o++)
{
        //for(theta2=0;theta2<=360;theta2+=10)
        //{
        theta2=o*10;
        k1=((a*cos(theta1))+(b*cos(theta2)));
        k2=((a*sin(theta1))+(b*sin(theta2)));
        k3=(((d*d)-(k1*k1)-(k2*k2)-(c*c))/(2*c));
```

```
A=-k1-k3;
B=2*k2;
C=k1-k3;
theta31=2*atan((-B+sqrt((D*D)-(4*A*C)))/(2*A));
theta32=2*atan((-B-sqrt((D*D)-(4*A*C)))/(2*A));
if(theta31>0)
theta3=theta31;
else if(theta32>0)
theta3=theta32;
k4=((a*cos(theta1))+(b*cos(theta2)));
k5=((a*sin(theta1))+(b*sin(theta2)));
k6=(((c*c)-(k4*k4)-(k5*k5)-(d*d))/(2*d));
D=-k4-k5;
E=2*k5;
F=k4-k6;
theta41=2*atan((-E+sqrt(E*E-(4*D*F)))/(2*D));
theta42=2*atan((-E-sqrt(E*E-(4*D*F)))/(2*D));
if(theta41>0)
theta4=theta41;
else if(theta42>0)
theta4=theta42;
//}
//SECOND LOOP
thetaai=acos(((i*i)+(a*a)-(e*e))/(2*i*e));
thetac=thetaai+15;
beta=165;
thetakh=asin((c*sin(theta3-180))/h);
theta7=thetakh+180;
//}
//for(m=0;m<36;m++)
//{
```

```
//Displacement analysis
k7=((d*cos(theta4))+(i*cos(thetac))+(h*cos(theta7)));
k8=((d*sin(theta4))+(i*sin(thetac))+(h*sin(theta7)));
k9=((f*f-g*g-k7*k7-k8*k8)/(2*g));
G=k9+1;
H=2;
I=k9-1;
theta61=2*atan((-H+sqrt((H*H)-(4*G*I)))/(2*G));
theta62=2*atan((-H-sqrt((H*H)-(4*G*I)))/(2*G));
if(theta61>0)
theta6=theta61;
else if(theta62>0)
theta6=theta62;
k10=(((g*g)-(f*f)-(k7*k7)-(k8*k8))/(2*f));
J=k10+1;
K=2;
L=k10-1;
theta51=2*atan((-K+sqrt((K*K)-(4*J*L)))/(2*J));
theta52=2*atan((-K-sqrt((K*K)-(4*J*L)))/(2*J));
if(theta51>0)
theta5=theta51;
else if(theta52>0)
theta5=theta52;
//}
        printf("%d\t",theta1);
        printf("%d\t",theta2);
        printf("%f\t",theta3);
        printf("%f\t",theta4);
        printf("%f\t",theta5);
        printf("%f\t",theta6);
        printf("%f\n\n",theta7);
```

CHAPTER 7

7. CONCLUSIONS

1. In this project design, kinematic analysis and fabrication using 3d printing technology of Klann mechanism is performed.
2. Equations are derived for position, angular velocity and angular acceleration of every link of Klann's linkage using complex Algebraic method.
3. A C-code is written for the calculations obtained using complex algebraic method.
4. A 4 legged model of walking mechanism whose legs are based on Klann mechanism is designed using Solidworks.
5. The different parts of the walking mechanism are 3d printed using PLA material for the selected dimensions.
6. The fabricated parts are then assembled and further electronic operations are performed.

CHAPTER 8

8. REFERENCES

1. A. Aan and M. Heinloo "Analysis and synthesis of the walking linkage of Theo Jansen with a flywheel"
2. Hyun Gyu Kim , JaeNeung Choi ,TaeWon Seo and Kyungmin Jeong "Optimal Design of Klann-based Walking Mechanism for Water-running Robots"
3. Jaichandar Kulandaidaasan Sheba ; Edgar Martínez-García ; Mohan Rajesh Elara ; Le Tan-Phuc. (ICICS 2015)
4. Kim, Hyun-Gyu;Jung, Min-Suck;Shin, Jae-Kyun;Seo, TaeWon."Optimal Design of Klann-linkage based Walking Mechanism for Amphibious Locomotion on Water and Ground".(Journal of Institute of Control, Robotics and Systems 2014.09.01)
5. Madugula Jagadeesh . Y V Chaitanya Kumar and Reddipalli Revathi "Design and optimization of a one-degree-of-freedom six-bar linkage Klann mechanism"
6. Shunsuke Nansaia, Mohan Rajesh Elarab, Masami Iwase. "Dynamic Analysis and Modeling of Jansen Mechanism". (Elseviser 2013)
7. V. V. Pharate, S. M. Patil, O. M. Prajapati, S. P. Patil. "Kinematic Synthesis And Optimum Selection Of Planar Straight Line Mechanism".(IOSR-JMCE)