3D-Printable All-Terrain Biomimetic platform

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***Abstract*— In the battle for robotic platforms to expand past the asphalt into jungle, rocky and other uneven terrain, wheels are becoming increasingly irrelevant. To fix this, solutions such as maglev trains, hovercrafts, caterpillar tracks, sleds, pedrail wheels, legged & linkage walking mechanisms were invented. Legged platforms have always been favoured for their superior manoeuvrability over wheeled platforms for non-prepared terrain, and the 2 of such legged mechanisms are the Klann Linkage and Jansen Linkage. However, the Jansen Linkage is more suitable for stable locomotion due to low change in its centre of mass during locomotion. This applied research focuses on improving the Jansen Linkage's utility & mobility. The enhanced 3D model design was first created and analysed virtually by using a commercial modelling software – Solidworks. Subsequently the validated model was then prototyped by an industrial Stereo Lithography Apparatus (SLA) printer. Results showed that the new invented features such as circular feet, shock absorbers, spring chambers, folding mechanism, weight reducer & anti-jamming pieces have significantly expanded the general utility of the platform, as well as its efficiency and functionality in uneven, unprepared terrain. The design intent demonstrated here is, in our opinion, highly meaningful and potentially translatable into practices (such as weaponry, consumer and military land transport and also consumer robotics), yet deals with an important & ubiquitous challenge of further enhancing such complex linkage mechanism in a generally applicable manner.**

***Keywords* - 3D printing; 3D- Printing; Biomimetic; 3D-Printable; Jansen; Linkage; All-Terrain; Defence; Walking; Mechanism; Strandbeest**

I. INTRODUCTION

The invention of the wheels was a leap forward for mankind but they have proven themselves to be less effective in the world of robots. While wheels triumph over legs on prepared surfaces such as roads due to their higher energy efficiency, they encounter difficulties accessing uneven terrain. This is where legged robots shine as their manoeuvrability allows them to navigate surfaces inaccessible to wheeled robots by stepping over obstacles. In essence, legged robots are far more versatile and manoeuvrable than both tracked & wheeled robots. The recent years had also seen a growth in the research of legged mechanisms for applications such as planetary exploration, walking chairs for the disabled, military transport and rescue operations in radioactive zones or other hostile environments.

A. The Jansen Linkage

This research had been limited to the usage of Jansen Linkage (**Appendix L**) since it offers many advantages with its scalable design, energy efficiency, biomimetic locomotion & deterministic foot trajectory. In his wind-powered Strandbeests (**Fig. 1**), Theo Jansen proposed the "Jansen Linkage" which consists of 11 rods and mimics a skeleton of animal legs (**Fig. 2a**). The proportions of lengths provide a smooth locomotive leg movement, i.e. animals gaits with a sharp-pointed elliptic orbit.

Figure 1: Theo Jansen's Wind-Powered Strandbeest[1]

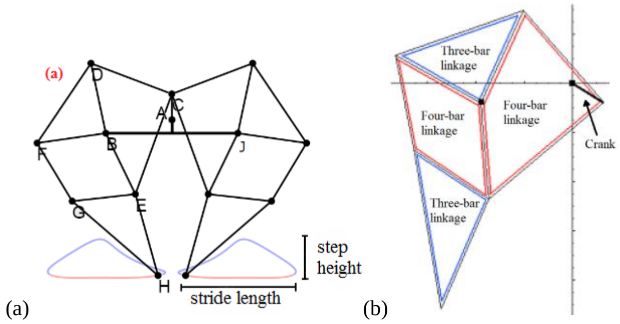


Figure 2: Jansen Linkage (a) Locus of 1 Pair of Legs and (b) Linkages in 1 Foot[3]

The Jansen Linkage consists of 7 links per leg, excluding the linkage at the foot since its fixed. The lengths of the different parts have been optimised by Theo Jansen to his “11 holy numbers”[2] (**Appendix M**), prioritizing energy efficiency and stride length. The path travelled by the lowest point of the foot, touching the ground, is the “locus” of the foot. The flat base of the loci (red), indicate the feet being in contact with the ground and is the “stride length” as it is the length travelled every cycle. The incline and decline (blue) indicate the feet being lifted forward[2] and the cumulative motion of the pair drives the entire mechanism forward. The maximum height of the locus is defined as the “step height” (**Fig. 2a**). The mechanism itself consists of two 4-bar linkages and two 3-bar linkages (**Fig. 2b**). 1 set of the Jansen Linkage, consisting of 2 feet, will be referred to as “1 pair of legs”

Rotation of the crank (**Fig. 2a** Part AC) moves the 4-bar linkage attached to it, creating movement in the rest of the linkages and the leg. The pair of legs move in the same direction as the rotation of the crankshaft; clockwise rotation of the crankshaft results in the pair of legs moving to the right and vice versa. As the foot is off the ground for more than half the time of the leg’s motion[4], more than 2 pairs of legs were required for stable movement and thus most models were made with 3 pairs of legs using a 120° phase difference between each pair of legs in the crankshaft to maintain stability.

In this research, the Jansen Linkage will be modified & enhanced to be applied in a 3D-printed motor powered legged mechanism, focusing on improving its utility & mobility. Furthermore, modifications were made to the mechanism for a more efficient transport across all terrains, in particular, uneven terrains.

II. METHODOLOGY

B. Designing the Model in Solidworks

Solidworks is a commercial Computer Aided Design (CAD) software that allows for quick modifications by changing dimensions of each part during the design process. It can also run simulations of the designs to trace the motion of a point or check for technical problems. The Jansen Linkage was modelled and modified in Solidworks, but for early prototyping, parts of the mechanism had to be printed separately before manual assembly due to the limitations of the machine that was used, the MakerBot Replicator 2 (**Appendix Fig. 11**). The final product was sent to an external vendor for high definition printing where even parts to create hinges could be 3D-printed. Important changes that were made include modelling DFB & GEH as triangles, as it provided more structural stability. The part AC was changed into a crankshaft, set at different phases, as the pairs of legs were connected via the crankshaft so it could be powered by 1 motor. Points B & J were connected through with a single rod directly to the platform, so that the legs were always level and directly connected to each other.

C. 3D-Printing

The 2 methods of printing utilized were Fused Deposition Modelling (FDM) (**Appendix Fig. 12a**) and Stereo Lithography Apparatus (SLA) (**Appendix Fig. 12b**). FDM uses a solid-based rapid prototyping system such as thermoplastic like Polylactide (PLA) Filament that melts at a high temperature whereas SLA uses a liquid-based rapid prototyping system and solidifies liquid resin under a laser.[5][6] Despite these differences, supports were still needed and the model had to be built layer by layer in both systems. However, for the particular SLA printer used, the support material could be washed off with acid.

The FDM-based MakerBot Replicator 2 was used during the design optimization process as the material was relatively cheap and the printing speed was rapid. The biggest limitation, however, was that the bonding force of FDM-type printers was not very strong, leading to layer separation that compromised on the resolution and surface smoothness of the object being printed[7]. Furthermore, it was unable to print parts for hinges unlike the SLA printer from an external vendor as they were too small.

D. Optimising the MakerBot Replicator 2

With settings that range from fast draft to finer resolution, the speed & quality of printing could be easily set to meet the demands of the user. MakerBot Desktop, software programmed for the 3D printer, where groups of models could be dragged into the virtual space and modified was similarly straightforward to use. This was especially so since details such as infill patterns and supports would be shown.

Settings used to print the 3D models in the Replicator 2 were as follows (explained in **Appendix N**):

Temperature: 230 °C
Infill: 5%
Layer Height: 0.30 mm
Speed while extruding: 90 mm/s
Speed while travelling: 150 mm/s

E. Rapid Prototyping

Although the entire assembly was virtually assembled in Solidworks to analyse its movement, minor physical limitations that were difficult to realize in animations could potentially pose problems in real life (e.g. the whole model might collapse under its own weight should the parts be too thin). Rapid prototyping allows for incremental improvements to be made over a short period of time and allowed variations of the parts to be printed for quick comparisons to pick the most suitable parts. For example, the width of the printed parts had to be reduced as they would come in contact with one another when in motion but they could not be made too thin so as to support the weight of the model. Individual printed parts were connected using satay sticks and the crankshaft was substituted with a piece of carefully bent steel wire during the prototyping process. At first, 1 pair of legs was built (**Fig. 3a**) as an experiment for the modelled parts. After ensuring that the pair of legs was functional, a six-legged assembly with 2 motors and a platform was placed between each trio of legs (**Fig. 3b**).

III. Results and Dicussion

Using the Replicator 2 for rapid prototyping, problems in the initial design that could not be reflected in a mathematical model were found and the improvements were made to the design.

F. Circular Foot

It was found that the foot of the model, extended out from the bottom of the triangle at a predetermined length from the other points in the mechanism is a point and would wear down or break quickly. A circular foot wore down slower than an edge or point, as different parts of it contacted the ground at different times. Therefore, a circular foot (**Fig. 4a**) was modelled around the "ideal point" instead.

Further examination of the loci revealed that an extended foot caused an undesirable change in the foot locus. Specifically, an extended point from the "ideal point" acted as a foot and caused the locus to flatten and widen (**Fig. 4b**). Wearing down of the extended foot would also reduce the distance from the lowest point to other parts of the leg thus changing the foot's locus. These changes would not occur if this was replaced with a circle around the "ideal point". Instead, the locus travelled by the lowest point on the circle at each instant was the same as the locus travelled by the centre of the circle but at distance "r" beneath it (**Fig. 4c**). Even though the circle rotates while it moves the lowest point of the circle would always be "r" beneath the centre (**Fig. 4d & 4e**).

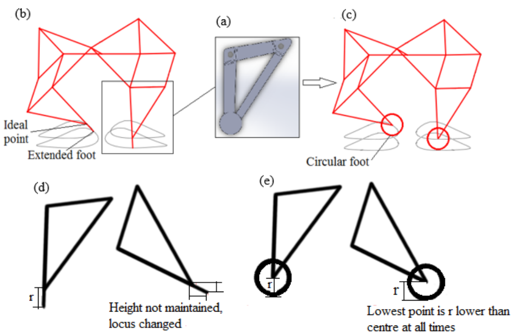


Figure 4: Effect of Circular Foot (a) Modified with Circular Foot, (b) Locus of Extended Foot, (c) Locus of Circular Foot, (d) Height not Maintained with Extended Foot & (e) Height Maintained at "r" with Circular Foot

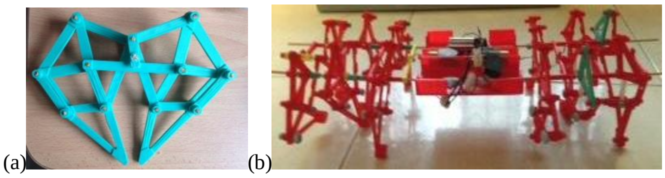


Figure 3: Preliminary Prototypes of (a) Pair of Legs & (b) 6-Legged Walking Model

However, with a circular foot, obstacles easily got stuck at the vertex between the circle and side GH of the triangle (**Fig. 5a**). To prevent this, a flat continuous surface had to be formed from point G to the bottom of the circular foot. However, instead of simply moving the side GH towards the edge of the circle, it was widened such that the width of GH spanned the radius of the circle (**Fig. 5b**). This increased the structural strength as these pieces at the bottom would have to support the entire weight of the robot. This was also reflected later on in the final design (**Appendix Fig. 14**).

G. Shock Absorbers

In the event the model fell from sufficient height, the linkages might break due to the shock. Therefore, rubber was

added to the bottom of the foot to act as a shock absorber and reduce chances of the model breaking. Additionally, the rubber added to the bottom of the foot increased friction and reduced slippage.

H. Weight Reduction

The model was made thinner & lighter so as to reduce the cost of printing, time needed to print, and energy required for the mechanism to move. Cuts were added to the pieces such that it reduced the overall weight of the model without compromising on its structural strength (**Appendix Fig. 14 to 21**). By dividing the width of the parts into 2, two waves that overlapped similar to "destructive interference" were cut. This ensured that no point on the structure would snap easily, while also reducing the weight. The bottom & top triangles were also remodelled to use up less material. Instead of using triangles, extensions from the centre of the triangle to each corner were used forming a shape similar to a Y.

I. Jamming Prevention

The quadrilateral FBGE sometimes folded inwards under its own weight in a certain orientation. States 1 & 2 show the normal & jammed quadrilateral respectively (**Fig. 6a**). Whenever it folded inwards, the mechanism would stop functioning as the legs are not able to move past that point.

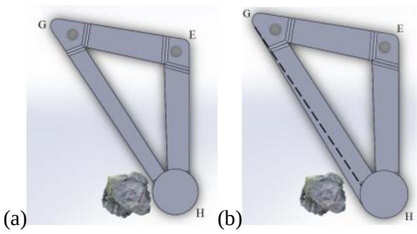


Figure 5: Bottom Triangle (a) Original Bottom Triangle & (b) Amended Bottom Triangle

An anti-jamming piece was added at G to prevent the linkage from folding inwards (**Fig. 6b**), by preventing the linkage G from going past 180o while still allowing them to move uninterrupted throughout the motion.

J. Spring System to Increase Step Height

Theo Jansen’s optimization focused on energy efficiency & stride length, compromising on the step height. The resulting model encountered difficulties in travelling across rocky or uneven terrain as many obstacles would be taller than the step height. This heavily limited its applicability as a transport mechanism. It was found that to significantly increase the step height of the optimised locus (**Fig. 7a**), only a small decrease in the length of GE (**Fig. 7b**) would be needed. By splitting GE into 2 pieces and fixing a spring between them, GE could compress as it contacts an obstacle and return to its normal length after clearing it. This allowed it to remain optimized for energy efficiency on flat ground while only increasing step height upon encountering an obstacle.

Point H was turned into a hinge for GH & GE to turn around and part GE was converted into 2 parts, a spring pusher (hinged at point G) and a spring chamber (hinged at point E). When the model contacted the obstacle near point G, the spring would compress.

However, when an obstacle was met near point H, the force was insufficient to compress the spring. Hence, a bent lever was added, hinged along length GH and extended behind point E (**Fig. 8a**). This would instead push behind the spring chamber to compress the spring (**Fig. 8b**) thus increasing step height.

K. Folding Mechanism for Storage

The shape of this model was impractical for storage, and thus a mechanism to fold the model into a more practical shape for stacking & storage was devised. A rod that runs through the middle of the platform and 2 cross-shaped handles attached to the front & back of the rod were installed.

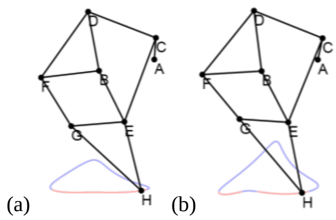


Figure 7: Step Height with (a) Original Length of GE & (b) Shortened Length of GE[3]

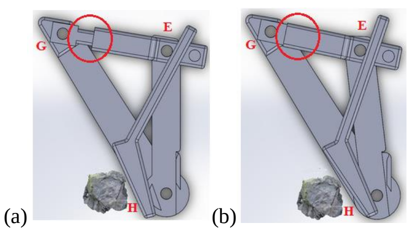


Figure 8: Spring System with (a) Spring Uncompressed & (b) Spring Compressed

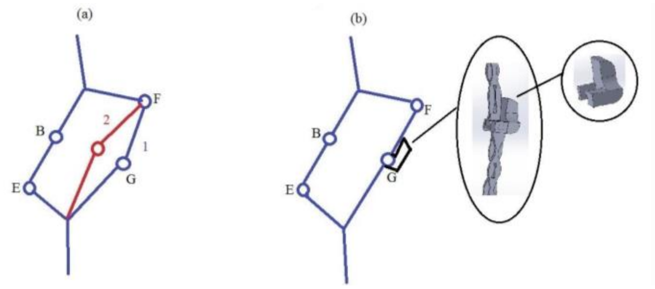


Figure 6: Bottom Triangle in (a) Jammed State & with (b) Anti-Jamming Mechanism

Magnetized hinges were added to the feet and the rod was attached to the top & bottom tips of the feet by strings (**Fig. 9a**). By turning the handles to wind the strings, the feet would fold inwards and the model would thus collapse (**Fig. 9b**). During storage, the mechanism could be locked to retain this collapsed shape. To return the mechanism to its original shape, the magnets would attract each other once it was unlocked and unwind the strings, pulling the legs back upright.

For the final model, the improvements included were the circular foot, shock absorbers, weight reduction & anti-jamming mechanism. The model consisted of a platform in the middle to hold the motor and items to be transported with 2 pairs of legs on both sides of the platform for a total 4 legs running at a 90° phase difference in the crankshaft. While it could be resolved by adding an extra pair of legs on each side and changing each trio to be 120° out of phase, it was decided that the resultant improvement was not worth the increased weight and size of the model, as well as the additional resources required to fabricate it.

Two separate models were built for the spring system & folding mechanism as they were still under experimentation. For the spring system, 1 leg was built with the spring system and another without to use as comparison for walking over a tall obstacle. For improvement 3, a model with a platform and only 2 pairs of legs, 1 on each side, was built with the middle rod, strings & hinges to showcase the folding mechanism.

IV. CONCLUSION

The final model which was entirely 3D-printed is an enhanced design based on the Jansen Linkage, improving its utility & mobility. 3D-printing was useful both as a tool to speed up the design process, as well as a method to fabricate the final product. Improvements made to the model helped to adapt it better for uneven terrain thus increasing its applicability.

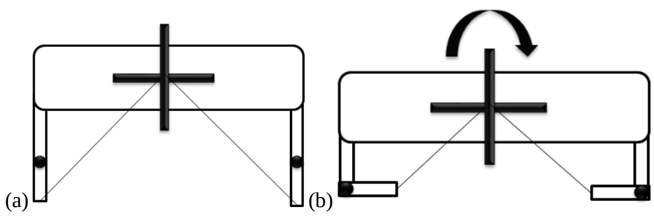
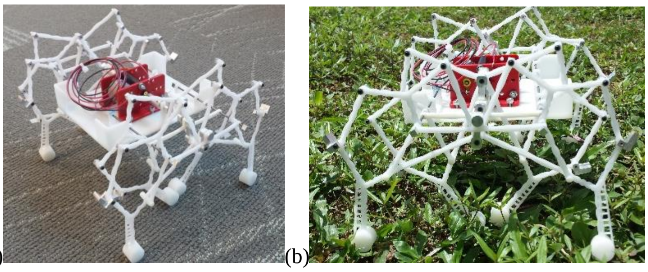


Figure 9: Folding Mechanism in (a) Standing Position & (b) Collapsed Position


(a) (b)
Figure 10: The Final 3D-Printed Model on (a) Carpet & (b) Grass

V. Future Work

In the presence of strong winds, the model might tip forwards or backwards as it is laterally elongated. In order to prevent this, the previously mentioned storage mechanism can be applied to fold its legs of the model and collapse inwards in strong wind. This stops the motion of the model and lowers the centre of gravity to minimize the possibility of the model falling over, while increases the area of contact and thus static friction against the ground.

Because each leg is out of phase, each leg will be in a different position. In order to ensure the hinges on each leg can be folded at the same time, the mechanism would have to be stopped in a specific alignment. An additional motor to turn the centre rod can be implemented, and an anemometer can be connected to all the motors in the system. When local wind speeds exceed a pre-set value, the motors powering the legs will stop at a predetermined position, and the motor attached to the rod will rotate it to retract the strings and fold the hinges of the legs.

The "Spring System to Increase Step Height" could not be used in a walking model as the motor was unable to supply sufficient force to compress the spring. However, by making a functional model of only the spring-loaded sections, the research could potentially be extended by using a motor with a higher torque on a model and tested on real terrain.

Apart from this, many other modifications could potentially be made to the model to add specific functionality for different roles such as the ability to climb stairs and jump over obstacles. It could be also used for surveillance purposes, re-broadcasting of communications, weaponization, or simply to transport small objects. Due to the flexibility of designs and availability of 3D-printing, improvements can easily be made to suit the different uses of the legged mechanism.

Acknowledgment (Heading 5)

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Appendix

L. *The Klann Linkage*

Another linkage with possible practical application is the Klann Linkage (**Fig. 10**) by Joe Klann. It offers the advantage of having only 6 links per leg[8], less than the Jansen Linkage, and so has less friction, weight and material cost. It also has a higher step height, lower centre of gravity[8] and requires only 2 legs to be stable[8] as each leg spends more than half the time on the ground[4]. However, the Klann Linkage has a motion that is less smooth than Jansen Linkage as the high step height results in a big change in the centre of mass thus making it less suitable as a transport mechanism. It also requires more energy to bring about this change thus making it less energy efficient[8].

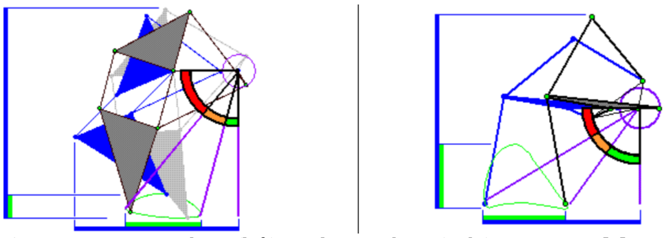

Figure 10: Jansen Linkage (left) & Klann Linkage (right) Comparison[8]

M. *Theo Jansen's 11 Holy Number[2]*

The locus of the foot is dependent on the length ratio of the 11 different rods of the leg. The time needed for a computer to generate all of the possible combinations would take about 100,000 years though, so Theo Jansen had to use the evolutionary method to get that lengths.

The final 11 holy numbers which denote the ideal lengths of the required rods were churned out by Theo Jansen using a genetic algorithm. By generating 1500 legs with rods of different lengths in the computer, only the best 100 legs which approached the ideal walking curve was chosen. These rods were copied and combined into another 1500 new legs which went through the same analysis and this process was repeated for many generations.

However, the final result, leg of Animaris Currens Vulgaris, would encounter problems walking from time to time and a new computer evolution had to produce the lengths of legs which followed. These lengths are:

BD=41.5, BE=39.3, AC=15, BF=40.1, FG=39.4, EG=36.7, GH=65.7, EH=49, CE=61.9, DF=55.8, By=7.8.

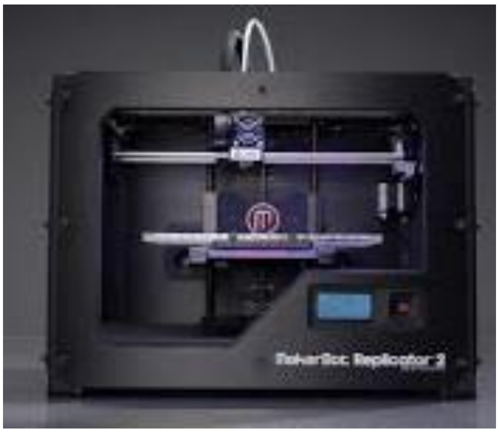

Figure 11: MakerBot Replicator 2

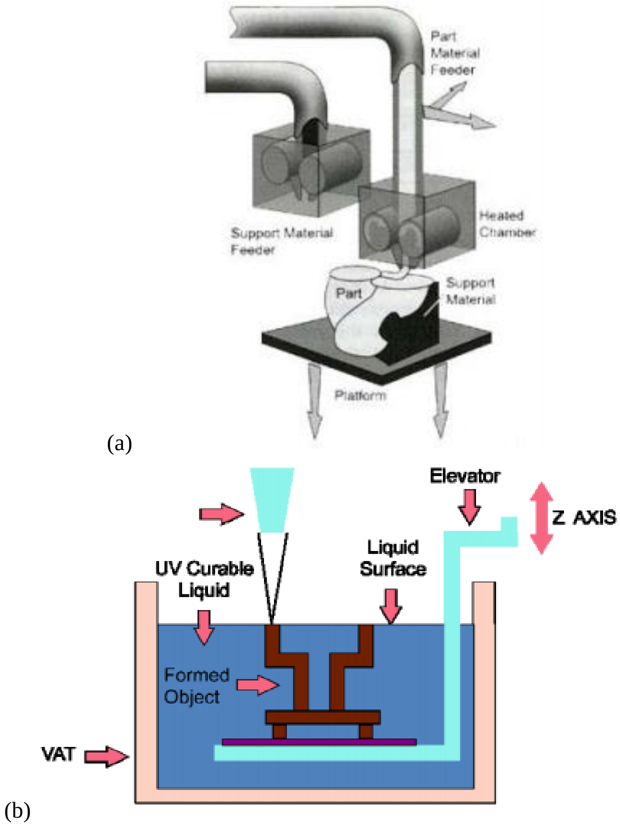

Figure 12: Schematic Diagram of (a) FDM Process; (b) SLA Process[5]

N. *Print Settings*

Even though higher temperatures allows printed layers to adhere better to other layers and the print surface, filament may leak from the extruder to form "threads" between parts or warp the plastic should the temperature be too high[9]. The optimum temperature was decided increasing the temperature by 5°C until a good print was obtained.

Most 3D-printed pieces are not fully solid. While it seemed solid from the outside, the insides were usually only partially filled. This reduced printing time & amount of materials used while still maintaining the structural integrity of the piece. Infill percentage (Appendix Fig. 13) refers to the density of the pattern used to fill the space within the print. Higher percentages of infill creates more solid structures but take longer to print[10] and vice versa. For prototyping, a very low percentage of infill (5%) was all that was required, given that the pieces were already very thin and had little space to fill.

Layer height controls the height of each layer added to the print. A finer layer height produces a more detailed print but would take much longer to print[10]. Since the model needed in the earlier stages only had to be functional instead of being pleasing to the eyes, the layer height was adjusted to the maximum within the recommended range.

"Speed while extruding" controls the speed of the extruder when material was being extruded. This could not be too fast as it was essential to give sufficient time for the layers to fuse with the platform or the layer below it. “Speed while travelling” could be faster as no material was being extruded[11] and moving faster could save more time. It was found that 90 mm/s & 150 mm/s for extruding & travelling speeds respectively produced better quality prints.

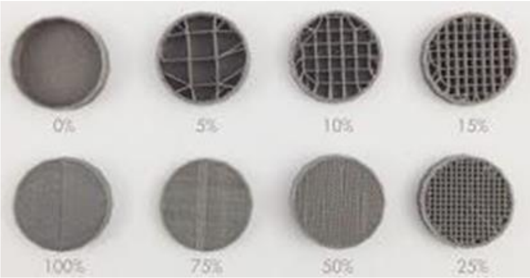

Figure 13: Infill Percentage

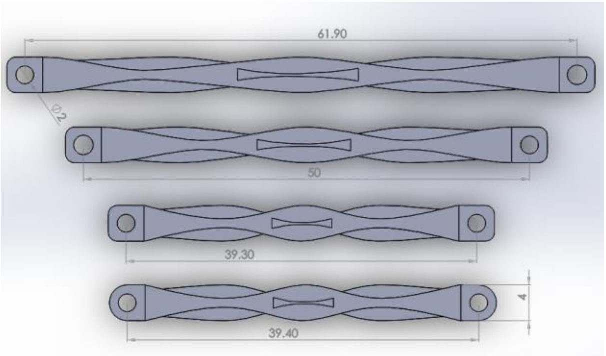

Figure 14: (From Top) CE, CD, BE, FG

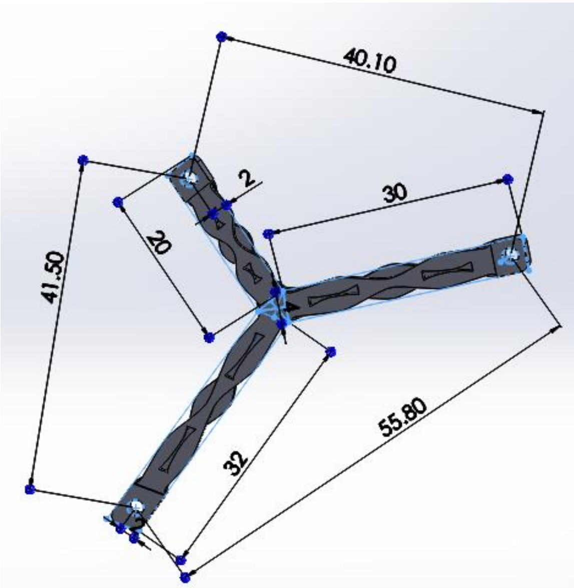

Figure 15: Top Triangle, DBF

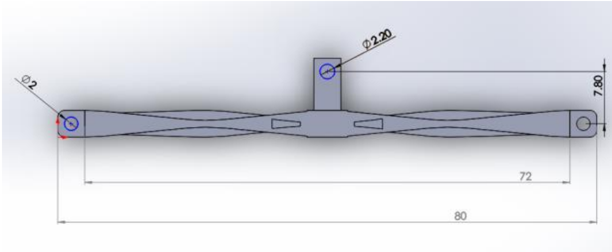

Figure 16: Part BAJ

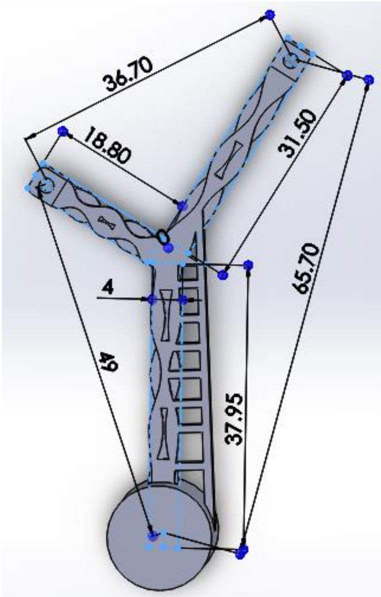

Figure 17: Bottom Triangle, GEH

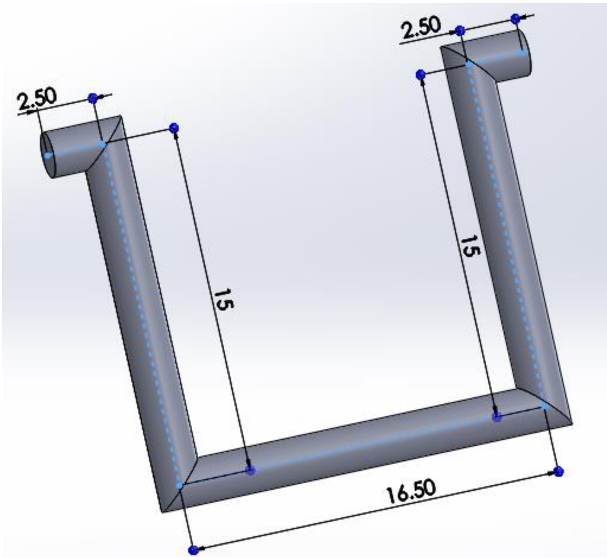

Figure 18: Repeated Section of Crankshaft

Figure 19: Bottom Platform

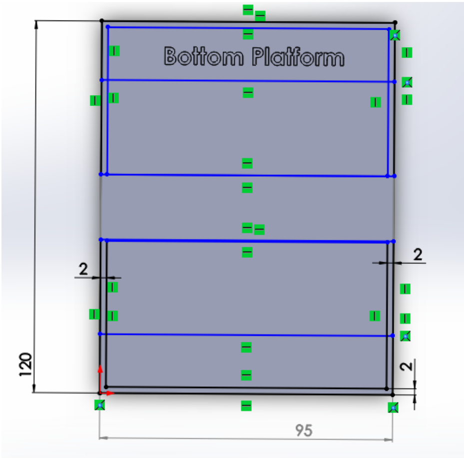

Figure 20: Dimensions of Bottom Platform

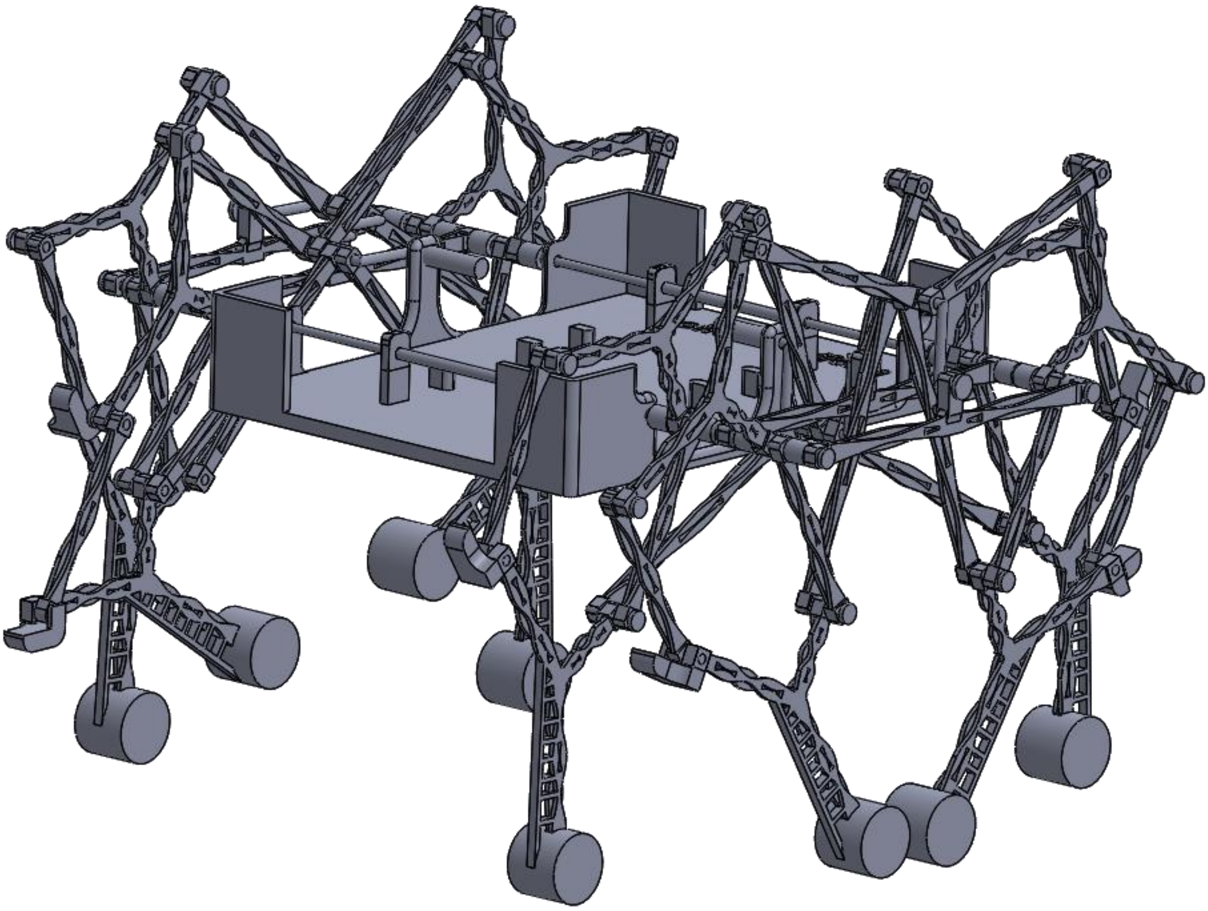

Figure 21: Design of Full Model