Omnidirectional Insect Treadmill Group Project

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11 April 2022
Word count: 4904

Acknowledgements

We thank the Evolutionary Biomechanics Research Group from Imperial College London for the loyal supervision, continuous support, and brilliant ideas. In particular we thank Dr David Labonte for bringing the team together, and PhD students Fabian Plum, Hendrik Beck, Liv Walthaus, and Dilanka Deegala for answering our many (many, many) questions.

"Why think? Why not try the experiment?"

(John Hunter)

Abstract

Studies in insect locomotion are often limited by the number of walking cycles that can be captured by a researcher. Attempts to manually prompt the insect to move can lead to an altered walking pattern due to stress. To combat this, researchers have used motion-compensators and treadmills that allow the insect to walk undisturbed while keeping it in a certain area that can be recorded. Previous designs of these devices are restrictive due to non-planar walking surfaces, uni-directional motion, or a need to tether the insect. Here, a design is proposed for an omni-directional treadmill that can be seen as a 'treadmill on a treadmill'. This was produced through an iterative prototyping method with a particular focus on 3D printing custom parts. The design consists of 21 narrow treadmill segments that move independently in one direction, but are also connected in a continuous loop in order to move together in the perpendicular direction. This design, alongside a computer-vision based control system, creates a planar 'endless' surface on which the insect can move freely. The design also allows many walking cycles to be captured without constant human supervision. Future testing and fine-tuning is required to optimise the set-up and provide the test subjects with an environment where they can exhibit natural locomotion. With the necessary adjustments, the omni-directional treadmill could enable a new range of insect locomotion studies.

1 Introduction

Insect biomimetics is a fascinating field that has made valuable contributions to the fields of engineering, science, and medicine, having inspired novel creations of robotics, bio-adhesives, and other bio-inspired materials [1]. Insects display a diverse range of complex motion on a variety of surfaces and at arbitrary angles; feats of motion that other organisms are incapable of. Therefore, insect locomotion is a crucial topic within biomimetics, with various studies being conducted in order to understand the biology, neurophysiology, and physical processes involved in this motion [2]. By conducting increasingly advanced research into this field, novel breakthroughs in the design of biomimetic technologies can be made.

Previous insect locomotion studies have been done but experience several limitations. Most use combinations of camera modules and machine learning to monitor insect gait and create models of the inherent patterns. However, for these studies to be accurate, a large number of continuous gait cycles need to be recorded. This is difficult to achieve with a moving insect and stationary camera setup [3] [4].

To overcome this problem, previous studies have used motion compensation designs. This has allowed for long, uninterrupted periods of gait cycles to be monitored, as the insect is kept within the view of the camera as it walks. This has been achieved through three primary designs. One of these is a simple unidirectional treadmill [5]. This comprises a single belt with a closed-loop speed control mechanism. The opportunities for accurate gait analysis are limited however, as a unidirectional treadmill requires insects to only walk in one direction, and any deviation could result in the insect leaving the usable belt surface. These treadmills thus generally require constant observation, and occasional direct motivation of the insect to walk in the desired direction.

One current motion compensator design that solves this problem comprises a polyethylene ball suspended on a cushion of air[6]. This allows for omnidirectional and continuous movement to be recorded but also has notable limitations. This setup requires the insect to be tethered which has the potential to interrupt gait by triggering a 'fight-or-flight' response for the insect[7]. Another design comprises a polyphenolic sphere resting on a ball bearing and powered by servo motors [8]. An important limitation of both this design and the prior is that the walking surface is curved. A planar surface for testing locomotion is useful for providing a important baseline in these studies, as it enables arguably the most basic form of locomotion. As such it is imperative that omnidirectional locomotion studies for insects can be done on planar surfaces.

Planar omnidirectional treadmills are used in virtual reality video games and involve using segmented belts aligned in the x and y direction to allow for omnidirectional motion compensation. The individual segments are operated by large segment-mounted motors [9] or by frame-mounted geared 'omniwheels'. The omniwheels fit into toothed belts connected to pullies which drive the belts in one direction whilst simultaneously providing passive motion in the orthogonal direction[10]. Whilst aspects of these designs are transferable, the components involved are too large and heavy to be used in a smaller treadmill[11].

Computer vision and feedback control are key considerations for motion compensation treadmills. This aspect of the design is fundamental in ensuring a large number of continuous strides can be recorded as it maintains the insect's position at the centre of the treadmill. This feedback control has been achieved through the use of a combination of high-speed cameras [8], micro-controllers [12], and small computers such as Raspberry Pi[13].

Our aim is to create a novel omnidirectional treadmill for the assessment of insect locomotion, based on the planar design used in virtual reality. This treadmill will be the first of its kind enabling the collection of large volumes of data for locomotion studies. In order to do this, the treadmill must be planar; it must have negligible gaps between different components of the surface to avoid trapping of the insect's feet; it must incorporate computer vision and feedback control to keep the insect centred and enable a large number of continuous strides to be recorded; and it must be able to fit into a chamber for metabolic experiments to be conducted. Following the creation of the treadmill, further design modifications such as 360 degree rotation of the treadmill and uneven belt surfaces can be considered, to mimic other walking environments.

2 Methods

Following discussions with the project supervisor, it was concluded that due to the nature of the project no ethical approval was needed, with the project complying with the Imperial College Ethics Code [14].

Before starting the design process, a product specification document (PSD) was put together to lay out all of the design requirements and rank them according to importance (Appendix 6.5). This was used throughout the design process as a guide to govern the form and dimensions of all parts. Most notably, the treadmill needed to be as small as possible to fit in a chamber for metabolic experiments, and its primary function is to bring the insect back to the centre regardless of the direction in which it walked. Based on these design constraints, a segmented belt design was chosen, inspired by virtual reality gaming treadmills. Fig.1 is a CAD rendering made by Fabian Plum and Hendrik Beck, showing the orientation of the coordinate system. Several narrow belts are aligned and individually rotated in one direction by wheels (deemed 'y-direction'), and moved together in the perpendicular direction in a continuous loop by a chain (deemed 'x-direction'). Appendix 6.2 provides an overview of the segmented belt design with the terminology referring to the components used included. The specific parts needed for this design were identified, sketched, and later designed using CAD software to begin the iterative design process.

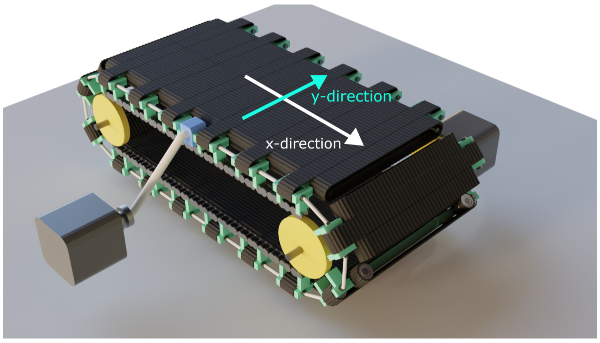


Figure 1: CAD rendering of segmented belt design, by Fabian Plum and Hendrik Beck, showing the orientation of the coordinate system

The final design was reached through a process of many prototype iterations. Where possible, parts were 3D printed using a Prusa i3 MK3 printer, with PLA filament. This allowed prototype parts to be designed and printed quickly and at low cost. Parts that needed to be custom-made such as the carrier and wheels were designed using SolidWorks, exported as STL files, printed, and tested. This process was repeated until the part was deemed satisfactory with constant adjustments to the dimensions made until a perfect fit was achieved. This was necessary as special attention needs to be made to the tolerances inherent in the process of 3D printing.

The tolerances to consider were as follows. Any circular holes that are included in a printed model must be made 0.3mm larger in diameter than intended. This offsets the issue with the 3D printing process that approximates round shapes with straight lines, resulting in all circular holes being undersized relative to the design [15]. When designing parts to fit together, or fit with another non-printed component, it was also necessary to design with tolerances in mind. The Prusa i3 MK3 has tolerances of between 0.5mm and 3mm in the X-Y plane [16], which becomes important when designing parts with sizes on the order of 10mm as was done in this project. Designing with respect to this issue was specific to the components. For example, the chain clip (described later in this report) design was improved by printing the part smaller than necessary and then removing material by hand. This was also true for other parts that necessitated a tight fit onto a metal part, such as the sprockets and axles.

The chain was purchased in a single length and cut by hand to be made into loops. This was done using a chain cutting tool for bicycle chains, purchased from Amazon [17]. The tool was used to push a chain link pin almost all the way out at which point the links could be disconnected. The resulting length of chain was then looped around and reconnected by gentle application of a hammer to the end of the protruding pin once the links were lined up correctly. Care was taken that the two loops were of identical length.

The flexible metal shaft was also purchased in a single length and cut into two segments of length proportional to the chain loops. For simplicity, all axles and all bolts were purchased in the same diameters respectively.

The code for the treadmill's control system was written in Python and uploaded to a Raspberry Pi 4 for remote use in the treadmill. It drew from the work on a unidirectional treadmill by Sam Hufflett [18]. This code was adapted and expanded upon for application to an omnidirectional treadmill.

3 Results

Within this section, a brief design overview is followed by a description of each individual component and the subsequent process of assembly, encompassing their contribution and function to the final overall design.

All the digital deliverables of this project (CAD files and Python code) necessary to build a functional prototype are made open-source on Github [19].

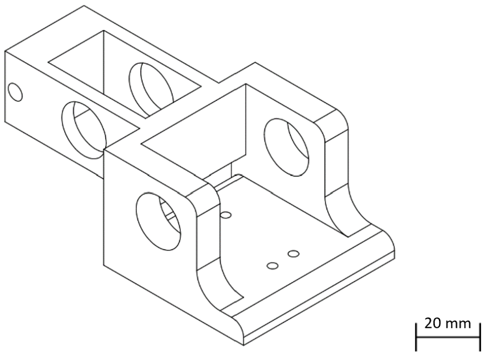
3.1 Design Overview

A sketch of the final design is shown in Fig.3. The principle of operation is as described in the Methods section: the so-called "x-direction" motion involves moving all the belts together via a conveyor chain, while in the "y-direction" the belts are individually actuated by a system of wheels driven by a flexible shaft. This design is often termed "segmented belt design", or "treadmill-on-a-treadmill", due to the bidirectional nature of movement of each segment.

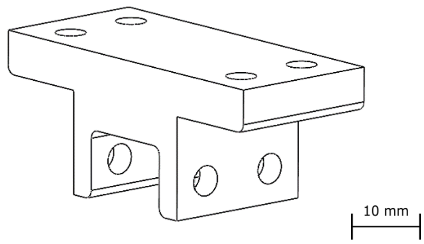
The prototype currently measures 350mm in width and length, 150mm in height, and has a mass of 4.12kg. Below are details of each individual component, as well as a summary of how to assemble the treadmill. All technical drawings are given in Appendix 6.6.

3.2 Carrier

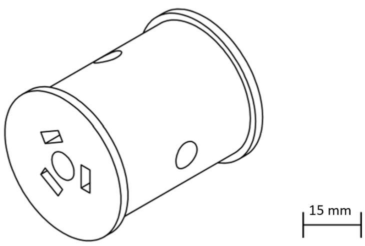
An isometric view of the carrier is shown in Fig.2a. It was manufactured via 3D printing with



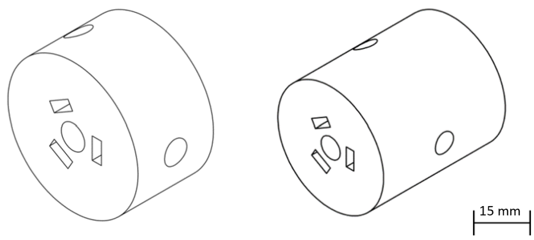
(a) Carrier



(b) Chain clip



(c) Active wheel



(d) Passive wheels

Figure 2: Isometric views of individual parts

PLA, fitting within a volume of 118mm x 65mm x 43mm, and weighing approximately 102.4g. Its purpose is to house the wheels that transfer the motion of Motor Y to the treadmill belts.

3.3 'Nut and bolt'

In order to secure parts to their axles, nut and bolt slots were included in the design (as can be seen in the technical drawings). The mechanism screws the wheels onto their axles to provide power transmission. All bolts are of size M3 with varying lengths depending on the part. For 3D printed parts, it was found that including a tolerance of +0.5mm to hole diameters ensures the bolt can fit easily.

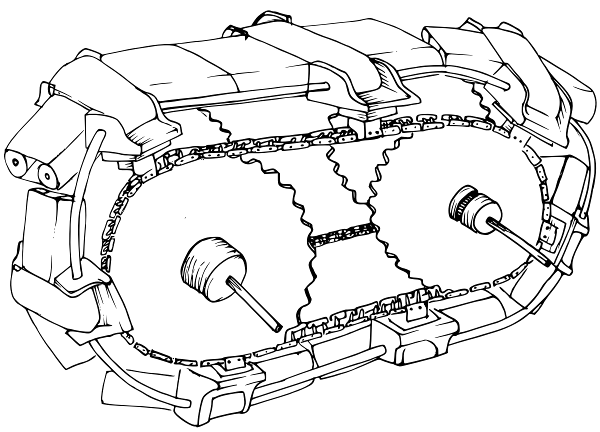


Figure 3: Sketch of final treadmill design

3.4 Sprockets

The sprockets that the chains sit on were designed to fit the Renold 06B-1 standard. They have 50 teeth each, and an outside diameter of 155.70mm. These sizes were chosen according to the width of the carriers. This becomes relevant when the carriers rotate around the front and back ends of the treadmill. One of the sprockets incorporates a 6mm MXL timing belt pulley. This is connected via a 6mm MXL timing belt to Motor X. The sprockets are mounted on two stainless steel axles which rotate within bearings in the support structure.

3.5 Chain clip

The chain clip part was designed to fit the 06B-1 chain standard (Fig.2b). It was 3D printed using PLA and fits within a volume of 40mm x 18mm x 17mm. Its purpose is to clip onto a single link of chain and serve as an attachment between the chain and the carrier. It has holes in its sides which, when the part is clipped on, sit over the protruding chain pins and hold the part in place. The carrier part is bolted on to it via the holes in the top using M3 nuts and bolts.

3.6 Wheels

A carrier houses four wheels: one 'active' wheel and three 'passive' wheels, including one middle passive wheel and two side passive wheels. The active wheel is rotated by the flexible shaft, which in turn drives the canvas belts. The belt is in contact with the passive middle wheel and causes it to rotate through direct friction. All three passive wheels are secured to the same axle, so the rotation of the passive middle wheel drives the rotation of the side wheels and thus the movement of the side belts. All four wheels are secured to their axle with three M3 bolts and nuts each, and were 3D printed using PLA.

3.6.1 Active wheel

The active wheel (Fig.2c) is on the outer side of the carrier such that the flexible shaft passes through it. Flanges of height 1.5mm are included to ensure that the belt does not slide off the side of the wheel. The wheel diameter without the flanges is 30mm.

3.6.2 Passive wheels

The passive wheels (Fig.2d) are driven by the friction force between the rotating belt and the middle passive wheel. The middle passive wheels have a slightly larger diameter (35mm) than the active wheel, to increase contact area and implicitly the magnitude of the friction force. The passive side wheels share the same larger diameter so that the adjacent belts are coincident. They also have no flanges to avoid creating separation between the individual belts. All three wheels share the same axle, so that they rotate with the exact same velocity.

3.7 Fabric belts

The belts are made of canvas fabric strips: 391.7mm long and 36mm wide for the middle belt, 204.3mm long and 40mm wide for the two side belts. They are sewn into a loop around the wheels and through the carrier using a standard straight stitch. Canvas was chosen for its robustness and perceived high friction coefficient relative to other available fabrics. Light grey fabric was chosen to maximise contrast with the insect for the object detection stage.

3.8 Assembly

Assembly of the components to form the complete treadmill follows:

1. The chain clip is bolted onto the bottom of the carrier via 4xM3 screws of length 16mm. This will allow the attachment of the carrier unit to the driver chain.

2. The carrier is fitted with 4 bearings in the 19mm diameter holes.

3. The carrier is fitted with a set of 3 wheels, as shown in Fig.4a: 1x passive middle wheel (red), 2x passive side wheel (blue). The pictured yellow wheel is fitted later in the assembly process.

4. All three of the passive wheels (red and blue) are attached via the ‘nut and bolt’ mechanism to one M3 rod that acts as an axle, which is passed through the inner hole of the ball bearings. The rod is 10.6cm long, such that it is long enough to reach the edges of both blue wheels, but short enough to not stick out and interfere with the assembly.

5. The sprockets are pushed onto the steel axles with the hubs facing outwards and held in place with the ‘nut and bolt’ mechanism. Care is taken to ensure that the sprockets are in the same orientation (mirror images of each other, where the teeth of each sprocket are in line). This can be done easily by aligning the ‘nut and bolt’ mechanisms with a mark made along the axle. There is a distance of 166mm between the inward-facing sides of the two sprockets on a single axle.

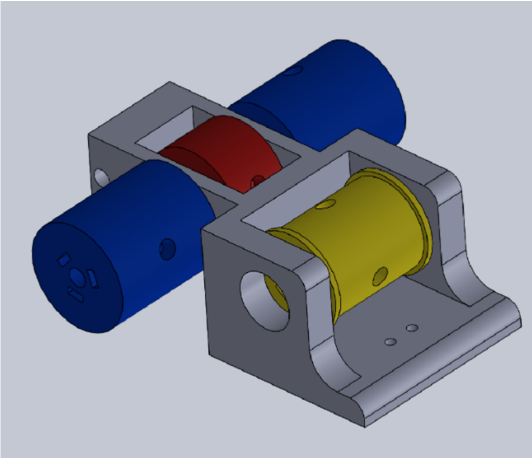
6. The chain is made into two loops of 0.742m circumference, and the flexible shaft is cut into two lengths of length 0.900m and 0.925m respectively.

7. The chain loops are fitted onto the sprockets, and the 6mm timing belt is looped around the pulley in the hub of the driving sprocket. The axles are then inserted into the bearings in the support structure so that the chain becomes appropriately tensioned.

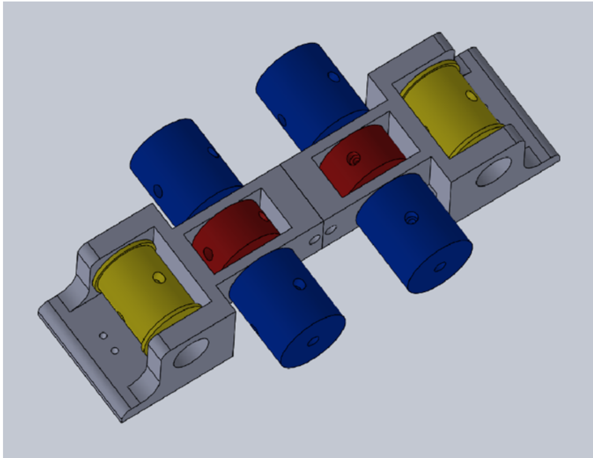
8. For a chain loop of 0.742m, there can be 7 carriers on each side of the treadmill (for a total of 14). Once all of them have been fitted with the wheels and chain clips, the carriers are attached to the driver chain (7 on each of the two loops) via the clip. The carriers on opposite sides of the treadmill should face each other and be in contact (Fig.4b).

9. The yellow active wheels, shown in Fig.4a, are fitted one by one and on one side at a time. One length of flexible shaft is fed through until it passes through all of the wheels in all of the carriers on one side. This process is repeated for the opposite side of the treadmill with the other length of flexible shaft.

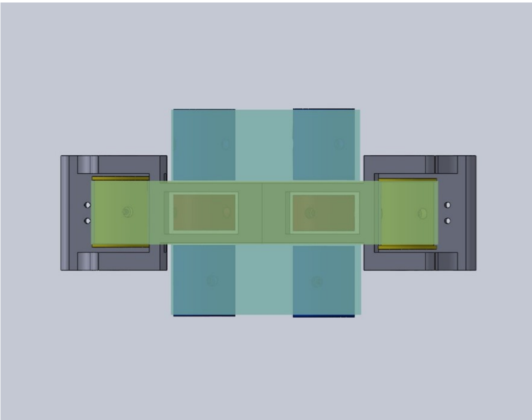
10. The 90-degree gearbox is attached to the chain using the gearbox attachment part, and it is then attached via the printed coupler to one end of the flexible shaft. Another length of flexible shaft is cut, according to the chosen position of Motor Y, and attached to the perpendicular end of the gearbox. Motor Y is attached to this length of flexible shaft using the printed coupler.



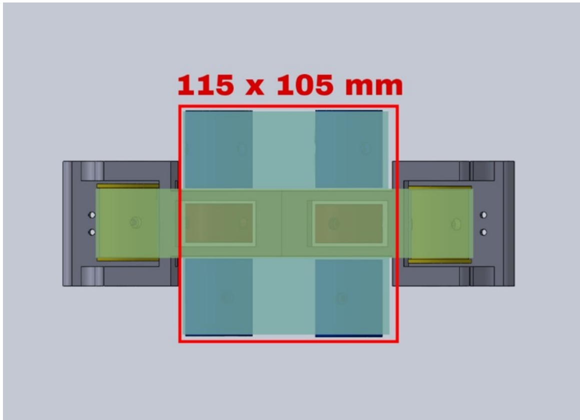
(a) Carrier fitted with the three wheel types (active, passive middle, passive side)



(b) Carriers on opposite sides of the treadmill should face each other and be in contact



(c) Carrier fitted with the two belt types (middle, side)



(d) Effective usable area per carrier unit fitted with belts

Figure 4: Simulated assemblies of carrier units

11. Each pair of carriers is fitted with a set of 3 belts, as shown in Fig.4c: 1x middle belt (transparent green) and 2x side belts (transparent blue). Due to the nature of the fabric, the belts are easily sewn shut in a loop with a needle and thread. The middle belt loops around the yellow wheels of each carrier. The side belts loop around the blue wheels sitting on either side of the middle belt. The effective usable area per carrier unit upon which the subject can walk is the red box in Fig.4d, which has an area of 115x105mm.

After installing the two chain loops on the sprockets, and the 7 carrier pairs on the chains, the final assembly should look like the drawing in Fig.3.

3.9 Support frame

The support frame is made of aluminium extrusion beams connected with 3D printed joint attachments (preliminary CAD shown in Fig.5). Five 3D printed support mounts are added to the beams to support the two main axles (green) and Motor X (red). No support component was added for Motor Y, as it is thought this would rest on the bench. Development of the support frame is on-going.

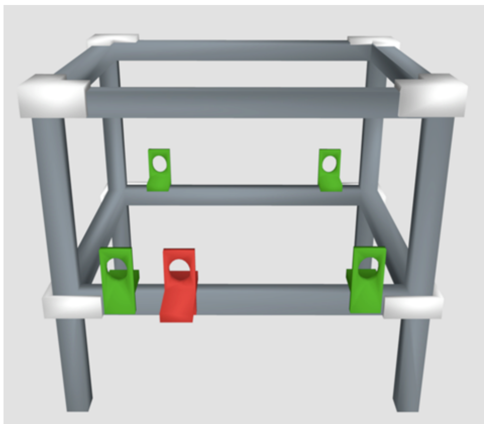


Figure 5: Preliminary CAD of support frame from aluminium extrusion beams

3.10 Computer vision

In order for the treadmill to compensate for the insect's motion autonomously, it was paired with a custom Python script which was adapted from Sam

Hufflet's thesis [20]. This was run on a Raspberry Pi 4. This microprocessor offers several unique functions, most importantly the ability to connect external devices directly and control them all using a single Python script. This was the chosen method for insect detection because being able to directly connect a camera module reduces the response time of the system, thus allowing for a more accurate reading of the insect's position on the treadmill.

The Python script processes frame data from the camera module and detects the insect's position using methods from OpenCV [21]. The code converts the colour images into a binary image and then uses thresholding processes to mask out the background making it easier to pick up the darker coloured insect on the brighter belts. The position coordinates in the x- and y-axes are then used to calculate the velocity of the treadmill belts in both directions, and this information is sent to the two stepper motors.

3.11 Motor control

The chain holding the carriers and the flexible shaft must spin independently to ensure the movement in perpendicular directions required to keep the insect in the centre of the treadmill so it can be recorded. This is achieved by using a stepper motor and a driver to allow for accurate stepped movement. Based on rough calculations, included in Appendix 6.4, two 'RTELLIGENT 57A2' Nema 23 stepper motors were chosen coupled with TB6600 stepper motor drivers. The calculations show they provide enough torque to move the entire weight of the treadmill and the flexible shafts.

4 Discussion

The aim of this project was to design an omnidirectional motion compensation treadmill to aid in the study of insect locomotion. The treadmill would provide an infinite, planar surface that provides the capability to record multiple gait cycles, while fitting within a 2.5L chamber for the purposes of metabolic study. To achieve this, a segmented belt design was developed, capable of producing independent movement in the X and Y axes and thus keeping the insect in the centre of the treadmill. Movement is provided by two stepper motors controlled by a Raspberry Pi using real-time camera feedback of the insect's location.

The overall final volume of the treadmill is 350mm x 350mm x 150mm, or 18.4L. This is 7.8 times larger than the initial proposed 2.5L, meaning that the device cannot fit in the experimental chamber for metabolism investigation, a requirement outlined in the PSD. The size had to be increased during the design process for several reasons. Firstly, the carriers needed to be fitted with bearings, however finding sufficiently small bearings proved challenging within the constraints of the budget. Secondly, the flexible shaft was stiffer than expected, and the height of the treadmill was dictated by the maximum degree to which the shaft could be bent (radius of 16cm). Finally, 3D printed structures are limited by their anisotropic material characteristics and become more prone to failure as they become smaller. Hence, the total size of the treadmill grew proportionally with the individual part dimensions. Future iterations should attempt to scale down the treadmill, by sourcing smaller bearings, a more pliable flexible shaft, and re-designing the 3D printed parts. However, smaller components may result in larger stress concentrations, reducing the safety factor of the components, which must be considered prior to implementation [22].

3D printing was used as the primary manufacture technique due to its suitability for rapid iterative prototyping. This allowed quick and easy fine-tuning of custom-made parts, but presented limitations in long term use [23]. 3D printed custom parts are known to be prone to failure, by attribute of their lower stress tolerance compared to injection moulded parts due to the lack of quality control and presence of a semi-hollow structure [23]. One way to improve the strength and durability of the parts is by printing on a higher infill setting with underlying hexagonal patterns[24]. However, this would increase the printing time, amount of filament used, and overall weight of the part, potentially posing further complications. Furthermore, the custom parts could be 3D printed with polycarbonate in place of PLA, which exhibits a higher yield strength, but comparable fatigue life[25]. Regarding reproducibility, care should be taken to adjust tolerances and filament settings for the specific printer being used to avoid drastically altering the properties of the part[26][25].

There were also difficulties finding suitable methods to attach the carriers to the chain. Sourcing a chain with pre-made attachments was not possible within the project time frame due to stock issues and delivery delays. The chosen solution was to use a standard roller chain and a custom 3D printed chain clip. 3D-printing this part allowed easy fine-tuning of dimensions, cheap and easy attachment of the carriers to the chain for prototyping, and easy reprinting in cases of failure. In its current state this part lacks stability when combined with the heavy carriers, and is at a high risk of failure under cyclic loading due to the relatively weak plastic material. These factors make it unsuitable for the long running times required of this device. Hence, for future work, sourcing a chain with a pre-made K-1 attachment would be more appropriate, allowing a sturdier platform for the carrier connection[27].

In light of the limitations of 3D printing, an optimal version of the treadmill should be produced with different materials and techniques which allow greater resistance to wear. This will permit viable function over long, continuous cycles, wherein all parts (particularly the wheels and sprockets) would be subject to cyclical loading for extended periods of time. For example, replacing the wheels and sprockets with similar metal components which provide a longer fatigue life, increasing the service interval of the treadmill[23]. A ferrous metal such as steel would be preferred due to its endurance limit, meaning that whilst stresses are low, the parts will never fail under fatigue. However, it's relatively high density may mean lighter metals such as aluminium would be optimal. Computational finite element analysis should be conducted on each part, as well as the full assembly, to determine the stress distributions and failure potential of the device. This may be subsequently used to locate any weak points within the design which can then be specifically amended.

Weight is a common restraint when designing omnidirectional segmented belt treadmills, impacting the functionality, portability, and possible applications [10]. In previous work this has been attributed to the weight of each individual 'carrier' unit, amounting to high torque requirements to move the segmented belts in the X direction [10]. This was also seen in the novel design. Despite the carriers, wheels and belts being constructed of light materials, they still made up 59% of the total mass of the treadmill, in comparison, the much denser steel chain contributed to only 17% of the total mass. This is due to the need to increase the overall size of the treadmill, implicitly increasing the total mass of the carriers and their component parts. Lighter carriers would allow higher speeds and finer acceleration control.

Another improvement involves the treadmill belts. The current design uses hand-cut and hand-sewn canvas belts, where measurements and cutting are prone to human error and inconsistent sewing can result in bunching up of material and frayed edges. There are also considerations of which materials are suitable for the insects being studied. If the purpose of the device is to allow the subject to exhibit natural locomotion patterns, the fabric of the belt must not impact gait or induce abnormal responses[28]. Literature reviews of other locomotion studies and possible further experiments should be performed to determine the ideal belt fabric characteristics. The composite assembly design described in this report could be applied easily to such experiments, since disassembly and reassembly of the treadmill proves a simple process. In this way, different belt materials could be tested using the design and insect behaviour could be observed.

Preliminary tests have been conducted to assess functionality of the design. The experiments confirmed that the treadmill exhibits movement in both directions, where the power transmission from both motors performs as expected. However, the functionality of the treadmill design is yet to be tested on a subject. The additional weight of the subject should be negligible enough to not impact motor performance, however the potential challenge of the gap size between adjacent belts remains. Currently, the largest gaps are less than 1mm wide. This is most likely suitable for larger stick insects, but it may be a problem for smaller subjects such as ants, where it is theorised that gaps of this size would significantly impact locomotion. Moreover, it is currently unknown how the subject will behave when placed on the treadmill. Other experiments, such as those described in Sam Hufflett's thesis [20], have observed a tendency for insects to move towards the side of the treadmill. This would not be an issue with the new design, as the motion compensation would keep the insect roughly in the centre of the treadmill. However, there is potential for vibrations and noise from the motors to influence the behaviour of the insects, possibly triggering a 'fight or flight' response [29][30]. Influence on the insect behaviour from relative accelerations would also need to be considered further, although this has already been investigated for the control section of the described design[30]. Finally, the motivation of the subject to move is a topic that has featured in previous research[29][30]. As no live tests have been done, the subject motivation on this treadmill is as yet unknown. Even if the device works as expected, studies cannot be conducted if the subjects refuse to exhibit locomotion; concordant understanding and application of insect locomotion motives should be applied in future studies involving this design.

Further experiments are needed to determine the methods of control and motion compensation that allow the insect to walk without significant interruption to its natural locomotion. Focus will be placed on the response time of the treadmill to changes in the insect's position; too quick a response time and the insect will experience an unnatural 'jerking' motion, too slow and the insect may be able to walk out of the desired area. For a smoother change in velocity, the estimates of the insect's acceleration range could be calculated and applied to the acceleration of the belts in both directions. This would involve more comprehensive calculations based on the insect's detected position and parameters that affect the estimate of acceleration. The value of these parameters would need to be deduced through further experimentation. A possible future improvement would be to separate the video feed and motor control tasks with two microcontrollers, for compartmentalisation and optimisation purposes and to prevent overloading of a single microprocessor.

5 Conclusion

The treadmill design described in this report allows omnidirectional movement while providing a planar surface of walking. The constructed prototype serves as a proof of concept for both factors, although it is yet to be tested on live subjects. Several limitations such as size, control, and sub-optimal parts need to be addressed before it can be usefully applied within locomotive and metabolic studies of insects. With the additional aim for the treadmill to be replicable in laboratories around the world, the CAD models and code are made available open-source [19]. This is useful not only to accelerate the experimental implementation of the improvements outlined in the Discussion section, but also to allow more research groups to investigate insect locomotion and metabolism. The estimated cost of building a fully functional device as described is calculated at £167. If, with the necessary adjustments, the treadmill performs well and allows for the recording of many unmonitored continuous walking cycles, a new range of insect locomotion studies will become achievable. Enabling a better understanding of locomotion could then drive many new findings within the larger fields of biomimicry, robotics, and biomaterials.

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6 Appendix

6.1 Project Management Assessment

6.1.1 Project Planning

In the Project Pitch, we laid out the Gantt chart shown in Fig.6. Our schedule was split roughly into three phases: literature review, design and prototyping, and final manufacture. Phase One was carried out according to schedule, with background research taking up the first month of the project. Brainstorming design ideas took several weeks, and eventually the first CAD models were created in Week 9, slightly ahead of schedule. An unexpected departure from the project plan was the impact of the Winter Exams, which required us to shift focus from the project to our assessments. Therefore, 3D printing parts and prototyping only commenced in Week 17 of the project (as opposed to the originally-proposed Weeks 13-16). Many unforeseen issues (such as supplier delays or printing problems) arose during prototyping, so Phase Two lasted beyond the planned Week 26, and is still underway. Similarly, software development was scheduled for Weeks 21-24, but due to its close connection with mechanical development, this is also being pushed forward into the month of May. Although our schedule has suffered serious delays, the actual design laid out in the Project Pitch remains unchanged and has only been subject to minor departures (such as tolerance fits).

6.1.2 Project Management Lessons

Lesson 1: “Formatting”

Due to the design nature of the project, it often involved creating iterative CAD models, which had to be shared between group members. In total, over 50 total models of 4 components were created. We quickly became confused as to which file represented the latest model, which parts had been printed already, and which ones still needed work. We learnt the importance of consistent centralization, formatting, and naming of files. Firstly, knowing where to find necessary information is an easy way to save time during a rapid prototyping process. Secondly, having a clear naming convention reduces ambiguity and ensures all team members are aware of the updated versions of a certain part. Lastly, a precise organization of 3D-printed component files minimizes manufacturing mistakes; for example, we learnt that a good technique is having a “Print Queue” folder and a separate folder for parts that had already been printed.

Lesson 2: “Communication”

We kept a strict meeting schedule throughout the project, meeting weekly with the team members and bi-weekly with the supervisors. The latter sessions consisted of a short progress presentation that outlined what we had previously done and what we were planning to do in the coming weeks. Meeting minutes were written in OneNote and organized by date. Additionally, we kept close contact via two main channels of communication: Microsoft Teams and a WhatsApp group chat. These measures proved very useful in ensuring we had a record of all things discussed and everyone was kept in the loop regarding the project progress. However, excessive meetings can sometimes cause more harm than good, so we learnt how to restrict ourselves to productive conversations, how to prepare efficient meeting agendas, and how to maximize the benefit of each supervisor meeting by having questions prepared in advance.

Lesson 3: “Life does not always go to plan”

The largest causes of unproductivity in our project have been supplier delays, ordering wrong components, and printing times. We compiled shopping lists to bulk-order components (such as bearings, chains, belts, and motors), but often found that the delivery would take up to one month. What’s more, after receiving the components, they would sometimes not be exactly as we imagined (for example, the timing belts were too stiff to be driven by our motors). This introduced unnecessary delays which put our progress behind schedule. We have thus learnt the importance of time management and risk aversion by having a back-up plan if components do not work, or adjusting the schedule to do other tasks while we wait for deliveries. We also learnt that design and research projects can get very unpredictable and we need to be prepared for failure even after taking several precautionary measures.

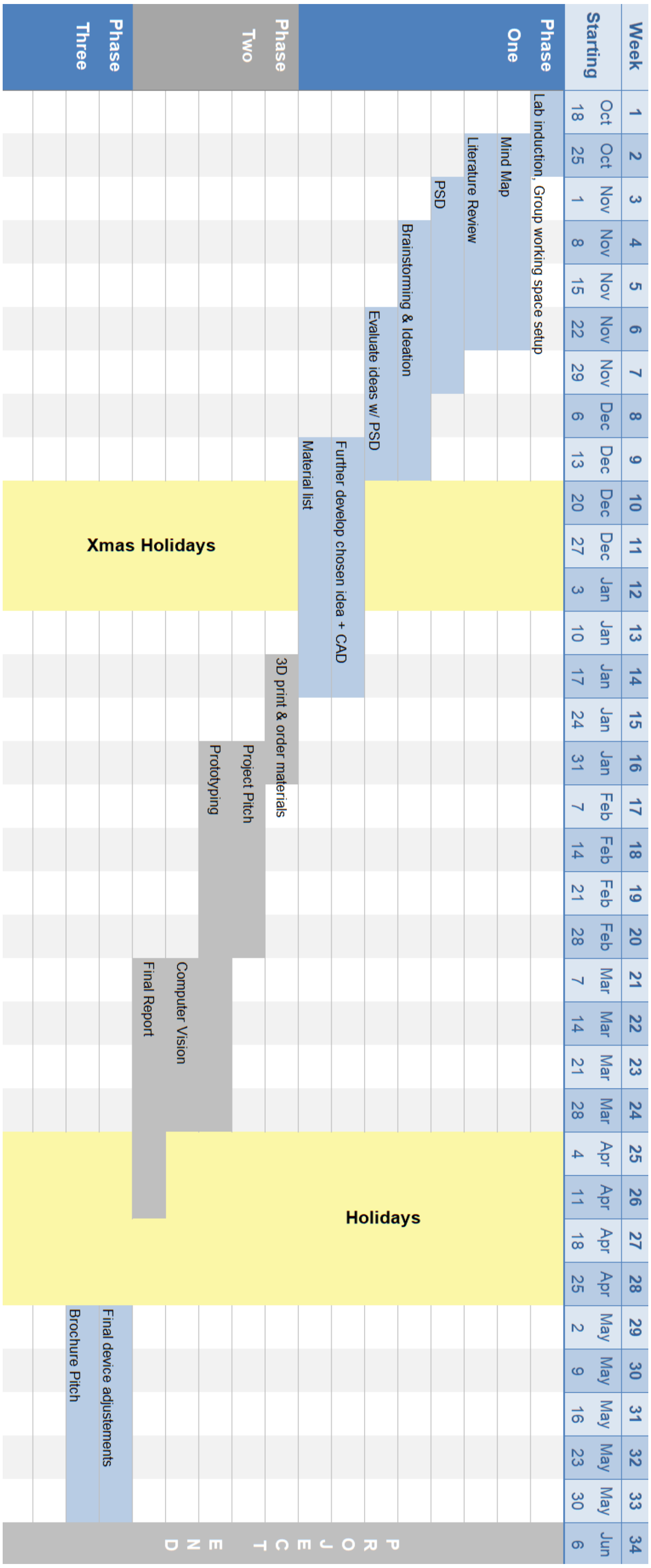

Figure 6: Gantt chart

6.2 Terminology

An early concept rendering created by Fabian Plum and Hendrik Beck is shown in Fig.7, with labels for specific design components. The design terminology in Tb.1 is employed throughout this report.

Part on Fig.7	**Label on Fig.7**	**Terminology**
Yellow wheel	S	Sprocket
Wheel axles	A	Axle
Green housing	Cr	Carrier
Chain	Ch	Chain
White connecting rods	F	Flexible shaft
Long strip of belt	MB	Middle belt
Short strip of belt	SB	Side belt
Motor for x-axis motion	MX	Motor X
Motor for y-axis motion	MY	Motor Y
Blue gearbox	G	90-degree gearbox

Table 1: Terminology for labels on Fig.7

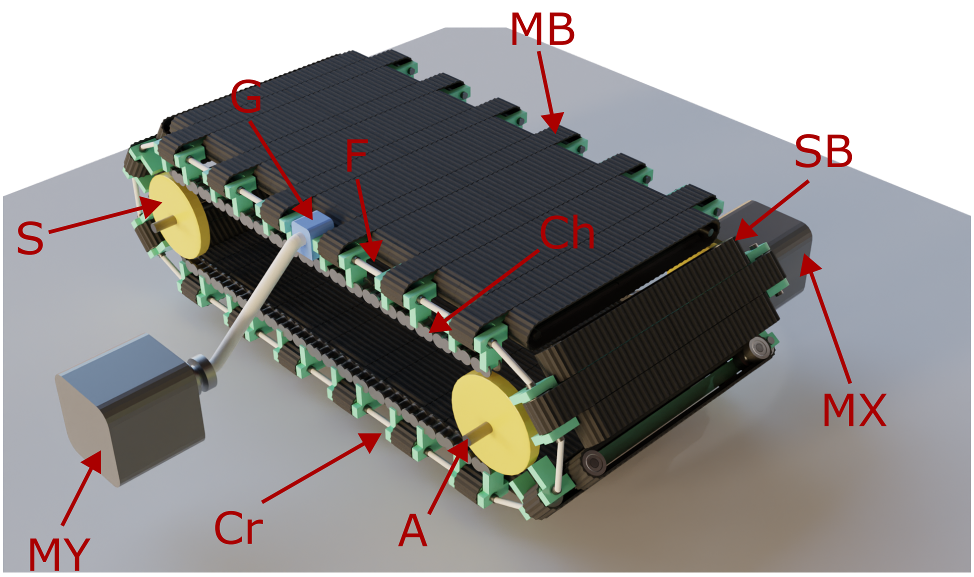

Figure 7: Concept rendering with labels for specific design components

6.3 Parts List

Please see Tb.2 for a list of all of the purchased parts used in the final treadmill, and see Tb.3 for a list of all of the 3D-printed parts.

Part name	**No. of units**	**Total cost (£)**
10mm x 300mm steel rod	2	18.02
Renold 06B-1 roller chain	1	29.84
Flexible shaft set	1	39.90
Huco L Gearbox	1	16.50
6mm timing belt	2	3.08
M6 threaded rod	5	20.79
6mm I.D. bearing	8	22.00
10mm I.D. bearing	4	12.08
Canvas fabric - iced grey	1	7.47
Raspberry Pi 4 4GB	1	44.84
Raspberry Pi Camera Module V2.1	1	24.00
RTELLIGENT 57A2 stepper motor	2	59.62
TB6600 stepper motor driver	2	19.96
M3 threaded bolts	236	-
M3 threaded nuts	236	-
Total	**-**	**166.34**

Table 2: All purchased parts

Part name	**No. of units**
Passive sprocket	3
Driver sprocket	1
Carrier	14
Chain clip	14
Active wheel	14
Side wheel	28
Middle wheel	14
Coupler (motor to flex shaft)*	1
Coupler (gearbox to flex shaft)*	2
Gearbox attachment*	1

Table 3: All 3D printed parts [*Not yet designed]

6.4 Motor Control Calculations

The calculations and thought process used to confirm if a chosen stepper motor is strong enough to move the entire treadmill are as follows:

1. Determine the gear ratio of the setup, which can be estimated using the diameter proportions of the toothed section of the sprockets involved. In our case, this would be the ratio between the 33mm diameter of the chain sprocket (at the toothed/timing belt section) and the 15.3 mm diameter of the motor axle timing belt pulley:

$$GR = \frac{33mm}{15.3mm} \approx 2.15$$

15.3 mm was chosen as the toothed section diameter for the stepper motor axle pulley of 8mm in shaft diameter because it followed the same diameter proportions as the standard 5mm stepper motor shaft diameter timing belt pulley:

$$\begin{aligned} 5\ mm\ axle\ \emptyset\ &\rightarrow 9.55\ mm\ toothed\ \emptyset \\ \therefore 8\ mm\ axle\ \emptyset\ &\rightarrow 15.30\ mm\ toothed\ \emptyset \end{aligned}$$

2. Estimate if 'RTELLIGENT 57A2' stepper motor [31] would be strong enough. Using its torque vs angular speed graph [31], decide on a likely maximum speed at which the motor would have to spin: 300 pps (pulse per second, equivalent to steps per second). Since each motor step covers 1.8°, each full revolution is equivalent to 200 steps. Hence the angular speed of the motor axle at 300 steps per second is given by:

$$300 \left[\frac{steps}{second}\right] \cdot \frac{1}{200} \left[\frac{rev}{steps}\right] = 1.5 \left[\frac{rev}{sec}\right] \approx 9.4\ rad\ s^{-1}$$

3. At 300 steps per second, the motor axle has an angular speed of 9.4 $rad\ s^{-1}$. Using the gear ratio, the angular speed of the chain sprocket and by extension the linear speed at the treadmill surface can be determined:

$$GR = \frac{Ang.Speed_{in}}{Ang.Speed_{out}} = \frac{\omega_{in}}{\omega_{out}}$$

$$\omega_{out} = \frac{\omega_{in}}{GR} = \frac{9.4\ rad\ s^{-1}}{2.15} \approx 4.37\ rad\ s^{-1}$$

This is far greater than the expected maximum linear speed of stick insects (the model insect to be studied) of $0.06ms^{-1}$, which approximates to 0.79 $rads^{-1}$ at the chain sprocket's edge, so the chosen motor easily passes the speed requirements. This would mean that the motor would need to spin at speeds much lower than as 300 steps per second, so it would have a greater overall holding torque too.

4. At 300 steps per second (worst case scenario), the motor has an effective holding torque of about $2Nm$, based on its torque vs angular speed graph [31]. Using the gear ratio, the output torque of the chain sprocket at the point where the chain attaches can be determined. The torque of the motor axle is transmitted through the timing belt to the chain sprocket:

$$GR = \frac{Torque_{out}}{Torque_{in}}$$

$$Torque_{out} = GR \cdot Torque_{in} = 2.15 \cdot 2\ Nm = 4.3\ Nm$$

The output torque at the outer chain sprocket radius is therefore:

$$\frac{4.3Nm}{75.85mm} \approx 56.74N$$

This is greater than the maximum weight of the entire treadmill of 40.46N (according to Tb.4), so the chosen motor is strong enough.

Part name	**Weight of unit (kg)**	**Total weight (kg)**
Two carriers, with belts, wheels and chain clips	0.3500	2.45
Driver sprocket	0.0899	0.0899
Passive sprocket	0.0731	0.2193
Axle	0.1851	0.3702
Chain loop	0.3408	0.6816
Flexible shaft	0.1565	0.313
Treadmill		**4.124**

Table 4: Weight of treadmill parts

6.5 Product Specification Document

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Product Specification Document

Project Name:	Insect Treadmill
Date:	06/12/2021
Release Number:	V2 – Latest feedback included

Max priority	
Medium	
Low	

Rating	Aspect	Objective	Specification
	Functionality and Performance	**Move in x-axis**	Independent x-axis movement
		Move in y-axis	Independent y-axis movement
		Keep insect in designated area	Movement of platform should aim to prevent insect from leaving the field of view of recording camera. The distance between the monitoring camera FOV's centre and the insect's centre should tend to 0.
		Record continuous walking cycle	Insect to not stop at edges of treadmill, but be able to walk as if on an infinite surface
		Planar walking surface	Flat platform to encourage normal locomotion
		Automated control	Feedback loop used to actuate motors to return the insect's current position to the desired one, avoiding manual control. Maybe achieved with camera/computer vison, (PID) control
		Minimise disturbance to insect	Minimise vibration and noise to avoid distressing or disrupting insect in locomotion
	Size and Weight	**Fit within 2.5L**	Be small enough to fit within 2.5L, or be able to be scaled down to fit these dimensions
	Usability, Interface and Ergonomics	**Insects should be untethered**	Walking surface should move with the insect – they choose where to walk and surface opposes their movement

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		Orientable	Ability for product to be oriented at different angles for improved variety of test conditions
		Natural material on surface	The surface the insect walks on should not be such as to inhibit or discourage natural gait, and allow adequate friction for insect to walk without slipping
		Interface	Buttons to start or stop the treadmill, LEDs to indicate the state of the system (green - ON, red - OFF)
	Envir onme ntal	**Minimise environmental impact**	Use sustainable material, not create excessive waste
	Portability	**Portable power source**	Plugged into a socket, but treadmill will sit inside sealed box – cable?
	Safety & Security	**Emergency stop**	Override stop button
		Prevent insect from leaving platform	Stop all motors if insect gets too close to the edge
		No gaps	Feet can get stuck in gaps, hence must be a continuous surface (or have gaps no larger than [insect (TARSUS) leg size]).
	Life, Reliability and Maintenance	**Widely available components**	Avoid using unique components to allow easy maintenance
		Can be used for multiple experiments	
		Can run for long periods of time	Setup can be used unsupervised for prolonged periods of time, eg 1h
	Cost and Manufacturing	**Minimally expensive**	Cost should be kept as low as possible to allow reproducibility of product
		Open source	Any software used should be open-source for reproducibility and cost reasons
	Legal and Regulatory	**Ethical considerations**	Minimise suffering of test subjects

Figure 8: Product Specification Document

6.6 Technical Drawings

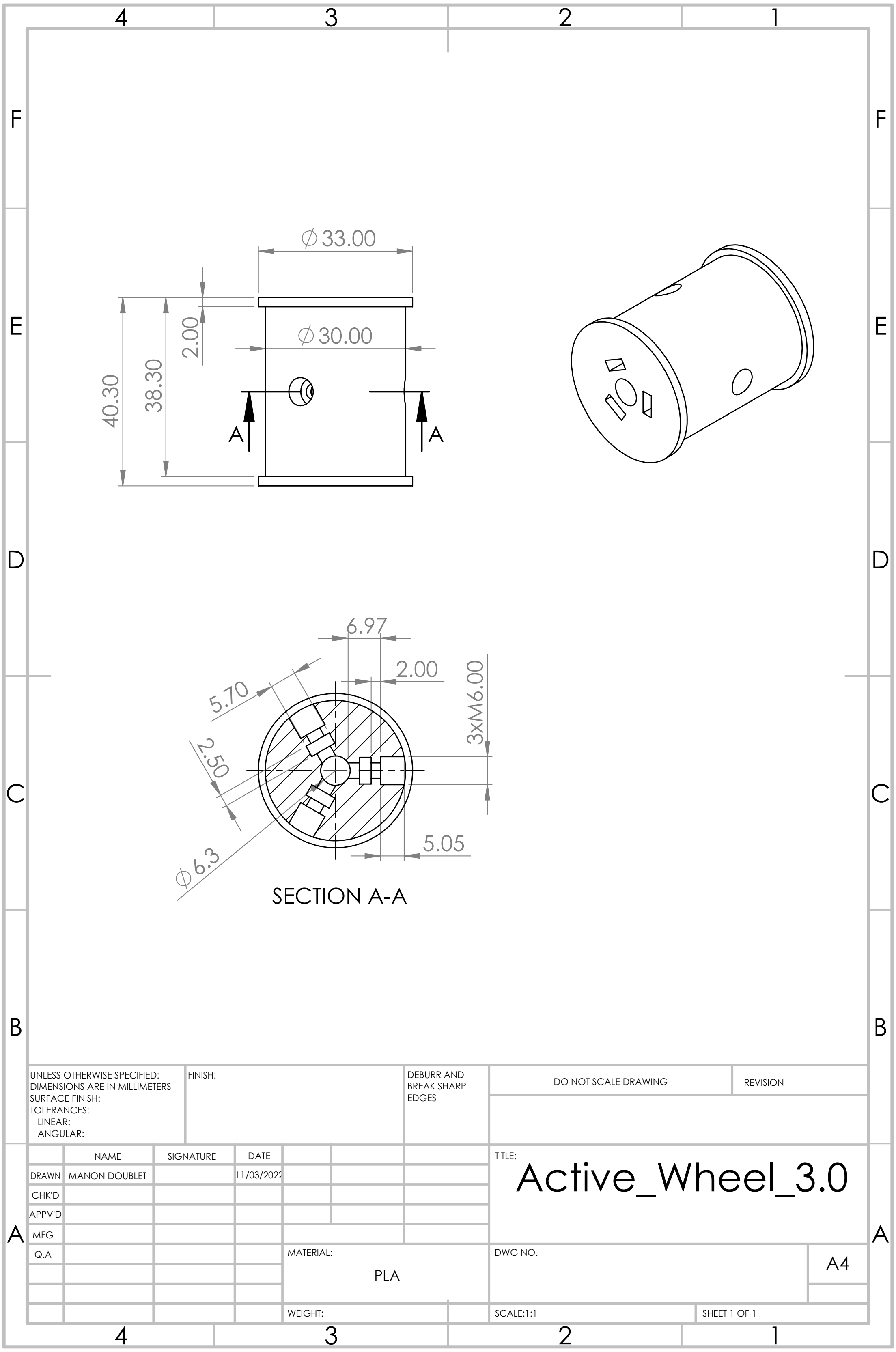

Figure 9: Technical drawing of active wheel

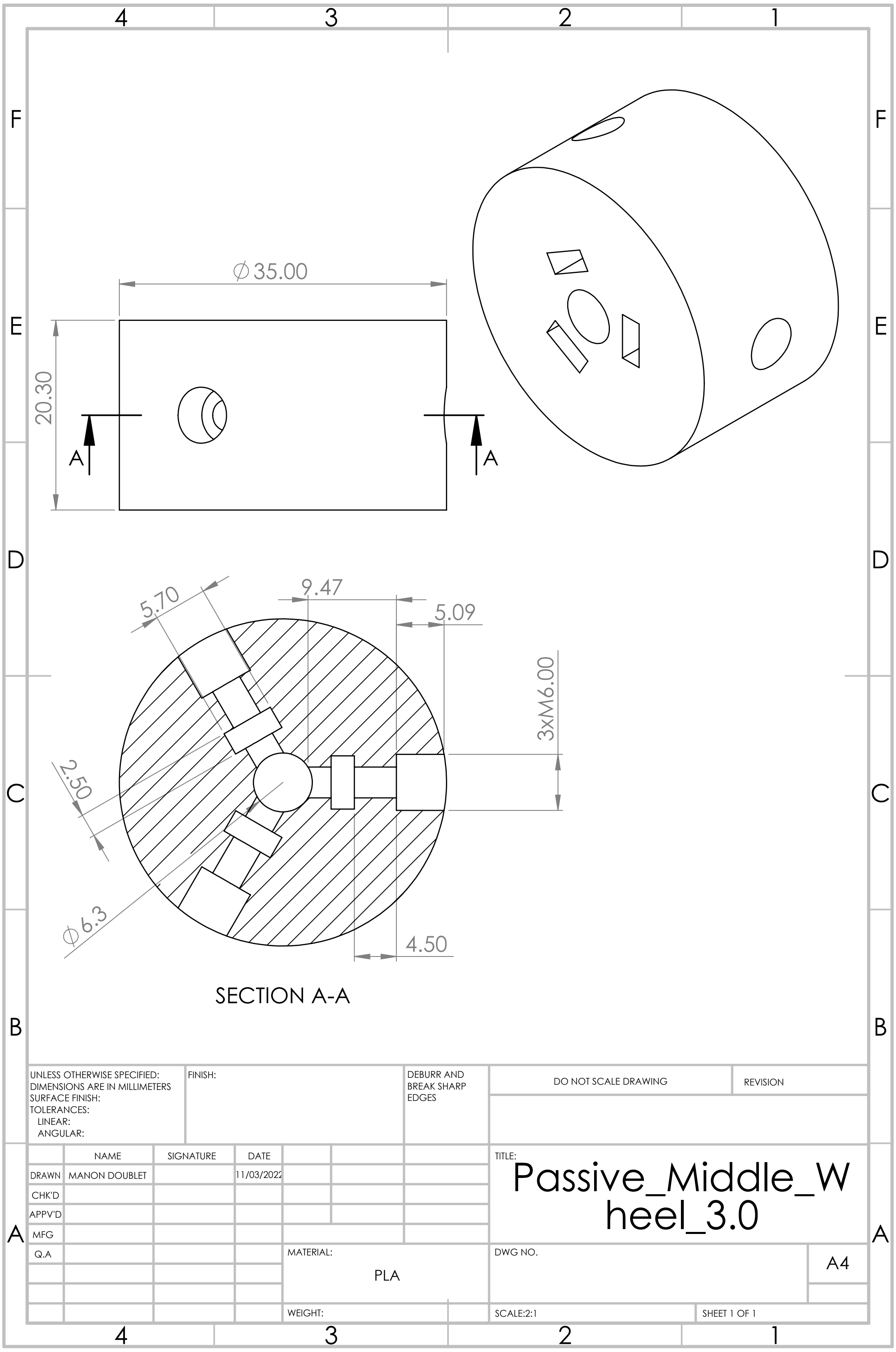

Figure 10: Technical drawing of passive middle wheel

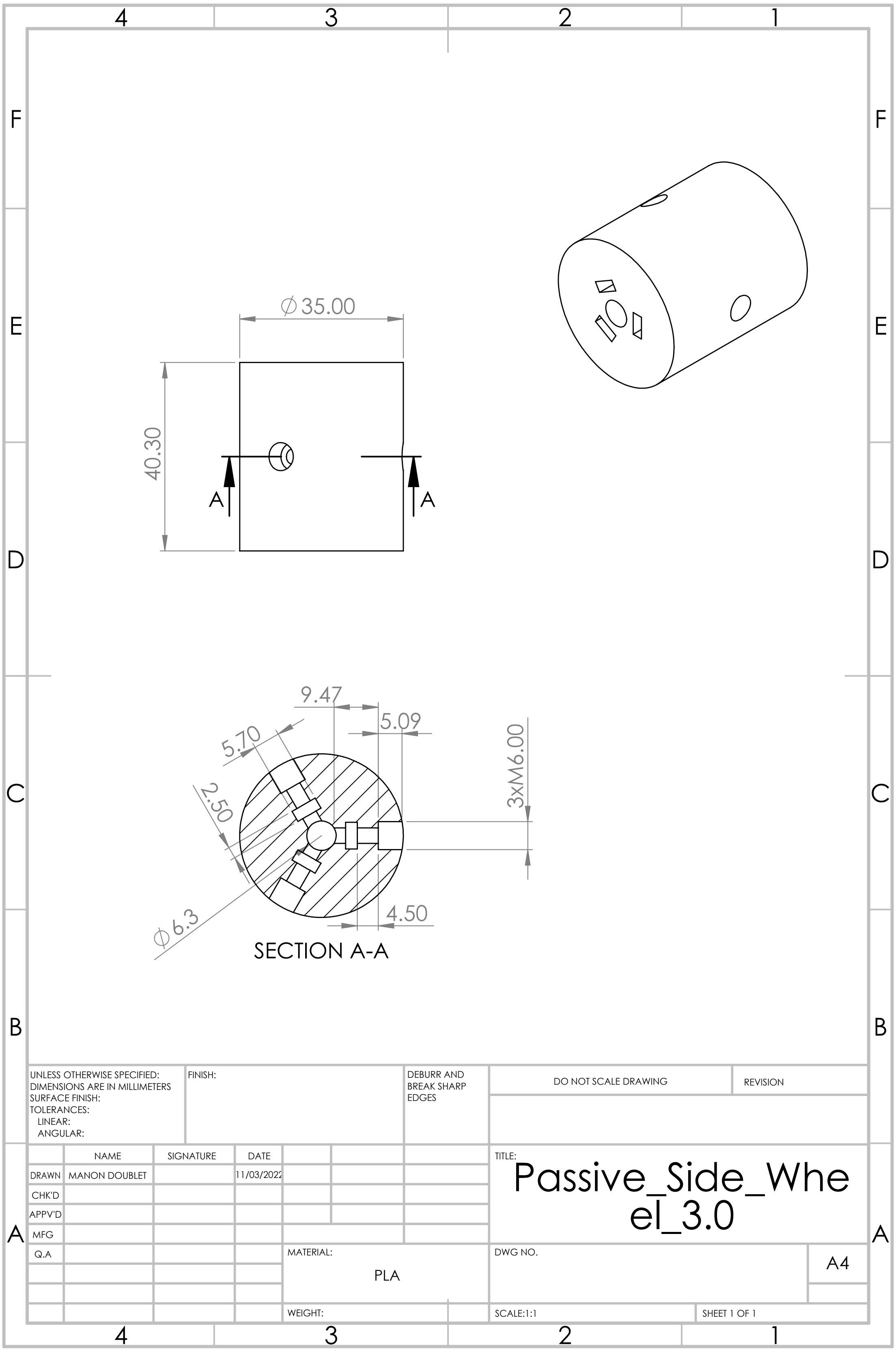

Figure 11: Technical drawing of passive side wheel

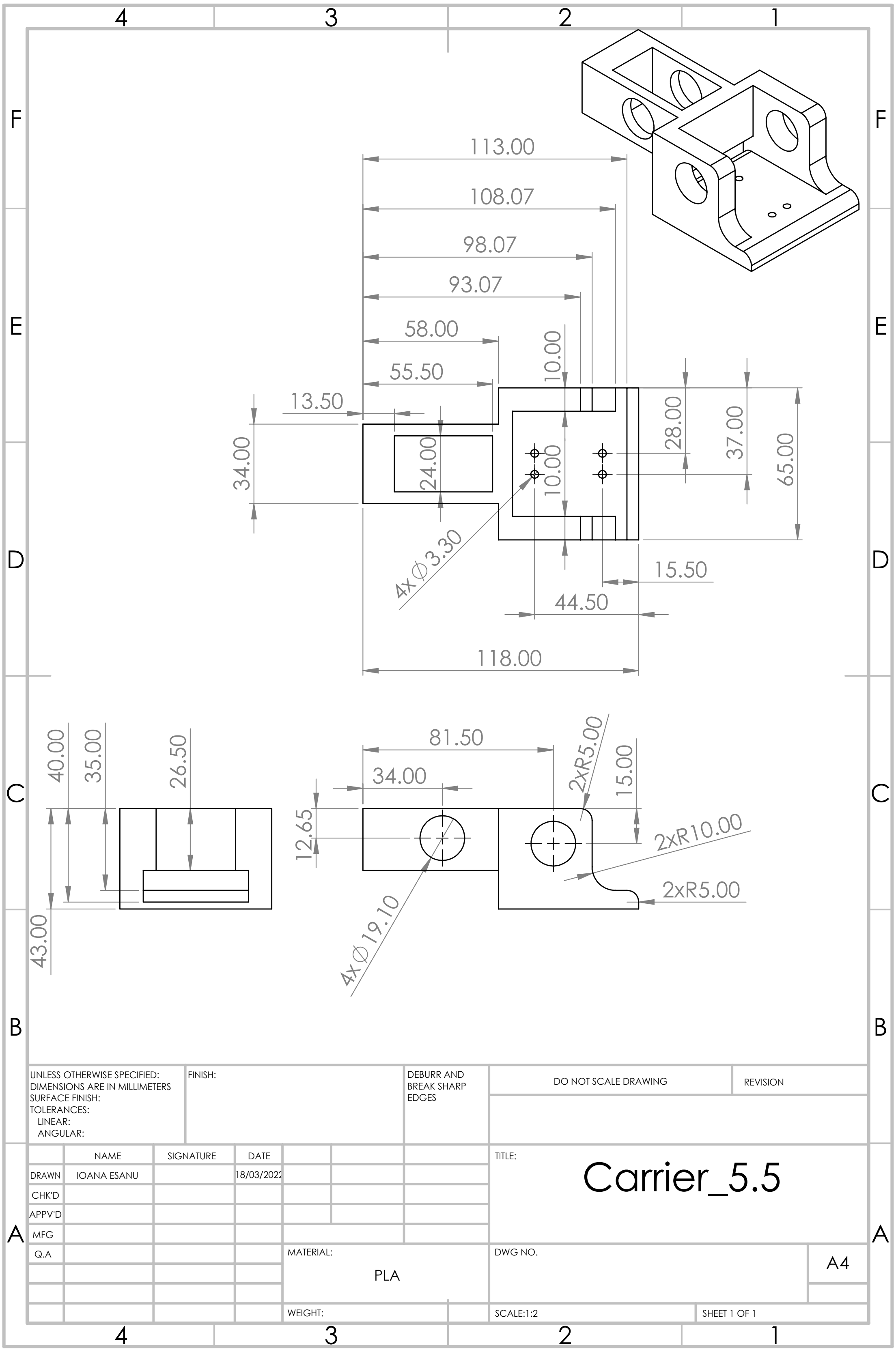

Figure 12: Technical drawing of carrier

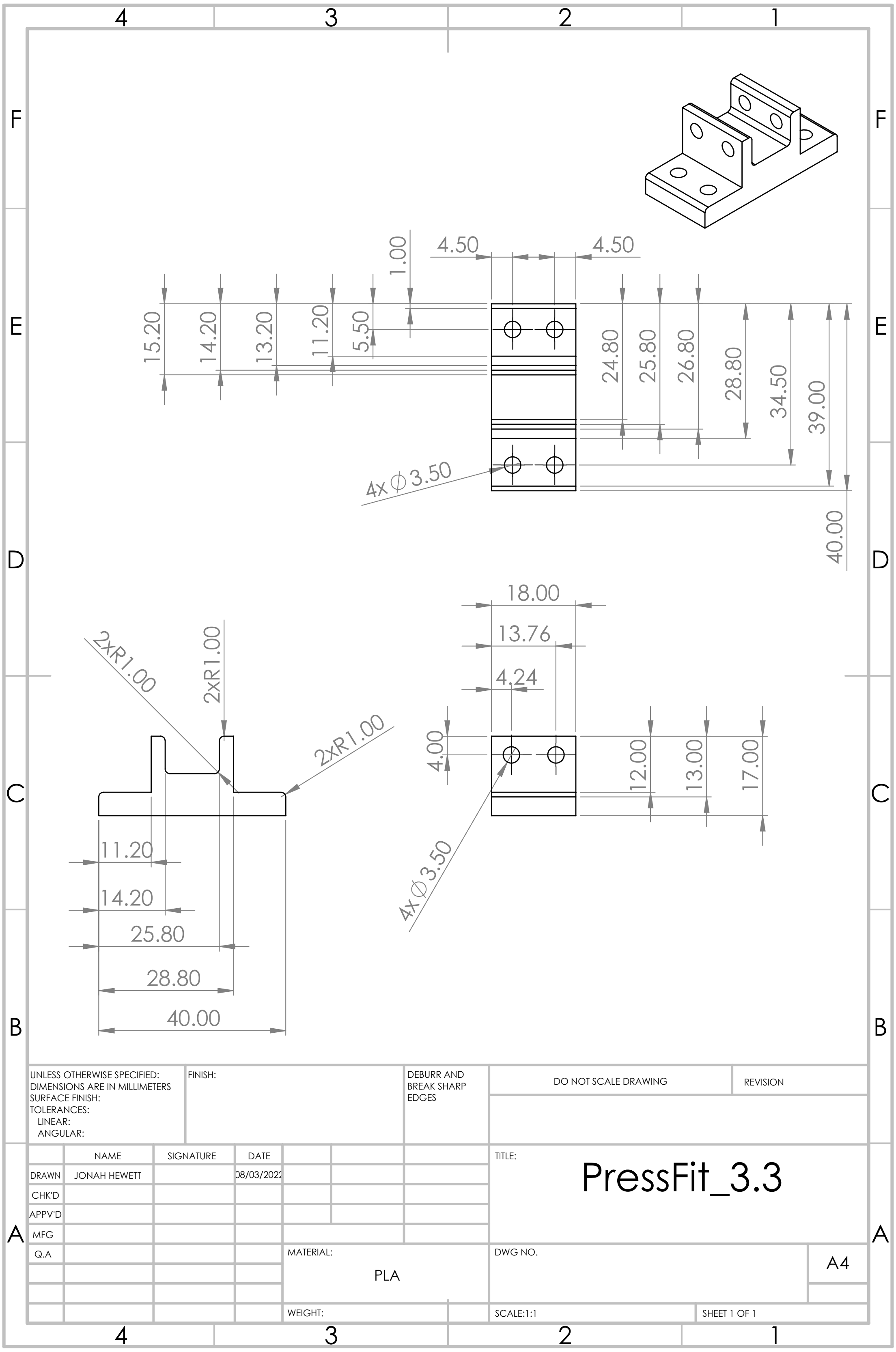

Figure 13: Technical drawing of chain clip

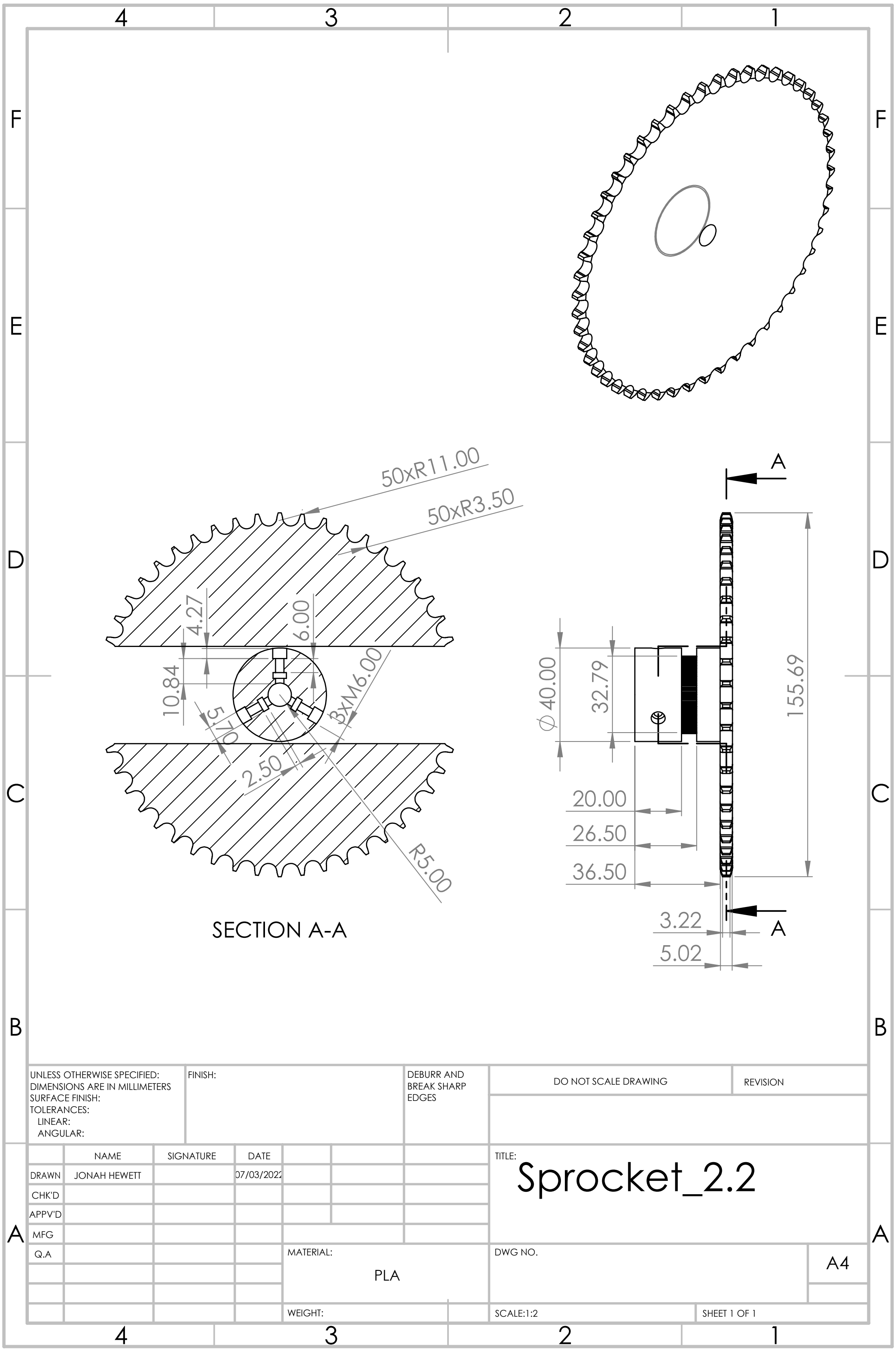

Figure 14: Technical drawing of sprocket