Department of Mechanical & Aerospace Engineering

ME524 Group Project Abroad - Gijon

Design and Manufacture of a Semi-Automatic Radio Shuttle Prototype for Use in an Industrial Warehouse – Final Report

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Abstract

In the following report, work from the ME524 MEng Group Project Abroad is detailed. The project was undertaken at the University of Oviedo (Gijon polytechnic school of engineering) during the first semester of the academic year 2017/18 as part of an Erasmus exchange. The group consisted of four students from the University of Strathclyde and were supervised by Dr Jose Manuel Sierra Velasco who acted as the client for the project.

The team was tasked with designing and manufacturing a prototype radio shuttle. This was to be achieved within a specific budget whilst being as efficient as possible in every aspect of the project. The prototype designed and manufactured had to be delivered in conjunction with the client's preferences and modified accordingly.

Pugh's total design method was utilised in order to develop and eventually manufacture the prototype. Extensive concept design was undertaken, followed by the manufacturing and testing of the prototype. Re-designing certain components and alterations to the radio shuttle prototype were implemented as necessary. At the end of the exchange the prototype was delivered to the client who was satisfied with the finished product.

A key component of the project revolved around the project management of the team and the duties of individuals. Therefore, the planning of all project aspects were as extensive as possible.

The work involving the radio shuttle prototype could be furthered by making it more conducive to an industry environment and plans were in place for students of the University of Oviedo to continue the work of the Scottish students.

Contents

Nomenclature

σ_{max} - Maximum total stress due to bending and torsion

$\sigma_{\max bending}$ - Maximum stress due to bending

c_l – Coefficient of rolling resistance

d – Diameter

ε - Eccentricity of the bearing involved in rotation of the lifting mechanism

F_{Max} – Maximum load to be lifted

$F_{Resistive}$ – Resistive force drive motor must overcome

g – Gravitational field strength

J - Stress due to torsion

m - Mass

$M_{bending}$ - Total moment of bending in the lifting mechanism shaft

M_{bh} - Moment of bending horizontally in the lifting mechanism shaft

M_{bv} - Moment of bending vertically in the lifting mechanism shaft

M_t - Moment due to torsion in the lifting mechanism shaft

η – Efficiency of timing belt

η_{Motor} – Efficiency of the drive motor

Φ – Diameter of Cam Bearing

P_{Motor} – Power generated by the drive motor

$P_{Required}$ – Power required from the drive motor

$P_{Req\ Lift}$ - Power required of the lift motor

r – Radius of Drive Wheels

r_{drum} - Radius of the drum for the lifting mechanism

s_e - Endurance limit to fatigue

s_e' - Ideal endurance limit to fatigue

S_{ut} - Ultimate tensile strength

τ – Torque of lift shaft

T - Tension in the belt for the lifting mechanism

v – Velocity of radio shuttle

W_b - Inertia for bending of a shaft

W_t - Inertia for torsion of a shaft

ω_{motor} – Rotational speed of drive motor

$\omega_{driveshaft}$ – Rotational speed of drive shaft

$\omega_{liftshaft}$ – Lift Shaft Rotational Speed

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1.0 Introduction

1.1 Project Design Brief

The overall aim of this group project was to develop a prototype of an industrial machine, namely a radio shuttle that could be manufactured and implemented in warehouses or storage facilities at a low cost. Radio shuttles should assist with the loading and unloading of pallets (commonly used to carry stock in industry) onto warehouse shelves that may be inaccessible otherwise. When in operation, the shuttle will slide on a rail underneath the shelves. If it is being used to load a pallet; a forklift or other elevating device will place the pallet on the radio shuttle which will raise it slightly above the shelf and then transport it to the deepest available space. The shuttle must then place the pallet back down on the shelf before returning to the point of loading to collect the next pallet. If it is unloading, the shuttle will position itself beneath the pallet to be collected before raising it a small distance off the shelf and returning to the shelf exit.

Consideration to the target industry (mass warehouse applications) was be maintained throughout. Construction and application at a low cost whilst still functioning were therefore the main targets. Another industry aim is to utilise space in warehouses and was therefore also a primary aim for the project.

The shuttle had the following prescribed criteria to fulfill:

- Lift a pallet and load a minimum of 20mm before transporting it.
- Must be capable of lifting a minimum of 2kg (including pallet weight).
- Must be smaller than half of a standard pallet size (600mm x 400 mm)
- The total Shuttle height must not exceed 150 mm.

1.2 Project Environment

The advisor, Dr Manuel Sierra Velasco allocated the group a small office space. This office had a station for each member to work at and was used almost exclusively by the group. The office was well equipped as it held four computers all with Microsoft Office, Solidworks 2017 and Eduroam connections. Additionally it was in a quiet area of the University across the corridor from the project client. The group swiftly built up a habit of working the standard hours of 9am-5pm which proved to be ample time to complete daily objectives. For the first time the group had a project to work on without the outside influences of other projects, lectures or exams. This meant that all of the member's time was spent on the Radio Shuttle project. Unlike past project experiences project work was readily at the front of people's minds and team members were always together. Therefore the team took to the project in a very cohesive and unreserved fashion.

The team also had to quickly acclimatise to the city transportation, accommodation, University, University staff and facilities. Outside of University the main challenge was becoming accustomed to using the Spanish language. In order to overcome this the group made use of the language tutoring application 'Duolingo' and attended several Bilingual Erasmus events to build upon Spanish skills. Additionally this was the first time for each member of the team to have moved out of their own home (excluding student accommodation) and dealt with a significant shift in independence.

1.3 Project Client

Jose Manuel Sierra Velasco, a professor at the University of Oviedo acted as the client and general group advisor for the project. Contact with the client began before the exchange when the client suggested one or two ideas for possible projects to be completed. Dr. Sierra's background in machine mechanisms and suggestion for a practical design and manufacture project made this an ideal fit for the group's aspirations.

During the group's first meeting with the advisor the workspace was presented and the group were introduced to some other staff at the University who would be helpful for the project. This included the technician for the closest laboratories. From there, the proposal was discussed and considered by both parties.

In order to produce a successful product, constant dialogue between the team and the client was required to maintain specifications set out. In the early design stages of the project the client was consistently made aware of the plans in order to make sure the general plan for the project remained on course with expectations. For example when using Solidworks to design the initial concepts of the radio shuttle, the client was kept informed multiple times of progress and given ample opportunity to view the model and make suggestions regarding any changes that were to be made. Due to the relaying of this information to the client on a consistent basis: serious errors, or designs which strayed away from the client’s preference, were avoided and the alterations made to the model were to the client’s satisfaction. When the client mentioned a particular change which was required, the team would come together if necessary and develop hypothetical solutions and pitch them back to the client.

The project began with influence from the client to ensure that the general aims and goals were clearly defined and the project became more independent as it was progressed. Past the design stage of the project the client wanted to see the successful manufacture of the parts with safe and secure testing methods.

1.4 Project Budget

The group was not set an exact budget upon arrival in Oviedo however it was decided that it was not good practice to ignore the finances of the project completely. Management of the finances provided an excellent learning experience. The group decided it made sense to enforce the same budget they would have if the project was being carried out at the University of Strathclyde. This meant a budget of £100 pounds per group member was available which at the time of the group's arrival in Spain equated to a total budget of €446.

One of the stipulations laid out in the brief was that the group was to keep purchases of raw materials and parts to a minimum and instead utilise parts already in the University lab or the University's 3D printer. This meant that the majority of the budget would be spent on producing 3D printed parts in house rather than externally sourcing and purchasing parts from suppliers and manufacturers.

2.0 Product Information

2.1 Industry Relevance

After reviewing and accepting the proposal, it was necessary to investigate and research the role of radio shuttle devices in general. A radio shuttle is utilised to assist with high density storage in warehouse operations. The devices operate by transporting loads contained within a pallet across racking systems fitted in a warehouse. Such loads are either transferred on to the racks to be stored for a time or removed by a radio shuttle in order to be transported out of the warehouse and towards the next destination. Radio shuttles serve the purpose of maximising efficiency in three key areas when transporting loads; space, cost and time.

Regarding space, the limits of storage within a warehouse can be exploited via the use of a radio shuttle. Loads may be stored and removed deep within the storage structure which may had been previously inaccessible to conventional techniques. Standard non-automated warehouses will rely on either the use of forklifts/warehouse operatives to travel down the aisles of the space to retrieve certain products deep within the shelves leaving significant spaces vacant as illustrated by the image below.

Figure 1 - Standard Example of a Non-automated Warehouse (1)

Automated warehouses mean that devices can retrieve these deep lying products without the need for a person or forklift to travel down to collect them. This means that the storage can be more densely packed. An example of the type of storage in which a warehouse using radio shuttles can be used is shown in Figure 2.

Figure 2 - Example of a Semi-Automated/Automated Warehouse (2)

Furthermore, the accuracy of the load carrying devices is such that pallets may be stacked extremely tightly together (both vertically and latterly), thus utilising all available warehouse space. The space which can be utilised by a warehouse is dependent on the type of storage which it will be using. This will depend on a variety of factors including the range of products being stored and the length of time they will reside in the warehouse. If only one product is being stored in an automated warehouse then the organisation of the shelving system can be more flexible and would only have to consider factors such as product lifetime (e.g. expiration dates for food or drink). If there are a variety of products the location of pallets will be more rigorously organised. One such example would be the defining of shelving space. Each level of an aisle could be defined to contain only one product, so the retrieval of that product would always be simple. This avoids the necessity of having to retrieve pallets deep within the shelves which may be blocked by other products. The main two types of shelving policy which the group considered for use with the prototype were: 1.”Last in, First Out” policy (LIFO); and 2.”First in, First out” policy (FIFO).

LIFO is the most simple and space efficient policy. The first pallet is transported to the deepest point on the shelf. Any further pallets will be dropped in front of this one until there is no more space. When retrieving the product, the radio shuttle will enter the same side and retrieve the closest pallet which will be the one which has entered the racking system last. The system operates with a single front aisle that allows the pallets to be transported onto the shelving system and subsequently out of the warehouse. This system is best utilised with storage with a high turnover rate or storage which has no expiration date and can remain in the warehouse for a significant amount of time.

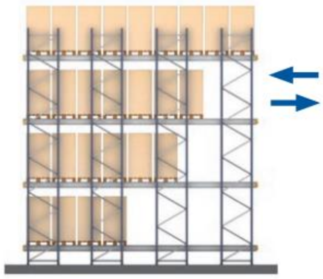

Figure 3 - Schematic of LIFO Policy (2)

FIFO operates a similar policy as the LIFO except it has a front and back aisle. The front aisle allows the placement of the radio shuttle and the pallet on to the shelving system, and like the LIFO system the shuttle transports the pallet to the deepest available space. The pallet will exit the warehouse via the back aisle. The warehouse will need two points of entry, one at each end of the shelving system. This policy is more conducive to products which cannot be kept in storage for an extended period of time. There is also an argument that this system is more efficient and potentially safer for a warehouse with an extremely high turnover rate. The front aisle is not as busy as a LIFO system since there is only an entry point.

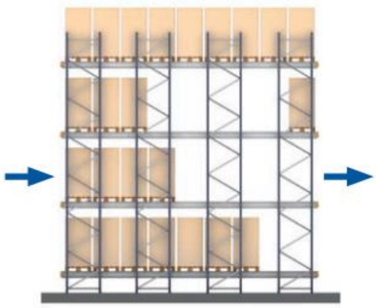

Figure 4 - Schematic of FIFO Policy (2)

To represent the type of increase of storage that is possible with this type of device, a relatively small warehouse size was considered. This size was 23 x 30 x 6m (Width of warehouse x length of warehouse x height of warehouse). Standard pallet sizes dictate that there must be at least 1.2m left per aisle (standard pallet: 1.2 x 0.8m). Each aisle of storage can allow for two pallets as long as there is a gap at either side of the aisle for forklifts to travel (i.e. essentially 2.4m per section). An average forklift truck has an approximate width of 2m. At least double this width should be left in order for the forklift to turn with relative ease and to allow for more than one forklift to operate in any given aisle at the same time. A standard height of 2m was used for the purpose of this representation, which allowed for three levels of storage. This analysis does not take into consideration the space necessary left for the length of the aisles, rather an ideal scenario where the entire length of the warehouse is available for storage. There is a gap left of 1.2m at each end of the width of the warehouse. With this, a storage volume of approximately $1728m^3$ is possible with approximately 900 spaces for pallets. With the addition of a radio shuttle automated system it would be possible to eliminate the aisles for the forklifts, which would allow for an additional 5 aisles of pallet storage from the 12m of forklift aisles that would no longer be necessary. This increase in number of aisles would increase the storage volume to $2808m^3$ with around 1462 spaces available for pallets. This theoretical warehouse change is summarised in Table 1 (NB 'Pallet Spaces Available' is a close approximation since total storage volume was considered).

Table 1- Radio Shuttle Racking Comparison

	Warehouse without Radio Shuttle Racking	Warehouse with Radio Shuttle Racking
Warehouse Width (m)	23	23
Warehouse Length (m)	30	30
Warehouse Height (m)	6	6
Warehouse Total Volume (m^3)	4140	4140
Aisles of Storage	8	13
Total Storage Volume (m^3)	1728	2808
Pallet Spaces Available	900	1462.5

Cost efficiency can be derived from maximising the storage space within a warehouse. If all the available space in a storage facility has been exercised, then potentially fewer resources, and costs, will be required to store remaining loads out with the premises. This could prove vital in storage warehouses which involve a cooler temperature setting for certain stock for example.

Productivity of warehouse operations is another factor improved with the introduction of radio shuttle devices. Being a semi-automatic device, once the radio shuttle is set in motion to retrieve or store a load, the operator is then able to undertake other tasks in the meantime, thus maximising working time. The smooth movement of stock by a radio shuttle also reduces the overall time to load and unload the racks.

The operation of a radio shuttle serves the purpose with minimal hassle. Numerous forklift configurations can elevate the shuttle to the required rack where a specific shelf would have been constructed for the shuttle to drive into, under the loads it intends to lift. Typically, a radio transmitter can be utilised to operate the shuttle and direct it to the desired load along the rack. Sensors built in the radio shuttle will accurately detect the correct position before a base plate on the shuttle is hoisted upwards. As the plate is extended vertically by the lifting mechanism, it will come into contact with the pallet above containing the stock. Once the plate has been fully erected, the pallet above will have been “freed” from its shelf above and only held in the centre by the shuttle. Now the radio shuttle is able to manoeuvre itself and the pallet across the rack to be “collected” by the forklift at the end of the shelf. The reverse action can be performed when delivering pallets and loads to the racks.

2.2 Market Research

The nature of this project dictated that market research on what the current industrial standards of similar products was imperative. To begin with, the entire group aimed to become familiar with the different environments in which radio shuttles are utilised. This included different warehouse setups based on the product which was being stored and in turn how the radio shuttle design was affected by the different type of shelving and operating systems. The radio shuttle, or an alternative to it, was found to be prevalent in the vast majority of both semi-automated and fully automated warehouses.

Another area in which the group decided to conduct market research was to attempt to contact companies who were listed to be in operation of radio shuttles.

The aim was to clarify certain aspects of the design and function of the shuttles from previous research. The companies were contacted by email asking a variety of questions about their automated/semi-automated warehouse. One such question was about any inherent safety features which were present in the warehouse and how they were implemented. Another was about the necessity of tracking wheels on the structure, or whether the width of it along the shelving system was sufficient to prevent the shuttle running off course or falling between the shelves. Unfortunately, response to these emails was limited; however they did point the group in the direction of any publically accessible warehouse safety manuals and "radio shuttle use" safety manuals which did prove useful.

As part of market research on motorized storage devices a tour of the local plastic packaging manufacturer LINPAC was arranged. The warehouse played host to a fully automated storage system. This system consisted of a conveyor belt moving arriving items to an autonomous pallet lifter. The lifter used mechanized forks and was programmed to transport goods to a desired position on large storage racks.

Figure 5 - LINPAC Warehouse Visit

Finding videos and schematics of the overall setup of the warehouses gave the group insight to what the necessary functions of the prototype would have to be. It also improved the viewpoint to build a datum on the initial ideas since it was now easier to determine what the priorities of design would be. For example, due to the fact that the product is rarely used where customers can see them, aesthetics was not a priority for the design. Discovering a demonstration of each function of the radio shuttle (for example the lifting mechanism) also helped with the design because the group had a clear idea of the end goal for the prototype.

The safety manuals which had been recommended to the group brought to light certain safety features which would be useful for the prototype which may not have been considered otherwise and may have proved difficult to add onto the structure after construction and will be further discussed in section 2.3.

While the LINPAC warehouse did not use radio shuttles themselves, it gave the group a clear vision as to how an automatic warehouse works as well as the potential scale of the operation. It was concluded that the use of a radio shuttle, combined with a lift mechanism or the operation of a forklift could be utilised in this setup. The group and the client recognised the positives and necessity to some extent of the LINPAC warehouse setup; however it was also noted that there were certain limitations within their methods which the group felt could be improved through the use of a radio shuttle. The primary improvement the group considered was that of a more efficient use of the space. While there were no aisles left completely free for forklifts to pass in and out of the aisles, the automated machine which moved the pallets took up its own set of space which would not allow pallets to be stored in this space. An approximated figure of the plan view of the warehouse storage is included below where the red parts of the figure represent where the running machine ran and the black parts represent the available storage in the warehouse.

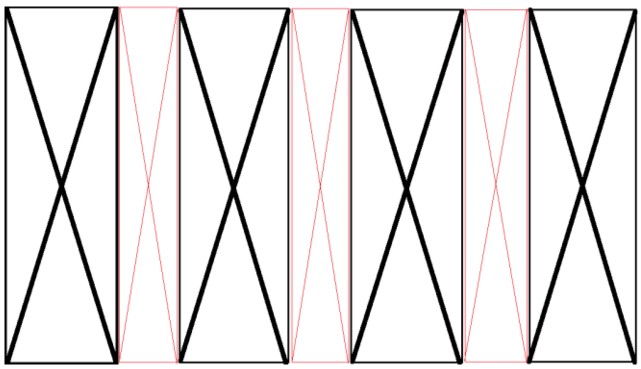

Figure 6 - Plan View Representation of LINPAC Warehouse Storage

This automated system still held advantages in comparison to a standard warehouse space such as the fewer employees necessary for the general running of the warehouse. The prototype which the group aimed to create would allow the red parts of Figure 6 to be removed and allow the same function to be performed whilst have another aisle for further storage. While this is true for a standard warehouse with a “first in-last out” pallet policy, or a “first in-first out” policy, the LINPAC warehouse setup would allow for a more flexible storage system where any pallet could be collected or dropped readily. The choice between the two setups would have to be considered depending on the output function of each warehouse in order to choose the most efficient but also effective method for storage.

2.3 Product Background

The design and manufacture aspect of the project meant that investigation into research papers was limited. The research was instead focused upon the current use of radio shuttles in industry as indicated in section 2.1. This gave an insight as to what areas of the prototype should be focused upon and how the typical design in industry is possible. A general better understanding of the use of radio shuttles was acquired through this process along with potential safety features which had previously not been considered. The main purpose of this research was to find out as much as information about current industry models, but also to understand their purpose to a full extent. This included the environments in which they are used and the types of industry that utilises them. With this the group felt that better judgment in the overall completion of design tasks would be available since a clear recognition of the end goal and the prototype’s eventual use would be present through the entirety of the design and manufacture.

The first source of information about the use of radio shuttles in industry was the investigation of patents. The early stages of radio shuttle production upon patenting aimed to set out the individuality of an automated pallet moving system. The earliest version that the group's research could find was a patent from the United States of America where a company named White-Sundstrand Machine Tool Inc. launched a patent into their automated warehouse settings (3). The patent was to validate their use of a complete automated warehouse system. Whilst there are similarities to the prototype for this project, the patent in question was more specific in that it covered the full operation and movement of a complex warehouse. Rather than just carrying along track bars, the operation they considered included rotations of the system as well, however since this patent dated back to 1976 it was noted that this type of technology was not a revolutionary idea for a prototype, far from it. The continued development of this type of technology and continued use in industry to this day showed that this type of work is something that retains relevance (4). White-Sundstrand Machine Tool Inc. launched a further patent in 1978 which coincided with an increase in scale to their previous work (5). Whilst the time frame of the earliest patent of this kind displays the long standing relevance of automated warehouse technology, the scale of this type of operation did not bear too much on the more general prototype for this project.

More specific research into radio shuttles was the next goal of research. This is where the safety manuals of current radio shuttles became useful. Section 2.1 discussed the operations and some of the potential operation systems which warehouses may employ (FILO, LILO). The applications in which these shuttles were used was displayed in section 2.1, but only considered the ideal scenario of a warehouse operating with one system. In reality many industry products will need more than one storage method (2). This mixed type of storage would be particularly prevalent in current businesses which do not employ an automated warehouse storage system but have aspirations to implement one. To radically change the entirety of their storage would be unappealing because too much change may disrupt their business in a negative manner. Mecalux's paper illustrates a few scenarios where it would be advantageous to have this mixed storage and still efficiently run a business. An example of one of these scenarios is displayed below:

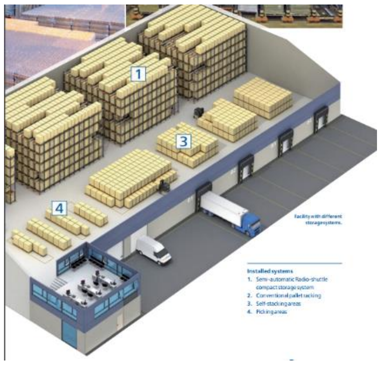

Figure 7 - Mixed Storage Example (2)

This consideration allowed the project to be moved forward for not only new warehouse storage units but proved that the implementation to current business could be possible and flexible to fit in with different working systems.

The Mecalux's safety manual also indicated some safety features which were discussed amongst the group and the client upon consideration. A safety bumper and an emergency stop were noted to be considered standard on these machines from a variety of safety manuals (e.g. Mecalux's, BT, Thistle) (6). Another feature that the group had not considered up until this point was a manual override button. This would allow the shuttle to be controlled by a joystick rather than using sensors as it would for the remainder of its industry life. This feature was one that was added to be an aim later in the project. One feature listed in some of the manuals was a 'low battery reserve.'(7) This would indicate when the shuttle would need to be returned to base to charge or replace its portable power source (usually a rechargeable battery). This would be an almost imperative feature in practice; however for the prototype creation it was concluded that this would not be necessary. It was also noted that it would be unlikely that the mechanics of the radio shuttle would not be affected by the addition of this feature.

Standard features for radio shuttles were sensors to control the automated movement of the radio shuttle. These sensors were often infrared sensors or light sensors to detect what was around the moving radio shuttle (other than the loaded pallet above it) (7). Whilst effective these types of sensors were noted as complex and potentially expensive. This expense was forgone in industry examples examined because of the dramatically increased effectiveness compared to interrupter sensors which could have caused problems in a large scale storage operation (8). It was noted at the early stage of research that this may be an area where the prototype for the project would differ from industry standard radio shuttles. The maximum load of the shuttles varied depending on their use in a specific storage system. BT listed the maximum capacity of a loaded pallet was 1200kg to ensure a safe and consistent storage environment (9).

All of the safety manuals and information referenced the importance of durability for radio shuttles. If the machine is inconsistent with its durability and reliability it renders the increased storage far less useful. From a practicality front, if the machine is not operating at a high level, the attempts to try and do useful work in a warehouse made for automated storage would be extremely difficult due to the inaccessibility of the majority of the storage in the warehouse. The financial aspect of an unreliable radio shuttle was also referenced by Thistle (8). The expense of the radio shuttle themselves as well as the complete design/redesign of a warehouse was noted to be significant so if this type of decision was to be made businesses would have to see it as an investment.

One example which was provided by Thistle was that of cold storage of bottled beverages. The case study displayed the significant cost of the implementation of the radio shuttle system (approximately £1,058,355 in this scenario) but also indicated that the number of pallets which could be stored was more than doubled (8). The increase in the number of pallets in the warehouse meant that the company made the money back from their investment in just 15 months. This return does also not take into account the reduced maintenance costs that would likely come with the implementation of the radio shuttle racking system as well as a reduction in damaged goods which Thistle claim is extremely likely. Some overhead costs which are reduced by the radio shuttle would be the decrease in lighting, staffing and the more efficient temperature control (for cold storage).

3.0 Project Management

3.1 Group Structure Responsibilities

After an early group meeting it was decided that there was no need for an overall project manager and that decisions would be taken on a case by case basis and only when every member of the group was satisfied with the direction the decision took the project in. This meant that everyone's concerns would always be addressed as the project progressed.

However with a group project which spans such a large time scale, designated management of some of the more prominent aspects was vital to the continued overall progress. In order to avoid efficiency issues, distinct roles were created for every team member. Dialogue across the team members was essential to remain on course with planned deadlines and to distribute resources accordingly.

For each role, the specific team member in charge was tasked with organising everything relevant to their role. While certain roles were assigned to individuals, it was often necessary to assign multiple team members to a single task due to size and complexity. Whilst specific roles were assigned for responsibility and overseeing purposes, all team members shared a significant degree of involvement in each task.

The four main roles that the group decided would best split up the main areas of responsibility are shown with a brief overview of each position:

Communication Manager – Responsible for organising weekly group meetings. Also responsible for relaying any additional information from the client to the rest of the team and organising client liaison.

Technical Manager – Responsible for overall design of project product(s), oversee CAD modelling, manufacturing and testing.

Data and Storage Manager – Responsible for organising files and making sure all calculations are accurate and complete. Also responsible for report documents and website design.

Financial and Resource Manager – Responsible for material acquisitions, sourcing parts, monitoring project budget, updating the Gantt chart and resource allocation.

Members of the group were assigned to these roles either because it was felt that a certain role played to a strength or because a role required a skill that a member wanted to develop. In either case whenever a role was allocated, it was given to someone who wanted to occupy it. An example of this occurred when Jonathan Wieland requested to be made the technical manager. Jonathan spent the summer working as a technical intern and so felt he was best placed to carry out these duties. Similarly, Fraser Williams requested to be the Communications Manager because of his ambition is to work in engineering project management and a previous managerial role in employment. While there was no position of project manager Fraser felt that practising his communication skills in a setting such as this one would be good personal experience.

In this way the positions mentioned above were allocated to members of the group as seen below:

Fraser Williams – Communications Manager

Jonathan Wieland – Technical Manager

Scott Lindsay – Data and Storage Manager

David Brown – Financial and Resource Manager

As the project centred largely on design and manufacturing, it appears that Jonathan Wieland, the technical manager, would have encountered more work than others. However as previously mentioned, that work was continuously delegated throughout the group at the technical manager's discretion. Therefore throughout the project the entire group was working in tandem with no single member enduring a larger work burden than the others.

3.2 Team Dynamic

A level of accountability between members was established by setting objectives at weekly group meetings, as well as at a short discussion at the beginning of each working day. These goals pushed individual members to finish all work asked of them and not slow down progress.

The group felt that having a dedicated work space that was free of disruptions maximised productivity as a full day worth of work could be planned without worrying about being uprooted for a class.

All members of the team made an effort to forge a strong team dynamic. Often this took place outside of the University and involved things which may seem inconsequential to the project such as socialising or excursions to explore the region. As the group was living together in unfamiliar surroundings this bonding was actually very important to create a level of familiarity between members which meant anyone felt comfortable making their voice heard.

3.3 Communication Management

A solid communication framework between team members and with the client was essential to the continued progression of the project. Lack of communication at any stage could have led to valuable time being wasted on work that was not necessary. In order to avoid this the communications manager put in place a plan which, if adhered to, would ensure that everyone knew what was demanded of them at all times and that the client would remain informed of all major decisions.

This became even more useful in the last few weeks of the project when the Scottish students were put in touch with a group of Latin American and Spanish students to assist with the design of the electronic system. The majority of communication between the two groups was carried out in English as the Latin American/Spanish students were studying in English. Despite speaking the same language it was important to ensure all communication was understood and that nothing was lost in translation.

The plan was designed to set out what methods the group would employ to communicate with each other and with the client as well the regularity of meetings. The plan was presented to the group by the communications manager at the start of the project and then amended to detail how communications would be carried out with the electronic students.

Table 2 - Communications Management

Communication Tool	Format of Communication	Reasons and Objectives	Participants Involved	Frequency
Daily Group Meetings	In Person	• Set daily work targets • Identify, discuss and address any issues	All Scottish students	Every day
Weekly Group Meetings	In Person	• Update Gantt Chart and review project progress • Review work completed in the last week • Decide priorities for the coming week	All Scottish students and electronics team	Every Week
Client Update	In Person/By email	• Inform client of progress made and confirm approval • Determine if client has any specific instruction for upcoming tasks	All Scottish students, electronics team and client	When necessary
Sharing Files	On Dropbox	• All files saved on a platform where they can be accessed by the entire group • Ensures all files are backed up	All Scottish students	When necessary
Group Chat	WhatsApp	• Group members can be easily reached if not in the office • Good way to quickly reach the electronics team	All Scottish students and electronics team	When necessary

3.4 Time Management

As with any long term project, keeping track of the progress being made and management of the remaining available time is vitally important. To ensure the deliverables of the project could be produced without effort being concentrated close to deadlines the group created a Gantt chart as one of their first tasks. After consultation with the client, the group compiled a list of the individual tasks which would comprise the project and estimated the time required to complete each one. All members then agreed on deadlines for each task and this data was organised into the Gantt chart.

The Gantt chart was constantly updated as the project progressed so that at no point was the group complacent about how much time remained and resources could be redirected towards certain tasks if some were completed ahead of schedule while others took longer than expected. The completed Gantt chart can be viewed in the appendices.

The use of a Gantt chart was a great aid for planning out a logical progression for the tasks to be completed. In addition it supplied weekly targets to the group which prevented any serious lapses from the schedule.

3.5 Technical Management

The technical management of the project was overseen by the technical manager who had ultimate responsibility over technical tasks including: CAD modelling; testing and manufacture; and quality control of everything produced. The technical manager was given the authority to delegate work during the concept generation and selection stage, the 3D modelling stage and the manufacturing stage.

The manufacture of the shelving unit involved welding and was therefore the section of the project that contained the biggest risk of physical harm. The technical manager observed all welding that was carried out and ensured proper lab safety procedures were followed at all times.

Another role of the technical manager was to perform a quality inspection whenever a part was produced by 3D printing or by another member of the group in the laboratory. This helped to ensure that potentially faulty pieces did not make it into any of the testing set ups or the final prototype.

3.6 Financial Management

All instances of financial management were undertaken by the financial manager. The main responsibility of this role was to make sure that expenditure on raw materials was kept to a minimum and that parts were either found in the University labs and re-purposed or produced in-house using the 3D printer. This was one of the key stipulations of the project brief so it was vital the financial manager ensured it was followed. Before the purchase of any part was made it was the duty of the financial manager to confirm that no similar usable part could be sourced from inside the University and that the part could not be 3D printed.

The financial manager also had to make sure that proper financial records were kept so that all expenditure was properly tracked and that any purchases could be reimbursed by the University.

A spreadsheet was created on Microsoft Excel and all financial outlay recorded. A separate spreadsheet was provided by the University which calculated money that was spent creating parts with the 3D printer. This was necessary as the cost of these parts was a function of the amount of support and base material used as well as the length of time the printer was operational.

3.7 Risk Management

The group was aware from the beginning that the project would involve a significant amount of laboratory work and that this would pose the biggest health and safety risk. Before any lab work commenced the technical manager constructed a risk assessment table that outlined the most significant risks; rated their likelihood to cause harm; and advised on how best to avoid injury. The risk assessment table is displayed in Table 3:

Table 3 - Risk Management Table

Risk	Description	Likelihood (1-10)	Severity (1-10)	Minimisation Strategy
Power Tool Operation	Power tools will be required for manufacturing. Fast moving parts could cause injury	5	8	Take care when using power tools and ask for direction from lab technicians if unsure how to use equipment. For more advanced procedures ask lab technicians to carry out. Always wear the proper protective clothing
Hand Tool Operation	Hand tools tend to have sharp edges which could cause injury	5	6	Again be careful when using hand tools. If a group member is unaware how to use a hand tool properly they should seek advice from another group member or a technician.
Slip Hazard	Spillages on the lab floor could cause someone to slip	3	7	When working with a substance that could potentially cause a slip make sure the floor is properly cleared afterwards.
Trip Hazard	Congestion in the lab could create trip hazards	5	7	Always ensure the lab is tidy and clear away all equipment after use. Ensure lab is always well lit.
Load Handling	Some objects such as the shelves will be heavy to carry	5	5	Don't attempt to lift anything that is too heavy/awkward. Always ask for help if you are unsure about lifting something.
Dust/Debris	Filing or sanding could create dust that could cause harm if it gets into the mouth or eyes	5	5	Wear eye and mouth protection when sanding or filing
Fire Hazards/ Burning	Welding could ignite a fire or burn the operator	2	8	Always take care when welding, ensure no one is standing in the immediate vicinity and wear the appropriate protective clothing
Noise	Some tools may create excessive noise	6	3	Wear protective ear equipment if operating a loud machine. Inform nearby group members if you are about to operate a loud machine.

There were possible risks that could have been encountered other than those that endangered health and safety such as: the project running behind schedule or too much money being spent. The group felt that the steps taken to outline the financial and time management of the project as seen in sections 3.4 and 3.6 would be adequate to combat these risks.

3.8 Design Philosophy

When designing key components of the Radio Shuttle, Pugh's Total Design Method was adopted to ensure the process of concept generation and selection was well structured and properly thought out. The market research carried out at the beginning of the project was the first step in this process. From there a project design specification was created to ensure that the subsequent product would be somewhat comparable to an industry model and would meet the demands of the client. Solutions were then hypothesised for the key operations of the Radio Shuttle, namely the lifting mechanism and the drive system. The generated concepts were then compared using Pugh's Selection Matrices which provided a platform for the group to discuss the advantages and disadvantages of each concept with reference to the specification.

When designing the radio shuttle body, a larger priority was given to certain aspects which contributed significantly to the overall function of the device (to move across the shelves and lift a pallet). Therefore components such as the drive system shafts, lifting shaft, lifting mechanism and all the components connected to these (such as the motors) were included in the design from the start. The layout of components within the radio shuttle body was prioritised so that none would interfere with each other during operation. This was made difficult to an extent due to the size constraints of the shuttle body that were set out by the client. Although the design stage was thorough and contained an array of pivotal components, some were neglected at this stage to be included later in the manufacturing process in order to reach attainable goals first. For instance, circuit boards and electronics for sensing the position of the shuttle were not developed fully until the radio shuttle body had been manufactured and was functioning mechanically.

4.0 Concept Generation and Selection

4.1 Drive System

A variety of potential driving systems were conceived, rated on whether or not they fulfilled certain performance criteria and then compared to one another as described in Section 3.8. The five potential driving systems that were considered were as follows:

1. Two Wheel Drive System

This idea was the most simple of those generated, a single drive shaft with two wheels secured at either end being driven by a motor via pulley transmission. A secondary, non-driven shaft would also be present in the shuttle to ensure its stability. Deciding which of the two shafts would be the driven shaft was not necessary at this stage as this would not affect the performance of the shuttle and would ultimately be dictated by which provided the simplest layout. In order to implement this design the shelving unit would only require a flat surface beneath the pallet shelf.

2. Four Wheel Drive System

The Four Wheel Drive concept had the same number of shafts and wheels, although in this case both shafts would be driven. This would have been achieved by introducing a secondary motor so that the two shafts would be driven independently by separate motors. This concept would also only require a flat surface on which the wheels could rest.

3. Tank Treads

This concept involved using a motor to turn a drive shaft but in place of wheels at either end there would be gears with tank treads fitted over them. The advantage of the tank treads would be that if the surface was grooved in such a way that the teeth of the tread fit perfectly with it then the radio shuttle would be totally stable. This design would include two driven shafts and two motors. It was thought that one motor would be unsuitable since the meshing of tank treads and rail would create added resistive forces to the shuttle motion.

4. Motorised Rails

This concept was unique among those generated because it was the only one in which no part of the drive system was fitted to the radio shuttle itself. Instead a motor would be mounted to the shelving unit which would drive a large gear. The gear would in turn give motion to a chain like rail on to which the radio shuttle could be placed.

5. Mag Lev

The most ambitious concept was generated to use magnets mounted on the radio shuttle and shelving unit to levitate the radio shuttle. By passing alternating currents through electromagnets in the shelves their polarity could be changed, thus propelling the radio shuttle in the desired direction.

All concepts were roughly sketched in order to help the group consider the mechanisms in their entireties. These sketches have been included in the appendices.

In order to select the concept best suited to meeting the requirements set out in the brief, a selection matrix was created. By consulting the specification and then discussing as a group, the most critical performance criteria that the drive system had to perform well in were chosen.

Table 4 - Drive System Selection Matrix

Concept / Criteria	Tank Treads	2 Wheel Drive	4 Wheel Drive	Motorised Shelving	Mag Lev
Cost	N/A	+	S	-	-
Availability	N/A	+	S	S	-
Reliability	N/A	+	S	S	S
Compactness	N/A	+	S	+	+
Ease of Manufacture	N/A	+	+	-	-
Ease of Assembly	N/A	+	+	-	+
Ease of Implementation	N/A	+	+	-	-
Safety	N/A	S	S	-	+
Weight	N/A	+	S	+	+
Stability	N/A	-	-	S	S
	Σ+	8	3	2	4
	Σ-	1	1	5	4
	ΣS	1	6	3	2

Availability was a key part of the selection matrix. It refers to the availability of parts that could be found in the University laboratories and therefore wouldn't have to be purchased. Since minimising expenditure on raw materials was a central part of the brief this was an important consideration for the drive system.

Ease of implementation was included to account for the fact that the shelving unit would in some way have to accommodate the radio shuttle. This was included in the matrix to assess how easily each concept’s required modifications could be made to the shelves.

The tank treads concept was chosen as a datum which the other concepts could be compared to. In this case the Two Wheel Drive System was clearly the most appropriate driving mechanism as it performed superiorly to the datum concept in eight of the ten criteria. The tank treads would be more stable in operation than the Two Wheel Drive. However it was noted that although it would be advantageous for the drive system to provide stability, it could be provided by other means.

The use of only one motor meant that: it cost less; it was more reliable; it was more compact; and it weighed less than the tank tread and Four Wheel Drive Concepts which used two motors. All these advantages came at essentially no cost to the performance of the radio shuttle as speed was not a key design requirement.

The complexity of the more ambitious concepts was the reason they were not selected. These ideas were innovative and their main attraction – that they took up no room inside the radio shuttle – would have allowed for the final design to be extremely compact. Despite this both designs would have been extremely costly to produce and very difficult to implement into the shelving design.

4.2 Lifting Mechanism

In order to support the pallet above the shelf, a lifting mechanism had to be developed. Due to the resources available within the University, it was more than likely an available motor would be utilised in some process to perform the lifting of the pallet. Pulley drums were also available to transmit the motor power should they be required.

The client stated preference of including a 4-bar linkage to support plates which would in-turn lift the pallet. The goal was to manufacture two of these linkages and develop a system which would be able to erect them and collapse them depending on whether a pallet was to be lifted or dropped on to the shelf.

After discussion at a weekly group meeting, the group came up with five potential solutions regarding the lifting mechanism:

1. Scissor lift (where the two rods would sit directly under the linkages)
2. Camshaft (where the cams would rest under the linkages)
3. Hydraulic actuator (would require a hydraulic motor)
4. Bike chain (where cam-like “humps” would be added to erect the linkage when appropriate)
5. Wired drum (where a chord would be attached to the linkages and raised/dropped as the drum rotated)

Again a selection matrix regarding the lifting mechanism was generated to assist the team in making a decision. These aspects were listed in table 5.

In particular, the group put great emphasis on the design of the lifting mechanism (as well as the rest of the project) being as cheap, reliable, safe and as easy to operate in conjunction with the tasks as stated in the project brief as possible. The selection matrix below was composed for the lifting mechanism.

The concept sketches for the lifting mechanism have been include in the appendices section.

Table 5 - Lifting Mechanism Concepts

Criteria \ Concept	Scissor Lift	Camshaft	Actuator	Bike Chain	Wire Drum
Cost	N/A	+	-	-	+
Availability	N/A	S	-	-	+
Reliability	N/A	S	+	-	-
Compactness	N/A	+	-	+	-
Auxiliary Components	N/A	+	-	+	-
Ease of Manufacture	N/A	+	N/A	-	+
Ease of Assembly	N/A	+	-	-	+
Easy of Control	N/A	S	+	S	S
Safety	N/A	-	+	S	-
Weight	N/A	+	-	+	+
Time	N/A	+	+	S	S
	Σ+	7	4	3	5
	Σ-	1	6	5	4
	ΣS	3	0	3	2

The camshaft was the most acceptable solution when analysing the criteria. This particular concept would theoretically perform better than the scissor lift in seven categories. This was most notable regarding the compactness of the design, the ease of manufacture and the ease of assembly. While several concepts could have potentially performed admirably in a number of key areas the group believed the camshaft would be able to adhere to the project needs with more efficiency than the other concepts.

Once the camshaft proposal was selected, the team moved forward and began the design of the lifting mechanism in its entirety.

5.0 Mechanical Design

5.1 Design Software

Viewing the designs in 3D was critical as it would make clear any flaws that may have been overlooked during the concept generation stage. The 3D model of the radio shuttle also proved very useful as it meant the design of the mechanisms could be altered to ensure the size constraints of the shuttle set out by the client could be met before any manufacture began.

All the 3D modelling was carried out on the CAD software SOLIDWORKS. The workload was delegated by the technical manager so that each group member was responsible for a different aspect of the modelling. The four tasks to be completed were the modelling of the shelves, lifting mechanism, drive system and the assembled radio shuttle. Further description of the work carried out for each of these tasks can be found later in this section. In all cases the first step was to model the parts found in the labs that were to be incorporated into the designs. From there the parts required to complete the design were added in one of two ways. In some cases a model of the required part would be made and then attempts would be made to source or purchase something which was as close to resembling the model as possible. If the purchased part differed at all from the model then the model would be altered to reflect these discrepancies and ensure they had no negative impact on the overall design. More often than not however, the pieces being modelled were created using the University of Oviedo's 3D printer, meaning less time had to be devoted to redesign and fulfilling the instruction of the brief to minimise the purchase of raw materials.

5.2 Shelving System

As with all facets of the project the design of the shelving system had to be created with consideration to numerous factors including: resources available; manufacturing processes; and the dimensions necessary for the prototype.

The first step taken to design the shelving system was to assess the necessary dimensions of the shelves. A pallet half the standard size was to be used for the entirety of the project. One was created on the 3D software Solidworks 2017 in order to be used to help model parts of the project. With these dimensions and an estimation of the size of the radio shuttle, basic minimum sizes of the shelves could be calculated. The maximum height of the radio shuttle set out by the client determined how much space was left above and below each level of shelving. A set dimension for above the wheel base was estimated which would allow the radio shuttle to pass below where the pallets would rest, whilst still being close enough that the lifting plates could lift the pallets.

Following this, the resources already available for the project were checked to see if the shelves could be assembled without requesting additional parts from the University. The vertical structure of the shelves were proposed to be made using hollow square and rectangular low carbon steel bars which were 3m in length, but needed to be cut down for the project. Two right square angle profiles (L-bars) and two T-bars were available and it was surmised that they could be used to hold the pallets. Suggested track bars were selected and modelled as follows:

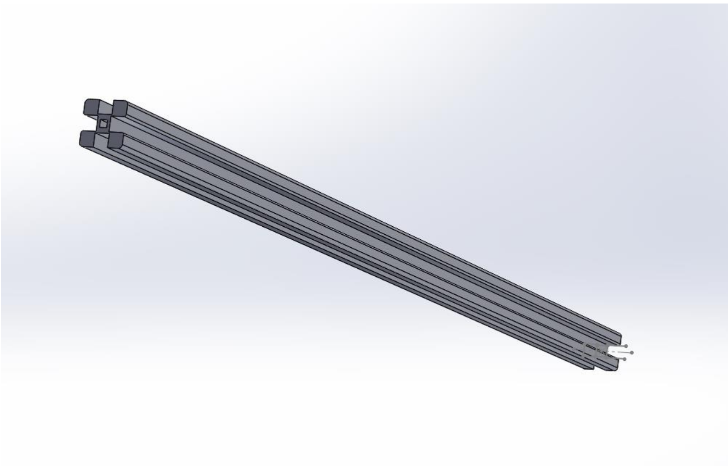

Figure 8 - 1st Suggested Shelving Track Bars

One idea was that the wheels used could be 3D printed with an indent to follow the inside track of this part and keep the shuttle steady. With the material available, it was recognised that it would only be possible to complete two levels with two spaces deep for pallets on each level. Each part was modelled on Solidworks after having dimensions measured by tape measures and callipers where necessary and subsequently assembled to give the following design. Cross sectional bars were positioned on the end of the shelving system in which the pallets would be stacked against to provide more stability and join the two ends of the shelves.

Figure 9 - 1st Shelving Unit Design (2x2)

However after consulting with the client, it was felt that three pallets deep would be more important to properly display the use of the prototype. This meant that he requested there to be funds available to improve this design which the financial manager approved. Four right angle profiles were purchased with length 2m.

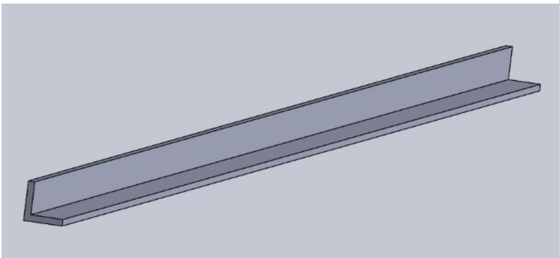

Figure 10 - Right Angle Profile Track Bars

This provided the capability to have two of these run as track bars and another two to rest the pallets upon. The same structural bars could be used while the original L-bars instead were decided to be used in the lateral direction of the shelves to provide a more stable structure. This gave the capability to build one level of shelving. However, the supporting bars of the structure were to be made tall enough that a second row of shelving could be included if the parts were acquired, or that the project could be continued further if successful. A further two support bars were included in the design since the length of the track bars was now much larger and would be supporting the load of the radio shuttle as well as a loaded pallet. It was known that the support bars on which the wheels would run would have to be closer together than the support bars on which the pallets would rest since the lifting mechanism on the radio shuttle could not collide with the above support bars. In order to do this, it was proposed that the extra support bars in the warehouse, could be cut into smaller sections and welded onto the original support bars where necessary, as shown in Figure 11:

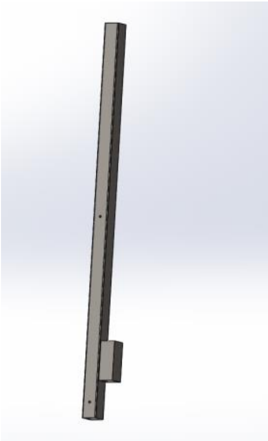

Figure 11 - Supporting Bar with Welded Block

A 3D version of the final design was created on Solidworks, which also allowed 2D technical drawings to be created. These were created with all the necessary reference dimensions which had been worked out previously. The estimated weight of the entire structure was also included in this table (approximately 80kg) as well as detailed information of the dimensions of all the parts included.

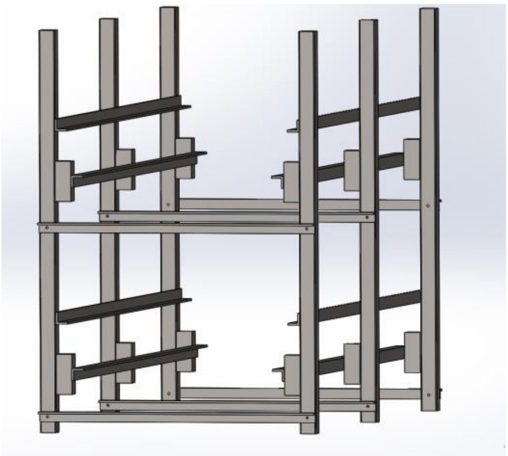

Figure 12 - Final Shelving Unit Design 3D Model

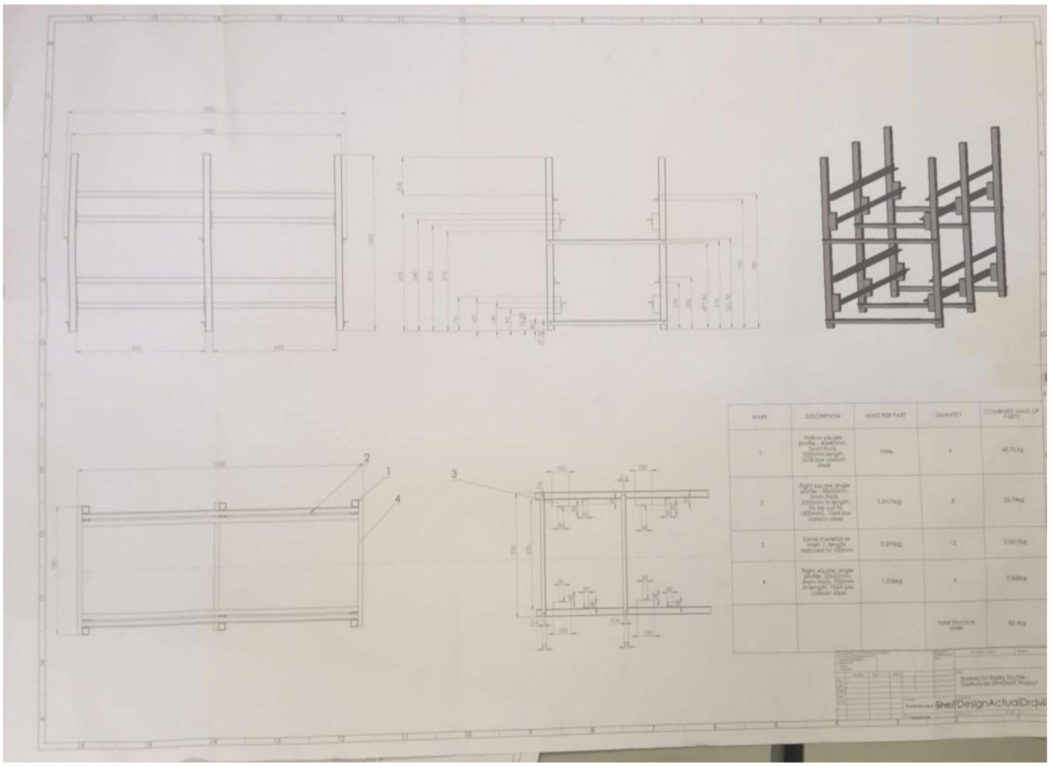

Figure 13 - Final Shelving Unit Design Technical Drawing

5.3 Lifting Mechanism

5.31 Cam Design

Once it was decided that the four-bar mechanism would be the chosen lifting mechanism for the prototype, the method was researched further and a plan for the design was made. The theory behind the design was that a motor would rotate a shaft through means of a pulley system. At either end of this shaft would be a large cam which would have a centre of rotation not at the centre of the part. This displacement from the centre created a change in the maximum height the structure reached. The change in maximum to minimum height was two times the displacement from the centre of the part to the centre of rotation.

It was concluded that the cam used to rotate the shaft and the potential eccentricity which could be used from this was the most important part of the design and should therefore be the starting point. The University resources were examined and two large bearings were found which had large enough a diameter for a significant eccentricity.

It was concluded that this bearing could be constructed with its centre of rotation 1.5cm from the centre of the part. This meant that a half rotation of the bearing could displace a total of 3cm. This allowed the expectations for the lifting mechanism to be met if the rest of the assembly could be constructed successfully around it.

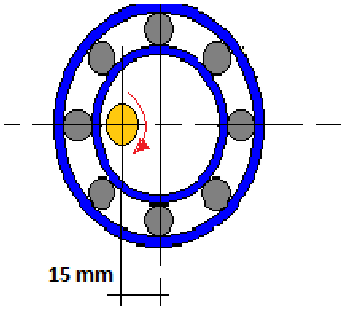

Figure 14 - Representation of Rotation of the Cam

The plan to implement this design was to use the 3D printer at the University to create a part which would be placed on the inside of this cam with a 'key hole' cut 1.5cm from the centre which a section of the shaft would pass through. The rotation of the shaft would cause the bearing to rotate, changing the height of the lifting mechanism.

Figure 15 - Example of the Cam with Filler Piece

5.32 Shaft Support and Design

A pulley system was selected to power the lifting mechanism (as well as the driving system). Drums to support this were acquired from the laboratory storage and modelled on Solidworks with the motor that had been selected. With only the pulley drum and the bearings at the end of the shaft it was estimated that there would not be enough strength to support the torque that the lifting mechanism would be subject to due to the length of the shaft. To accommodate, it was suggested that more bearings would be placed along the shaft to provide further structural support. A design for the supports for the bearings to be contained was created on Solidworks as two parts and assembled as follows (the design of which will be covered in more depth in section 5.5):

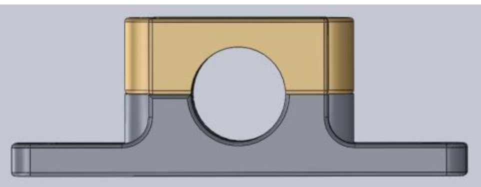

Figure 16 - Lifting Shaft Support Assembly

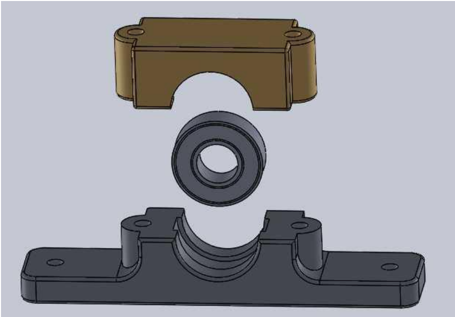

Figure 17 - Lifting Shaft Support Assembly Exploded View

Bolt holes were left in the far ends of the bottom part of the holder to allow it to be bolted into place wherever necessary, and also across the two joining parts which would allow the two parts to be held together by screws. These parts were made according to a set of small bearings that were found in the small workshop of the University. These were also modelled on Solidworks in order to complete the full model of the structure. The inner diameter of these bearings was 12.5mm, which determined the shaft which was to be used for the lifting mechanism. It also gave a final indication as to the relevant dimensions for the key part for the bearing which would be placed below the 4-bar mechanism.

The drum which was to be connected through a belt was connected to the shaft through means of a keyway. A small cut was to be taken from the centre of the shaft (where the drum was positioned on the model), and a key placed in this. A cylindrical piece was designed to fit around the shaft on the inner circle. A later design was required to hold the drum with the outer circle by means of an extrusion and a cut in the drum as will be discussed in section 7.1. This part was to be printed because of its small size and precise nature.

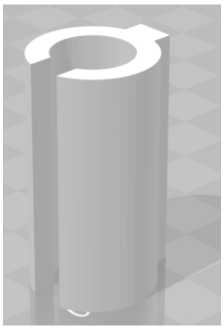

Figure 18 - Plastic Part to Join Drum to the Shaft

5.33 4-bar Mechanism Design

The dimensions of the entirety of the 4-bar mechanism were the most important parts to consider during the design. At this point of the overall design, the base plate had been decided upon as well as the aluminium profile strengthening and the rough positioning of the drive shaft. From this the overall height of the 4-bar mechanism at its lowest position could be determined since the shelves had already been manufactured at this point of the process. The aim was to have the lowest position of the structure to sit 5-10mm below the section of the shelves on which the pallets rested upon. The client requested that the top level of the 4-bar mechanism be as long as possible without interfering other areas of the design in order to make the lifting of the pallet as steady a process as possible since the support to the lifting plate would be spread more effectively. Upon research of the mechanism and recognition of the type of cycle the mechanism would undergo (a half cycle one way, followed by a half cycle in the opposite direction repeatedly) it was noted that the mechanism was not to ever be in a position to 'lock'. This meant that from angle from the ground to the vertical bar was not to be at an angle of 90 degrees. This was due to the fact that an external force would be required to aid the movement of the mechanism which would not be appropriate for the overall design of the radio shuttle. The group concluded that the best way to satisfy these targets was to situate the 4-bar mechanism at a relatively low angle at the low position. This would allow the mechanism to have more flexibility during construction and significantly minimise the chances of the mechanism ever locking. The slanted nature of the mechanism would also allow the length of the top bar of the mechanism to be longer and give the steady lifting process that the client requested. There were two primary limiting factors to this angle for the lifting mechanism. The first was the fact that the position of the cam meant that a full rotation had to be possible on the underside of the mechanism so it was imperative that the angle at the top of the mechanism could fit this rolling part beneath it. The other, more difficult problem was the problem of the mechanism contacting either the drive shaft or the rolling axel for the other wheel set. Because of the varying positions that the mechanism would undergo, it was decided to employ a trial and error approach to this angle and size of design. The mechanism would be created on Solidworks with the necessary degrees of freedom to demonstrate the movement and placed into the overall design file to ensure that the part would be suitable. To ensure the accuracy of this the technical manager of the group suggested that the group should decide upon which parts would be manufactured for the mechanism in order to be extremely specific with the design. At this point one of the group members had created an approximate Solidworks model of the 4-bar mechanism with appropriate dimensions but without a specific view to what parts to use.

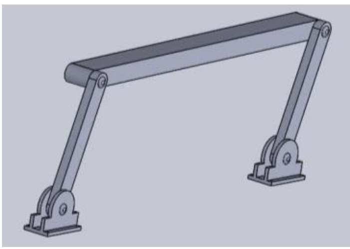

Figure 19 - 1st Design of 4-bar Mechanism

This design was based under the assumption that thin rods would be available to be bolted and rotate around the top corners. However the dimensions of the design at that point of the process dictated that the lifting mechanism would have to be a relatively small. The manufacture of the design would be tricky and would require the purchase of more parts. At a weekly meeting the financial manager indicated that at this reasonably early stage of the project he was reluctant to purchase more parts since manufacturing costs later in the process were to be expected. The process of deciding how to manufacture the 4-bar mechanism became the primary job for the group to work on.

One suggestion, due to the intricate and small nature of the part was that it could be created using the 3D printer. This solved the problem with regards to the manufacture of the parts, but caused more problems on the financial front due to the expense of printing. Another problem with this suggestion was keeping to the time frame of the Gantt chart since the part still had to be designed in full and the printing of parts of this size would be a lengthy procedure. The time constraint issue would have possibly been solved by rearranging the Gantt chart, but the data manager pointed out that should anything change in the design or any problems be encountered during manufacturing there would not be enough time or money to amend and reprint the parts.

It was decided that the 3D printing would be necessary to some extent for completion of a functioning lifting mechanism but that a compromise should be made in that only certain parts of the mechanism should be printed. There was leftover aluminium profile from the structure of the base plate which was also reasonably cheap to purchase as well as being deemed light enough for the mechanism. The thinness of the part also made the part ideal for manufacturing since it could be cut and drilled with ease. From this a basic design was created where two 3D printed parts could be slotted into the profile and bolted. There would be a square section at the bottom of the part to slot into the profile and the outer edges would slot together with a space for a bolt hole to join the two. These parts followed the basic design as follows:

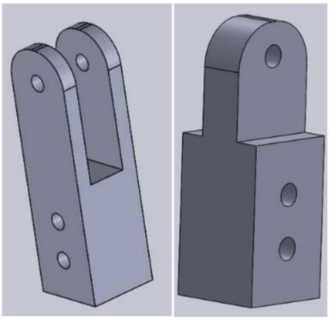

Figure 20 - Initial Joint Design for 4-bar Mechanism

With this the aluminium profile could be used as the primary body of the mechanism with 3D printed parts to join and bolt them together. The holes in the joint would line up with drilled holes in the aluminium profile in order to bolt them. A similar type of theory was used to mount the mechanism to the ground. The design of the mounting part is displayed below.

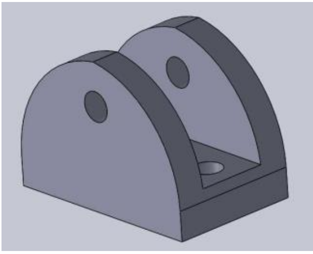

Figure 21 - Mounting Part for 4-bar Mechanism

The entirety of this design was then modelled on Solidworks with the bottom parts of the mounting joints fixed, representing how they would be bolted in the prototype. The degree of freedom allowed for the necessary movement which would be present for the final design.

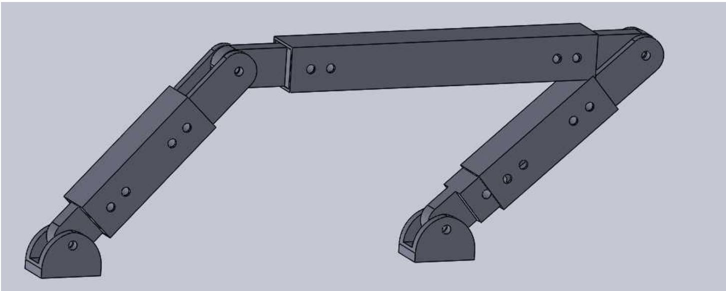

Figure 22 - Initial 4-bar Mechanism Design with Actual Parts

The problem this lifting mechanism posed was that when the angle between the ground and angled bar was small, the edges of the aluminium profile would collide with each other as shown in the top right corner of Figure 22. The difficulty of this was made more so because increasing the length of the 3D printed parts would: increase the cost of the part; minimise the size of the aluminium profile rendering the design less useful; and also expose the part to significant maximum forces from the loaded pallet during motion. Instead of this, it was decided to make the 3D parts that were to be printed curved as they exited the profile. An example of one of these parts is shown in Figure 23:

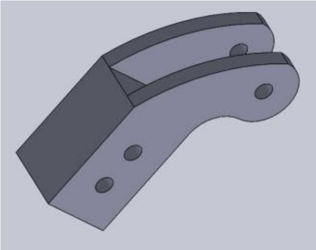

Figure 23 - Curved Joint Design for 4-bar Mechanism

At this point of the design process the parts to be used were essentially decided upon. The trial and error process began to fit in the relevant dimensions of the mechanism and then an attempt was made to fit the mechanism with the entire model. After a few iterations the final design was decided upon.

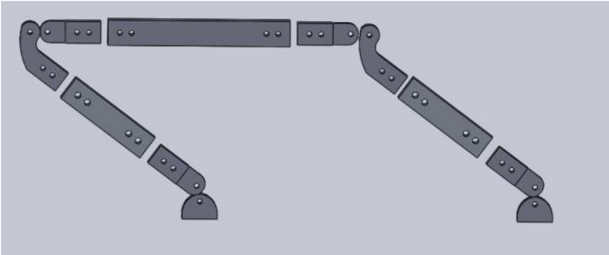

Figure 24 - Final 4-bar Mechanism Design Exploded View

To ensure that the mechanism fit into the model, one version of the assembly was fixed in the low position (LP) and another in the high position (HP). Both versions were implemented in the final overall model to make sure they did not clash with the other shafts.

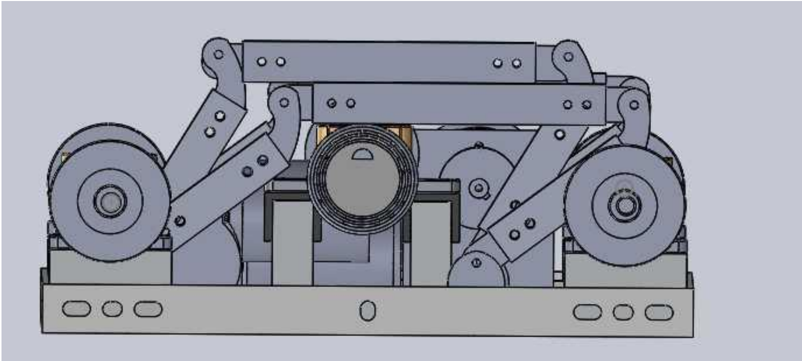

Figure 25 - Final 4-bar Mechanism within Overall Model at LP and HP

5.34 Lifting Shaft Calculations

5.341 Background Information

One section that was seriously considered for the prototype was the problem of fatigue loading on the lifting mechanism. The practical use of the radio shuttle would undergo a significantly high number of cycles in its lifetime. The design of the lifting mechanism should be able to withstand this motion with a loaded pallet. The length of the shaft for the lifting mechanism also made it susceptible to a potential failure. For the prototype itself it was necessary to calculate the maximum load that would be possible to test. However after a meeting with the client it was decided that to sufficiently consider the problem of fatigue failure a Matlab script was to be created where the diameter of the shaft, the length of the shaft, the maximum load and any other variable factors could be altered to ensure that it could be considered safe for use regardless of the scale of the new project. An example of this type of script that was created has been included in the appendices.

The fatigue of the shaft was considered at the centre of the shaft which was recognised as the most likely point of failure of the lifting mechanism shaft. This was because it was the furthest point from any of the supports, as well as the fact that during the motion of the lifting mechanism the tension of the belt will act on the shaft.

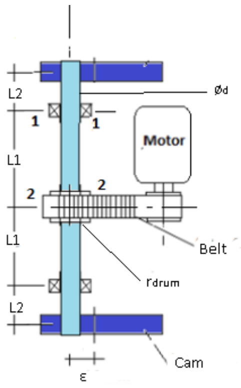

Figure 26 - Schematic of Lifting Mechanism Shaft

5.342 Fatigue Endurance for Actual Prototype with $F_{max} = 1000N$

Section 2-2 – The task was to check if this section (d=12.5mm) can withstand 1000N per the clients request. If not, the necessary diameter for this load was to be applied and what the actual maximum load for the prototype would be. Equations and coefficients to fit the clients request were provided and used for the theory of the endurance equations (10).

The first part of the section to consider was the torsion on the shaft.

$$M_t = \frac{F_{max}}{2} x\varepsilon \qquad \varepsilon = 15mm$$

$$J_{max} = (-J_{min}) = \frac{M_t}{W_t} = \frac{M_t}{\frac{\pi d^3}{16}}$$

$$J_{max} = 19.56MPa$$

After this the bending moment was calculated. To do this the bending in each direction had to be considered. First the bending cause by the tension in the belt was calculated, represented by:M_{bh}, followed by the bending due to the shear force, M_{bv}, which considered the distance L_1 between the centre of the shaft and the bearing holder. These were combined to give an overall bending moment.

$$M_{bh} = T\ x\ r_{drum} \qquad T = \frac{F_{max}}{2} \qquad r_{drum} == 31.5mm$$

$$M_{bv} = \frac{F_{max}}{2}\ x\ L_1 \qquad L_1 = 200mm$$

$$M_{bending} = \sqrt{(M_{bh})^2 + \left(M_{bv}{}^2\right)}$$

$$M_{bending} = 101232.7\ Nmm$$

Once the bending moment was calculated, the stress due to bending could be calculated.

$$\sigma_{\max bending} = \frac{M_{bending}}{W_b} = \frac{M_{bending}}{\frac{\pi d^3}{32}}$$

$$\sigma_{\max bending} = 527.95MPa$$

Using these two stress values, the overall maximum stress could be calculated.

$$\sigma_{max} = \sqrt{\left(\sigma_{\max bending}{}^2\right) + 3\left(J_{max}{}^2\right)}$$

$$\sigma_{max} = 529.04\ MPa$$

The next task was to check the endurance limit to fatigue for the 12.5mm diameter shaft in question. If this limit was higher than the overall maximum stress calculated then the maximum load was considered acceptable for an infinite number of cycles. If not, the system would be likely to fail under fatigue loading. The calculation for the endurance fatigue contained constants which were calculated based on the material type (factors such as surface coefficient), diameter of the shaft and the type of motion that the mechanism was subject to. These values were provided by the clients technician, and the calculations verified by the client. as follows:

$$s_e = s_e'\ x\ k_a\ x\ k_\sigma\ x\ k_e\ x\ k_c\ x\ k_d$$

(k_c and k_d were not relevant to this problem since they considered a change in temperature, their value was therefore considered as 1 for the purpose of these calculations)

$s_e' = 0.5\ S_{ut}$

$k_a = 4.51\ x\ S_{ut}^{-0.265}$ - considered the surface coefficient and motorised shaft aspect of the problem.

$k_\sigma = (\frac{d}{7.62})^{-0.133}$ - considered the size coefficient.

$k_e = 0.54$ - this constant considered irregularities in the part. The value used is the constant for the keyway which was positioned at point 2-2 in the shaft.

The shaft material had S_{ut} equal to 550MPa.

Therefore:

$$s_e = (0.5\ S_{ut})\ x\ (4.51\ x\ S_{ut}^{-0.265})\ x\ \left((\frac{d}{7.62})^{-0.133}\right)\ x\ (0.54)$$

$$s_e = 118.54MPa$$

This value is significantly lower than the maximum stress which would be required for infinite cycles, so it was recognised that a maximum load of 1000N would not be possible for the prototype.

5.343 Necessary Diameter for Lifting Shaft for 1000N Load

The next calculation was to calculate what diameter shaft would have been necessary to support this load. The necessary diameter was a lengthy calculation which was the reason for the creation of the Matlab script. The calculation was done by hand first to ensure that the working was consistent with the script. The basic mathematical premise for calculating the necessary diameter was the following equation:

For the absolute minimum necessary diameter: $s_e = \sigma_{max}$

Which for this specific example:

$$s_e'\ x\ k_a\ x\ k_\sigma\ x\ k_e = \sqrt{(\sigma_{\max bending}{}^2) +\ 3(J_{max}{}^2)}$$

$$(0.5\ S_{ut})\ x\ (4.51\ x\ S_{ut}^{-0.265})\ x\ \left((\frac{d}{7.62})^{-0.133}\right)\ x\ (0.54)$$

$$= \sqrt{\left(\left(\frac{M_{bending}}{\frac{\pi d^3}{32}}\right)^2\right) + 3\left(\left(\frac{M_t}{\frac{\pi d^3}{16}}\right)^2\right)}$$

$$subbing\ in\ earlier\ values\ for\ M_{bending}\ and\ M_t\ and\ rerranging\ for\ d\ gives:$$

$$d^{5.7734} = 42.46\ x\ 10^6$$

$$d = 20.95mm$$

This value for d was calculated to be the minimum necessary diameter for the lifting mechanism shaft for the project prototype if a maximum load of 1000N was sought after.

5.344 Maximum Load for 12.5mm Lift Shaft Diameter Prototype

A similar premise was followed for the calculation of the maximum load F. The process began at the start except F_{max} was treated as an unknown, while for the 12.5mm shaft it was known that $s_e = 118.54MPa$ from the first calculation.

Calculating the relative torsion in terms of F_{max} was the first task.

$$M_t = \frac{F_{max}}{2} x\varepsilon \qquad \varepsilon = 15mm$$

$$J_{max} = (-J_{min}) = \frac{M_t}{W_t} = \frac{M_t}{\frac{\pi d^3}{16}}$$

$$J_{max} = \frac{7.5F_{max}}{\frac{\pi d^3}{16}}$$

$$J_{max} = 19.56\ x\ 10^{-3} F_{max}$$

The next task was to calculate the bending in the shaft in terms ofF_{max}.

$$M_{bh} = T\ x\ r_{drum} \qquad T = \frac{F_{max}}{2} \qquad r_{drum} == 31.5mm$$

$$M_{bv} = \frac{F_{max}}{2}\ \ x\ L_1 \qquad L_1 = 200mm$$

$$M_{bending} = \sqrt{(15.75F_{max})^2 + \left(100F_{max}{}^2\right)}$$

$$M_{bending} = 101.23F_{max}$$

From this, the stress due to bending could be calculated:

$$\sigma_{\max bending} = \frac{M_{bending}}{W_b} = \frac{M_{bending}}{\frac{\pi d^3}{32}}$$

$$\sigma_{\max bending} = \frac{101.23F_{max}}{\frac{\pi d^3}{32}}$$

$$\sigma_{\max bending} = 0.528F_{max}$$

The assumption that to find the maximum force for a known diameter gives the following equation:

$$s_e = \sigma_{max} \qquad\qquad where\ s_e = 118.54MPa$$

$$s_e = \sqrt{((0.528F_{max})^2)\ 3((\ 19.56\ x\ 10^{-3}F_{max})^2)}$$

$$s_e = \sqrt{0.28F_{max}{}^2}$$

$$F_{max} = \sqrt{\frac{s_e{}^2}{0.28}}$$

It was found that the maximum load for the lifting mechanism of the prototype was:

$$F_{max} = 224.02N \qquad (Maximum\ mass\ \approx 22.4kg)$$

The script that was created to best display this information and allow for further research was made to be as simple to use as possible. The initial variables contained at the start of the script were those that apply to the prototype example. For a change in the model this is the only point in the script which would need to be changed for further research. The variables are the same as the listed equations which have been explained in this section and are relatively simple to understand. Once the variables have been entered and the script has been run the results from the Matlab script will give values for σ_{max} and s_e. If $\sigma_{max} < s_e$ then the suggested system is acceptable. This script could be manipulated or progressed for specific industry aims. For example if a safety factor is requested for the fatigue loading then $\frac{\sigma_{max}}{2} < s_e$.

5.345 Lift Motor Power Calculations

The power required from the lift motor was found through the following calculations: (11)

Known values:

Diameter of cam bearing $\Phi = 68\text{mm}$

Shaft-Bearing offset $\varepsilon = 15mm$

Maximum Load $F_{Max} \cong 224N$

Lift shaft rotational speed $\omega_{liftshaft} = 12rpm$

Torque due to maximum eccentricity

$$\tau = F_{Max} \times \varepsilon$$

$$\tau = 224N \times 15 \times 10^{-3}m$$

$$\tau = 3.36Nm$$

Power required of the lift motor

$$P_{Req\ Lift} = \tau \times \omega_{liftshaft}$$

$$P_{Req\ Lift} = 3.36Nm \times 12rpm$$

$$P_{Req\ Lift} = 3.36Nm \times 1.257rad/s$$

$$P_{Req\ Lift} = 4.22W$$

Assuming 100% efficiency of the lift motor and no slipping between the cam bearing and 4 bar linkage the required Wattage of a lift motor was found to be 4.22W. The sourced motor of 9.6W was therefore more than adequate for the function of powering the lift mechanism.

5.4 Drive System

The design began with the procurement of a motor from the University workshop. Original testing of the motor found that it exhibited an output speed of 40 rev/min when powered by a supply of 8 Volts. The group presented this information to the client who was satisfied that this would be sufficient to propel the motor without its speed becoming excessive. Once the design of the driving system was finalised the group carried out calculations to estimate the operating speed of the shuttle and the power consumption of the motor.

Once the motor was deemed to be satisfactory for use it was modelled on Solidworks.

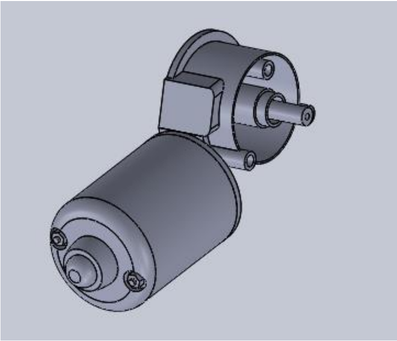

Figure 27 - 3D Model of Driving Motor

One of the advantages of using this motor was that it already came fitted with a gear speed reducer. This meant that during operation, once power was cut to the motor the motor shaft would immediately cease movement and the radio shuttle would stop instantly. The lack of a stopping distance would be very useful as it would result in the radio shuttle coming to a complete halt as soon as a sensor was tripped.

Several cylindrical metal rods of diameter 10mm and adequate length were also found which could serve as the driven and non-driven shafts. Models was created of 10mm diameter, 550mm long shafts and added to the design. The length was chosen so that the wheels of the drive system would fit on the rails of the shelving unit. The rods would then be cut to this length during the manufacturing stage.

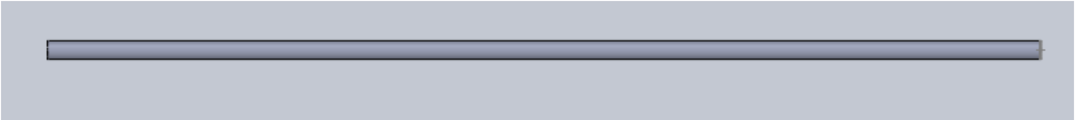

Figure 28 - 3D Model of Drive Mechanism Shaft

Wheels with a 10mm bore diameter were sourced and purchased from a local engineering warehouse. The model was then updated to include the purchased parts.

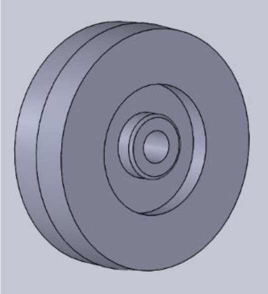

Figure 29 - 3D Model of Driving System Wheels

Once these parts were modelled all that was missing was a pulley system to transfer power from the motor to the drive shaft. A 300-3M-19 timing belt was found in the lab, unfortunately there were no accompanying pulley drums so it was decided these would have to be modelled and printed. Since the motor was capable of producing adequate power to propel the shuttle it was decided that a ratio of 1:1 between the diameters of the pulley drums would be sufficient. On the 3D model a number of different diameter drums were implemented to determine a dimension that would allow the drums to be joined by a 300mm belt and not create interference between the driving motor and the lifting shaft. Eventually a diameter of 47.5mm was chosen.

The motor chosen to power the drive system already had a key extruding from the motor shaft to avoid any gear mounted on it slipping. Therefore a small cut was made on the inside surface of the motor pulley drum.

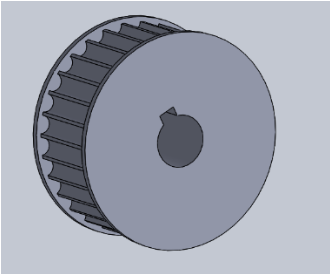

Figure 30 - 3D Model of Motor Shaft Pulley

The pulley drum to be mounted on the drive shaft was designed with excess material on one side that had a 5mm hole to allow for a bolt to be passed through and make contact with the shaft, ensuring transmission of power. A thread would have been too intricate for the 3D printer to fabricate, therefore a hole was created which would fit a 5mm nut. With the nut positioned inside the hole the bolt could be tightened until it made firm contact with the shaft.

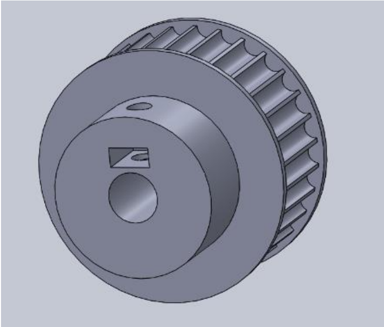

Figure 31 - 3D Model of Drive Shaft Pulley

These components were assembled to create the finalised model of the driving mechanism which is shown in Figure (32).

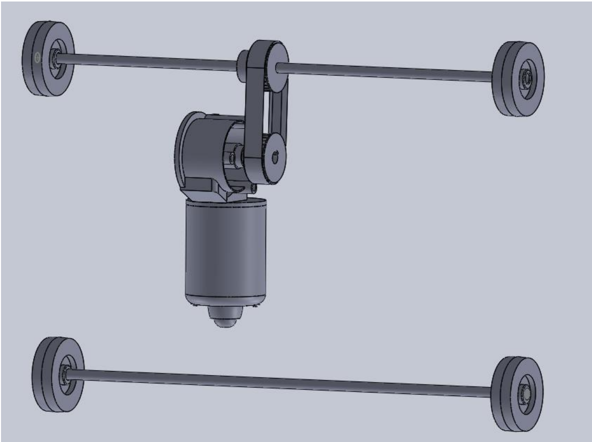

Figure 32 - 3D Model of Driving Mechanism

Once a design had been finalised for the driving system a small amount of calculation was done to estimate some performance characteristics. Firstly, the group wished to see what operating speed the shuttle would have when this mechanism was manufactured. To do this the rotational speed of the motor, measured in rev/min, was converted into rad/s:

$$\omega_{motor} = 40\ \frac{rev}{min} = 0.67\ \frac{rev}{s} = 4.19\ \frac{rad}{s}$$

Assuming the efficiency of the belt is 95% (12) then the rotational speed of the drive shaft would be:

$$\omega_{driveshaft} = \omega_{motor} \times \eta = 4.19 \times 0.95 = \frac{3.98rad}{s}$$

Then an estimate value for the velocity of the shuttle could be found using the radius of the wheels which was 37.5mm.

$$v = \omega_{driveshaft} \times r = 3.98 \times 0.0375 = 0.15\frac{m}{s}$$

At this velocity the shuttle would travel the length of the shelves in exactly 10 seconds. This was deemed an acceptable performance level for the prototype as the shuttle would move fast enough to be functional while still being smooth in operation.

Using this estimated velocity, a calculation was carried out to estimate the power required of the motor to drive the radio shuttle.

This involved approximating the resistive force the motor would have to overcome propel the shuttle using the following equation (13):

$$F_{Resistive} = c_l \cdot \frac{mg}{r}$$

An approximate mass of 30kg for the radio shuttle was used to obtain a rough value for the rolling resistance. The coefficient of rolling resistance for the rubber wheels interacting with the steel rails was taken to be 2mm (14):

$$F_{Resistive} = 2 \cdot \frac{30 \times 9.81}{37.5} = 15.7N$$

The power the motor would have to supply was then calculated using the following equation:

$$P_{Required} = \frac{F_{Resistive} \cdot v}{\eta_{Motor}}$$

Since the efficiency of the motor was completely unknown a cautious value of 0.8 was used.

$$P_{Required} = \frac{15.7 \times 0.15}{0.8} = 2.94W$$

During testing of the motor it was noted that the input value of 8V was accompanied by a current of 1.5A, assuming the same value of efficiency of the motor as that used above then the available power from the motor could be calculated as so:

$$P_{Motor} = \eta_{Motor} VI = 0.8 \times 8 \times 1.5 = 9.6W$$

These calculations indicated the motor would be capable of powering the drive system. However, it was still important to carry out tests before the system was implemented in a prototype to ensure this was the case.

5.5 Body and Auxiliary Pieces

In order to make a full 3D assembly model, several auxiliary pieces had to be created. This mainly involved designing supports for the key mechanisms.

The base plate was the main auxiliary component as everything would be directly or indirectly attached to it. Early iterations of the assembled model had a box like body that all the mechanisms of the shuttle would fit inside. An example of this can be seen below.

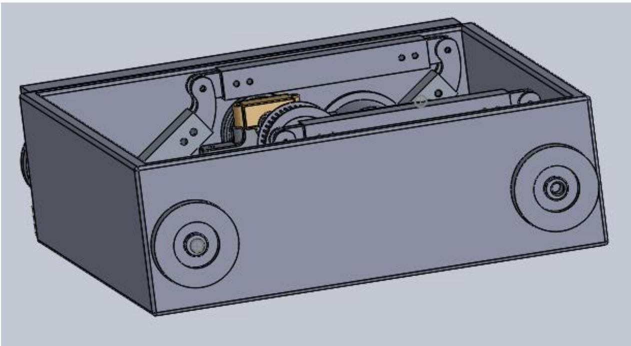

Figure 33 - Early Concept for Housing Radio Shuttle

However, during the design phase the client purchased a 600mmx400mmx1.5mm metal sheet which he requested be used as the base plate. This was incorporated into the model with the addition of hollow, square 25mmx25mm aluminium profile which the lifting mechanism would be mounted on to. This was necessary because the relative thinness of the base plate made it somewhat flimsy and most likely incapable of holding its shape while supporting the mechanisms.

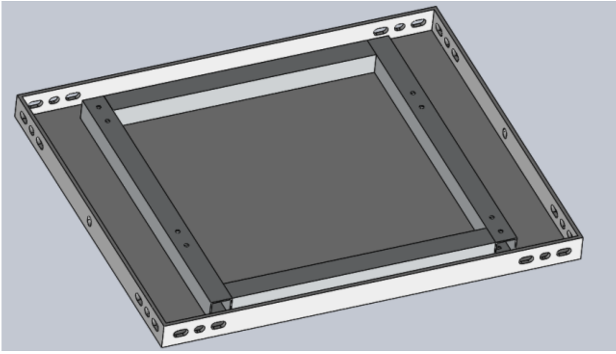

Figure 34 - 3D Model of Base Plate with Supports

It was also necessary to design supports for the lifting shaft and the driven and non-driven shafts of the driving mechanism. In both cases a similar design of bearing holder was used. The shafts of the lifting and driving mechanisms were designed to have diameters of 12mm and 10mm respectively. Bearings were found in the laboratory with both these bore diameters and a shared outer diameter of 28mm. The bearing holders were designed to be printed in two parts and then bolted together during manufacture. Both sets of bearing holders had a 28mm diameter groove designed in the middle to hold their respective bearings. As the bearings shared an outer diameter it was possible to design one upper part which would be used in both bearing holders, thus saving time on design. The bottom parts of the holders differed in height and width due to the different elevation required for each mechanism and the different width of each support.

For the shafts of the driving mechanism a slightly shorter bearing holder was used to allow the shafts to be closer to the respective ends of the shuttle. The bearing holder created can be seen in Figure 35.

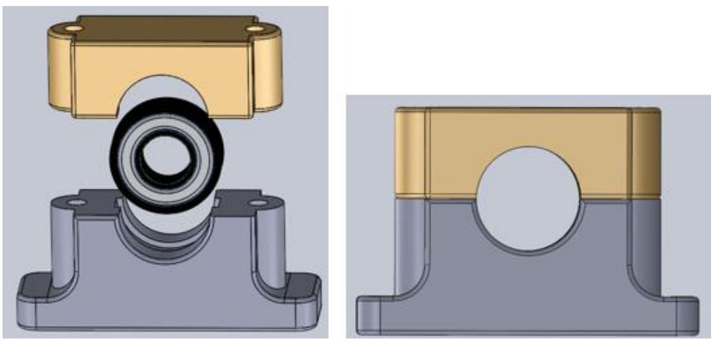

Figure 35 - 3D Model of Driveshaft Bearing Holder in Exploded and Assembled View

The height of the bearing holder was altered and it was mounted on additional supports so as to ensure the difference in height between the centre of the shafts and the top of the lifting mechanism at its lowest position was 72.5mm. This was the height difference that would allow the radio shuttle to pass beneath a pallet on the shelving unit without interfering with it yet be close enough to begin the lifting process as soon as the lifting mechanism was engaged.

The bearing holders for the drive shaft were to be elevated above the base plate using two 75mm long sections of the square aluminium profile mounted one on top of the other.

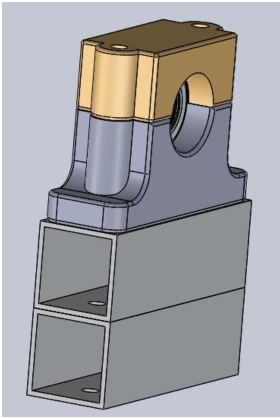

Figure 36 - 3D model of Support Mechanism for Drive System

Two of the supports shown in Figure 36 were mounted on each of the shafts in the driving mechanism.

The bearing holders for the lift shaft were made to be wider so that the weight it was supporting could be more spread out. Again the support was designed to be printed in two pieces and bolted together as referenced in section 5.32.

The bearing supports for the lifting mechanism had to be elevated to a height of 85mm above the base plate as this would again allow the radio shuttle to pass below a pallet on the shelving unit when the lifting mechanism was in its lowest position. To achieve this the square aluminium profile was again used although this time mounted vertically. In order to attach the profile to the base plate and the bearing support small pieces were designed which would fit inside the profile at either end and allow for bolting to the appropriate surface.

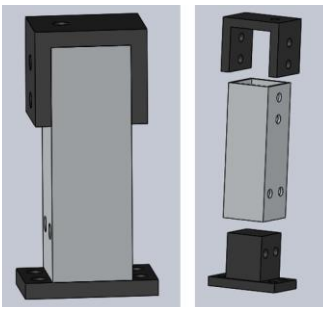

Figure 37 - 3D Model of Bearing Holder Supports in Assembled and Exploded Views

Two of the supports shown in Figure___ were used to support one bearing holder. The holes in the plastic component at the top of the support were designed to line up with the holes in the bottom piece of the bearing holder. During manufacturing the whole support could be joined by introducing a bolt and nut.

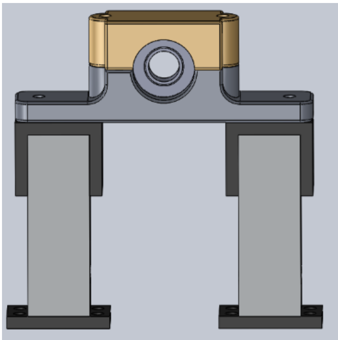

Figure 38 - 3D Model of Support Mechanism for Lifting System

The two motors which would power the key mechanisms of the radio shuttle also required support. This was done by designing L-shaped supports with holes to allow for bolting on using threads already present on the motors. Holes in the base of the supports were inserted so that they could be bolted to the base plate.

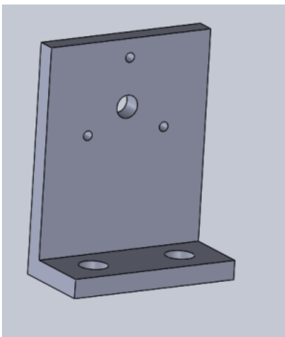

Figure 39 - 3D Model of Driving Motor Support

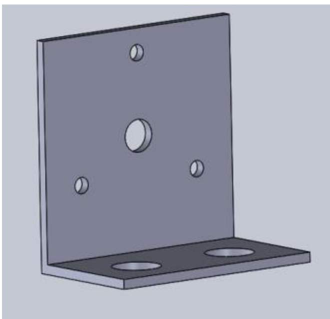

Figure 40 - 3D Model of Lifting Motor Support

5.6 Final Approved Model

Starting with the base, the model was assembled whilst carefully considering the position of each component in order to save space and avoid any interference. During the assembly process, some components positioning was modified constantly to try and provide the optimum layout. The 4-bar linkage, both motors and supports were re-positioned on numerous occasions to ensure the manufacturing process would be as trouble-free as possible.

Once the group was satisfied with the layout the final 3D model was presented to the client who was satisfied that it depicted a thorough and well thought out design which would satisfy the requirements of the brief once manufactured. An image of the final design presented to the client is shown in Figures 41 and 42.

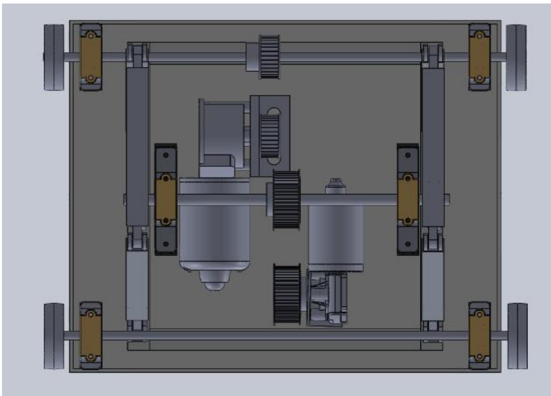

Figure 41 - Plan View of Final 3D CAD Model

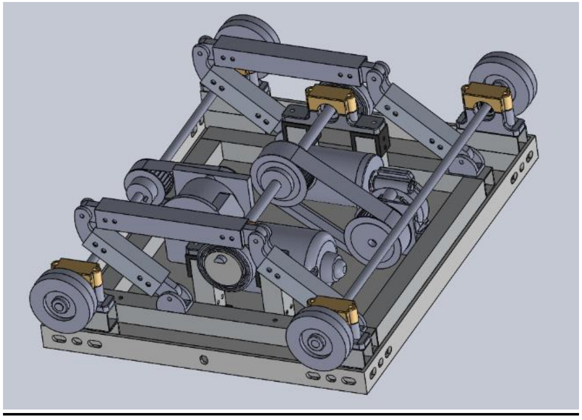

Figure 42 - Final 3D CAD Model

(Technical drawings of all the components mentioned in this section have been included in the Appendices)

6.0 Manufacturing and Testing

6.1 Shelving Unit Manufacture

Upon acquisition of the parts, the construction methods which would be used to successfully implement the potential design of the shelves with the available resources at the university were determined. It was identified that the low-carbon steel parts which had either been selected or purchased would all be able to be cut to required lengths where necessary. It was also recognised that the material would be suitable for welding, which was the chosen method for the majority of the construction. The transverse bars were decided that they could be bolted in, and holes would be drilled in selected places in the supporting bars to allow for this. It was also a possibility that the track bars for the wheel base would be bolted on to the construction, however this was to be consulted with the university technician. While bolting the track bars would give the system slightly more flexibility, it was also pointed out that having the primary components of the shelving system essentially being one part could be advantageous.

This assembly drawing was taken to the university technician with the acquired parts to consult which construction methods would be used. Permission to use a miter saw in the laboratory was given to us in order to cut the parts to their determined lengths, while the rough edges were to be removed using a rotary deburring machine. The position of the holes were indicated in the assembly drawing and were subsequently drilled into all necessary parts. These methods had been performed by all members of the group before on previous exchanges so after a short safety briefing the group successfully completed these tasks independently.

The method of welding was Arc welding. This was advantageous to the group as firstly arc welding creates a bond with similar strength properties to the parent material, giving the strength of bond required for use as shelves. Secondly group members were already experienced in Arc welding as it featured in previous University modules. The technician supervised the first welding job, which was joining the extra blocks onto the supporting bars and advised throughout. The second job was to weld the right angle bars along the length of the structure (for the track and for the pallets to rest upon). The technician advised that he would demonstrate the second job before allowing the group to attempt this due to the precise nature necessary for the building of this part.

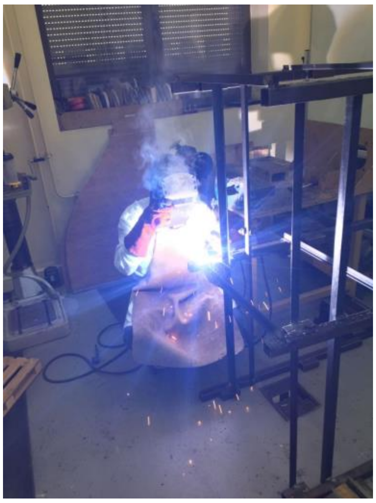

Figure 43 - Welding Example

The final job was to attach the transverse bars to bring the structure. The resources at the university dictated that not all of these bars could be identical, two of the bars were in fact extremely thin. The group were unsure whether bolting this bar would provide the necessary stability required for the project, so the design was altered to in fact have these bars also welded to the structure. This meant that the overall structure of the shelving was essentially one part and was completed as such. The first level was the only level completed at this point, but as mentioned previously this could be adapted later in the project if necessary.

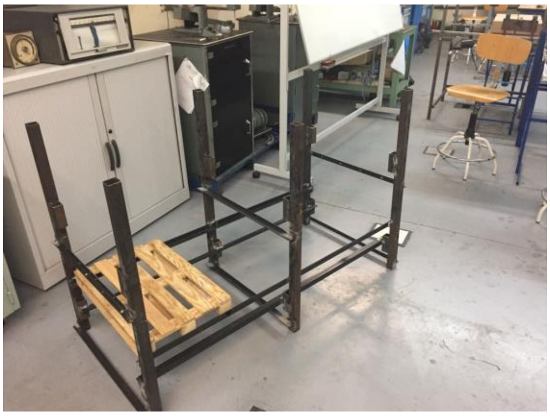

Figure 44 - Shelving Unit

The final stages of the shelving construction included spray painting the shelving to improve the aesthetics of the shelves and also to increase the lifetime of the prototype by protecting the parts. Another part that was included in the final construction of the shelving were plastic blocks which were inserted into the supporting bars closest to the ground. This protected the floor of the laboratory when testing the prototype and also gave a completely level surface from which to work upon.

6.2 Lifting Mechanism

6.21 Lifting Mechanism Manufacture

The following table summarises the manufacturing operations completed and selected materials of the individual components required for the lifting mechanism.

Table 6 - Lifting Mechanism Component's Materials and Operations

Part Description	Manufactured/Sourced	Material	Operations
Lift Shaft	Manufactured	1060 Steel	Milling
Shaft Bearings	Sourced	Various	-
Cam Bearings	Sourced	Various	-
Cam Bearing keys	Manufactured	ABS	3D Printing
4 Bar Linkage Links	Manufactured	2024 Aluminium Square Hollow Bar	Sawing, Deburring, Drilling
4 Bar Linkage Joints	Manufactured	ABS	3D Printing
Bearing Holder	Manufactured	ABS	3D Printing
Bearing Holder Top	Manufactured	ABS	3D Printing
Bearing Holder Mounts	Manufactured	2024 Aluminium Square Hollow Bar	Sawing, Deburring, Drilling
Top Mount Fixing	Manufactured	ABS	3D Printing
Bottom Mount Fixing	Manufactured	ABS	3D Printing
Belt Spools	Sourced	4310 Steel	-
Lifting Plate	Manufactured	2024 Aluminium	Drilling and bending
Belt	Sourced	Polypropylene	-
Motor	Sourced	Various	-
Fasteners	Sourced	18-8 Stainless Steel	-

<u>Lift Shaft</u>

A shaft used to transmit power from the electric motor to the lifting mechanism. One piece of 1060 steel bar, diameter 12mm, was cut to 370 mm using a Mitre saw and milled to produce a geometry that would fit into the bearing keys. The shaft was milled using a hybrid manual/CNC milling machine. This operation was carried out by a trained University technician.

<u>Shaft Bearings</u>

Bearings used to support the shaft and allow it to turn were sourced from the University warehouse. These were appropriately sized to accommodate the shaft.

Cam Bearings

Bearings to be used in a similar manner as cams were also sourced from the University warehouse. These were appropriately sized to accommodate the bearing keys attached to the lift shaft.

Cam Bearing Keys

Keys to fit inside the cam bearings and act as a connection between the bearing and the shaft were 3D printed using ABS plastic. Due to their complex profiles 3D printing was a more economically viable option than milling and turning a metal key. The process required an upload of the designed CAD file and typically took 2-3 hours to complete.

Figure 45 - Cam Bearing With Inserted Key

4 Bar Linkage: Links

The links for the 4 bar linkage to function as the lifting mechanism were manufactured from 2024 Aluminium. Hollow Square Aluminium bar was cut to length using a mitre saw and deburred. Holes were drilled to accommodate the fixings that joined the linkage. Aluminium was chosen due to its favourable strength to weight ratio for the function of the linkages.

4 Bar Linkage: Joints

Parts to connect the aforementioned aluminium links were created through 3D printing using ABS plastic. These parts possessed holes on one end that lined up with those of the aluminium links and were fastened together. On their other ends joint parts connected together to form pin joints. Due to their complex profile, these parts were 3D printed. This decision was made as machining these parts out of metal would prove expensive, time consuming and complex. Additionally ABS is considerably lighter and subsequently reduces the torque required of the motor to engage the lifting mechanism.

Figure 46 - Complete Four Bar Linkage

Bearing Holder (and Top)

Used to stop any translational movement of the bearings and keep them in place. The holders were sized to fit the bearings on the lift mechanism shaft and accommodate fasteners. Due to the complex profile of the holders these parts were also elected to be manufactured through 3D printing. This meant that these parts could be made quickly, accurately and kept the overall weight of the Shuttle down.

Bearing Holder Mounts

Mounts to position the Bearing holders and bearings at the correct height; i.e. at the designed height of the lift mechanism shaft. Hollow Square Aluminium bar was chosen due to its availability. Additionally its profile was appropriate for this role. Long and fairly thin, the Aluminium takes up little precious space inside the Shuttle. Moreover its high strength to weight ratio was very desirable, especially since there were four of this part. The parts were cut to length using a Mitre saw and deburred. Holes were then drilled using a pedestal drill for later fixings.

Mount Fixings

Parts used to fit inside the hollow square aluminium mounts on their top and bottom sides and fix them to bearing holders and the base of the Shuttle respectively. As they had to closely match the inside dimensions of the square bar, 3D printing was chosen as the manufacturing method due to its accuracy. This was justified as there were 8 of these parts in total. 3D printing ABS kept weight and geometric irregularities between them to a minimum.

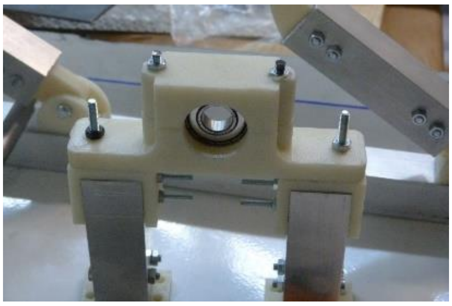

Figure 47 - Lifting Mechanism Bearing Holder Assembly

Lifting Plate

The lifting plate was the surface used to lift, carry and lower the pallet. A 1.5mm thin plate of 2024 Aluminium with a checker grating texture was sourced due to its light weight, workability and grip qualities. The plate was cut into two plates of dimensions 350mm x 140mm and bent along its length to fold over the lifting mechanism. Holes were drilled in the plates so that it could be fixed to the four bar linkage using fasteners.

Figure 48 - Lifting Plate

Sourced Components

Components which could not be manufactured where sourced from the University warehouse store or an external supplier. Their selection was largely based upon availability therefore the end design had to fit around the geometric and mechanical qualities of these components. Sourced components included; Belts, Belt Spools, Motors and Fasteners (Nuts and Bolts).

In summation materials and manufacturing methods have been selected with the intent of minimising weight of components and reducing required time to manufacture. The methods chosen also successfully worked around the constraints of available materials and components supplied by the University.

6.22 Lifting Mechanism Testing

Once all the relevant pieces had been manufactured or printed (including the drive shaft cut sections for the bearing filler pieces and key-way section) the lifting mechanism could be manually tested in order to determine if the design was sound and could be assembled into the radio shuttle design. A test station was composed to test the lifting mechanism separate from the shuttle body itself. This was in order to ensure adequate space was available for modifications and so that shaft or motor supports were not obstructing the view. The test of the lifting mechanism was undertaken separately in case the linkage was to fail at any point and damage components within the radio shuttle assembly.

The testing station was set up on a work top where multiple pieces of spare wood were used to create the appropriate height for the lifting shaft (subsequently the cam bearings) and the 4-bar linkage. Simple nails and screws were utilised to secure the structure to a suitable degree and there was an emphasis on keeping all dimensions (especially the distance between the bases of the 4-bar linkage) as close to the Solidworks model of the radio shuttle as possible. The testing station was deemed appropriate when the following were true:

- When the lift shaft was in the “fallen” position the main bearings remained in contact with the linkage, but caused no “lift”
- There was minimal lateral movement across the entire structure
- The 4-bar linkage returned to its default position once the bearing rotated towards its minimum position
- The pulley drum rotated with the lifting shaft without any slip

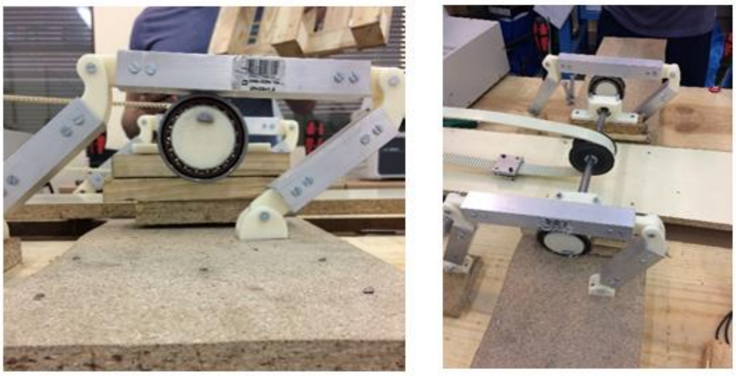

Figure 49 - Lifting Mechanism Test Setup

Once this had been confirmed, a quick manual test with a belt was proposed to determine if the sequence worked properly with a belt exerting tensile force to rotate the shaft. The only belt available at the time which was compatible with the teeth of the pulley drum contained a fastener and therefore was not a “clean” belt. Caution would have to be made during testing so that the fastener did not rotate around the pulley drum and possibly disrupt the operation.

Upon testing the mechanism by hand and in both a clockwise and anti-clockwise rotation, the linkage performed adequately and encountered virtually no issues, even when a pallet was placed directly on top. Very little resistance was encountered and the structure itself appeared very secure. The approximate achieved “lift” of the linkage was measured at this stage and it was extremely close to the desired 3cm target. The lifting motor was then introduced and the same test conducted to mimic the procedure within the radio shuttle itself where the motor would rotate the belt and subsequently the lifting shaft.

Figure 50 - Hand Manoeuvred Lifting Mechanism Test

Note that the inclusion of a motor with a speed gear reducer was vital for the lifting mechanism as it allowed the shaft to stop at the precise point to lift the linkage fully once the power had been cut. If this wasn't the case, the shaft would have over rotated and the linkage would raise a load to the maximum height. Therefore, the pallet would not have been able to be transported across the shelves as it would not have been lifted free from the track it rested on.

Before testing with the motor it was recognised a low voltage should be utilised when performing the lifting procedure, especially with relatively little load involved in case the rotation was too abrupt that it would cause the pallet to move out with the correct position or potentially damage any load contained within. Due to the fastener, only half rotations were performed during the test where the polarity of the wires was swapped once the bearing reached the maximum position. Due to the length of the belt, the motor had to be held slightly further apart from the testing station so that the belt remained in tension (an appropriate length of belt to be included in the radio shuttle body was made soon after once extra material was sourced).

Figure 51 - Lifting Motor

Initially, once the motor was switched on the pulley on the lift shaft rotated as normal and the linkage once again lifted and descended as it was designed to. Note that at this stage a low voltage (less than 5V was utilised). As the voltage was increased, it became troublesome to cut the power supply in time so the bearing would rest at its maximum position (electrical sensors to make the process automated would be extremely useful in this case).

Once a load was added on top of a pallet on the test station it was clear the motor was struggling to lift it, especially at a lower voltage. Additionally it was noted that the drum attached to the motor was actually slipping off the shaft gradually after each rotation. The team discovered there was a loose screw in a keyway of the shaft which secured the drum. Using an Allen key, the drum was properly fixed to the motor shaft and the test was performed again, this time without any unwanted movement independent of what voltage was supplied.

Unfortunately, when a larger load was placed on the pallet and a test was conducted, slip between the lift shaft and the pulley drum encompassing it was significant. While the drum was rotated due to the belt, the shaft did not always rotate in synchronisation and subsequently the linkage was not hoisted and the load was not lifted.

A slight modification to the “sleeve” connection within the pulley drum and lifting shaft itself was to be made in order to solve this issue (see section 5.32). With this measure in place, it was assumed the added friction between pulley drum and lifting shaft had been enhanced sufficiently enough to omit any slip. This was indeed the case when further testing was carried out with a substantial load. The belt rotated the pulley drum surrounding the lifting shaft and in-turn the shaft was rotated. Therefore, the bearings could appropriately support and then lift the linkage and subsequently support the load.

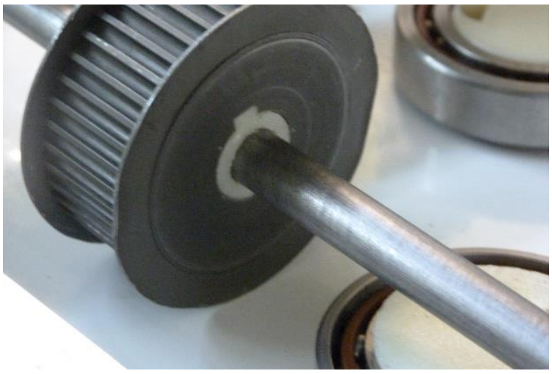

Figure 52 - Lifting Pulley Drum

Once the lifting mechanism had been tested and validated, it was possible to remove the nuts and screws fixing it to the testing station and instead secure them to the relevant points on the radio shuttle base plate and frame.

6.3 Drive System

6.31 Drive and Shuttle Base Manufacture

Table 7 - Drive System Component's Materials and Operations

Part Description	Manufactured/Sourced	Material	Operations
Drive Shaft	Manufactured	1060 Steel	Milling, Sawing
Shaft Bearings	Sourced	Various	-
Wheels	Sourced	Polyvinyl chloride	-
Shaft spacers	Manufactured	Copper	Sawing
Shaft stoppers	Manufactured	ABS	3D Printing
Bearing Holder	Manufactured	ABS	3D Printing
Bearing Holder Top	Manufactured	ABS	3D Printing
Bearing Holder Mounts	Manufactured	2024 Aluminium Square Hollow Bar	Sawing, Deburring, Drilling
Pulley Drums	Manufactured	ABS	3D Printing
Belt	Sourced	Polypropylene	-
Motor	Sourced	Various	-
Fasteners	Sourced	18-8 Stainless Steel	-

<u>Drive Shaft</u>

The component used to transfer power from the electric motor to the wheels of the Shuttle. One piece of 1060 steel bar, diameter 10mm, was cut to 530 mm using a Mitre saw. To later accommodate components that would prevent lateral translation of the shaft the geometries of the ends of the shaft had to be altered using a hybrid manual/CNC milling machine. This operation was carried out by a trained University technician.

<u>Shaft Spacers</u>

Thin hollow cylindrical pieces of copper were cut to length and were placed over the shaft between the wheels and the bearings to help prevent translational movement. The pieces were cut manually with a coping saw.

<u>Main Wheel Filler Piece (Shaft Stopper)</u>

Small pieces designed and 3D printed to fit on the ends of the shaft and fill the previously milled spaces. With one end of these pieces being of a larger diameter than the shaft and wheel bore, these pieces prevented translational movement of the drive shaft in the outward direction.

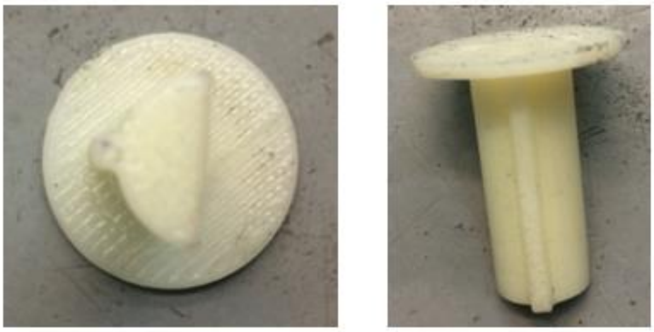

Figure 53 - Shaft Stoppers

Bearing Holders

Almost identical to the holders used in the aforementioned lifting mechanism these were used to stop translational movement of the bearings and keep them in place. The holders were also 3D printed.

Bearing Holder Mounts

Mounts to raise the bearing holders and bearings to the designed height of the drive shaft. These mounts consisted of small hollow rectangular 2024 Aluminium bar. The aluminium was chosen due to its availability in the University workshop. Additionally it was lightweight and large enough to comfortably accommodate a bearing holder. The Aluminium was cut to length with a Mitre saw and the cut cleaned. Holes were drilled for fasteners using a pedestal drill.

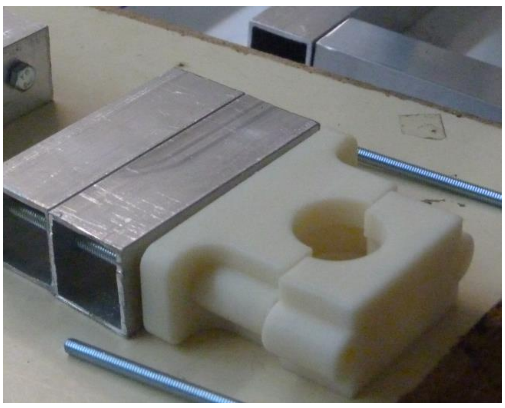

Figure 54 - Drive Mechanism Bearing Holder Assembly

Pulley Drums

Similar to gears, cylindrical components with small teeth matching those of the belt were constructed. These components were constrained to the design of the sourced belt to be used for the drive system. Since drums could not be sourced out with the University due to time and budgetary constraints the spools were designed on Solidworks and 3D printed.

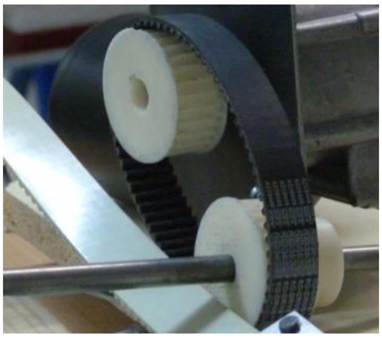

Figure 55 - Pulley Drums and Belt

Sourced Components

Once again, components which could not be manufactured such as the Belt, Drive Motor Wheels, Bearings and Fasteners were sourced from the University store or an external supplier. Due to availability the design of the Belt, Motor and Wheels dictated the design of the components to be manufactured.

The two aforementioned systems where fixed onto a base plate acting as the structure of the radio Shuttle. A plate of 1mm thick sheet aluminium with folded edges was cut to dimensions 490 mm x 400 mm. This plate was sourced from the external supplier Leroy Merlin. Due to the limited thickness of the plate it did not possess the required strength to hold the weight of all components without deformation. A simple structure designed to significantly increase rigidity was put in place to great effect. Four Aluminium Square Hollow Bars cut to length were fixed to the top of the plate and arranged in a square shape. This allowed for the heavy components of the drive and lift systems to be placed onto the plate without it flexing or buckling. The components of the two systems were all fixed onto the base plate or Aluminium structure by using nuts and bolts. These were chosen due to their availability, effectiveness and ease of application. Bolts that protruded through the base plate were shortened using hacksaws.

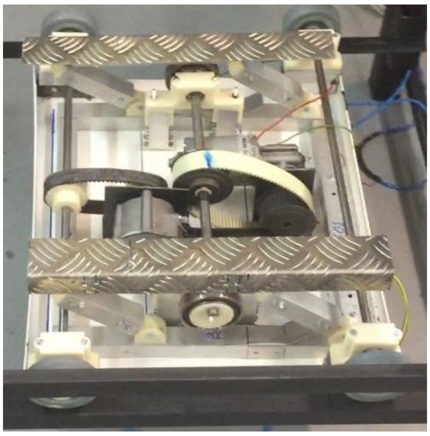

Figure 56 - Fully Assembled Radio Shuttle Prototype

The above orientation was designed with priorities of space saving and the lifting plate being able to be raised at least 20mm. With this set up, the plate can be lifted 30mm giving the pallet extra clearance from the shelves. The format of components had to be accurately designed so that all parts associated with the shafts would line up perfectly meaning great care was taken in the manufacture and assembly stage.

6.22 Drive System Testing

During testing of the drive system of the radio shuttle, the decision was made to secure the drive shaft to the radio shuttle itself and not separately. A factor in this decision was that the drive system was not as intricate as the lifting system and therefore all components could be viewed in their actual positions and extracted with relative ease if required. The effect on the bearing and motor supports could also be clearly identified in this set up, especially when a larger voltage was likely to be incorporated. Initially the drive system was tested when the radio shuttle wheels were not in contact with the ground so the shuttle would remain stationary. However, the same test was conducted again after the radio shuttle had been placed on the shelves.

The desired outcome of the drive test was that the wheels would rotate freely in both directions when controlled by the motor and without any slip in the belt or excessive displacement in any supports. Both the pulley drums would be key to the completion of the test.

Once the test was conducted it was noted by the team that filler pieces added to the ends of the drive shaft in order to improve grip during rotation worked very effectively. Both wheels rotated simultaneously with the drive shaft regardless of the voltage supplied to the motor.

Figure 57 - Drive Shaft Pulley Drums and Belt

There were no vibrations from the motor or supports which would be likely to interfere with the lifting mechanism of the radio shuttle or any other auxiliary parts.

However there were a couple of minor issues involving the pulley drum which was situated on the drive shaft itself. At a large voltage the belt began to slip off the drum. Extended use would have resulted in the belt falling off completely and the drive system would be rendered useless. Although this was not an issue up to approximately 12V, the group recommended to the client that it would be preferable using pulley drums and a belt that were specifically manufactured for one another to be implemented into the drive system. In addition, at points some slip occurred between the pulley drum fixed on the drive shaft and the shaft itself. When this occurred the wheels on the radio shuttle would not rotate with the shaft. The design to combine both the drive shaft and the pulley drum centred on a screw through a key way and on to the drive shaft. Tightening this connection reduced any sort of slip but for future iterations of the prototype a re-design would have been considered in order to ensure the shaft and pulley drum rotated together consistently.

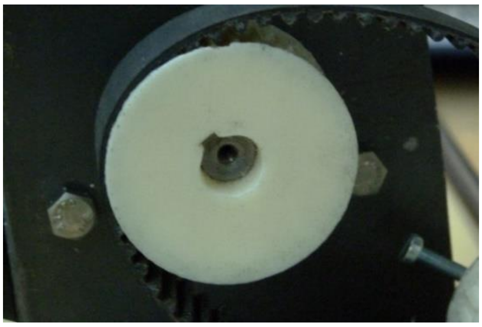

Figure 58 - Drive Shaft Pulley Drum

7.0 Redesign of the Prototype

7.1 Redesigning Features during Manufacture

During the manufacture and assembly of the prototype, any problems encountered would be resolved in the most efficient way possible regarding time, budget and availability of resources. With the effort and detail that was exhausted into the design aspect of the radio shuttle, it was presumed significant alterations to the design would be avoided. While this was indeed the case, a few issues had to be addressed in order that the radio shuttle could function properly according to the project requirements. The electrical circuits were still being designed but after liaising with the electrical group tasked with implementing the system, adequate room was left within the radio shuttle to body to include such components.

After the base plate of the radio shuttle was manufactured and holes were drilled for the base frame and all mounting components, it was noted that the plate looked rather uneven at parts. This was a concern to the team regarding if the plate would be able to support all the components of the radio shuttle, some of which were relatively heavy. A metal plate was sourced from the workshop to be fixed to the underside of the radio shuttle. This was to assist with supporting the base plate should it be weakened and fail, rendering the prototype useless.

Due to small errors in placement as a result of a lack of manufacturing experience: the position of the base frame (and subsequently the 4-bar linkage) and supports were slightly different compared to the CAD model of the radio shuttle. However, there was adequate space left to accommodate such changes and the radio shuttle would be able to perform sufficiently, therefore no re-design was required.

One aspect of the design which did necessitate alteration were the motor supports, primarily the lifting motor support. When first designed and manufactured, the motor supports included a centre hole for the motor shaft. This hole had a diameter equal to the shaft and the support rested at the base of the shaft. However, the pulley drums needed to rest at this position to ensure stability and that maximum was exerted on the lift/drive shaft. Therefore, slightly larger holes were drilled in the motor supports so they could sit further back from the base of the shaft and not impede the pulley drum in any way.

When the motor supports were placed within the base of the radio shuttle, it was deduced that additional metal at the height of the motor support would interfere with either the drive shaft, lifting plate or even the pallet resting on the shelves constructed. No complete re-design was required, but instead a portion of each motor support was removed in order to keep all moving components free from contact, which was successful.

Figure 59 - Lift Motor Support with Previously Drilled Holes

Regarding the lift motor support in particular, the holes drilled for the screws were realised to be too high as the motor body was in contact with the lift shaft itself. A re-design was implemented to the original motor support piece so that this contact was avoided. Every hole was to be "moved" downwards by 12.5mm. Measurements were taken and it was possible to drill new holes and still secure the motor appropriately. The re-design saved material and was deemed suitable for the prototype and further testing. A new support could be manufactured quickly for a later radio shuttle prototype, which would be more in keeping with industry standards.

The movement of the motor support holes created another problem though. It became impossible to fit the pulley drum onto the motor shaft due to the 12mm screws at the base of the motor plate blocking it. Rather than trying to incorporate a new support or screw, the base support screws were filed until the pulley could slide over them and be secured to the base of the motor shaft. Further filing was conducted on the screws to ensure the lifting belt would not catch on them during operation. Once all these adjustments had been made the motor supports were fixed to the radio shuttle base without further issue.

Figure 60 - Filed Screws on Motor Support

A potential problem was noted regarding the close proximity of the drive motor support to the pulley drum on the lift shaft. Whilst the two were not in contact, it was feared excessive vibration while the radio shuttle was in operation could result in an affect upon the lifting mechanism. The decision by the team was to test the set-up in that form and if an issue arose, the motor support would be corrected accordingly.

As a specific length of lifting belt compatible for the lifting pulley drums could not be sourced, the belt which was in-house was required to be cut to an appropriate length and fastened. A fastener was already included in the belt sourced, but when implementing the belt into the model, they were found to be unnecessarily thick which held the potential to make contact with multiple components as the belt rotated. A copy of the original fastener design was proposed, but with thinner metal enclosing the belt section. Scrap metal was sourced and new fasteners were manufactured. The new fasteners drastically limited the impact on surrounding components as the motor was put in motion. However, the fastener design still overlapped the edge of the belt which in-turn held the potential to cause damage to the pulley drum. Therefore, a new design was manufactured where only one fastener was utilised with screws and nuts fixing it to the belt. All parts included were made as thin as possible and the design was manufactured to be shorter than the width of the belt. Although not perfect compared to a full belt of the correct size, the new fastener did allow more motor rotation. For a prototype and demonstration this was deemed appropriate by the client but for a final model a correct belt size would have to be sourced (350mm).

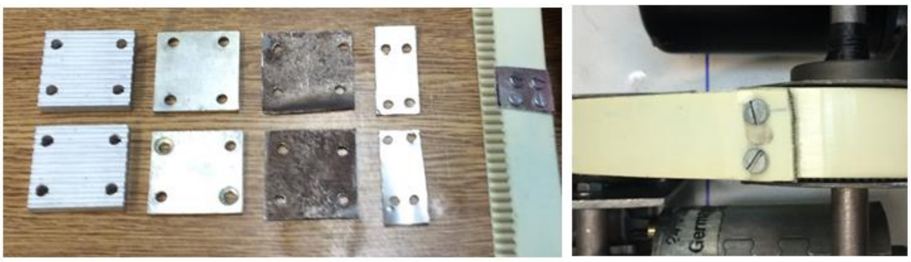

Figure 61 - Progression of Fastener Design and Final Fastened Lift Belt

It was found when attaching the lifting plate to the 4-bar linkage that the placements for one of the screws would directly contact the camshaft bearing performing the lifting operation on both sides of the radio shuttle prototype. Without two screws in place for the lifting plate, there was instability present when it was resting. It was assumed that the distributed weight of the pallet would cause the lifting plate to stabilise beneath. If when testing on the shelves this was found not to be the case, a re-design of the connection between the lifting plate and the radio shuttle would be conducted. Conceptions that were discussed included extra screws through the plate on to the linkage, a completely alternate connection to the linkage, or even a connection between the lifting plate and a separate component of the prototype which would allow the plate to rest on top of the linkage.

7.2 Redesigning Features during Testing

Manual testing of the prototype radio shuttle on the shelves commenced after all the relative modifications from section 7.1 and both the drive system and lifting had been independently tested. Only minor changes had to be introduced in order for the radio shuttle to operate properly at this stage.

After placing the shuttle on the shelf and rolling along the entire length, it was immediately noted that the drive shaft was too wide for a section of the racking unit and could not reach the end of the shelf. It was assumed this lack of width between the shelves occurred due to a manufacturing error. A decrease in drive shaft length from 550 to 530mm was proposed and then manufactured. The drive shaft was originally designed so that moving the wheel in 10mm either side would not impact the shaft supports or the main frame beneath. It should be noted that the main frame was at a depth beneath the wheels which did not require any modification once the drive shaft was shortened. Once the shaft was shortened, the radio shuttle could travel the length of the shelves.

When placing the pallet on to the lifting plates of the radio shuttle it was discovered the plates did not stretch across and support the entirety of the planks of wood at the pallets base. New plates were manufactured with just a slight increase in length (approximately 50mm).

Once the new plates were incorporated into the radio shuttle the pallet was hoisted and appeared relatively stable when stationary and in motion. The weight distribution of the pallet did stabilise the lifting plate underneath enough but the plate and pallet faces were not entirely coincident at one point in particular. This was believed to be a result of the uneven nature of the radio shuttle base but was not large enough an issue to warrant re-design.

A problem was encountered when attempting to manually move the radio shuttle beneath a pallet on the shelf in order to perform the lifting sequence. Even when the lifting mechanism was at the minimum position, one lifting plate in particular was catching on the pallet above and dragging it along the shelf. This was obviously not acceptable and a temporary solution was made to the mentioned plate by filing its end so it was able to slide under the pallet. While this did allow the radio shuttle to move under the pallet without disturbing it, further de-burring of screws on the lifting plate was required and it was therefore decided to manufacture new, thinner plates. When appropriate material was sourced and new plates were manufactured and implemented on to the model, the radio shuttle did not interfere with the pallet at all when in motion underneath.

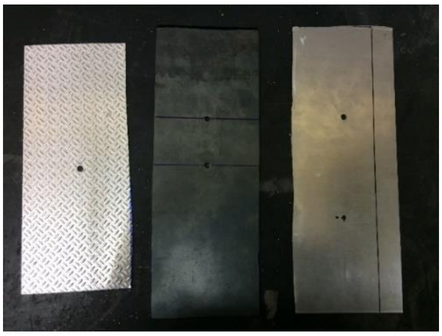

Figure 62 - Progression of the Lifting Plates

The client requested and then supplied more aesthetically pleasing aluminium lifting plates to incorporate in time for the demonstration. Once implemented, these plates were slightly thicker than the most recent version so had the potential to interfere with the pallet again. Although some contact between the pallet and plate was made, it was not extensive enough to ruin the demonstration and the functions of the radio shuttle were still able to be portrayed. An added bonus of the aluminium plates was the profile, which would make it more practical to attach electrical sensors to make the radio shuttle motions fully automated.

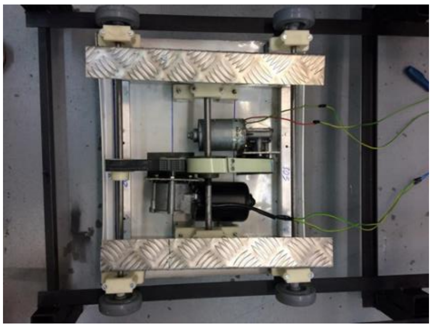

Figure 63 - Prototype Plan View with Aluminium Profile Lifting Plates

One particular design flaw in the shelving design was revealed when the team realised nothing was preventing the main wheels from sliding off the side of the shelf, should the drive be at a slight angle. With the shape of the shelf profile, it was possible to introduce some sort of “tracking” device which would correct or hold the radio shuttle’s path along the shelf in an appropriate place so the main wheels would remain fixed on the surface. This buffer would effectively make the shuttle wider underneath and if the prototype was to stray to one side, the tracking device would exert an opposing force on the shelf profile to counteract any horizontal movement. The new tracking piece introduced was not to impede the movement of the radio shuttle along the shelves in any way.

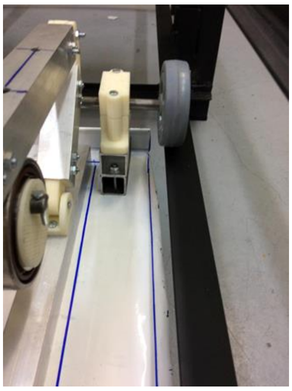

Figure 64 - Prototype Wheel Base Configuration before Track Wheel Addition

The client’s preference in this design was to include tracking wheels on the prototype and four were provided to the team to then incorporate. A concept was proposed which included fixing the tracking wheels to the main wheels and adding a side wall on top of the shelf surface for the tracking wheel to move along. However, after consideration this was deemed un-resourceful and would disrupt the design of the prototype emphatically. Another possibility involved attaching the tracking wheels to the side of the base frame which would then extrude outwards and be in contact with the underside of the shelf. Upon inspection, there was not enough space for the wheel in this configuration, but the premise was sound.

After deciding to go ahead with the second concept idea, it was discovered that securing the tracking wheels to the four shaft supports would provide the buffer necessary to prevent the main wheels from falling off the track above. The sides of the base frame were removed in order to attach the tracking wheels appropriately to the base of the wheel shaft supports. Therefore, each support was drilled at the appropriate height and the tracking wheels were implemented accordingly (one for each support) utilising simple nuts and bolts. The tracking wheels did indeed prevent the radio shuttle's main wheels from falling off the shelf completely and kept the shuttle extremely secure.

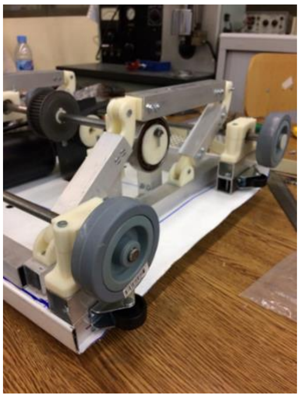

Figure 65 - Prototype with Implemented Tracking Wheels

8.0 Electrical Design

8.1 Overview

The electrical systems involved with the operation of the Shuttle had to accommodate its two main functions: 1 Finding the first loaded pallet it comes across in the shelves and retrieving it to its start position. 2 Finding the first available space in the shelves and storing a loaded pallet then returning to the start position.

In an effort to aid the team with the electrical system of the Radio Shuttle, the project supervisor saw fit to enlist the help of four Mechatronic students (Luis Estrada, Cristian Sara Lopez Cuesta, Mauricio-Vesta, Christian Mendoza Escobar). The following requirements were put to the Mechatronic students along with the schematics shown below and with our collaboration produced an electronic system for the Radio Shuttle.

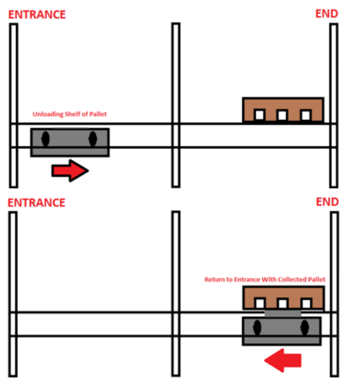

Figure 66 - Schematic of Retrieval Procedure

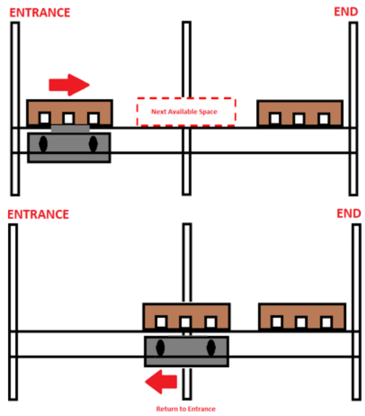

Figure 67 - Schematic of Storage Procedure

For Retrieval

1. The drive motor must turn on to move the Shuttle through the shelf.
2. The drive motor must switch off once the Shuttle is directly underneath the first available pallet.
3. The lift motor then must be powered on for one half revolution of the cam.
4. The drive motor then must be powered in reverse.
5. The Shuttle must stop at the end of the shelves.

For Storage

1. The lift motor then must be powered on for one half revolution of the cam.
2. The drive motor must turn on to move the Shuttle across the shelf.
3. The drive motor must switch off once the Shuttle is directly underneath the first available space.
4. The lift motor then must be powered in reverse for one half revolution of the cam.
5. The drive motor then must be powered in reverse.
6. The Shuttle must stop at the start of the shelves.

8.2 Electrical System and Components

An Arduino MEGA microcontroller and Protoboard were used to link the system input and outputs and run the program. For testing purposes a voltage source connected to the main ring circuits was used. The voltage source was directly connected to a voltage regulator to reduce the voltage from 24V to 5V to accommodate for the Microcontroller. The driver for the motors is also directly connected.

There were 10 inputs to the system. A joystick used to control the direction of rotation of the motors uses 4 inputs, there were 5 interrupter switches, and one for the “mode” switch. The mode switch was used to change between the two operational modes of the Shuttle. There were 6 outputs for the system. All were utilised by the motors (3 outputs for each) and connected to the relevant motor driver. The driver changed motor direction and also controlled the speed.

Initially light gates were considered as the most suitable type of sensor to be used to detect empty spaces and pallets however due to limited light low down in the shelves and our resources available the idea was rejected. Instead, pressure activated interrupter switches were to be incorporated. These switches positioning had been established and were to be connected to both the lift and drive motors and once activated, which would halt the power supplied to them.

The switches were to be housed at specific locations on the Radio Shuttle so they could function at specific points of the Shuttles operation.

Interrupter 1 was designed to be wedged between a four bar linkage and the Aluminium structure. During the lift shaft operation, the cam bearing would turn to the raised position and subsequently, one of the linkages would push against the switch and activate it.

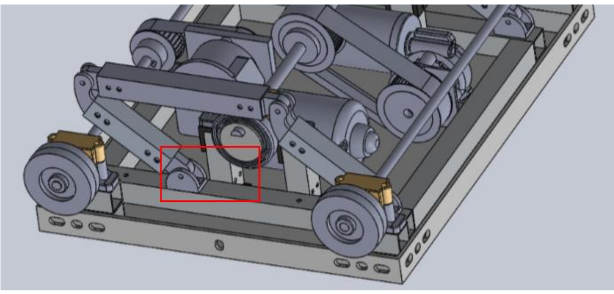

Figure 68 - Interrupter 1 Location

Interrupter 2 was to be placed between the alternate four bar linkage and the Aluminium structure. Meaning that when the lift shaft and the cam bearing turn to the lowered position one of the linkages would push against the switch and activate it.

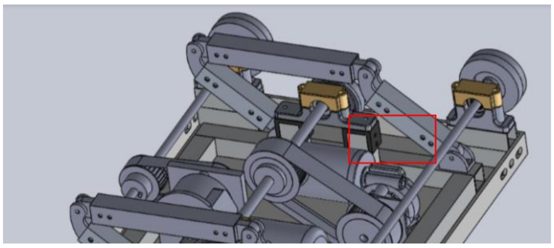

Figure 69 - Interrupter 2 Location

Interrupter 3 should be fixed to the lifting plate on the front of the Shuttle. The sensors position was designed to be placed at an angle where it can intersect with a stored pallet above and in front of the Shuttle. As the prototype moved along the shelves, the switch would be triggered as it would have been a certain distance away from the lifting plate so that multiple pallets on the shelves would not interfere with one another.

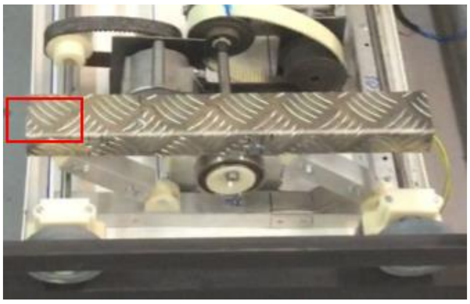

Figure 70 - Interrupter 3 Location

Interrupter 4 should be placed at the back of the Shuttle pointed downwards. The only object to ever come into its path would be one of the support bars at the end of the shelves. Once the Shuttle reached the end of the shelves the interrupter would be activated and the power supply would be cut to the drive motor so the prototype would not continue to drive and fall off the shelves.

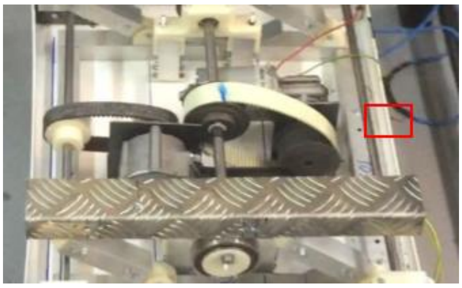

Figure 71 - Interrupter 4 Location

The final sensor, Interrupter 5, was to be connected to the lifting plate towards the back of the Shuttle. This sensor would be placed at an angle where it can intersect with a stored pallet above and behind the Shuttle would activate when a pallet was directly above the Shuttle.

Figure 72 - Interrupter 5 Location

8.3 Sequence of Operations

As per the design brief there are two modes of operation programmed to the Shuttle. An Arduino Controller was used to link the motors to the Interrupter switches. For the Shuttle to operate correctly in either of the two modes, it had to be set to its “origin position” at the start of any task. In the origin position, the 4-bar linkage was in its lowered position and the Shuttle would be stationary once it had been loaded on to the shelves. The control of both the lifting and driving motors was facilitated by a small joystick with four inputs:

Up Drive motor powered the Shuttle forward

Down Drive motor powered in reverse

Right Lift motor powered and linkage erected

Left Lift motor powered in reverse and lifting mechanism lowered

Sequences of operation for both the procedures the prototype would undertake are portrayed below.

First mode: 'Storing a Pallet'

1. The entire system will be on standby (Interrupters, Joystick, Motors);
2. Push the joystick to the right and the lift motor will raise the platform.
3. When interrupter 1 is active, the platform stops its movement.
4. Push the joystick up and the drive motor will power the Shuttle forward.
5. When interrupter 3 detects an object the drive motor stops.
6. Push the joystick left to lower the platform and release the pallet.
7. When the internal interrupter 2 is activated, the lift motor stops and the platform ends its movement.
8. Push the joystick down to power the drive motor in reverse and return the Shuttle to its previous position.
9. When the Interrupter 4 is activated the drive motor will stop and ends the sequence.
10.

Second mode: 'Retrieving the pallet'

1. Much like the first sequence, the first step is the system is on standby.

2. Push the joystick up and the drive motor will activate and power the Shuttle forward.

3. When the interrupter 5 is activated, the Shuttle will stop.

4. Push the joystick to the right to power the lift motor and raise the platform.

5. When the interrupter 1 is active, the platform stops its movement.

6. Push the joystick down to power the drive motor in reverse and move the Shuttle back to the starting position.

7. When interrupter 4 is activated the drive motor will stop.

8. Push the joystick left to power the lift motor and lower the lift platform.

9. When the interrupter 2 activates the lift motor and the platform stop. The sequence now ends.

It should be noted that human judgement was used instead of the sensors to judge the next available space or the maximum/minimum positions of the lifting mechanism during testing as the sensors were not implemented.

The following is a diagram of the electronic circuit. The 10 inputs and 6 motor outputs are shown connected to the Arduino Mega Microcontroller. In the diagram the interrupter switches are referred to as 'End Lines' due to the translation from the Mechatronic students.

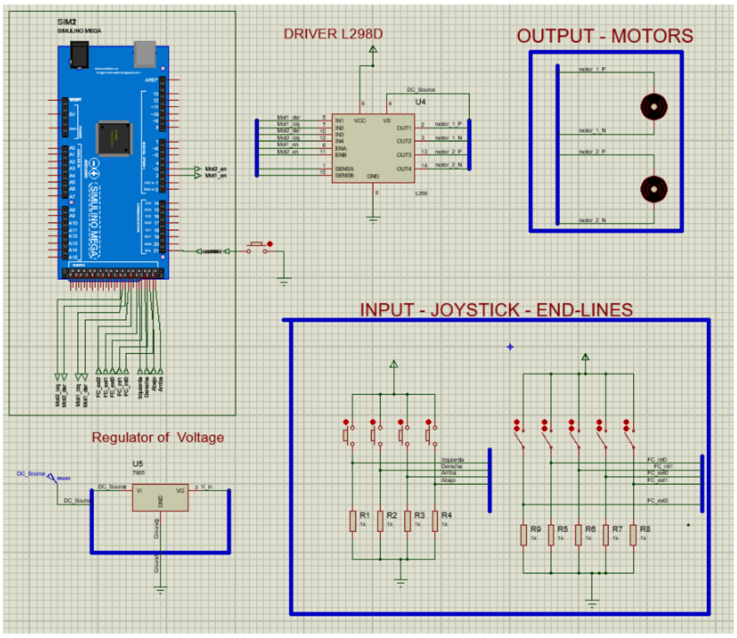

Figure 73 - Diagram of Electronic Circuit

9.0 Final Prototype

The prototype radio shuttle can be viewed from the picture beneath after all manufacturing had been completed. Numbers on the diagram represent certain components/parts of the model and a brief description of the purpose of these parts is given below.

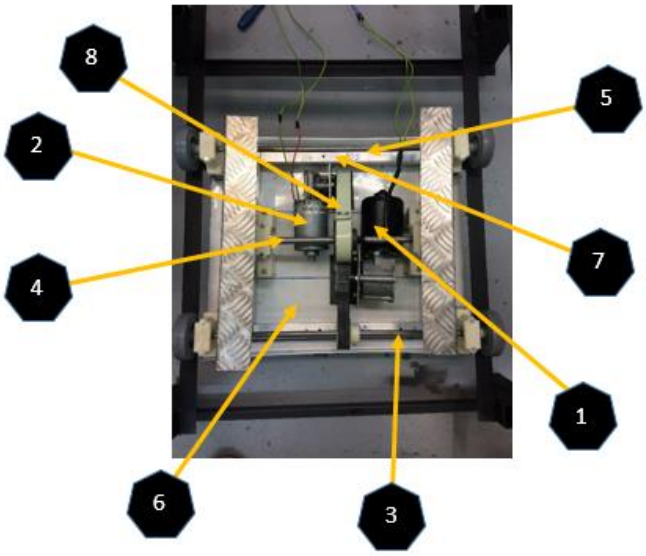

Figure 74 - Full Prototype View 1

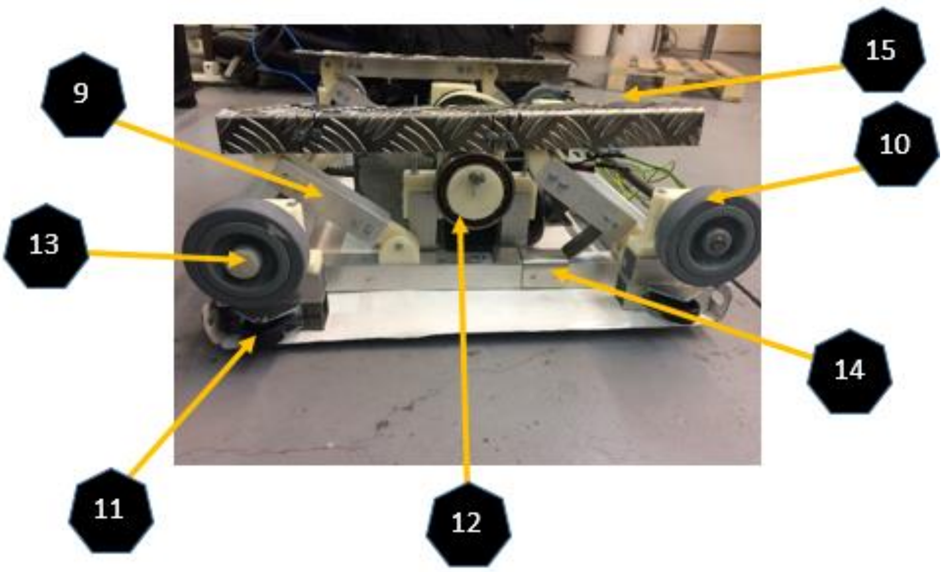

Figure 75 - Full Prototype View 2

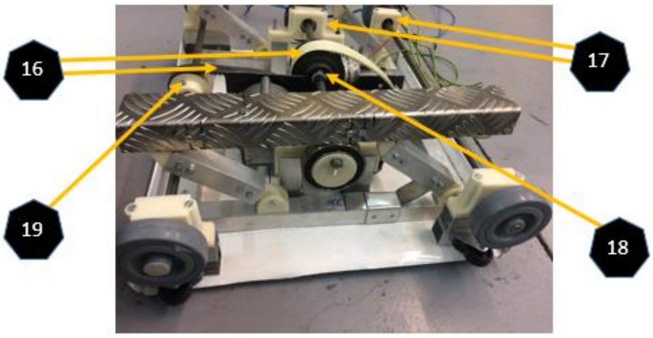

Figure 76 - Full Prototype View 3

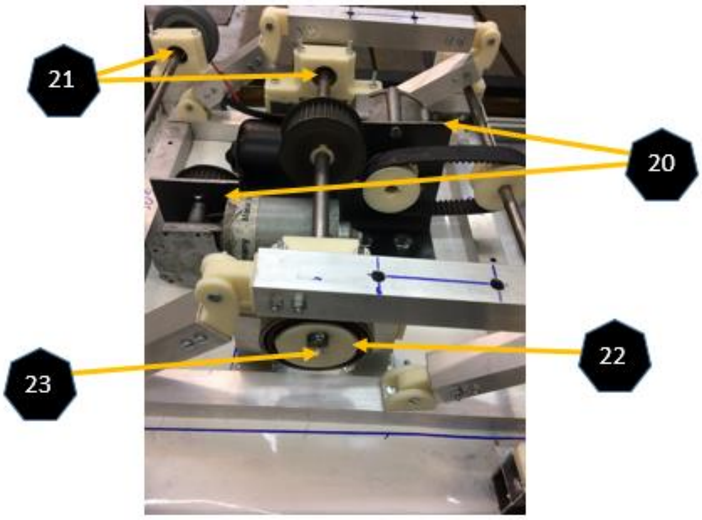

Figure 77 - Full Prototype View 4

1. Drive motor –powered the drive shaft of the shuttle
2. Lift motor –powered the lift shaft of the shuttle
3. Drive shaft – rotated the wheels and provided translational movement along the shelves for the shuttle
4. Lift shaft – rotated the cam bearings to subsequently erect the 4-bar linkage
5. Wheel shaft – attached to other wheels to bring balance to the shuttle
6. Base plate – held every component within and acted as the main body
7. Base frame – additional frame included to support both the linkages

8. Belt fastener – held lift motor belt together
9. 4-bar linkages (x2) – used to lift pallet from shelves and drop it back down when appropriate
10. Main wheels (x4) – allowed radio shuttle to move across the shelves
11. Tracking wheels (x4) – assisted in keeping the shuttle secure on the shelves
12. Cam bearings – as lift shaft rotated the bearings caused the linkages to rise or fall
13. Filler piece drive wheels (x2) – added to ensure wheels would rotate together with drive shaft and no slip occurred
14. Sensor support – demonstration piece to portray how a buffer sensor would be connected to the shuttle
15. Lifting plates (x2) – placed on top of the linkages as a stable support to lift the pallet
16. Belts (x2) – used in conjunction with the pulley drums
17. Bearing/shaft supports (x6) – held all shafts in place and protected them from potential failure
18. Filler piece lift shaft – connected the lift shaft and pulley drum so that rotation was simultaneous between the two
19. Screws for drive shaft pulley drum – secures the pulley drum to the drive shaft and makes sure both rotate simultaneously
20. Motor supports (x2) – held both the lift and drive motor in the correct place within the assembly
21. Shaft bearings (x6) – allowed continued controlled rotation of all shafts
22. Filler piece cam bearings (x2) – used to ensure bearings rotate with the lift shaft properly and prevent slip

23. Screws on lift shaft – placed to prevent cam bearings from sliding off the edge of the shaft and keep them directly underneath the linkages

The final radio shuttle prototype had to adhere to the requirements laid out in the project brief. More testing of the shuttle was necessary with the model operating on the shelves constructed.

Wired connections were made between the motors and the power supply which was also operating the electrical system to control the procedures.

Initially, the drive system and lifting mechanism were tested separately on the shelves in order demonstrate their capabilities.

From earlier, the previous drive system test involved a set up where the wheels did not actually touch a surface. Operating the drive system on the shelves, no further issues were noticed and the radio shuttle was able to move along the structure in both directions with absolute ease. Note that the inclusion of the tracking wheels dramatically enhanced the stability of the prototype on the shelves and no human input was required to prevent the model from falling off the side of the shelves during motion.

With the radio shuttle stationary, the lifting mechanism was operated after a pallet had been placed above. The lifting mechanism at maximum position sufficiently raised the pallet above the shelf so that no contact was present between the pallet and shelves. A pallet could therefore be transported without added friction. This was true concerning any point along the shelves. Furthermore, when the lifting mechanism was lowered, the pallet rested perfectly on the shelves and the prototype was able to move away to the other end of the shelf with minimal interference.

Once such tests had been conducted, the processes within the project brief could be carried out and reviewed. After undertaking such tests, both the driving system and lifting mechanism worked in tandem together to achieve the desired results. Our prototype was able to pick up the first available pallet and transport it to point on the shelf structure where it would be collected. Furthermore, the shuttle delivered a pallet to the next available space on the shelf structure before returning to the start again. Our website contains videos of the mentioned procedures.

While the power supply had to be operated by a team member and therefore the process was manual, manufacture had begun on brackets to implement the sensors to the prototype and shelves in order to create a semi-automated process. The electrical team had written a code for this process and without a microcontroller issue in the last few days of our exchange it may have been possible able to test this system.

Figure 78 - Final Testing Setup

10.0 Evaluation

10.1 Group Structure, Roles and Dynamic

Looking back over the project the group was extremely satisfied with the structure that was employed and the effective team dynamic it helped create. All group members gained invaluable experience of managing a key aspect of a project in unfamiliar territory, aiding to prepare them for their respective careers. Collaborating with a bilingual team was an especially excellent learning experience as it required the team's communication and instruction to be very clear so that it could be understood by people whose second language was English.

The group was also very pleased with how the group structure contributed to the efficiency with which work was completed and the positive team dynamic. Having each team member overseeing a particular section of the project ensured that nothing was ever being overlooked as it was each member's role to never lose sight of their designated subsection. Group members never had any problems taking on tasks as requested of them by the subsection managers as all requests were made respectfully and everyone understood that work was being completed for a common goal.

On reflection the group's decision not to appoint a project manager was certainly vindicated. The teamwork within the group was most definitely helped by each person having equal standing. The greatest proof of the effectiveness of the group's teamwork was seen in how issues were handled. A relaxed environment where everyone contributed was pivotal in reaching key decisions regarding the project. This was especially true at times when there was discussions about how best to proceed with the project as referenced in section 5.33. Issues such as designing around limited material availability were also handled professionally and not exclusively by individual members. Working and living in such close quarters was definitely a key factor in the delivery of this project as all group members were comfortable raising any issues with each other and searching for solutions as a collective unit.

10.2 Relationship with Client

The group made a large effort to form a good relationship with the client, Dr Sierra Velasco in order to create a decent working rapport. Playing a weekly football game and going on an excursion to an automated warehouse organised by the client allowed the group to familiarise themselves with Dr Sierra.

When the client mentioned a change which was required, the team would come together if necessary and develop potential solutions and pitch them back to the client. Subsequently, the client would select the most satisfactory solution and changes would be made based on this.

Some minor issues arose due to the changes requested by the client. However, none were critical to the continued progression of the project as the dialogue prevented the team from wavering too far from the assigned initial brief. In general the problems which were encountered from these changes largely centred upon rearranging the components within the body to comply with the shuttle dimensions requested by the client. As the project progressed trust was certainly built between the group and the client as the project was completed extremely independently.

10.3 Time Management

The creation of a manually operated radio shuttle within the relatively short time span of one semester indicated to the group that the time management of the project was a success. As the semester progressed it was the duty of the resource manager to update the Gantt chart each week and remind the group what progress was required in the coming days. This was made possible on a consistent basis due to the regular and organised meetings of the group. A copy of the completed Gantt chart is shown in the appendices.

As can be seen from the Gantt chart there were often times when the group deviated from the timetable set out at the beginning of the semester. The main reason for this was that the start and completion dates for all tasks were estimates and the group did not know with certainty how long each task would take to complete. For example, the group made a joint decision at the beginning of October to push back the start date of the Interim Report as four weeks was thought to be an excessive time that task. This allowed for the first iteration of the 3D CAD Modelling to be started earlier than anticipated and subsequently completed in time to be included in the Interim Report. There was an instance at the end of November where the group fell slightly behind schedule. This was because the manufacturing time was underestimated at the beginning of the semester. This put the project a week behind schedule for tasks such as manufacturing the prototype and implementing any changes. By consulting the Gantt chart the group was always aware that this delay was present and everyone felt comfortable that the project would be completed on time as plans were progressed. While the Gantt chart was not followed religiously, it proved an extremely useful guidance tool for showing the group a solid estimation of what progress was required at what times. Disciplined updating of the Gantt chart was certainly a large contributing factor to the group being able to produce a prototype during such a short stay in Spain.

There were problems encountered during the project which could have caused delays if they were not well managed. It was decided early on that the most likely cause of delays would be the sourcing and purchasing of products, especially if they had to be delivered from afar. To account for scenarios like this the resource manager always ensured everyone was aware of additional tasks they could be carrying out if there was a delay on a particular task.

It also became clear to the group that there were more public holidays in Spain than they were accustomed to. This was not a problem at the start of the project as most of the work could be continued outside the University. However, towards the end of the semester when the manufacturing of the radio shuttle was taking place, the group had to request an academic calendar to ensure practical work was not planned for days the University would be closed.

10.4 Communications Management

Upon reflection of the work done over the semester it is clear that the communications manager did an excellent job of ensuring communications between all parties was clear and concise. All team members were always aware what their daily and weekly targets were thanks to the meetings which were set out in the communication plan. The communication manager also arranged several meetings with the client over the semester which helped the group gain answers to any queries and kept the client up to date with all the significant progress.

The Dropbox link proved especially useful during the report writing stage of the project as all group members had instant access to each other's work even once the Scottish students had returned home. The WhatsApp group which included the electronics team was a fast and simple way to compare observations and suggest times to meet and discuss any issues further. This was helpful as the Latin American and Spanish students had other classes to attend so their ability to conduct face to face meetings was limited.

The primary obstacle of communications during the project was with the lab technician who was responsible for operating the 3D printing of parts. Limited language skills from both parties led to some confusion at points of the project. One example of this was the printing of drive shaft bearing holders where only three of the four parts were printed due to a breakdown in communication. After this point only the communications manager organised the manufacture of parts with the technician and aimed to consistently use email confirmation to ensure there were no more mistakes.

All in all, the communication framework that was put in place at the beginning of the project made a significant contribution to the efficiency with which the project was completed.

10.5 Financial Management

The role of the financial manager in this project was to manage the budget and ensure as few purchases as possible were made. A breakdown of all the purchases made and costs incurred by 3D printing is shown below. Whenever the 3D printer was used the group tried to print as many pieces at one time so as not to inconvenience the lab technicians so regularly. On many occasions several different pieces were printed together and the group was only supplied with information for the total amount of material used in each operation of the printer. This made it difficult to establish the individual cost of each component, only the total cost of the pieces created. Therefore, the overall spend breakdown contains a list of all the pieces manufactured in the 3D printer but not their individual cost.

Table 8 - Table of Purchases

Part	Quantity	Purchased/3D Printed	Cost
Driving Wheel	4	Purchased	€12
Tracking Wheel	4	Purchased	€9.96
25mmx25mmx1000mm Aluminium Profile	3	Purchased	€24.90
Base Plate	1	Purchased	€16.95
25mmx25mmx1500mm Steel L Bar	2	Purchased	€24.98
Cam Bearing Filler Piece	2	3D Printed	-
Drive Shaft Bearing Support Bottom Half	4	3D Printed	-
Drive Shaft Bearing Support Upper Half	4	3D Printed	-
Lift Shaft Bearing Support Bottom Half	2	3D Printed	-
Lift Shaft Bearing Support Upper Half	2	3D Printed	-
Driving Motor Pulley Drum	1	3D Printed	-
Driving Shaft Pulley Drum	1	3D Printed	-
Lift Shaft to Gear Connector	1	3D Printed	-
Bottom Fixing for Lift Shaft Support	4	3D Printed	-
Top Fixing for Lift Shaft Support	4	3D Printed	-
Drive Wheel Securers	4	3D Printed	-
4 Bar Support Mounting Piece	4	3D Printed	-
4 Bar Support Joining Piece	8	3D Printed	-
4 Bar Support Curved Piece	4	3D Printed	-
Total Cost of 3D Printing			€388.42

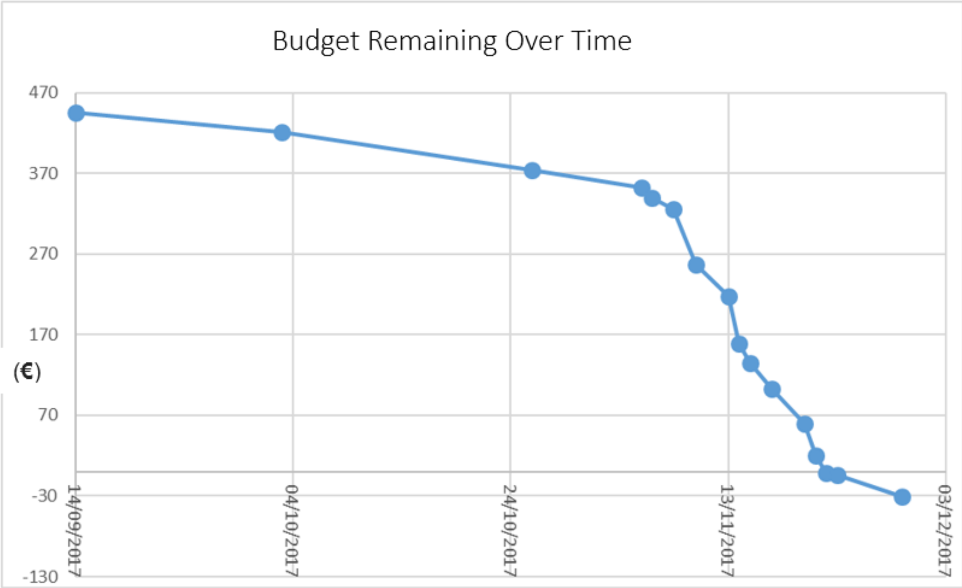

Figure 79 - Budget over Time

Using the record of how much material was used each time the printer was operational it was possible to create a graph of how the budget decreased over the semester.

It was the duty of the resource manager to ensure costs were kept to a minimum. At times this meant advising the group that certain ideas could not be pursued as they would put too much strain on the budget. For example as referenced in section 4.33, when it was proposed that the entire 4 bar linkage from the lifting mechanism be 3D printed the resource manager intervened and suggested that some of the square aluminium profile which had already been purchased be incorporated into the design instead. Another example of this occurred when a timing belt to be used in the design of the driving system was found in the University labs with no matching pulley drums. It was suggested that matching pulley drums be purchased however after research was carried out into how much this would cost the resource manager requested that they be printed to minimise expenditure.

The total costs incurred were €477.21. This meant the original budget was exceeded by €31.21. Whilst this was slightly disappointing it was acknowledged that the 3D printing was hard to track financially as the resource manager could never be sure how much a piece would cost when it was sent to be printed. Whilst efforts were made to construct the shelving unit purely out of recycled materials from the labs there simply was not enough suitable material to achieve this, which meant money had to be spent on steel bars. The final product involved such a large quantity of components that it would always have been difficult to not exceed the budget. The resource manager was diligent in ensuring no parts could be repurposed from the labs before money was spent so this would not be an option for reducing the costs. While this was frustrating at times for the other group members it was a vital part of the project.

Despite this there were instances when the option of purchasing components was not thoroughly investigated and they were 3D printed perhaps prematurely. In part this was done to comply with the brief however it is possible the project could have been delivered closer to or on budget if this avenue was explored more often.

10.6 Technical Management

Over the course of the project the technical manager oversaw many of the key aspects including the concept generation and selection, the 3D design process and the manufacturing of the radio shuttle. Inspections were also carried out on all 3D printed pieces and manufacturing processes to ensure quality in the final product. During the manufacturing stage the technical manager utilised past technical experiences to complete and advise upon workshop tasks. Such examples included using welding and drilling techniques whilst advising other members on the less challenging manufacturing and assembling techniques. The technical manager was also frequently in contact with the Mechatronic students who were to devise an electronic system for the Radio Shuttle. Instructions and requirements were issued and from there both parties collaborated in designing a system which enabled the Radio Shuttle to carry out its necessitated operations.

10.7 Risk Management

As mentioned at the beginning of this report the main area of risk encountered during the project was that to the health and safety of the group members while carrying out practical work in the University laboratory. The health and safety risk minimisation principles set out in the risk assessment helped ensure that no injuries were incurred during the completion of the project. At all times while practical work was being carried out the group made sure they followed all necessary precautions to prevent injury and made steps to ensure they were always using machinery and tools in the proper, safe manner.

10.8 Future Development of the Project

Although the group felt the radio shuttle performed admirably relating to the project brief, there were a few aspects to the design that could be enhanced by the time our exchange had concluded. While some improvements were not integral to the overall functionality of the radio shuttle, the design would be more complete with them included.

Firstly, an appropriate belt for the lifting mechanism would have been implemented to allow a full rotation of the motor without any interference from a fastener. Failing this, alternate pulley drums and an accompanying belt could be incorporated into the radio shuttle design. The team was provided with these components by the client in the final days but there was not sufficient time to implement and at the same time test the radio shuttle with the electrical components.

Figure 80 - New Pulley Drums for Drive Shaft

Another short term goal which the team were keen to complete surrounded the compatibility of the lifting plates with the pallet. When in operation, the prototype still made slight contact with the pallet moving in one direction in particular. A possible solution to remedy this was to widen the distance between the 4-bar linkage bases in order to have a “fallen” position slightly lower than previously, but still be able to lift the pallet sufficiently. This would involve drilling new holes in the metal frame in the shuttle base and securing the linkage again.

By the time our exchange was nearing the end, the electrical team had completed generating programme codes for the manual and automated operation of the radio shuttle. The semi-automated sequence required implementation of the interrupters which would detect; when the lifting mechanism was fully up or down, when a pallet was directly above the shuttle, and where the start and end points of the shelves were. Work had begun on manufacturing brackets to support the sensors but an electrical fault concerning the microcontroller slowed progress on this process until the manual operation was successfully working again. Should our brackets have been completed and secured correctly as per our design, achieving a semi-automated design was possible within a few days.

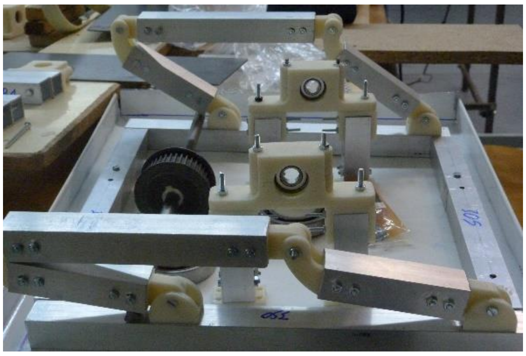

Figure 81 - Base Plate of the Radio Shuttle

The radio shuttle base plate was a source of frustration for the group during the manufacturing and testing stages of the project. The material of the base was too easily deformed and left the team wondering if it would be able to consistently support a load without failing. It was believed this deformation was the primary cause of the uneven lifting plate on one side, hampering motion of the shuttle underneath a pallet. If alternate material was provided by the client or found within the University to manufacture another base (or secure the previously sourced sheet to the current base), it would result in a more stable structure which carried out the required operations with enhanced security.

After completing minor tasks such as including flat head screws or filing certain parts, the only other aspect which the group felt needed developed was the amount of testing with an array of loads being carried by the radio shuttle and at multiple speeds in order to draw further substantial conclusions from the operation of the prototype.

In manufacturing a prototype, the project has the potential to be advanced to a more industry standard device in a variety of aspects. Further client preferences could be included as well. Some suggestions to continue work concerning the prototype are discussed below.

Initially, the most pressing task for any group hoping to progress our project should involve making the radio shuttle operations as automated as possible. Fully implementing and then optimising the electrical design and sensors so the shuttle will drop off and collect pallets appropriately with minimal input would fulfil everything in the original project brief.

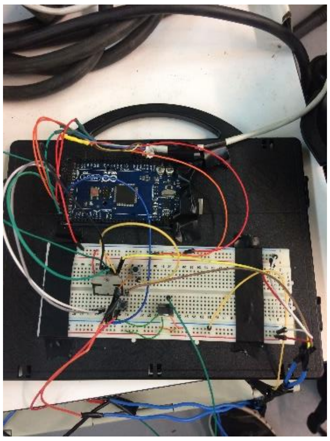

Figure 82 - Current Electrical Circuit

While the manual operation of the radio shuttle was successful, a constant wire connection was required from the two motors to the one power supply during operation. Within a warehouse setting, this would not be feasible and the radio shuttle would include an independent power supply. Implementing batteries for both motors within the radio shuttle body (where there was sufficient space) would mean the shuttle would not require a constant connection to a power supply and if the batteries could be operated remotely then this would be a major step forward.

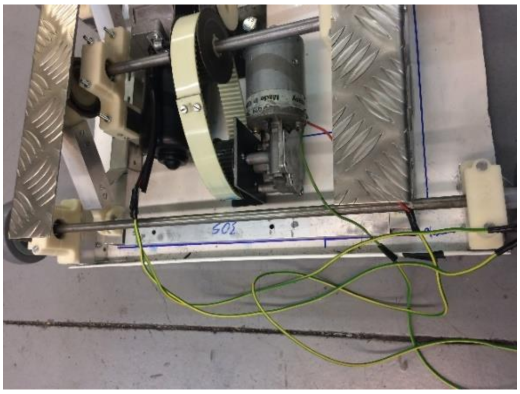

Figure 83 - Wired Connections to Prototype

The client mentioned he would prefer the shuttle to be enclosed to protect the internal components but with a transparent top where they could remain visible during operation. It was also put to the group that the shuttle should have an inherent safety feature included in order for someone to immediately retrieve it or halt it in the case of an emergency. A handle to be used to retrieve the shuttle was available and other ideas for retrieval were discussed amongst the group such as a pulley system. Implementing both to the prototype would be a worthwhile endeavour.

Furthermore, a solution to mount and dismount the radio shuttle (with or without a pallet on top) could be devised in order to mimic an actual warehouse operation with a forklift. In this scenario, the shuttle would need to recognise where the "start" of the shelf was and navigate to this point to begin or end an operation with precision. Incorporating two levels of shelves could be a further option in this case along with the addition of more pallets to fully portray the radio shuttle's capabilities.

Apart from these suggestions, another team could look to optimise the mechanical design as much as possible regarding the material utilised, lifting and drive systems and also the motors incorporated once extensive data has been accrued in testing.

11.0 Conclusions

In conclusion, this project presented the group with a wide variety of new challenges and experiences. As a team all members dealt admirably with being in unfamiliar territory, both academically and culturally. The final radio shuttle prototype which was presented to the client fulfilled all the key aspects of the brief. The shuttle was capable of lifting a pallet and load of the required mass to the height specified in the brief. It did this while meeting the dimension requirements set out by the client. The shuttle was also capable of performing loading and unloading operations when manually operated. The group managed to manufacture the prototype by purchasing only a metallic base plate, some hollow aluminium square profiles to use as supports and tracking and driving wheels. The remainder of the parts were either 3D printed or recycled from the University labs. The group had therefore strongly adhered to that section of the brief. It was slightly disappointing that the Scottish students did not have more time to collaborate with the electronics students in order to automate the loading and unloading processes. A sensor array was designed so that this could be achieved but the Scottish students required assistance with the coding process. It is thought that automatizing the shuttle could prove an interesting future undertaking for students of the electronics school in Oviedo.

No team member had experience of a group project of this magnitude so management skills took on added significance. The fact that all areas of the project were very well managed throughout was one of the most pleasing aspects to the team. All work was completed in a timely manner and to a high standard which was testament to the management strategies that the group conceived at the very outset of the semester.

The success of the project became clear when the group presented the final prototype to the client, an assortment of students, professors and an industry representative at the University of Oviedo. The client was extremely pleased with the work ethic the team displayed and the quality of the radio shuttle. The presentation was received very well and the students and industry representative in particular were interested in the mechanisms, asking many questions about how the design process was conducted.

12.0 References

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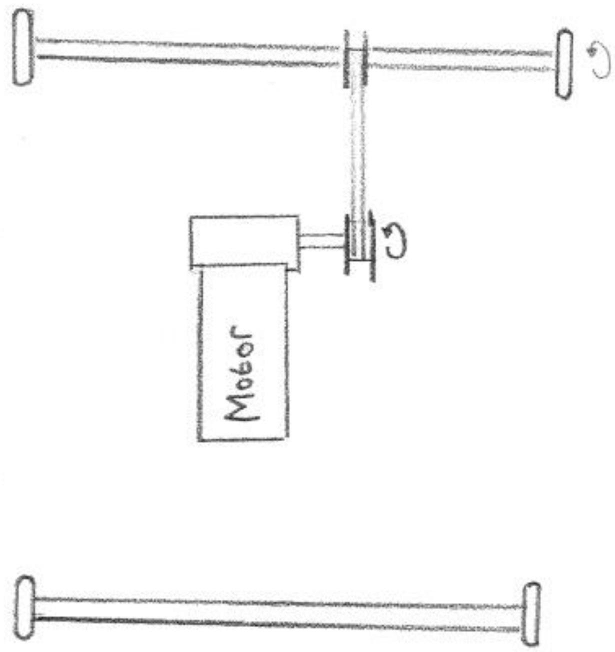
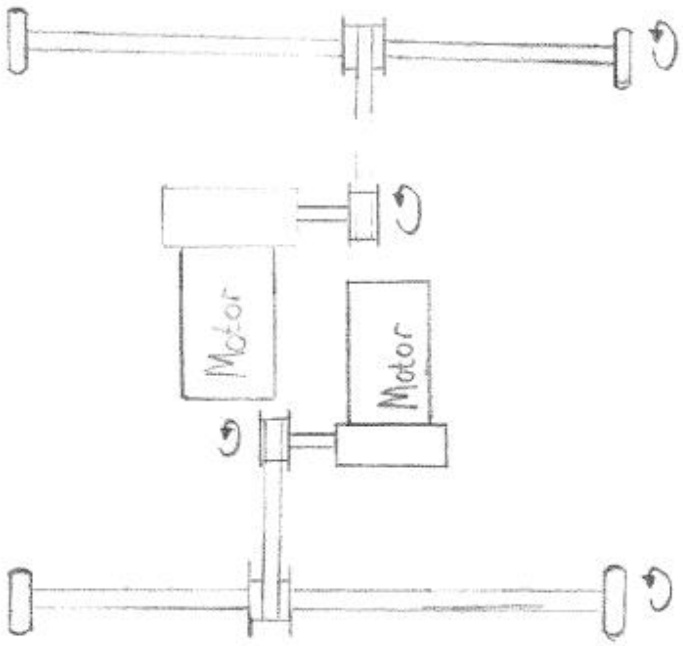
13.0 Appendices

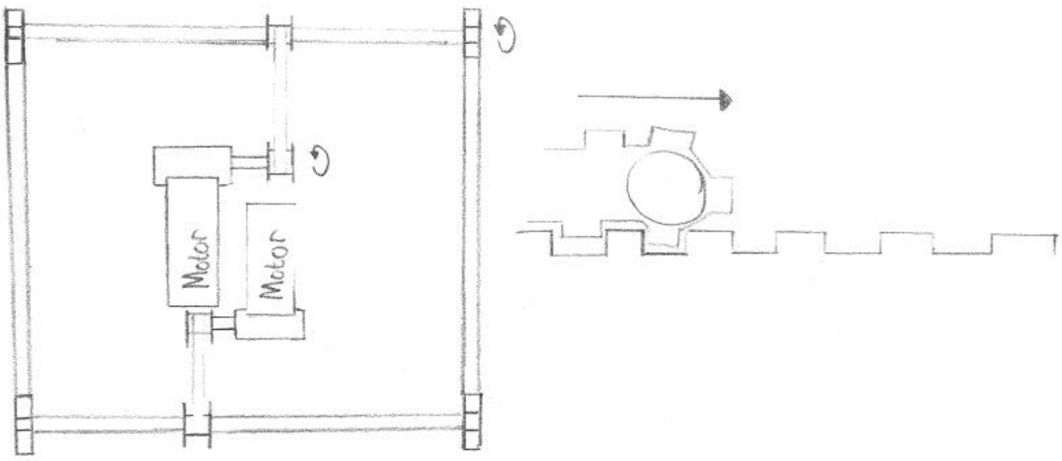
<u>Appendix 1 – Drive System Concepts</u>



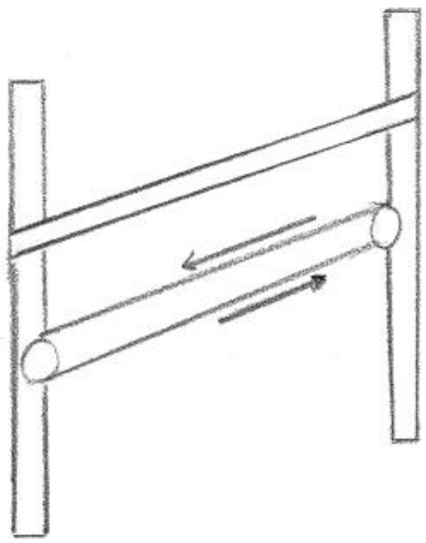
2 Wheel Drive Concept



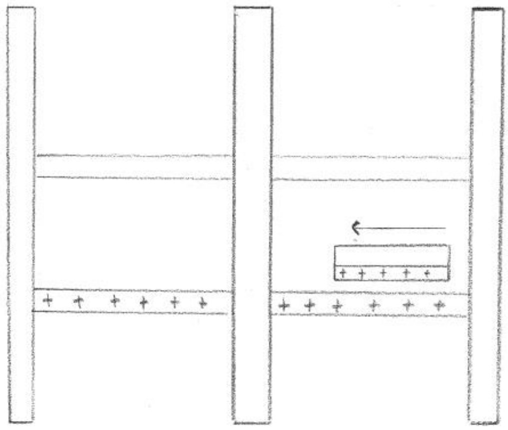
4 Wheel Drive Concept



Tank Treads Concept

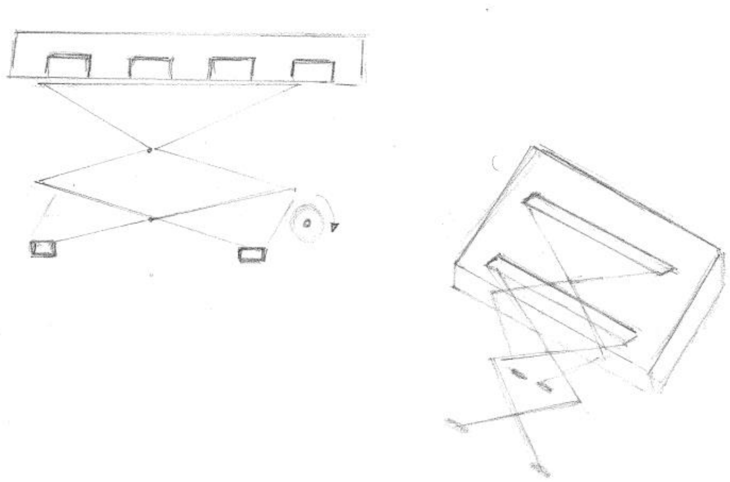


Motorised Rail Concept

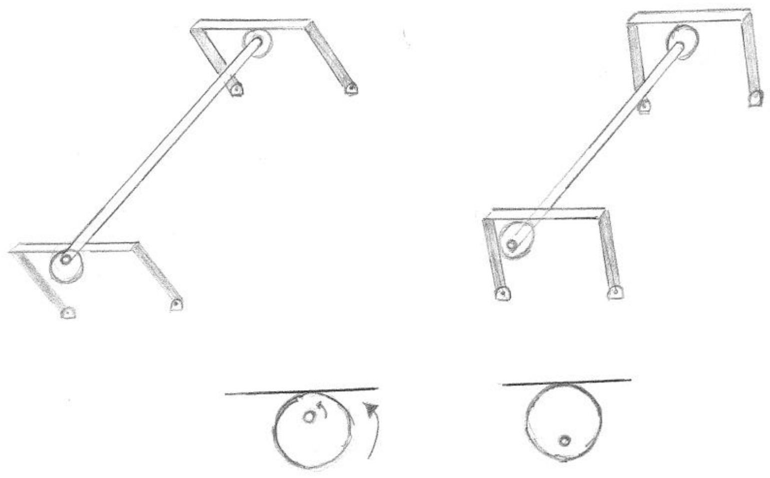


Mag Lev Concept

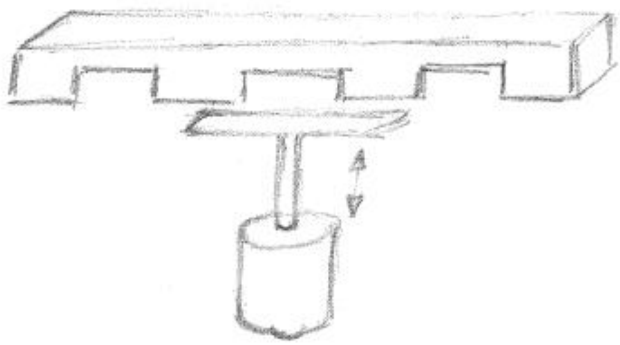
Appendix 2 – Lifting Mechanism Concepts



Scissor Lift Concept

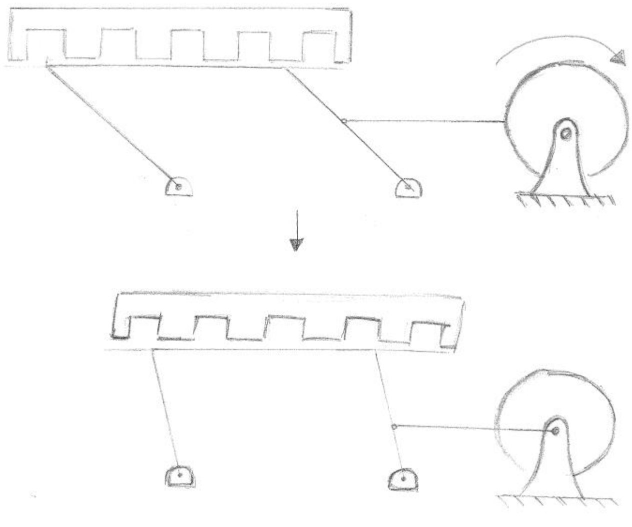


Cam Bearing Concept



Hydraulic Motor and Actuator Concept

Bike Chain Concept



Wire Drum Concept

Appendix 3 – Arduino Control Code

```
/* Speed variables */
byte vel=64;
byte vel1=128;
/* Input signals */
int pin_arriba=22;
int pin_abajo=24;
int pin_derecha=26;
int pin_izquierda=28;
int pin_FC_int0=23;
int pin_FC_int1=25;
int pin_FC_ext0=27;
int pin_FC_ext1=29;
int pin_FC_ext2=31;
/* Output signals */
int pin_motor1=2;
int pin_motor1_der=32;
int pin_motor1_izq=34;
int pin_motor2=3;
int pin_motor2_der=33;
int pin_motor2_izq=35;
/* Auxiliar variables */
int pin_control=21;
boolean E1=0,E2=0,E3=0;
boolean R1=0,R2=0,R3=0;
boolean E0=1,R0=1;
boolean condi=true;

/* Start of the program (this runs once) */
// configuration of the pins as inputs or outputs
void setup() {
```

```
 Serial.begin(9600);
 pinMode(pin_arriba,INPUT);
 pinMode(pin_abajo,INPUT);
 pinMode(pin_derecha,INPUT);
 pinMode(pin_izquierda,INPUT);
 pinMode(pin_FC_int0,INPUT);
 pinMode(pin_FC_int1,INPUT);
 pinMode(pin_FC_ext0,INPUT);
 pinMode(pin_FC_ext1,INPUT);
 pinMode(pin_FC_ext2,INPUT);
 pinMode(pin_control,INPUT);
 pinMode(pin_motor1,OUTPUT);
 pinMode(pin_motor1_izq,OUTPUT);
 pinMode(pin_motor1_der,OUTPUT);
 pinMode(pin_motor2,OUTPUT);
 pinMode(pin_motor2_izq,OUTPUT);
 pinMode(pin_motor2_der,OUTPUT);
 pinMode(13,OUTPUT);

/* --- Activate the pull-up resistors.--- */
 digitalWrite(pin_arriba,HIGH);
 digitalWrite(pin_abajo,HIGH);
 digitalWrite(pin_derecha,HIGH);
 digitalWrite(pin_izquierda,HIGH);
 digitalWrite(pin_FC_int0,HIGH);
 digitalWrite(pin_FC_int1,HIGH);
 digitalWrite(pin_FC_ext0,HIGH);
 digitalWrite(pin_FC_ext1,HIGH);
 digitalWrite(pin_FC_ext2,HIGH);
 digitalWrite(pin_control,HIGH);
}
```

```
/* Main program (this runs on a loop) */

void loop() {

 /* -------- Read the inputs.--------- */

 boolean arriba=digitalRead(pin_arriba);

 boolean abajo=digitalRead(pin_abajo);

 boolean derecha=digitalRead(pin_derecha);

 boolean izquierda=digitalRead(pin_izquierda);

 boolean FC_int0=digitalRead(pin_FC_int0);

 boolean FC_int1=digitalRead(pin_FC_int1);

 boolean FC_ext0=digitalRead(pin_FC_ext0);

 boolean FC_ext1=digitalRead(pin_FC_ext1);

 boolean FC_ext2=digitalRead(pin_FC_ext2);

 boolean control=digitalRead(pin_control);


 posicion_origen(); //original position mode

 if (control)

  {depositar_paquete();} //placing the pallet mode (calling to the function below)

 else

  {recoger_paquete();} //picking up the pallet mode (calling to the function below)

}

// end of loop


// FUNCTIONS

boolean movimiento(int pin_ent,int pin_fin_carr,int sal,int sal_der,int sal_izq,int veloc) // general
function for the movement of the shuttle

{

 // It reads the inputs to know which position of the joystick is activated to turn on the
corresponding motors and also reads the sensors signal

 // to stop the motors when needed.

 boolean cond=false;

 while(cond==false)
```

```
 {
   boolean a=digitalRead(pin_ent);
   if(!a)
   {
    Serial.println("Mov");
    boolean fin_carr=digitalRead(pin_fin_carr);
    if (fin_carr)
    {
      digitalWrite(13,LOW);
      digitalWrite(sal_der,LOW);
      digitalWrite(sal_izq,LOW);
      cond=true;
    }
    else
    {
      analogWrite(sal,veloc);
      digitalWrite(13,HIGH);
      digitalWrite(sal_der,LOW);
      digitalWrite(sal_izq,HIGH);
    }
   }
   else
    {
      digitalWrite(sal_der,LOW);
      digitalWrite(sal_izq,LOW);
    }
 }
 return(cond);
}

void depositar_paquete() // function of mode 1
```

```
{
 // Raising the platform.
 if(E0)
  {
   Serial.println("Movimiento del pale arriba");
   E1=movimiento(pin_derecha,pin_FC_int1,pin_motor1,pin_motor1_izq,pin_motor1_der,vel);
  }
 digitalWrite(18,E1);
 // Movement (+) of the radio shuttel.
 if(E1)
  {
   Serial.println("Movimiento (+) del radioshatel");
   E2=movimiento(pin_arriba,pin_FC_ext1,pin_motor2,pin_motor2_izq,pin_motor2_der,vel1);
   E1=false;
  }
 digitalWrite(19,E2);
 if(E2)
 // Lowering the platform.
  {
   Serial.println("Movimiento del pale abajo");
   E3=movimiento(pin_izquierda,pin_FC_int0,pin_motor1,pin_motor1_der,pin_motor1_izq,vel);
   E2=false;
  }
 digitalWrite(20,E3);
 // Movement (-) of the radio shuttel.
 if(E3)
  {
   Serial.println("Movimiento (-) del radioshatel");
   E0=movimiento(pin_abajo,pin_FC_ext0,pin_motor2,pin_motor2_der,pin_motor2_izq,vel1);
   E3=false;
  }
```

```
 digitalWrite(21,E3);
}

void recoger_paquete() // function of mode 2
{
  if(R0)
 // Movement (+) of the radio shuttel.
 {
   Serial.println("Movimiento (+) del radioshatel");
   R1=movimiento(pin_arriba,pin_FC_ext2,pin_motor2,pin_motor2_izq,pin_motor2_der,vel1);
 }
 digitalWrite(18,R1);
 // Raising the platform.
 if(R1)
 {
   Serial.println("Movimiento del pale arriba");
   R2=movimiento(pin_derecha,pin_FC_int1,pin_motor1,pin_motor1_izq,pin_motor1_der,vel);
   R0=false;
 }
 // Movement (-) of the radio shuttel.
 digitalWrite(19,R2);
 if(R2)
 {
   Serial.println("Movimiento (-) del radioshatel");
   R3=movimiento(pin_abajo,pin_FC_ext0,pin_motor2,pin_motor2_der,pin_motor2_izq,vel1);
   R2=false;
 }
 digitalWrite(20,R3);
 if(R3)
 // Lowering the platform.
 {
```

```
    Serial.println("Movimiento del pale abajo");
    R0=movimiento(pin_izquierda,pin_FC_int0,pin_motor1,pin_motor1_der,pin_motor1_izq,vel);
    R3=false;
  }
  digitalWrite(21,R0);
}



boolean mov_inicial(int fin_carr_int,int sal,int sal_der,int sal_izq,int veloc) // general function to
move the shuttle to the original position
{
   boolean a=digitalRead(fin_carr_int);
  while(!a)
  {
    analogWrite(sal,veloc);
    digitalWrite(sal_der,LOW);
    digitalWrite(sal_izq,HIGH);
    a=digitalRead(fin_carr_int);
  }
  analogWrite(sal,0);
  digitalWrite(sal_der,LOW);
  digitalWrite(sal_izq,LOW);
}
void posicion_origen() // function of mode 'original position'
{
  mov_inicial(pin_FC_int0,pin_motor1,pin_motor1_der,pin_motor1_izq,vel);
  mov_inicial(pin_FC_ext0,pin_motor2,pin_motor2_der,pin_motor2_izq,vel1);
}
```

Color code:

Green: comments in the code.

Blue: type of variable (any time you create a new variable you need to specify it’s type).

Orange: internal functions of the Arduino software.

Black: code.

Appendix 4 – Matlab Code for Lifting Mechanism Fatigue Endurance Calculation

```
%Consideration for the lfiting mechanism at the point where the belt
is
%placed. This is the centre of the shaft and should be the highest
point of
%stress due to the tension of the belt as well as being the furthest
part
%from the supports.

d=26.3; %mm
e = 15; %mm
L1 = 200; %mm
r_drum = 31.5; %mm
S_ut = 550; %MPa
SC = 4.51;
MS = -0.265;
k_e = 0.54; %represents the keyway element in the shaft
F=2000; %N

Torque_Max = F*e; %e is the eccentricity of the cam

%Torsion Consideration
Moment_torsion_max = Torque_Max/2;
J_max = Moment_torsion_max/((pi*(d^3))/16);

%bending consideration
Moment_bend_vertical = (F/2)*L1; %L1 is distance between drum and
bearing
Moment_bend_lateral = (F/2)*r_drum;
Moment_bend =
sqrt((Moment_bend_vertical^2)+(Moment_bend_lateral^2));

sigma_max_bend = Moment_bend/((pi*(d^3))/32); %MPa

%total actual stress of the shaft at that point
sigma_total = sqrt((sigma_max_bend)^2+(3*(J_max^2))); %MPa


%Consider fatigue factors

S_E = S_ut/2; %S-ut ultimate tensile strength of material
k_a = SC*(S_ut^MS); %SC is surface coefficient, MS represents the
type of machine, in this case motorised shaft)
k_sigma = (d/7.62)^(-0.1133); %size coefficient


S_e = S_E*k_a*k_sigma*k_e; %where S_e represents the maximum stress
at which unlimited cycles can occur without failure)

%This script can now either determine the diameter of the shaft
which would
%be necessary for the a chosen load (i.e F), or the diameter of the
shaft
%can be determined first, while the maximum load can be calculated.
Other
%variable elements of the system could be the radius of the drum or
L1 (the
```

```
%distance between the drum and the bearing). This can be done by
%manipulation of the first part of the script where variables are
either
%entered or deleted.
```

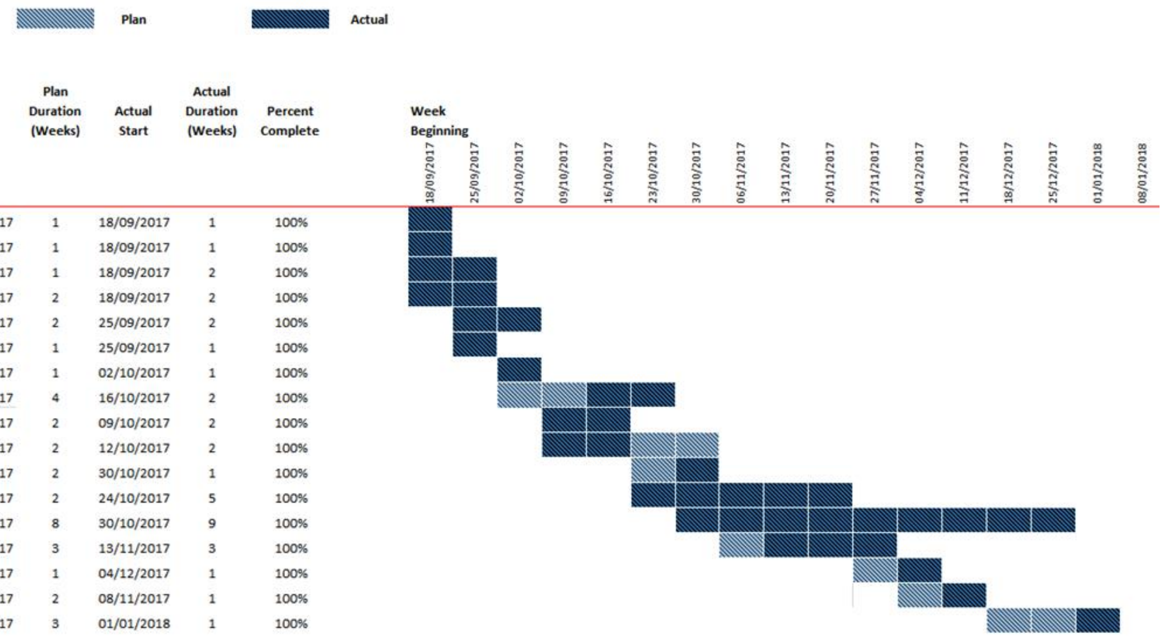
Appendix 5 – Completed Gannt Chart

Gijon Masters Group Project 2017

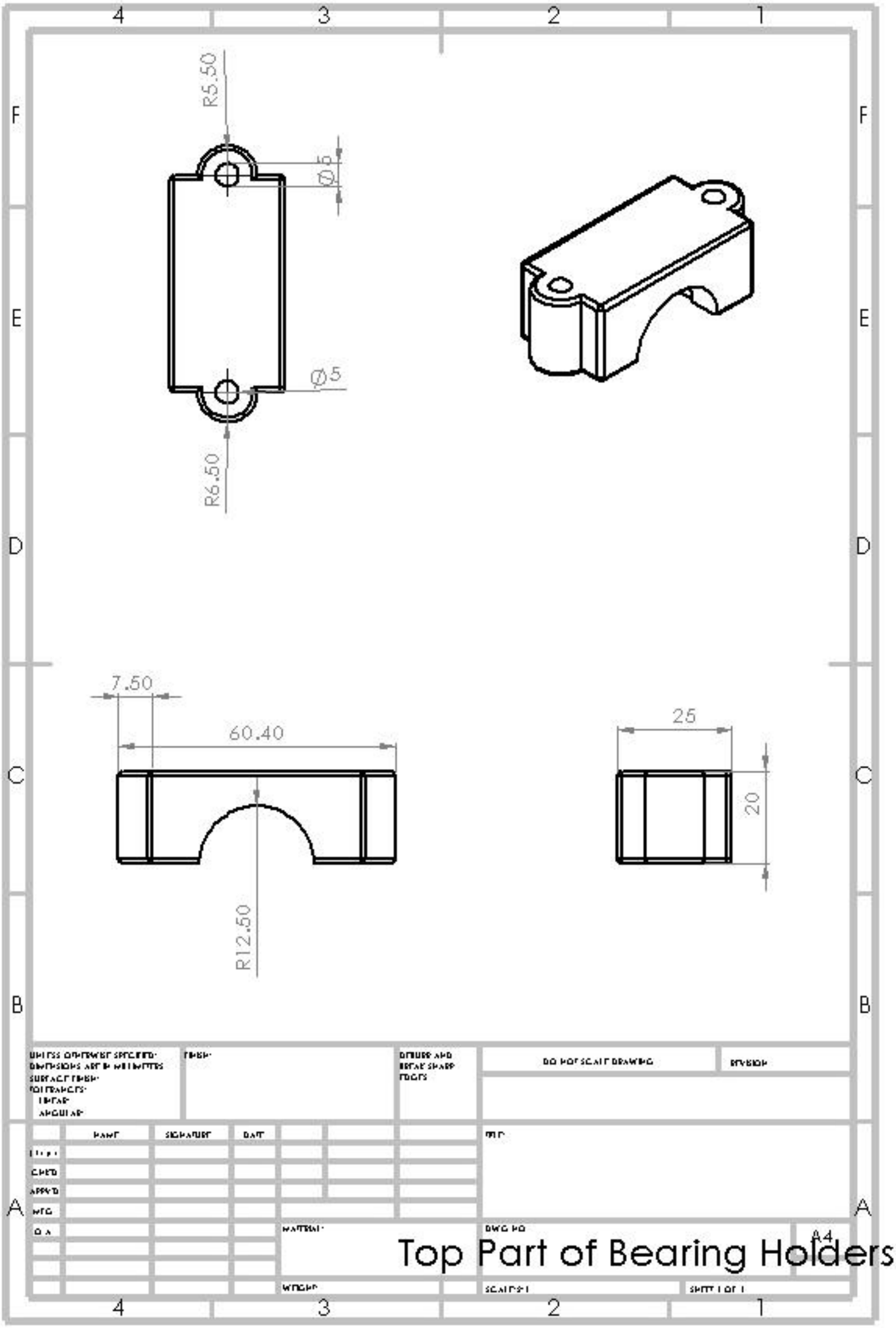
Design and Manufacture of a Semi-Automatic Radio Shuttle Prototype for Use in an Industrial Warehouse'

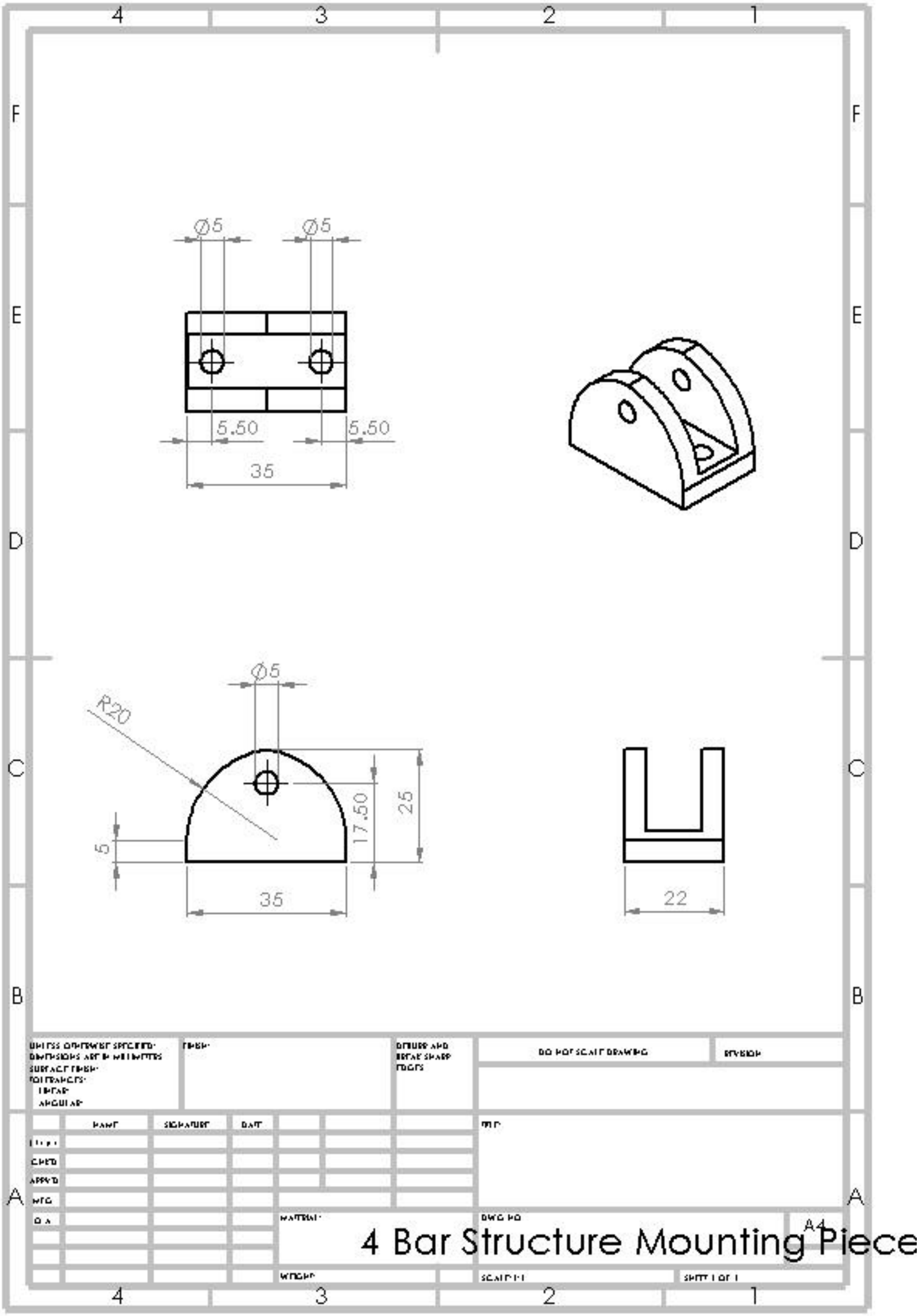
Gantt Chart

Task	Plan Start	Plan Duration (Weeks)	Actual Start	Actual Duration (Weeks)	Percent Complete
Find Supervisor and Choose Project	18/09/2017	1	18/09/2017	1	100%
Background Reading	18/09/2017	1	18/09/2017	1	100%
Research and Warehouse Visit	18/09/2017	1	18/09/2017	2	100%
Practice With Unfamiliar Software (Solidworks, Working Model, Cype)	18/09/2017	2	18/09/2017	2	100%
Design and Structural Assessment of Shelves using Solidworks	25/09/2017	2	25/09/2017	2	100%
Radio Shuttle Concept Generation	25/09/2017	1	25/09/2017	1	100%
Radio Shuttle Concept Selection	02/10/2017	1	02/10/2017	1	100%
Begin Writing Interim Report	02/10/2017	4	16/10/2017	2	100%
Shelf Construction	09/10/2017	2	09/10/2017	2	100%
CAD Model of Chosen Design	23/10/2017	2	12/10/2017	2	100%
Evaluation of Forces in Chosen Design	23/10/2017	2	30/10/2017	1	100%
Order and Begin Manufacture of Required Parts	30/10/2017	2	24/10/2017	5	100%
Begin Writing Final Report	30/10/2017	8	30/10/2017	9	100%
Construction and Testing of Prototype	06/11/2017	3	13/11/2017	3	100%
Re-Model Shuttle With Any Improvements	27/11/2017	1	04/12/2017	1	100%
Final Design Construction	04/12/2017	2	08/11/2017	1	100%
Prepare For Presentation	18/12/2017	3	01/01/2018	1	100%



Appendix 6 – Technical Drawings





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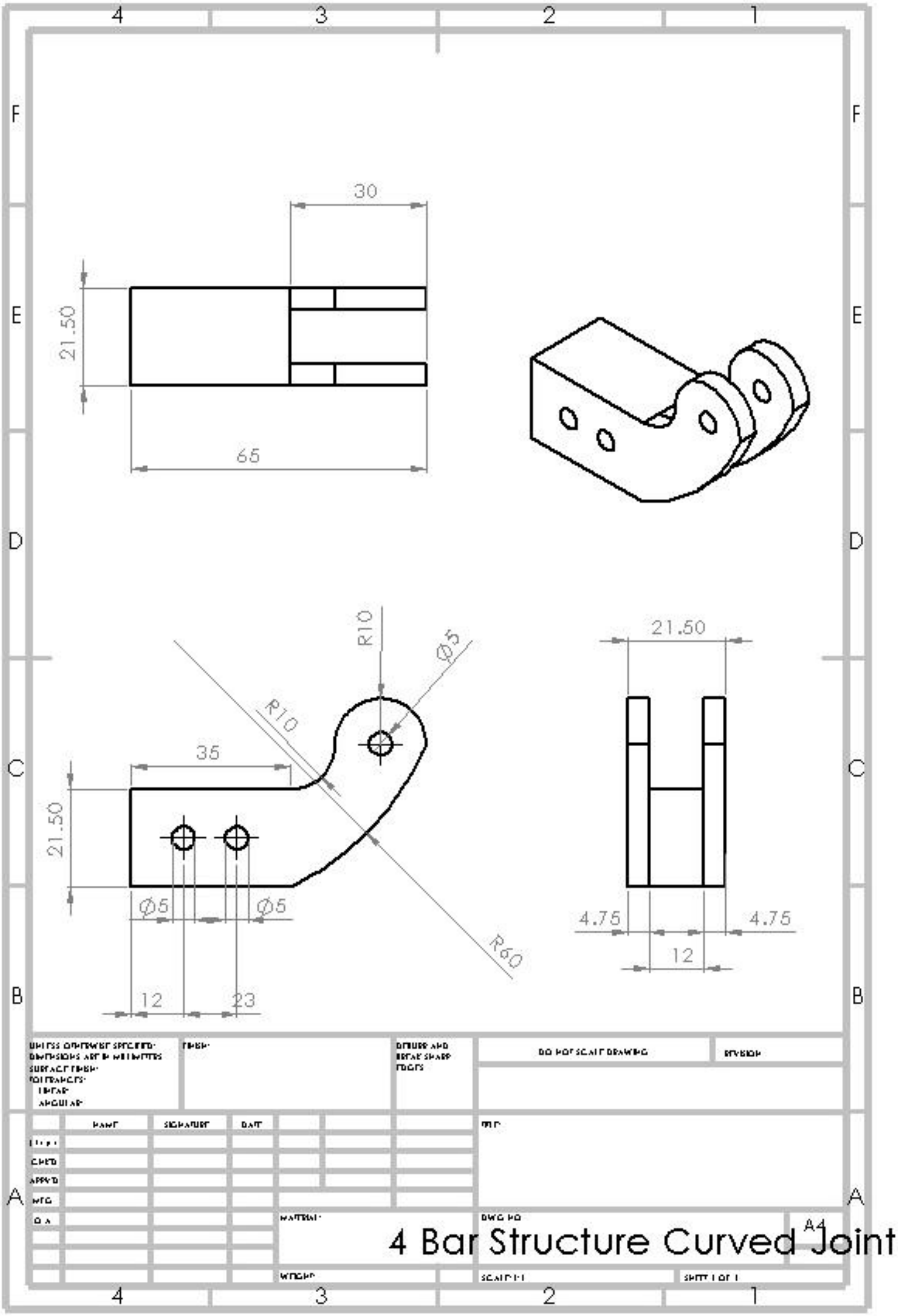
DO NOT SCALE DRAWING
REVISION
A4
4 Bar Structure Mounting Piece


30
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R10
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R60
12
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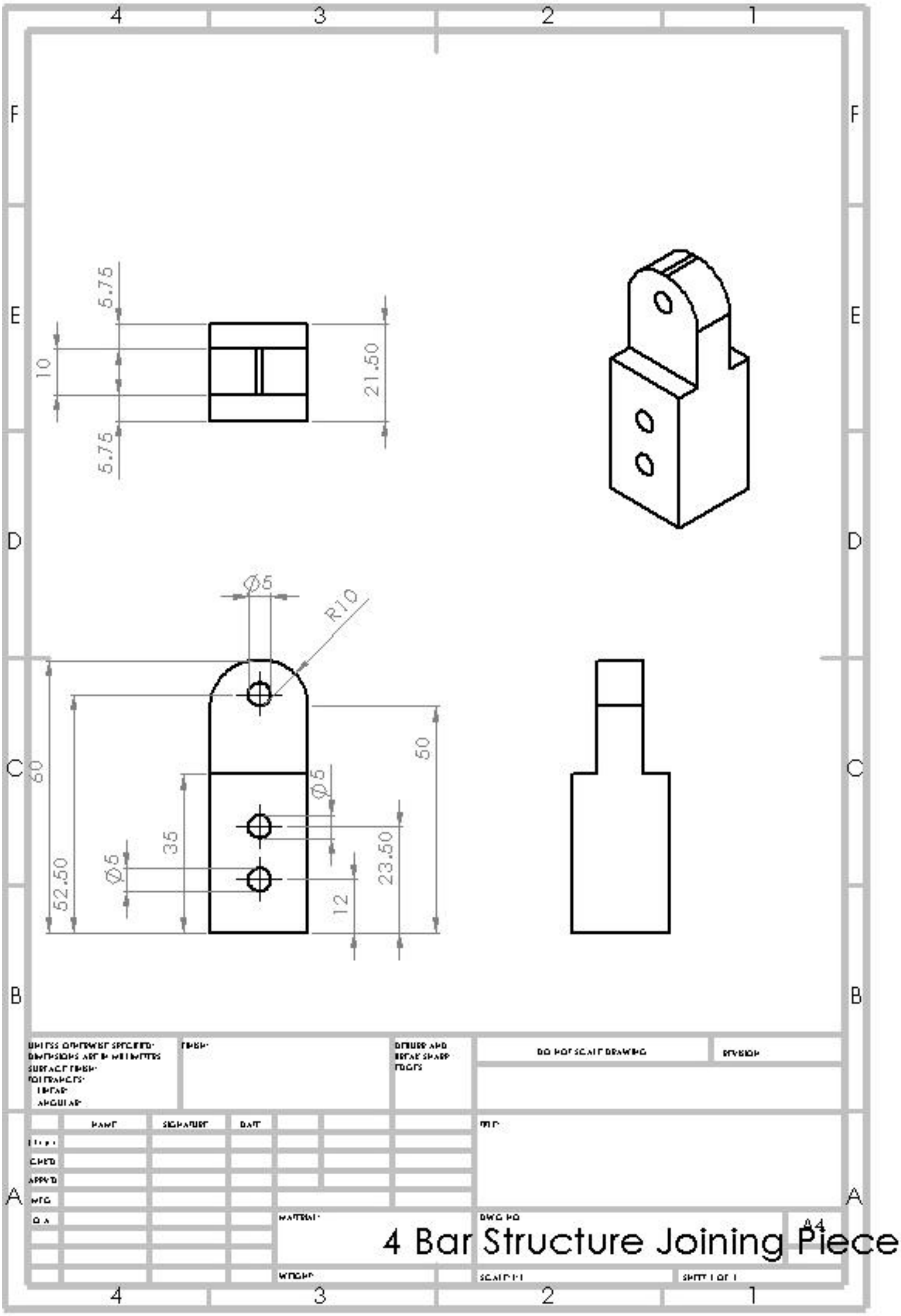
4.75
12
4 Bar Structure Curved Joint
A4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12
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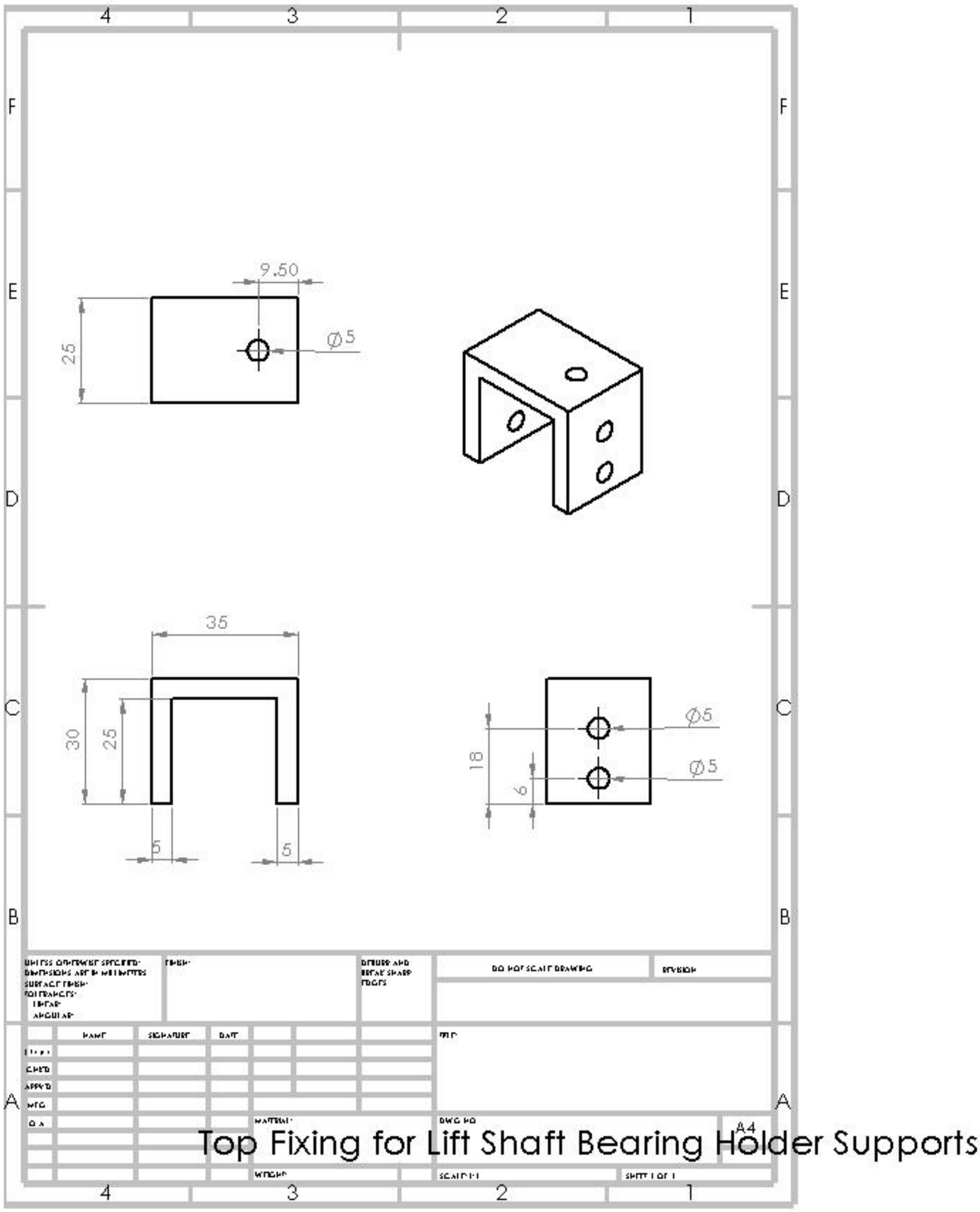
SIGNATURE
DATE
MATERIAL:
DWG NO.
WEIGHT:
A4
4 Bar Structure Joining Piece


9.50
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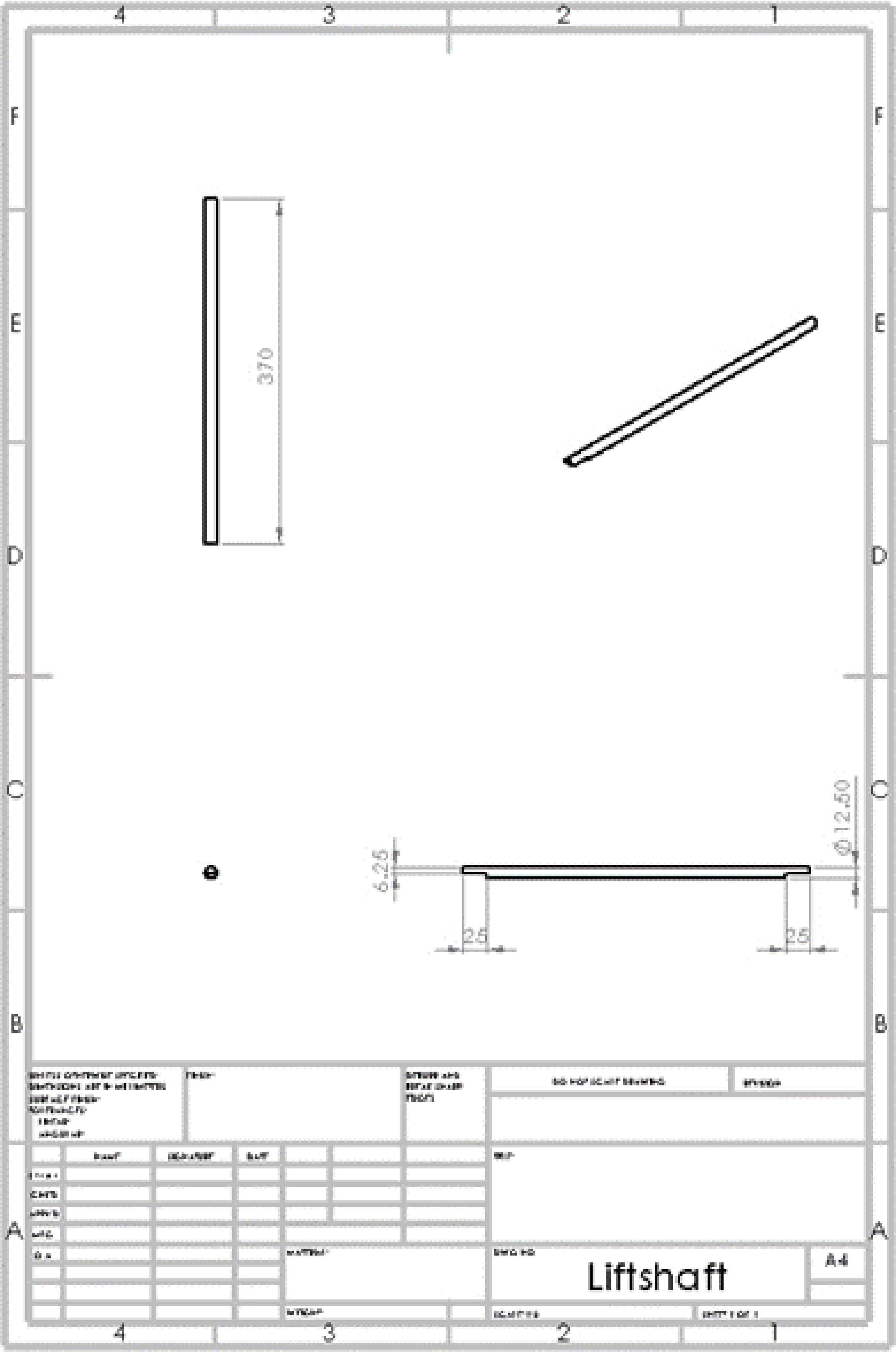
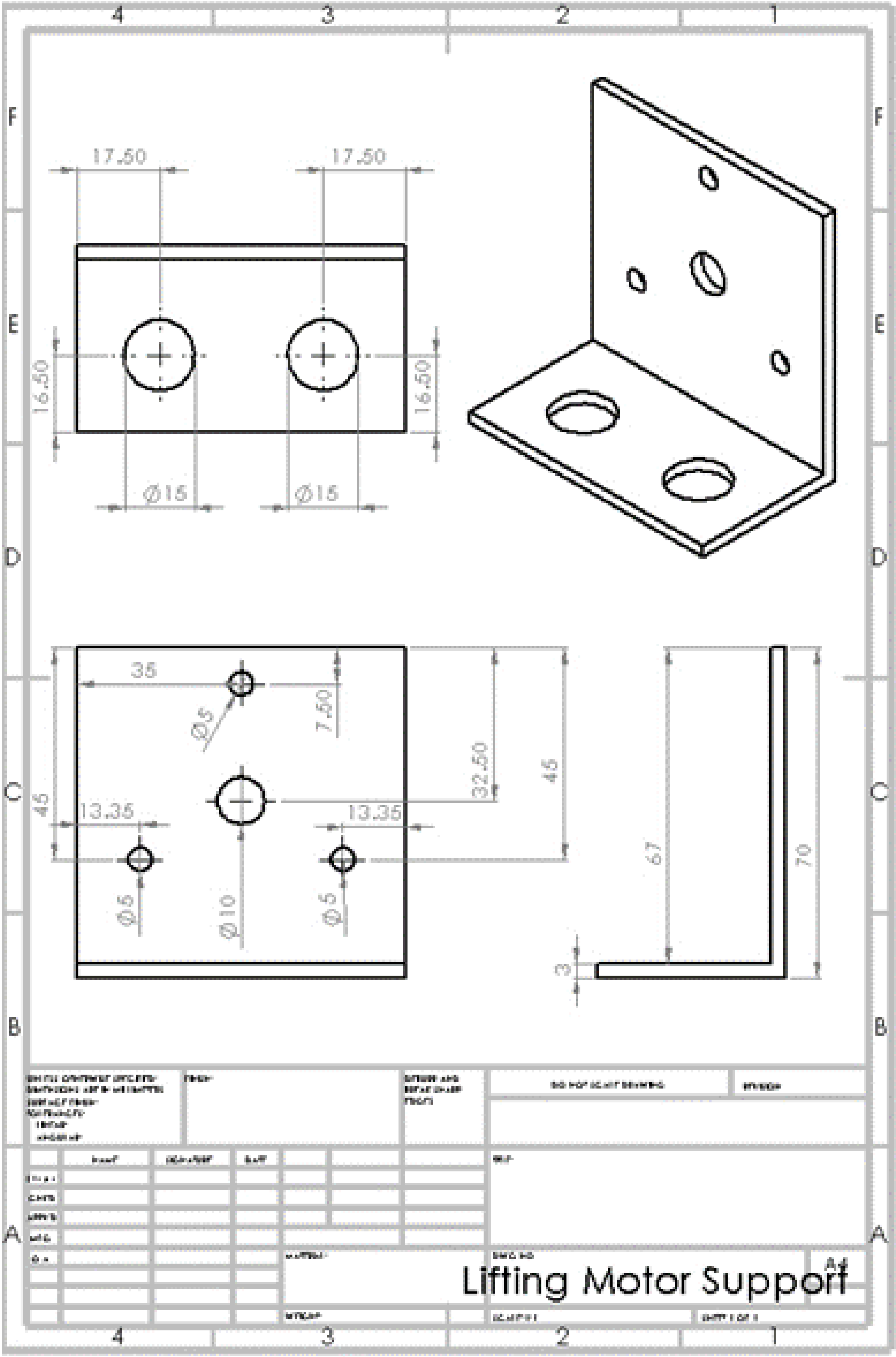
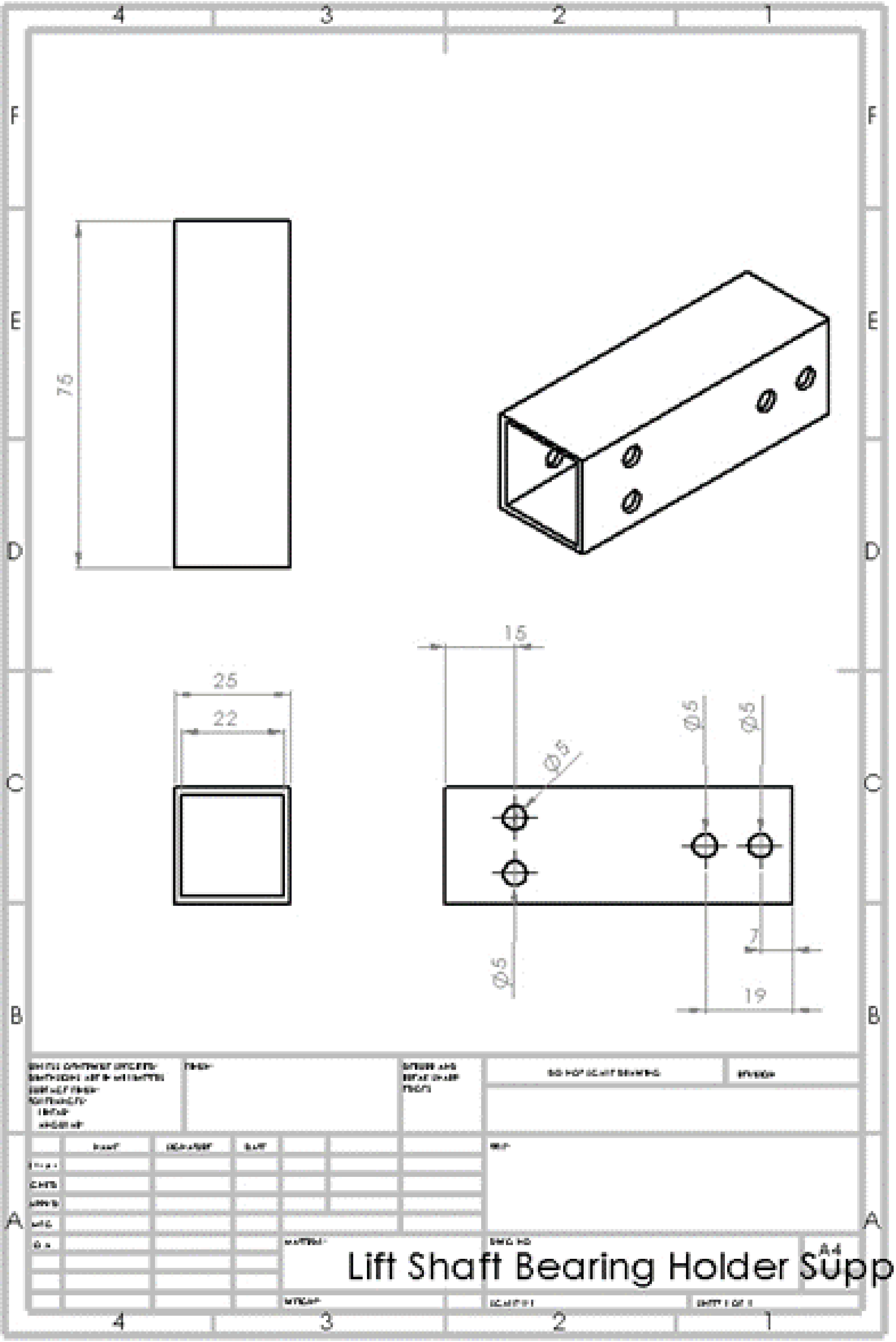
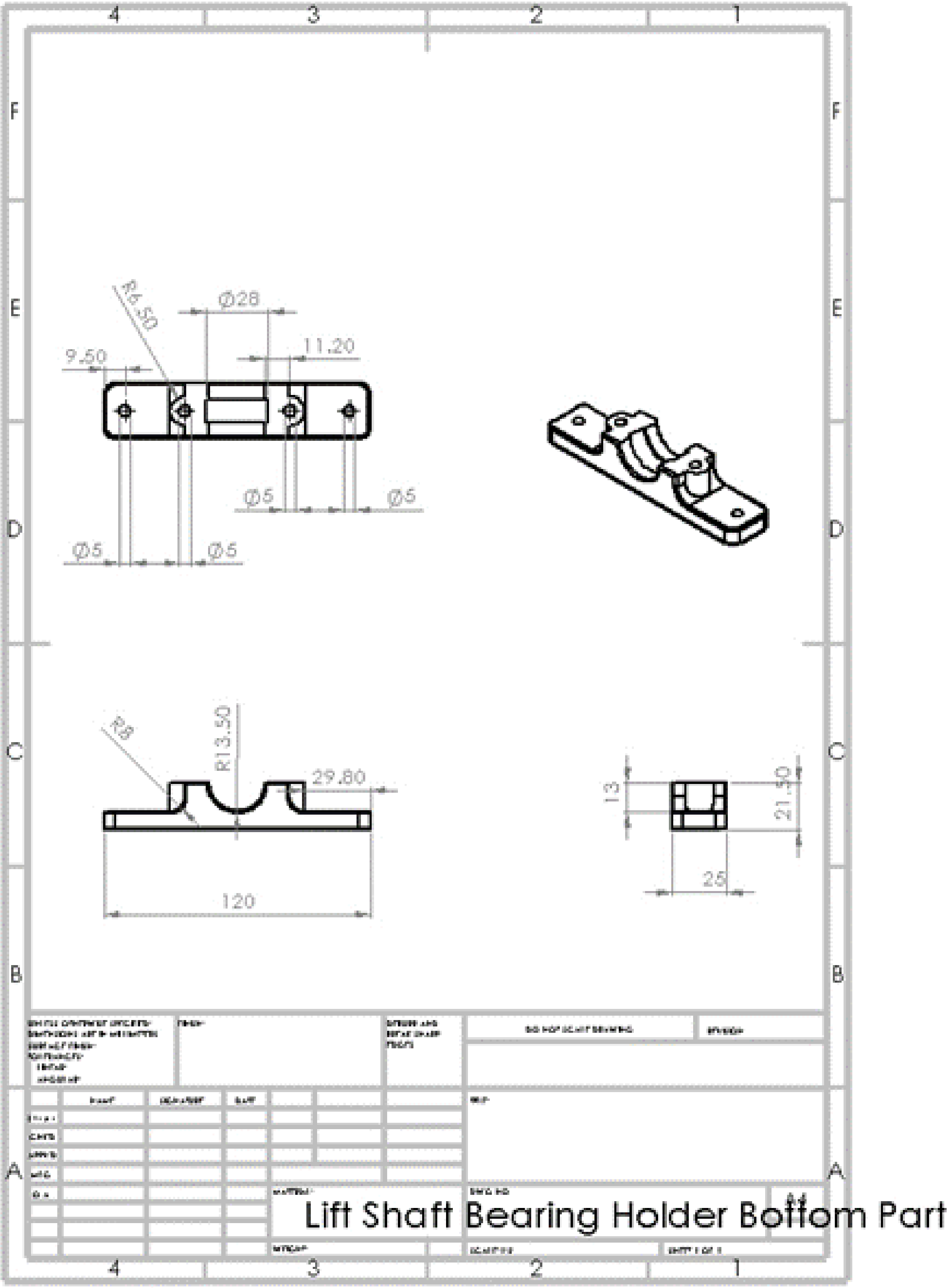
A4
Top Fixing for Lift Shaft Bearing Holder Supports

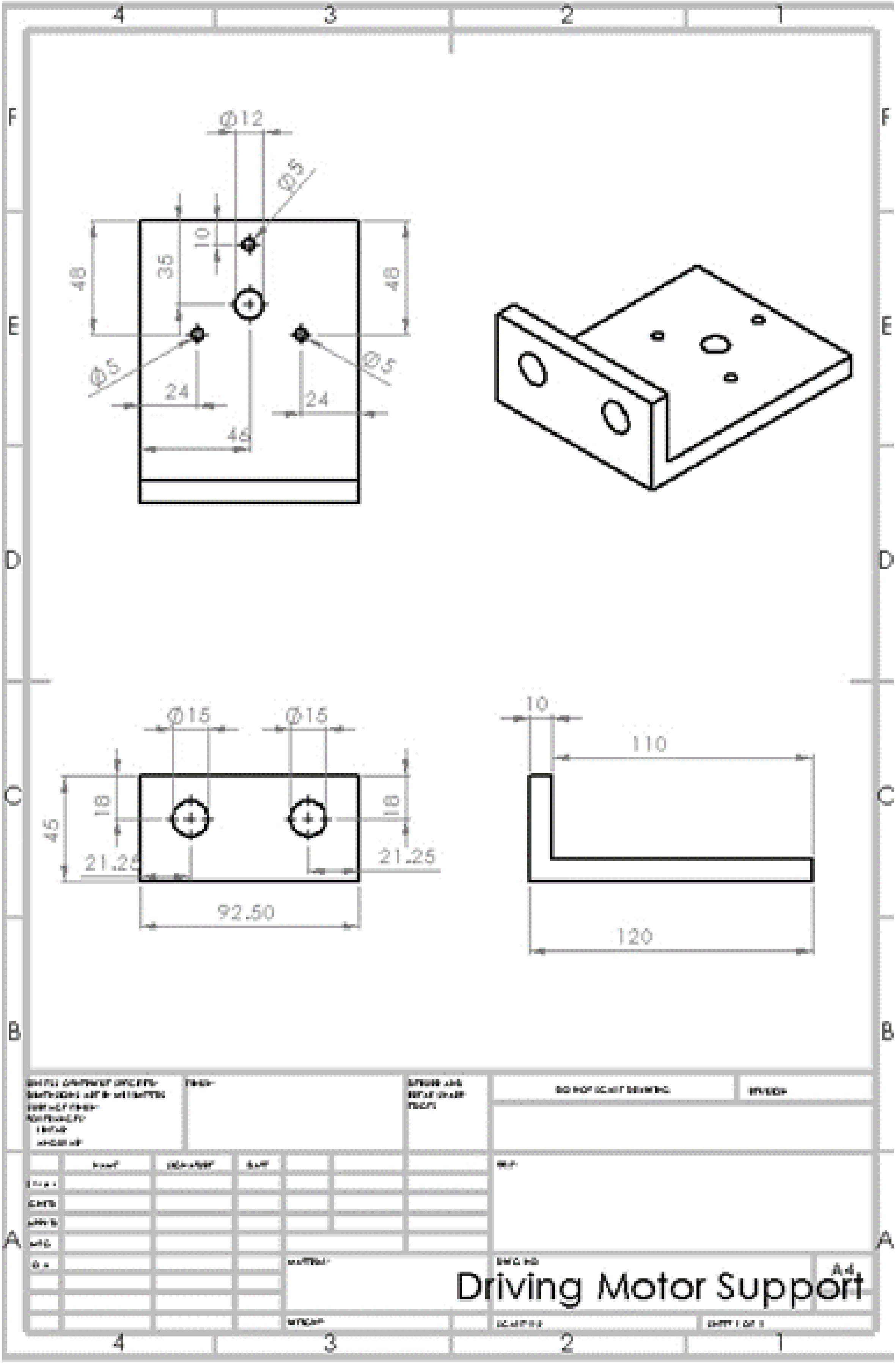

370
6.25
Ø12.50
25
25
Liftshaft
A4

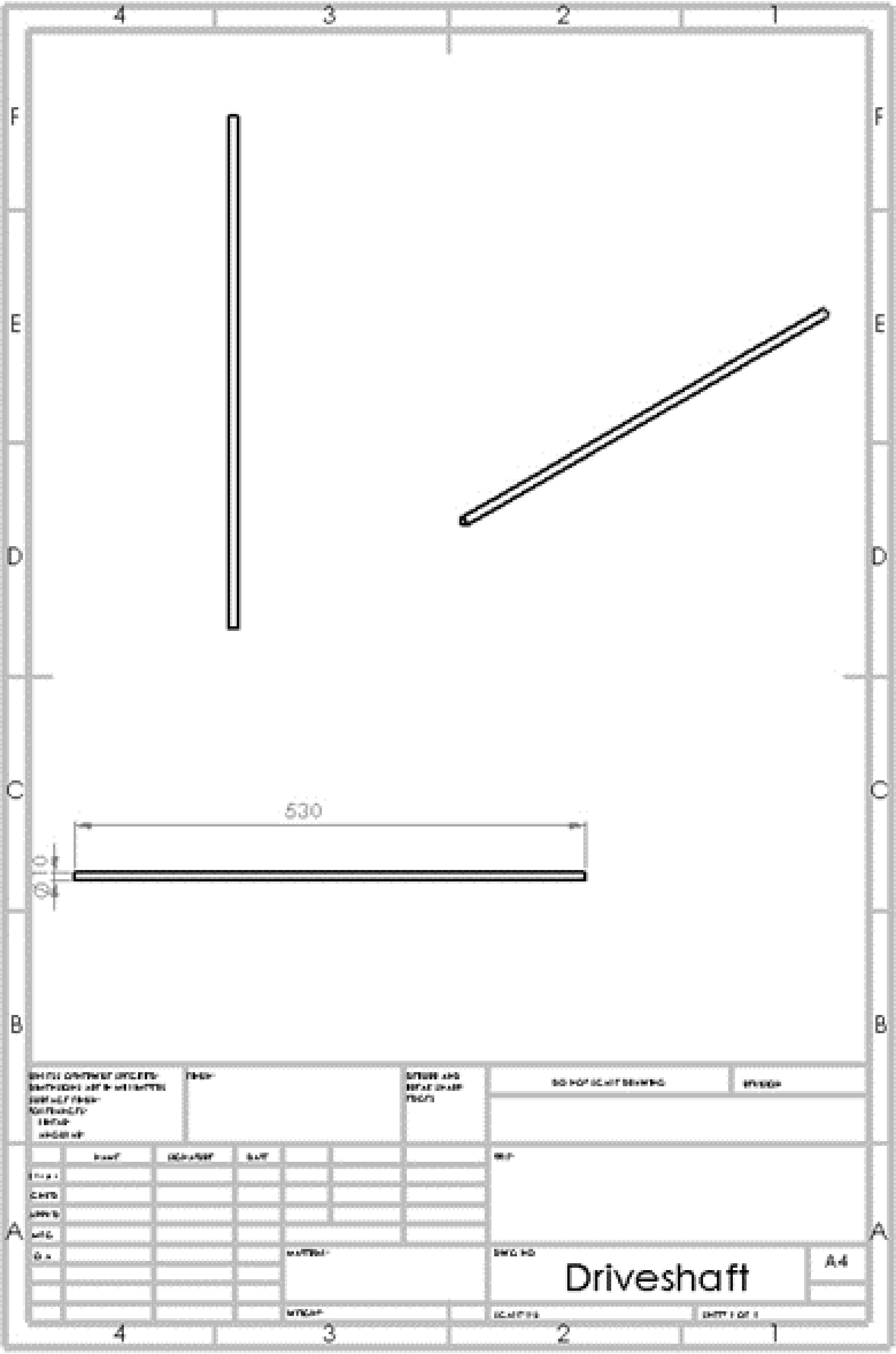

17.50
17.50
16.50
16.50
Ø15
Ø15
35
Ø5
7.50
32.50
45
45
13.35
13.35
Ø5
Ø10
Ø5
67
70
3
A4
Lifting Motor Support

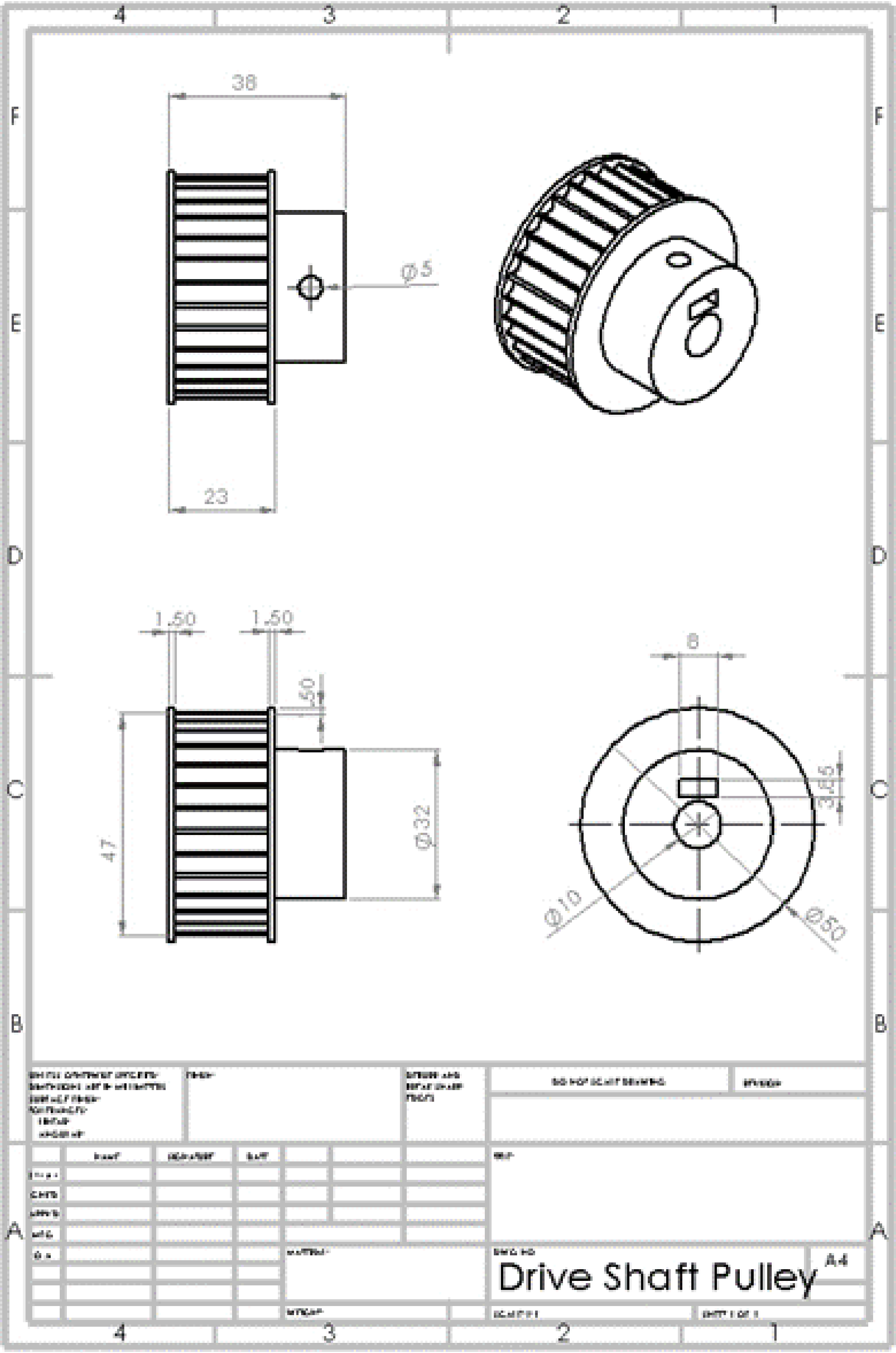

75
25
22
15
Ø5
Ø5
Ø5
Ø5
7
19
A4
Lift Shaft Bearing Holder Supports



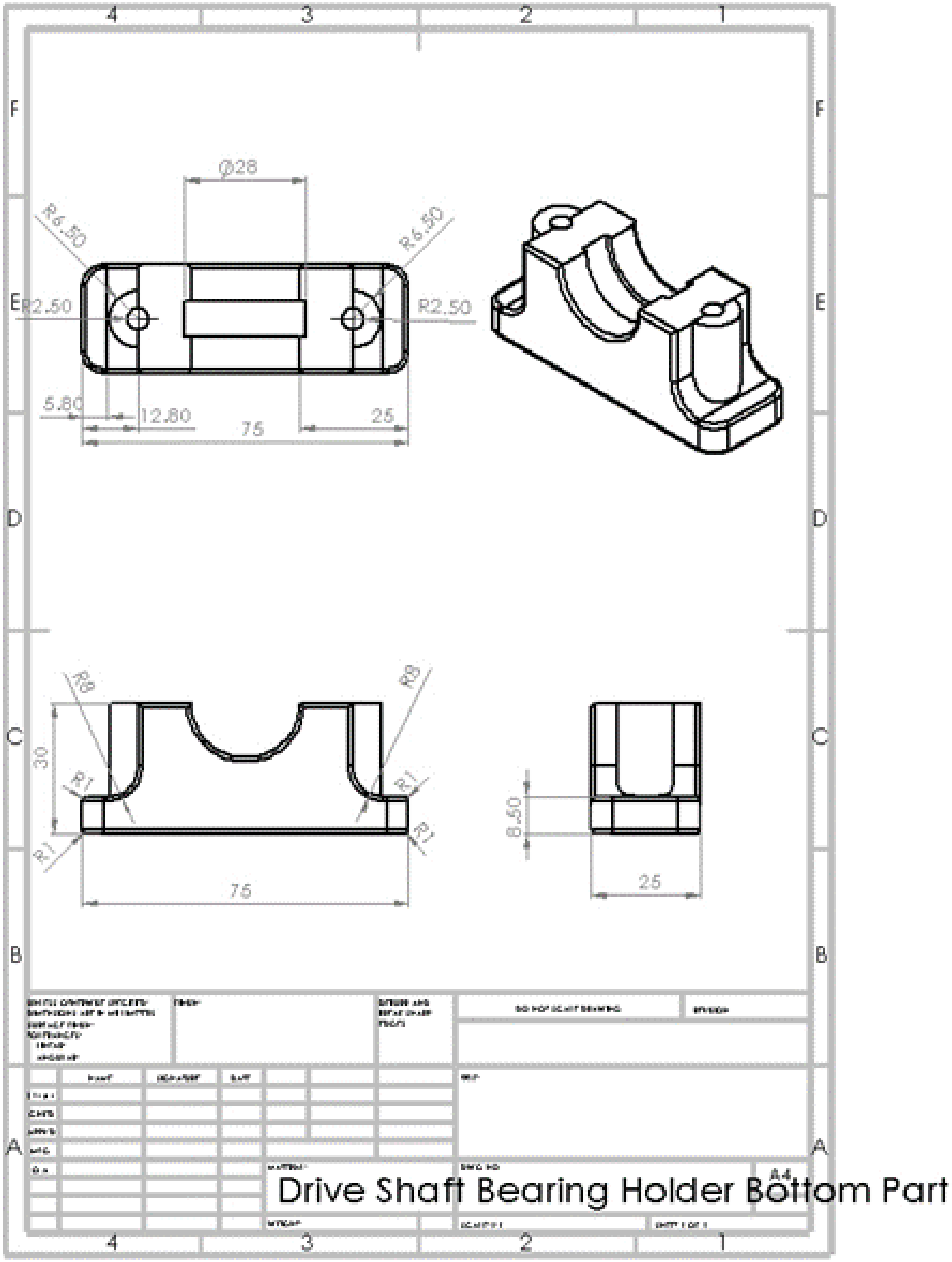
R6.50
Ø28
11.20
9.50
Ø5
Ø5
Ø5
Ø5
R8
R13.50
29.80
120
13
21.50
25
DO NOT SCALE DRAWING
Lift Shaft Bearing Holder Bottom Part

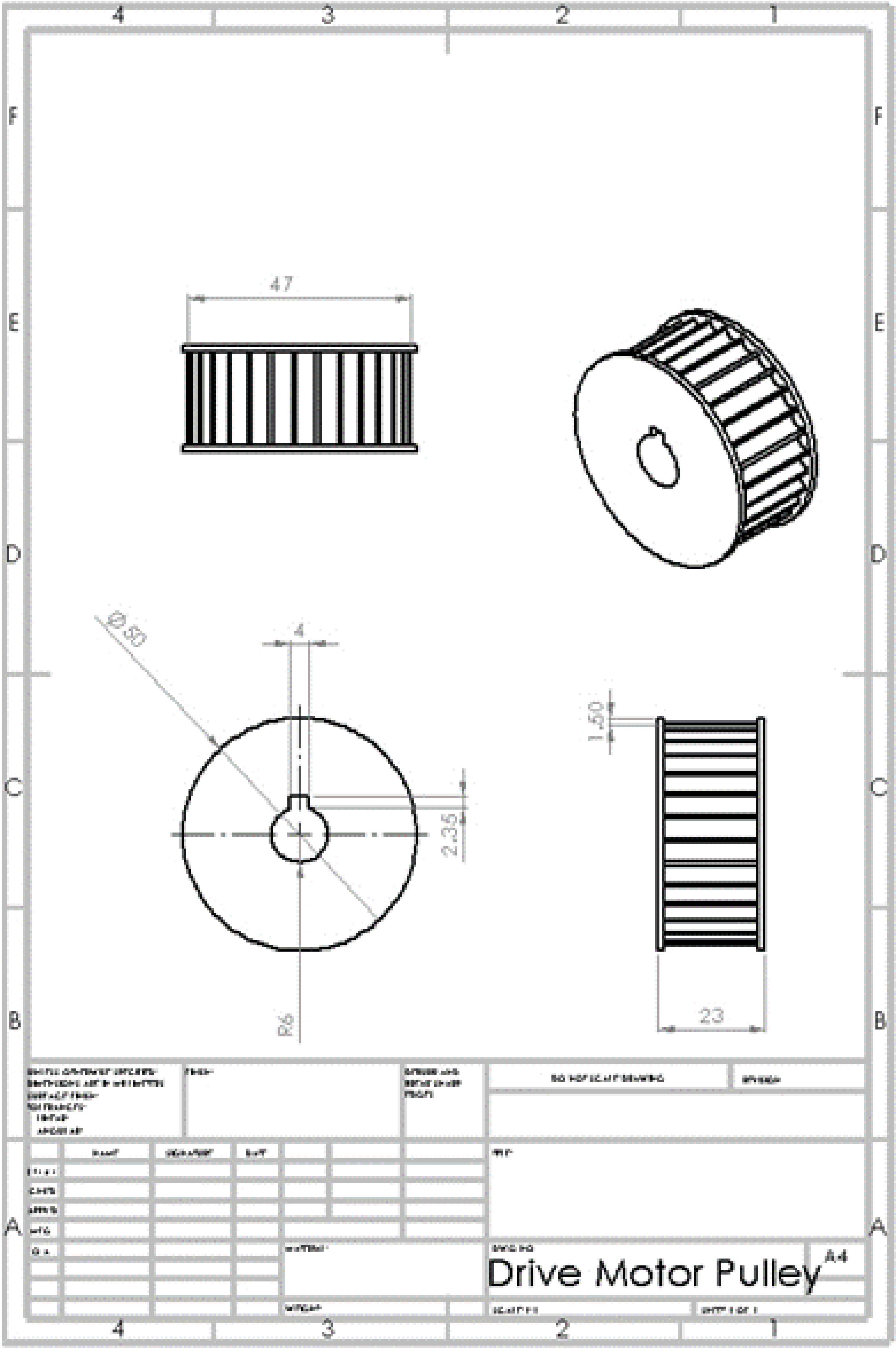

Ø12
Ø5
10
35
48
48
Ø5
Ø5
24
24
46
Ø15
Ø15
18
18
45
21.25
21.25
92.50
10
110
120
Driving Motor Support
A4


530
Driveshaft
A4

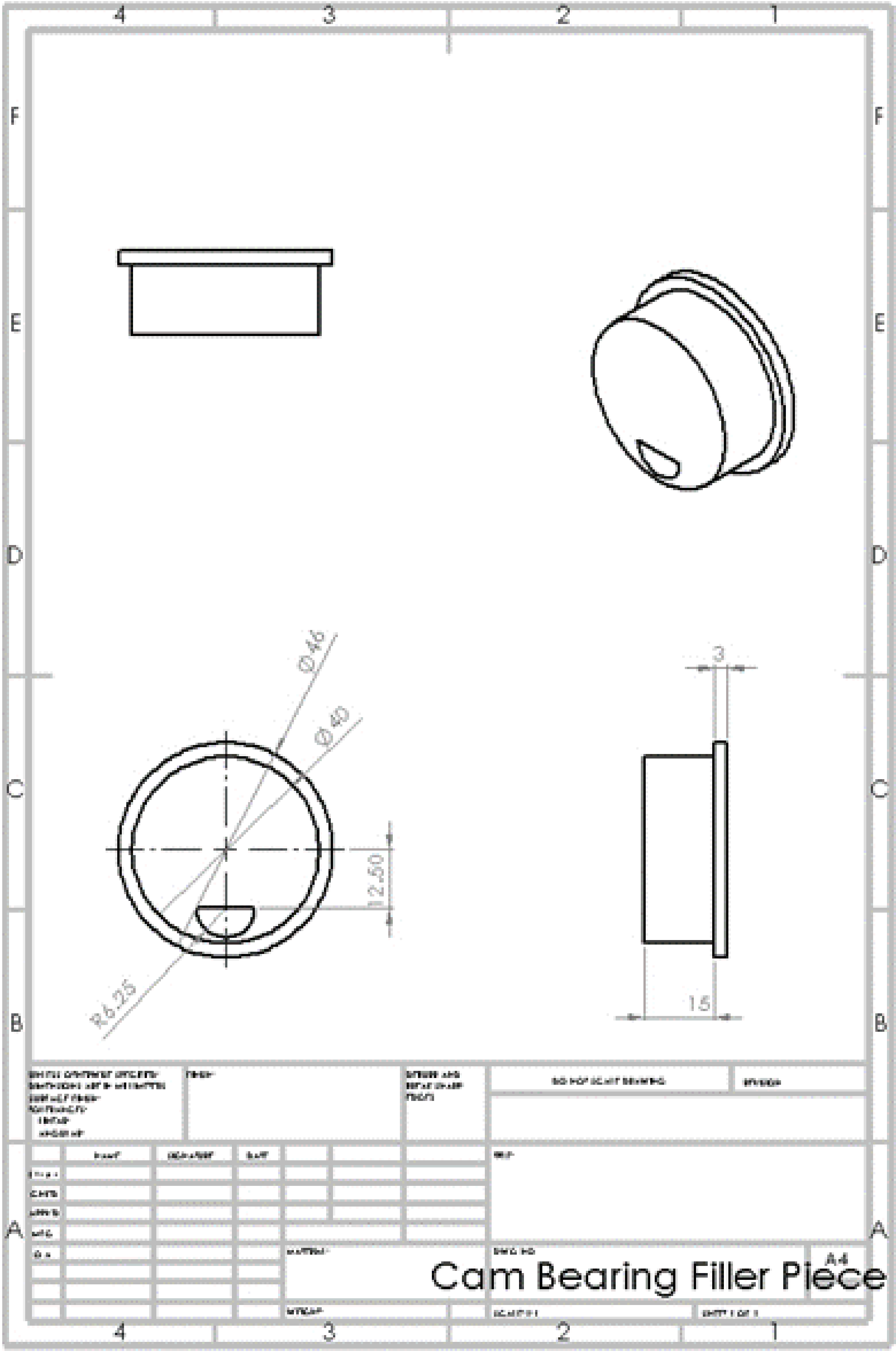


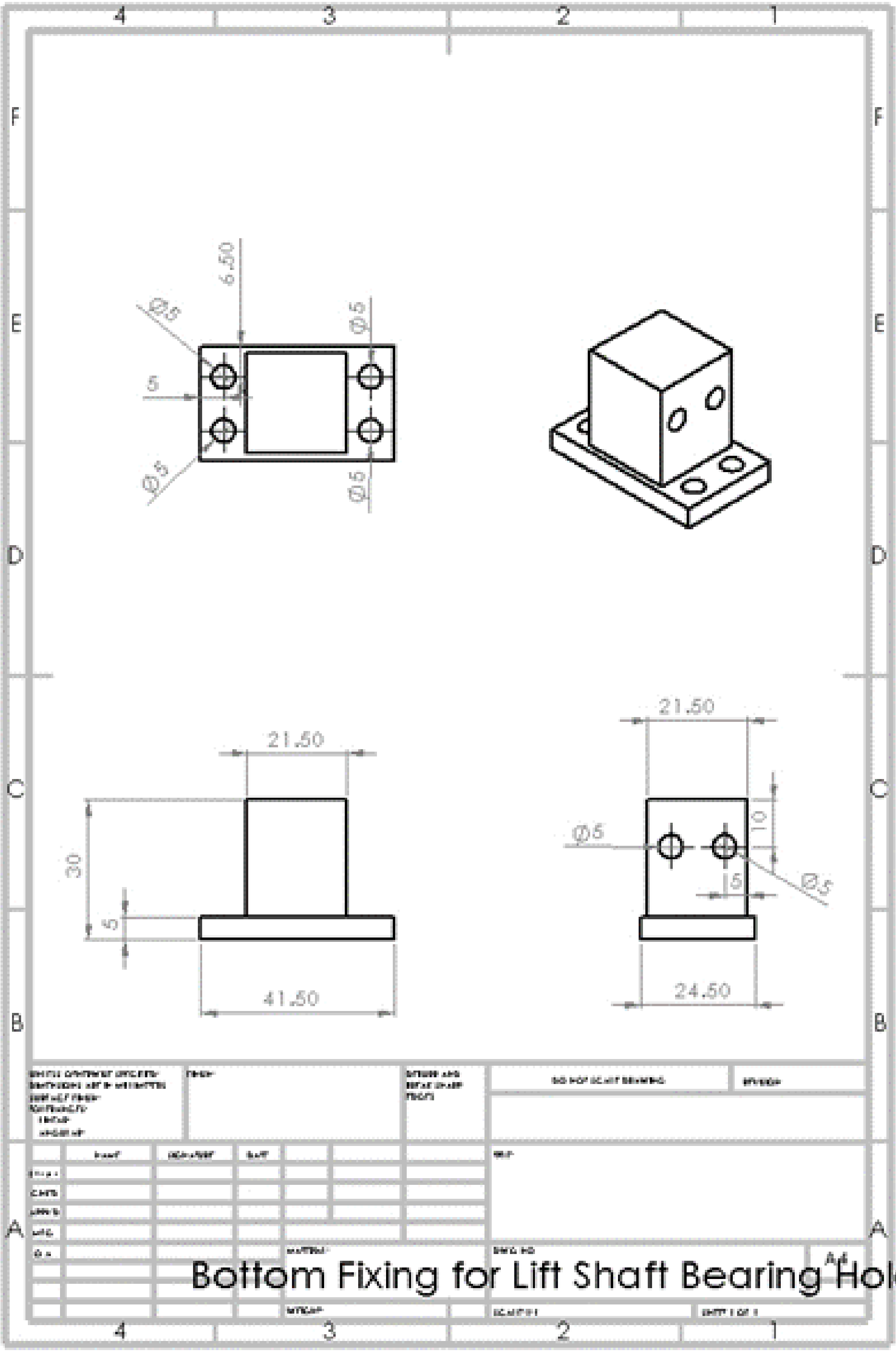
38
Ø5
23
1.50
1.50
.50
47
Ø32
8
3.65
Ø10
Ø50
Drive Shaft Pulley
A4


Ø28
R6.50
R6.50
R2.50
R2.50
5.80
12.80
75
25
R8
R8
30
R1
R1
R1
R1
75
8.50
25
DO NOT SCALE DRAWING
Drive Shaft Bearing Holder Bottom Part
A4

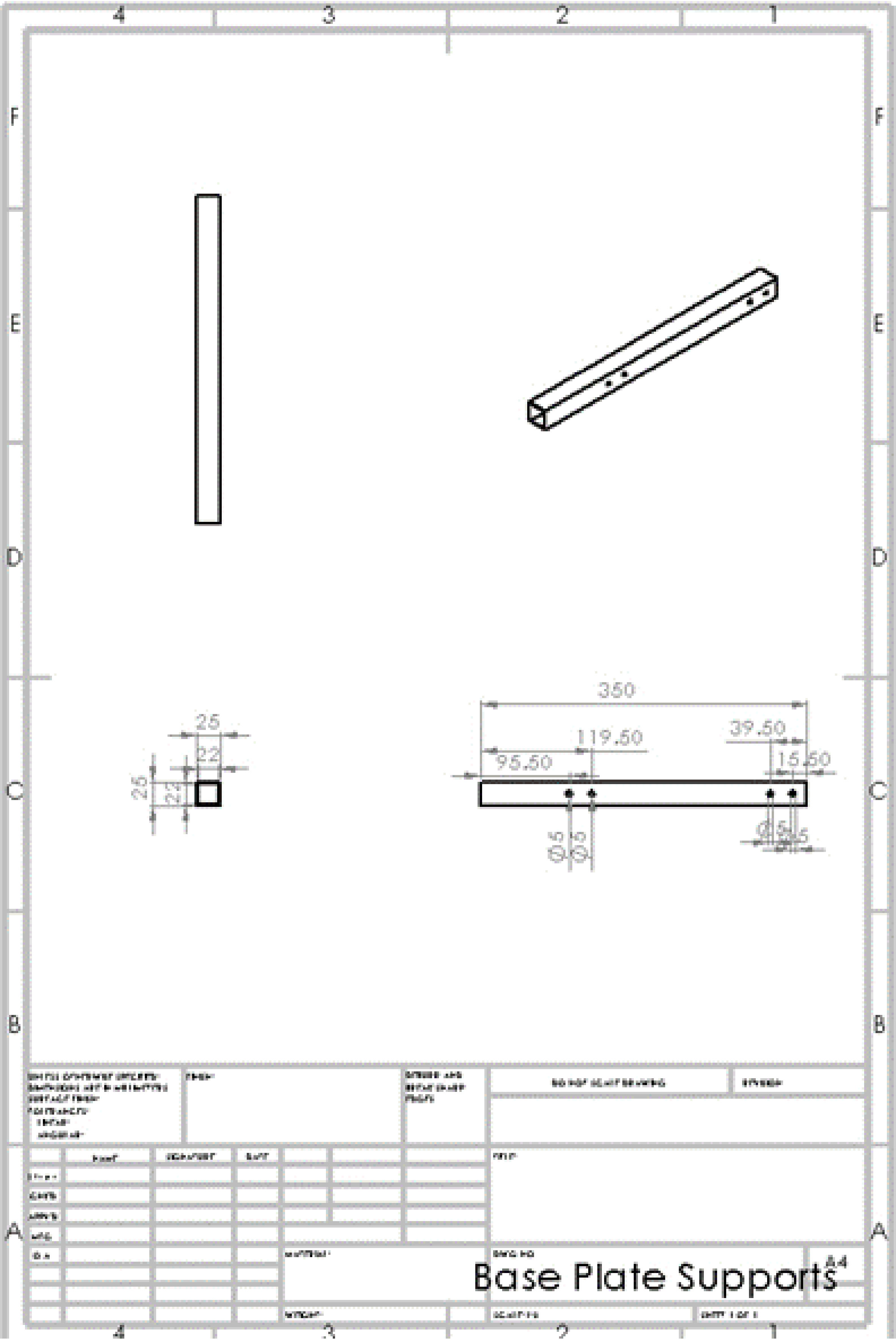


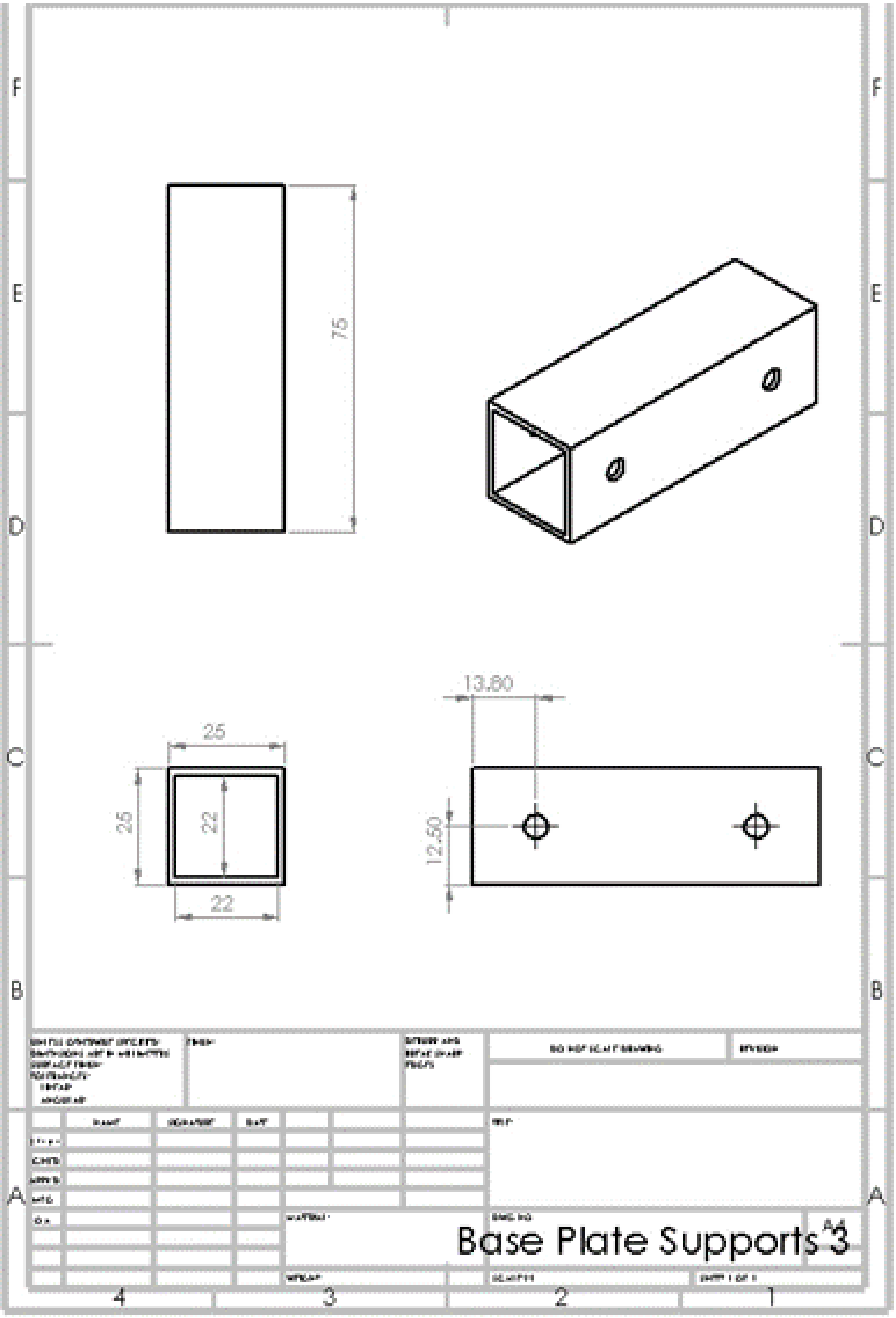
47
Ø50
4
2.35
1.50
R6
23
DO NOT SCALE DRAWING
Drive Motor Pulley
A4

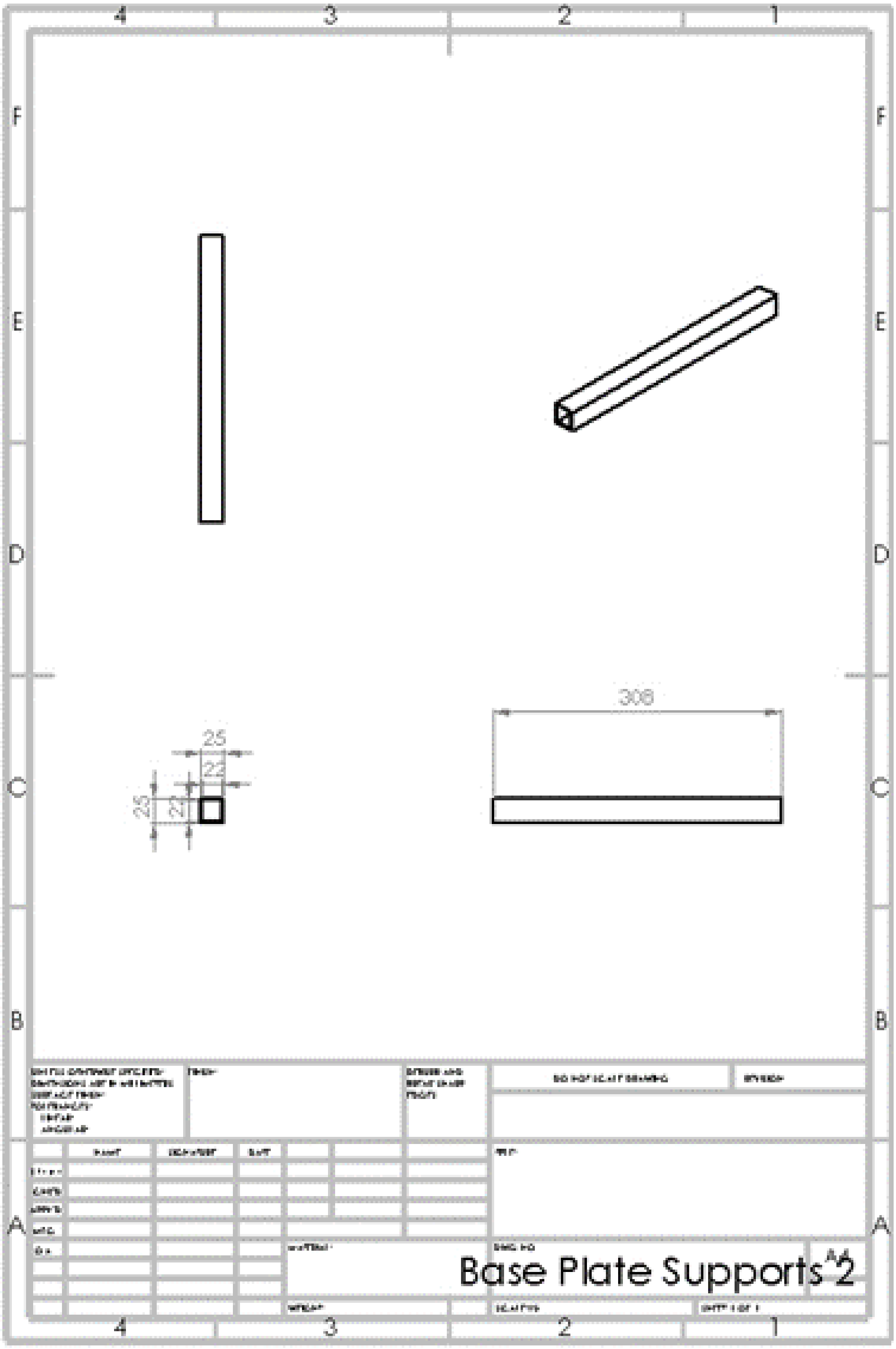

Ø46
Ø40
12.50
R6.25
3
15
A4
Cam Bearing Filler Piece

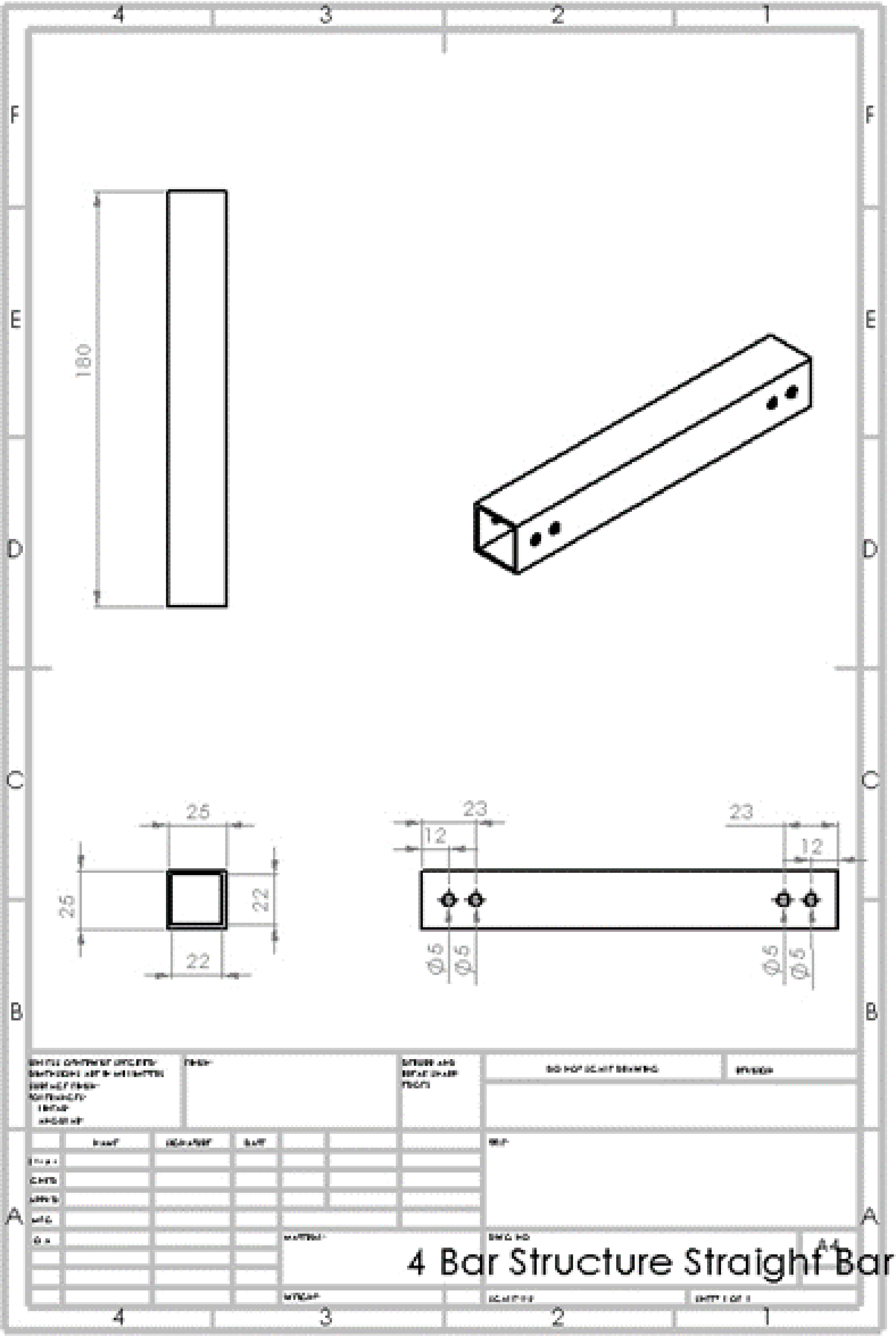


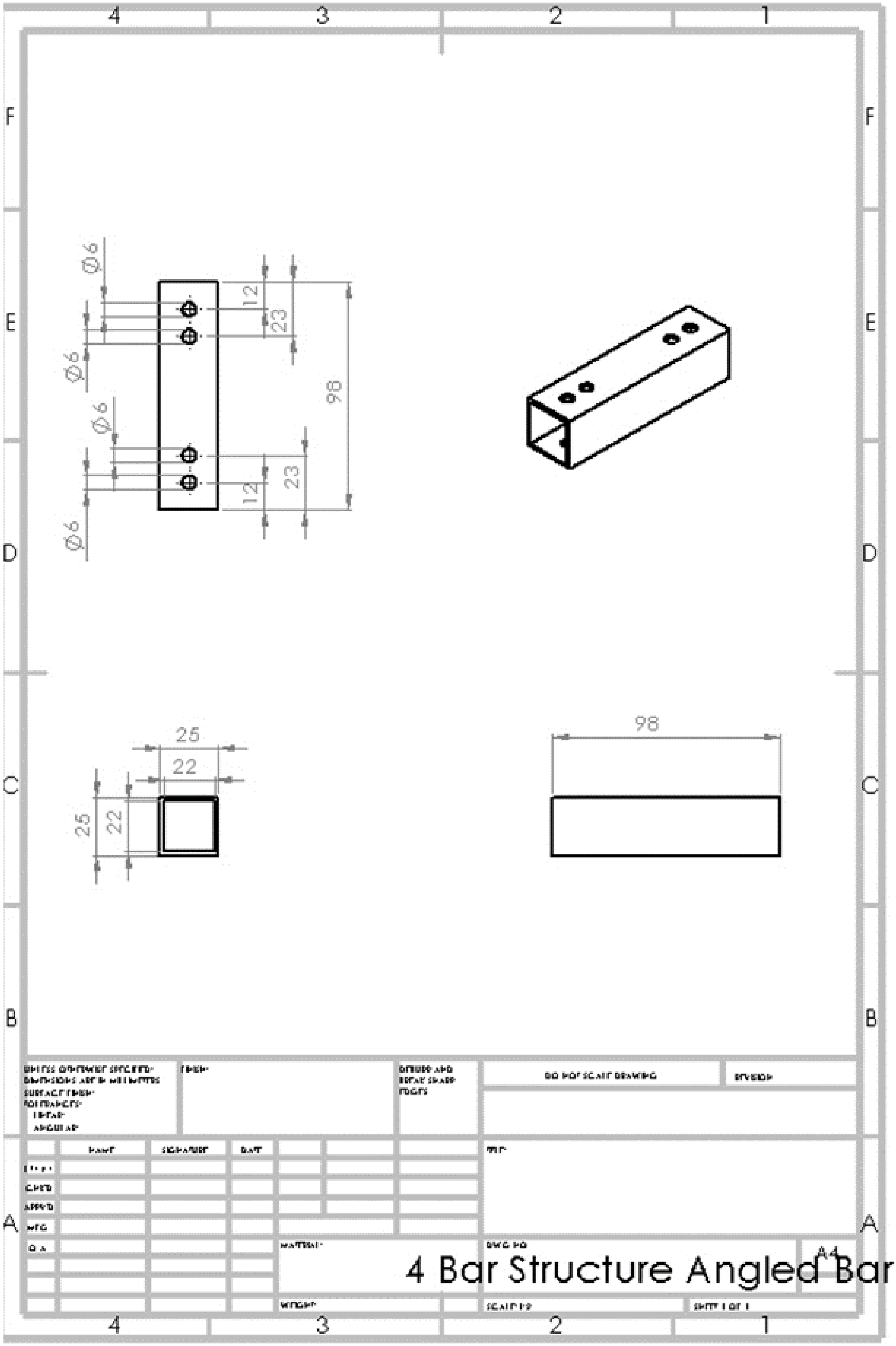
Bottom Fixing for Lift Shaft Bearing Holder Supports


350
119.50
95.50
39.50
15.50
25
22
Base Plate Supports
A4


75
25
25
22
22
13.80
12.50
DO NOT SCALE DRAWING
Base Plate Supports 3
A4


308
25
22
25
22
Base Plate Supports 2
A4


4 Bar Structure Straight Bar
180
25
25
22
22
23
12
23
12
Ø5
Ø5
Ø5
Ø5
A4


Ø6
12
23
98
25
22
DO NOT SCALE DRAWING
4 Bar Structure Angled Bar
A4