University of Southern Queensland

Faculty of Health, Engineering and Sciences

# Digitally Fabricated Reduction Drive for Low-Cost Robotics Applications

A dissertation submitted by

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Towards the degree of

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# Abstract

Throughout the robotics industry there is a widespread requirement for high-speed electric motors to be slowed down, to increase accuracy and precision, while increasing the torque output. Electric motors are most efficient at high RPM's; the robotics industry requires outputs that have control, high accuracy, precision, and torque. To achieve this, a gearbox/reduction drive must be utilised to reduce the output speed and increase the torque of the motor.

Reduction drives can be a substantial expense in the overall project costing, with drives starting at $120 and ranging up to $4,000. This amount adds up significantly when several drives are required for a project. In addition to low cost, another key criterion is zero backlash (backlash impacts the accuracy of the drive). An emerging reduction drive, known as the Archimedes drive, utilises steel rollers instead of teeth to provide a high reduction, high precision drive. With the potential of being able to digitally fabricate this type of drive it will enable cost-effective prototyping, allowing for greater innovation in other aspects of mechatronics.  However, it will likely be difficult to digitally manufacture a reduction drive to the required specifications.

The primary aim of the project was to digitally manufature a cost-effective reduction drive for use in mechatronics, particularly for research and education. A reduction drive concept was designed and manufactured using a 3D FDM printer and then evaluated. A design, build and test methodology was employed to firstly determine the suitability of digitally producing a reduction drive and secondly evaluate its performance. The newly developed Archimedes friction drive was selected as the most appropriate model to be digitally fabricated for the desired purpose. However, as the Archimedes drive has not yet been released to the public, nor are there many available details on its design, there were some gaps in determining how the drive was put together. Therefore, for this project, several protypes have been 3D printed to determine that the best design was being carried forward. Once the design of the prototype was finalised, the drive was evaluated by physically measuring and analysing the movement of the drive while measuring key parameters such as backlash and torque output.

Another challenge for the project was material selection. There is a wide and ever-increasing array of 3D printable filaments, these filaments could be further evaluated and utilised in the design. Additionally, different digital fabrication processes could be utilised, including a

combination of various processes which may allow for greater precision and strength. While the final reduction drive prototype was not perfect, there is certainly potential to develop the desired drive with further design and research. Overall, the final drive prototype provides a solid foundation to allow for rapid prototyping and further research.

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# Nomenclature and Acronyms

RPM – Revolutions Per Minute

SLA – Stereolithography

SLS – Selective Laser Sintering

FDM – Fused Deposition Modelling

FFF – Fused Filament Fabrication

JM – Material Jetting

BJ – Binder Jetting

EBM – Electron Beam Melting

PLA – Polylactic Acid

ABS – Acrylonitrile Butadiene Styrene

PA – Polyamide (Nylon)

PC – Polycarbonate

PETG – Polyethylene terephthalate glycol

PVA – Poly Vinyl Alcohol

# Chapter 1 - Background

## 1.1. Outline of the Study

The foundation of this project is to design, develop and evaluate a low-cost reduction drive for use in mechatronics and other fields where high precision, zero backlash and large gear reductions in a compact package is required. The utilisation of digital fabrication methods allows for the drive to be affordable and easily accessible.

## 1.2. Introduction

Throughout the robotics industry there is a widespread requirement for high-speed electric motors to be slowed down, to increase accuracy and consistency, while increasing the torque output. Electric motors are most efficient at high RPM's; the robotics industry requires outputs that have control, high accuracy, precision, and torque. To achieve this, a reduction drive must be utilised to reduce the output speed and increase the torque of the motor. However, there is a significant cost associated with such a reduction drive which can negatively impact innovation in the robotics industry. Low-cost reduction drives with the below characteristics are required to enable the growth and innovation of robotics, allowing the focus to be on other aspects of design.

Therefore, the key characteristics of the reduction drive need to be:

- Low cost
- No backlash
- High reduction
- Utilisation of digital fabrication methods
- Materials – Tribological filaments
- Light duty work (generally)

The need for a reduction drive with these characteristics is demonstrated by companies such as Haddington Dynamics who have started a micro-factory, DCISIV (pronounced Decisive), in the regional city of Toowoomba, Queensland, Australia. Haddington Dynamics have developed a cost-effective robotic arm, named ‘Dexter’. This arm is made up entirely of 3D printed elements, allowing rapid prototyping of components without the need for expensive retooling (Hackster, 2018). The most popular reduction drives currently available include strain wave gearing, cycloidal gearing, planetary gearing, and Archimedes drives (also known as friction drives). These reduction drives have the following features:

| Features | Strain Wave | Cycloidal | Planetary | Archimedes |
| --- | --- | --- | --- | --- |
| **Noise** | Low | High | High | Low |
| **Vibration** | Low | High | Low | Low |
| **Backlash** | Zero | Low | Medium | Zero |
| **Reduction** | High | High | Med-High | High |
| **Manufacturing Precision** | High | Low | Medium | Medium |
| **Torque** | Low | Low | High | Low |
| **Weight** | Low | Medium | High | Low |
| **Wear** | Unknown | Medium | Medium | Unknown |
| **Size** | Small | Medium | Large | Small |
| **Cost** | High | Medium | Low | High |

**Table 1.2.1: Reduction Drive Comparison**
(Compact Gearboxes for Modern Robotics: A Review | Frontiers, 2020)

## 1.3. The Problem

As foreshadowed above, the main issue with the currently available reduction drives is cost, with typical industrial reduction drives starting at $120 per drive and ranging up to $4,000. This cost adds up significantly when several drives are required for a project. Increased costs are associated with the most desirable characteristics in a reduction drive being low backlash, high torque transmission, high reduction and durability, with the most significant costs being associated with high torque transmission and durability. However, in many robotic applications (industrial, research and education) we only need low backlash and high reduction, without the high price tag associated with high torque transmission and durability. The idea behind this project is to reduce the cost of the drive by digitally fabricating a drive that has low backlash and high reduction, without the focus on high torque transmission and durability. However, digital fabrication comes with its own set of challenges. It will likely be difficult to digitally manufacture a reduction drive with zero backlash to suit the specific requirements of the project.

## 1.4. Research Aim and Objectives

The aim of this research project is to design, manufacture and evaluate a low-cost, digitally produced reduction drive for use in robotics. The drive should be easily manufactured without expensive tooling or prohibitive costs. It should also be able to be easily redesigned and manufactured to suit various projects specifically and allow for rapid prototyping.

Key components of this research will include:

- Evaluation of the current literature and review the principles and designs of existing reduction drives
- Research costs of existing reduction drives and investigate where potential savings could be made
- Select a suitable design or reduction drive principle with potential for further development and refinement to ensure the drive is suitable for the intended application
- Evaluation of digitally fabricated products, materials and methods to determine suitable design methodology and material selection
- Design and digitally manufacture a reduction drive
- Evaluate the performance of the digitally fabricated reduction drive

## 1.5. Consequential Effects

This project has limited sustainability, safety or ethical issues associated with it. Although, the use of appropriately suitable and sourced material is very important. The materials should be sourced from a reputable manufacturer/supplier to ensure quality and that no hazardous materials or additives have been included. It is imperative to ensure that there are no potential health or environmental issues from the handling or manufacturing/usage of the materials. Key components to consider when selecting materials include a full life cycle analysis, recyclability, ease of production and supply chain logistics, availability of raw materials and noting any sustainability certifications by the manufacturer. Additionally, the ability and methods of disposing the material need to be ascertained to ensure there are minimal effects on the environment.

Positive consequential effects include the ability for low-cost robotic design and manufacture allowing better flexibility with design. This aids in the creation of distributed manufacturing enabling for greater focus to be placed upon innovation.

## 1.6. Conclusions

This project aims to determine whether it is possible to digitally fabricate a reduction drive suitable for use in mechatronics. A literature review for this research project will identify a suitable digital fabrication method (including material selection), an appropriate/ideal reduction drive to be utilised in prototyping and the methodology to be used to determine the projects suitability for use in the field. The design and testing process will test the suitability and practicality of the selected digital fabrication method and material selection, as well as whether the selected reduction drive is actually appropriate/ideal for the intended purpose.

# Chapter 2 - Literature Review

## 2.1. Introduction

In the robotics field there is a requirement for a compact, high reduction drive with zero backlash as it is an integral part of robotics (Frontiers 2020). This literature review will investigate several, compact, high reduction drives including strain wave drives, cycloidal drives, planetary drives, traction drives and friction ('Archimedes') drives. The issues surrounding digital fabrication of a reduction drive are also explored. Further, this review will identify the evaluation methods for reduction drives and motors to ensure the most appropriate methods are implemented in this project. Finally, given material selection is a critical component of designing and manufacturing an appropriate reduction drive, it will also be discussed in this review. Overall, it appears there is a gap in the literature in relation to an inexpensive and zero backlash reduction drive, which indicates the necessity for such a drive to be produced.

## 2.2. Drive Types

### 2.2.1. Strain Wave Drives

The strain wave drive was invented in 1955 and was broadly used within the aerospace industry in the 1970's with its major application in the lunar rover vehicle on Apollo 15 in 1971 (Frontiers 2020). The strain wave drive is made of three main components. There is a fixed ring gear with external teeth.  There is also a flexible ring gear with internal teeth, this cup is a smaller diameter than the fixed gear and contains fewer teeth. A centrally mounted, elliptical wave generator sits inside the flexible ring gear (Robotics Tomorrow 2016). The below figures illustrate a strain wave drive:

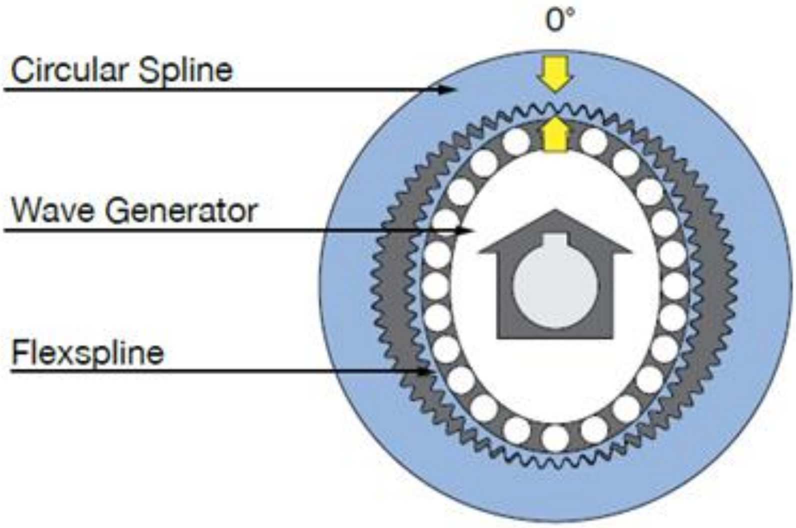


**Figure 2.2.1 : Harmonic Drive**
(Harmonic Drive, 2021)

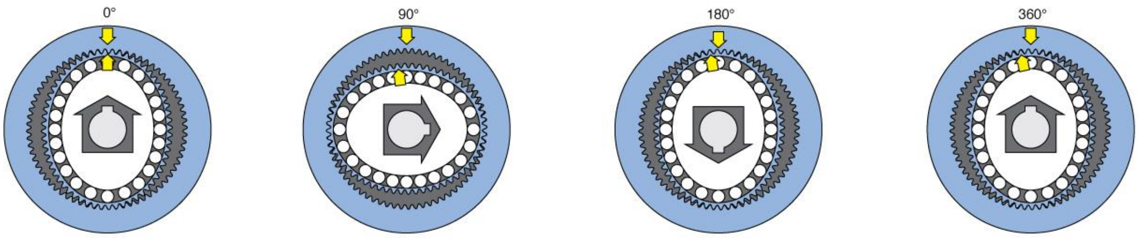


**Figure 2.2.2 : Harmonic Drive Wave generator**
(Harmonic Drive, 2021)

The combination of the three main components results in a drive with high reduction (30:1 to 320:1), zero backlash (<1 arcmin) and low weight (1kg) which is all housed in a compact package (Ø107x52). Strain wave drives are back driveable and have high torque levels. The downsides to this drive are precision manufacturing tooling, costly materials and more recently the performance (backlash) has shown to be not as great as originally believed (Frontiers 2020). The drive is also quite expensive, with units starting at $232AUD (Igus 2021).

### 2.2.2. Cycloidal Drives

The cycloidal drive was invented by Lorenz Braren in 1927 (Frontiers 2020). Cycloidal drives are used in many applications and recently have been frequently used in robotics (Frontiers 2020). The drive consists of an input shaft which drives an eccentric bearing which, in turn, drives a cycloidal disc in an eccentric, cycloidal motion (IDC Technologies 2012). The below figure demonstrates the layout of the cycloidal drive:

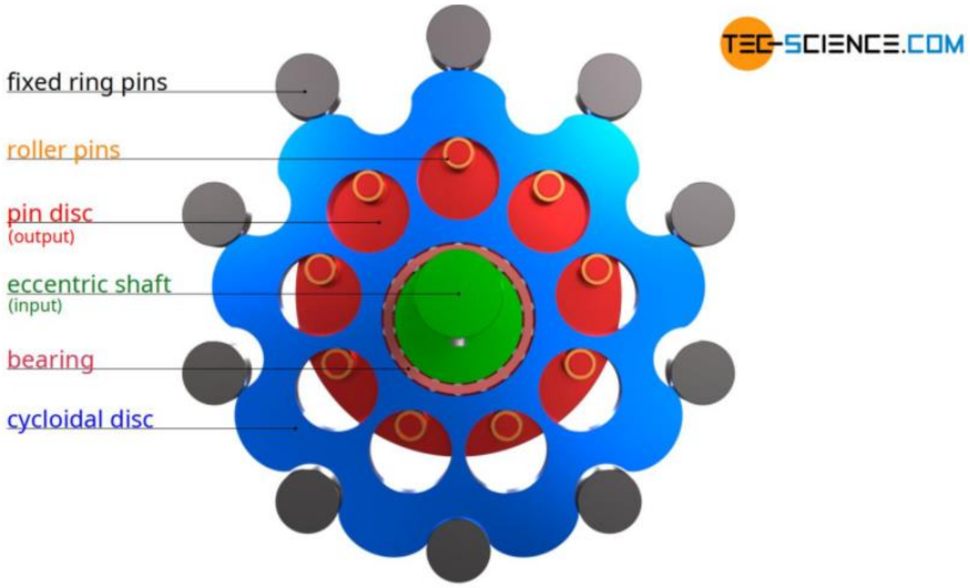


**Figure 2.2.3 : Cycloidal Drive Layout**
(Tec-Science, 2019)

The benefits of cycloidal drives include zero (or very low) backlash, low wear, high torsional stiffness, compact design (Machine Design 2011), and high reduction ratios (29:1 to 179:1) (Sumitomo 2020). Additionally, cycloid drives are superior to traditional gearsets as they only operate with rolling force and are not exposed to shear forces, allowing greater shock absorption and uniform load distribution (IDC Technologies 2012). However, due to the eccentric nature of the drive, there is an inherent vibration transmitted through the system, increasing component wear and noise. To reduce this imbalance, secondary discs or a counterbalance is required, adding weight and complexity to the drive (Wikipedia 2021) also, these drives are not back driveable (Cyclo Drives 2021). Cycloidal drives are priced similarly to strain wave gearing, starting at $267 AUD (AliExpress 2021).

### 2.2.3. Planetary Drives

Planetary gears were developed by the people of Ancient Greece, over 2000 years ago, to predict planetary orbital paths (The Drive 2021). Planetary drives consist of three main elements: a large sun gear, three or more smaller planetary gears and an internal ring gear. These gears can also be compounded for greater reductions, although this adds considerable size and weight to the unit (Machine Design 2011). The below figure demonstrates a planetary gear layout:

**Figure 2.2.4 : Single Stage Planetary Gear Layout**
(Design World, 2019)

These reduction drives (3:1 to 100:1) (Vex Robotics 2021), have low-medium backlash, high efficiency, high torque transfer and are cost effective to mass produce (Design 2011). The main downside, however, is package size and weight when compared to the alternatives (Machine Design 2011). The use of planetary reduction drives within the robotics industry has declined recently due to the limitations of reducing backlash and weight. There are methods of reducing this backlash although these are at the cost of efficiency (Frontiers 2020). Planetary drives suitable for robotics start at around $160 (Vex Robotics 2021).

### 2.2.4. Traction Drives

Traction drives work in a manner similar to the wheels on a train, by using normal force to generate tractive force, except these drives utilise a special multi-viscosity traction fluid to provide traction (Mide Blog 2018). Power is transmitted from the driven roller to an output annulus via the passive rollers utilising this traction fluid. As the rollers rotate against each other they increase the fluid pressure. The high fluid pressure increases the coefficient of friction, providing tractive force (Shimpo Traction Drive 2015). This fluid also prevents metal on metal contact as well as distributing the pressure contact patch and transmitting torque. The drives require a mechanism to apply the normal force to the roller. This mechanism allows for increase in component life as a constant normal force would result in high contact stresses and hence result in a shortened life. Additionally, this force allows for slipping of the drive so as to not overdrive the gearbox, resulting in a very precise drive with incredibly low backlash of ≤0.08 arc-min (Mide Blog 2018). The below figure illustrates how a traction drive works:

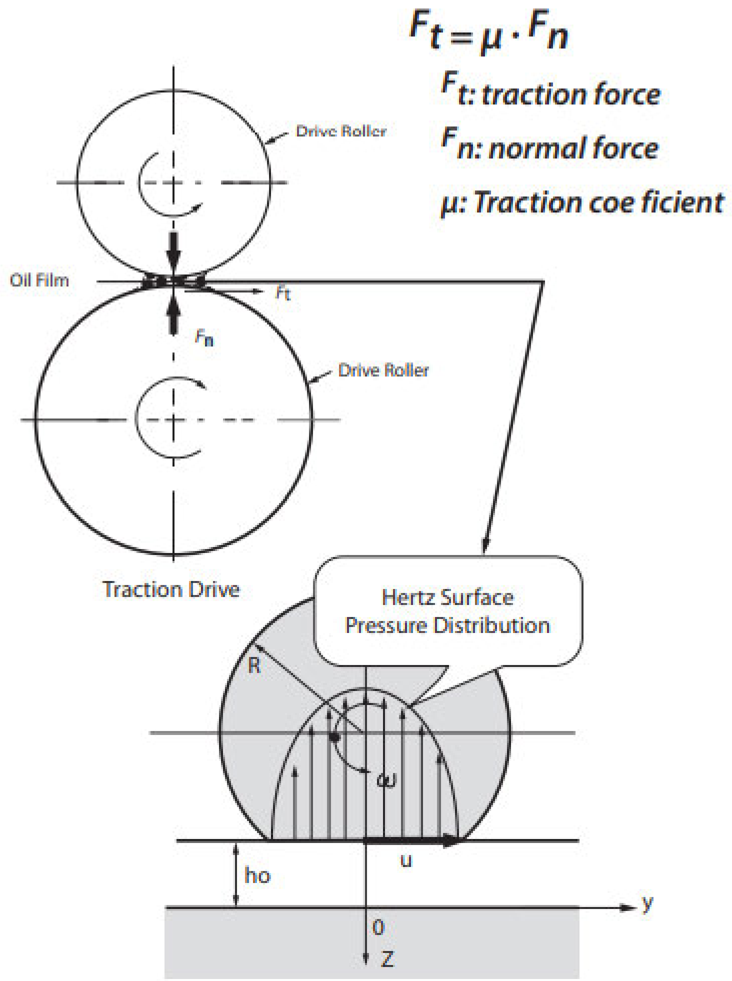


**Figure 2.2.5 : Traction Drive – Traction Fluid**
(Breaking Through the Limitations of Gear Technology, Shimpo Traction Drive, 2015)

The downsides to this type of drive are the relatively low reduction ratios available, with the Shimpo drives achieving only up to 20:1 reduction within a single stage (Shimpo Traction Drive 2015). Another downside is the extra complexity of the drive caused by the necessity to apply a suitable normal force to the rollers (Mide Blog 2018). The extra complexity of the drive increases the cost of the drive. The cost of traction drives is variable, depending on factors such as size, and starts at approximately $300 per drive.

### 2.2.5. Friction Drives

The friction drive, known commercially as the ‘Archimedes drive’ was, to some extent, invented by James White in 1786 (Nick Parker 2021). It was further developed by the National Ignition Facility in the 1990’s before finally being commercialised by Jack Schorsch of IMSystems in 2014 (Nick Parker 2021) (IMSystems 2021). This drive is based on a planetary gearset (discussed above), without any gear teeth, utilising stepped rollers instead of geared wheels. This gearset requires a controlled deformation of the rollers to transmit torque through the drive (Frontiers 2020).

Currently, there is not a lot of publicly available information on these drives but, based on the information available (SHIMPO 2015), friction drives are promising to be smooth and quiet, with high gear reductions in a compact package, as well as zero backlash. The planet rollers are dependent on the spring constant to determine the normal force applied to the central sun roller (Nick Parker 2021). This design allows for a combination of material selection and tolerances to determine the torque which can be transmitted. The below figure illustrates the layout of the drive:

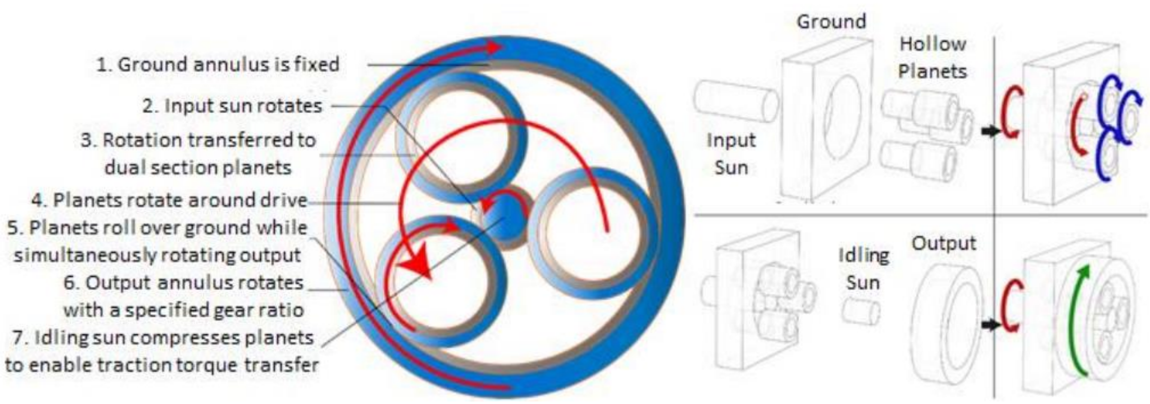


**Figure 2.2.6 : Archimedes Drive Layout**
(IM Systems, 2021)

As with the other drive types, there are some significant disadvantages of the friction drive including: speciality material requirements (resulting in high manufacturing costs), lower torque outputs and unknown longevity and wear (Nick Parker 2021). Additionally, whilst the price of the Archimedes Drive is yet to be finalised, the current development kit is approximately $4000 (IMSystems 2021).

### 2.2.6. Conclusion

To ensure the most appropriate reduction drive is selected for the application, several factors should be considered, including (but not limited to), the size of the load, serviceability, environment, ambient temperatures, shock loading and life (A3 2015), precision and accuracy, form factor, torque requirements and cost (Robots for Roboticists 2014). Additionally, as will be explored below, the ability to digitally fabricate the drive is a key factor.

Based on the research conducted, a reduction drive derived from the Archimedes drive design will be selected due to the characteristics of zero backlash and high reduction all within a compact package. The ability to digitally manufacture this drive will allow for varying spring constants to fine tune the normal force exerted on the planet rollers by varying material and tolerancing. This should help alleviate any dimensional inconsistencies with digital fabrication. Additionally, given the high price point of the Archimedes drive there will likely be demand for a low-cost equivalent.

## 2.3. Digital Fabrication

Digital fabrication is a fabrication method utilising computer-aided models which are sent to a digitally controlled manufacturing device. The digitally controlled manufacturing device allows for rapid, customised prototyping (Formlabs 2021) decreasing the time required between each design iteration. This fabrication method allows for graphical simulation of the manufacturing process (IGI Global 2021) allowing greater control of the manufacturing process by the designer.

There are several different digital fabrication methods available with the main processes being additive or subtractive manufacturing. Additive fabrication includes building up the object with the chosen material layer by layer. While subtractive manufacturing involves removing material to create the desired piece (Formlabs 2021). As discussed, one of the main aspects of this project is to investigate low-cost manufacturing which can be done easily and without expensive tooling. Additive manufacturing is relatively low cost. Additionally, digital manufacturing provides the ability to easily replicate and modify existing designs to suit the individual project requirements. This allows for rapid prototyping with minimal tooling. Therefore, the project will be focusing on additive manufacturing.

There are several different methods for additive manufacturing, including Stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modelling (FDM) also known as Fused Filament Fabrication (FFF), Material Jetting (JM), Binder Jetting (BJ) and Electron Beam Melting (EBM). This research project will be focussing on the more accessible methods of 3D printing which includes SLA, SLS and FDM. The below table compares each of these methods:

| | **SLA** | **SLS** | **FDM/FFF** |
|---|---|---|---|
| **Resolution** | Very Good | Good | Poor |
| **Accuracy** | Very Good | Very Good | Good |
| **Surface Finish** | Very Good | Good | Poor |
| **Throughput** | Good | Very Good | Good |
| **Complex Designs** | Good | Very Good | Average |
| **Ease of Use** | Excellent | Very Good | Very Good |

| | | | |
|---|---|---|---|
| **Pro's** | High Accuracy<br>Smooth surface finishes<br>Range of function applications | Strong, functional parts<br>No need for support structures | Fast, low-cost, consumer grade equipment, great material choice |
| **Con's** | Sensitive to long exposure of UV light | Rough Surface Finish<br>Limited Material Options | Low Accuracy<br>Low complexity prints |
| **Applications** | Function prototyping of patterns, moulds, and tooling, Suitable for dental, jewellery and model making | Functional prototyping, short-run, bridge, or custom manufacturing | Low-cost rapid prototyping, basic proof of concept models |
| **Print Volume/Size** | 150x150x200 for benchtop models | 165x165x300 for benchtop models | 200x150x250 for benchtop models |
| **Materials** | Variety of resins (thermosetting plastics), standard, engineering (ABS, PP, flexible, heat resistant), castable and medical (biocompatible) | Engineering thermoplastics | Standard thermoplastics such as ABS, PLA and several different blends. Including several composite materials. |
| **Training** | Low | Moderate | Low |
| **Facility Requirements** | Office environment | Workshop | Constant temperature with suitable ventilation |
| **Ancillary Requirements** | Post-curing station, washing station, finishing tools | Post-processing station for part cleaning and material recovery | Finishing tools and a support removal system with soluble supports<br>Post processing is required for higher finishes |
| **Equipment Costs** | From a $200 - $15,000+ | $10,000 + | $200 - $10,000+ |
| **Material Costs** | $40-$300/L for most materials and resins | $80+/kg for most materials | $15-$250/kg for most materials |

**Table 2.3.1 : Digital Fabrication Comparison**

(3D Printing Technology Comparison: FDM vs. SLA vs. SLS, Formlabs, 2021)

(3D Printer Material Cost: The Real Cost, all3dp, 2021)

As indicated by the data above, a stereolithography printer addresses most of the requirements with very good surface finish and accuracy. Its main drawback, however, is the lack of material selection and slightly overall higher manufacturing costs (HUBS 2020). On the other hand, FDM printing is becoming more popular, increasing the already vast array of materials available while the purchase price decreases.

Further, dimensional accuracy is a key component to any fabrication with different manufacturing processes resulting in differing precisions. It has been shown that the dimensional accuracy of FDM 3D printing is highly variable, depending on the material selection, with colour and temperature being the main contributing factors (Hanon, Zsidai and Ma 2021). However, it is possible to resolve that issue by undergoing test prints using the 3D printer and chosen material to confirm dimensional accuracies. That process may result in the adjustment of the design to allow for any inconsistencies. The overall low manufacturing costs, combined with the huge range of materials available, which enables many different combinations, make FDM 3D printing the manufacturing method of choice for this project.

## 2.4. Evaluation of Reduction Drives

The research shows there is no standard evaluation procedure for evaluating the effectiveness of reduction drives and each research project evaluates the drives differently. For example, during Heebner's research on strain wave drives they measured torque, no load speed, breakaway torque, and backlash (Heebner 2021). While another research project focused more on input and output speeds, voltage, current, input torque and holding torque (Sutar et al 2016). Yet another research project noted the evaluation process as four main parts: backlash, precision, life, and efficiency tests (MPDI 2020). The backlash and precision tests can be further broken down into continuous operation and random angle tests, while the life and efficiency tests can be broken down into continuous operation and swing operation. Additionally, the error of the drive can be defined as the deviation between the expected output position and the actual output position. (MPDI 2020)

Of particular significance for this project is evaluating the backlash. Backlash can be calculated at corresponding points by rotating through a range of 360° at predetermined angles and then reversing the process. The backlash is the difference between the initial starting position and the position the drive completes the test (MPDI 2020). Further, another method of determining accuracy is determining the linear position of the drive. There are several methods of determining linear positions of the drive, one such method is utilising a laser interferometer to measure linear position errors, which has been proved to be very effective (Industrial Robot 2013).

The below figures demonstrate methods of testing the capabilities of reduction drives:

**Figure 2.4.1 : Test Rigs**
(Igus. 2021)

**Figure 2.4.2 : Testing Drive**
(Naclerio, et al, 2019)

## 2.5. Material Selection

A major factor in evaluating and selecting suitable materials will be based on wear properties and the ability to run the reduction drive without any lubrication as well as the cost, bearing in mind that a low-cost drive is the aim. This research project will not delve into the evaluation of tribology as that is not the aim.

Briefly, tribology includes three main areas: friction, wear, and lubrication. Where friction is the resistance to relative motion, wear is loss of material due to friction and lubrication is the use of a medium to minimise friction and thereby reduce wear. Additionally, the reduction of friction and wear has a net increase in efficiency (STLE 2021). To achieve a low-cost reduction drive, the main cost of the drive itself and manufacturing costs are important, as is long life and low maintenance requirements. An integral part of maintenance and life is component wear. There are several tribological filaments that can be used in 3D printers. These filaments are stronger, tougher and with greater abrasive properties compared to existing (non-tribological) filaments such as ABS plastic (IGUS 2020).

The below table compares the different properties of several available filaments:

| | PLA | ABS | ABS PRO | PA (NYLON) | PC | PETG | PVA | PEARL | I180-PF |
|---|---|---|---|---|---|---|---|---|---|
| **Print Temp (°C)** | 190-220 | 220-240 | 220-240 | 220-260 | 240-260 | 220-260 | 190-220 | 190-220 | 250-260 |
| **Print Speed (mm/s)** | 60-90 | 60-90 | 60-90 | 60-90 | 60-90 | 60-90 | 60-90 | 60-90 | 50/20 FIRST LAYER |
| **Print Layer Resolution (mm)** | 0.1-0.2 | 0.1-0.2 | 0.1-0.2 | 0.1-0.2 | 0.1-0.2 | 0.1-0.2 | 0.2 | 0.1-0.2 | 0.1-0.3 |
| **Hot Bed Temp (°C)** | - | 80-110 | 50-100 | 80-110 | 100-120 | 80-100 | - | - | 80-100 |
| **Print Raft** | NO | YES | NO | YES | YES | NO | NO | NO | - |
| **Tensile Strength (MPa)** | >60 | >43 | >53 | >50 | >50 | >52 | >52 | >10 | - |
| **Flexural Strength (MPa)** | >60 | >70 | >70 | >60 | - | >88 | >15 | >50 | 46 |
| **Flexural Modulus (MPa)** | >2500 | >2300 | >2300 | >1500 | >2200 | >2200 | >190 | >2300 | 1000 |
| **Impact Strength (IZOD 23°C, J/m, ASTM D256)** | 16 | 108 | 108 | 105 | 700 | - | 16 | 25 | 66 (SHORE D) |
| **Elongation at Break (%)** | 3 | 30 | 30 | 150 | 50 | 150 | 11 | 50 | - |
| **Distortion Temp (°C)** | >55 | >88 | >88 | >100 | >125 | >70 | >55 | >125 | 100 |
| **Cost ($/kg)** | 35 | 35 | 35 | 60 | 50 | 40 | 90 | 55 | 240 |

**Table 2.5.1 : Filament Comparison**

(Filament Comparison Chart | Flashforge, 2021)

(Iglidur I180-BL-PF, 3D Print Filament | iglidur, 2021)

(Filaments and Resins | 3D Printer Superstore, 2021)

(3D Printers Online, 2021)

| Material | Friction Coefficient |
|---|---|
| PTFE (Teflon) | 0.04 to 0.05 |
| Sintered Bronze | 0.12 |
| Bronze | 0.16 |
| Brass | 0.19 |
| POM | 0.2 |
| PET-P | 0.2 |
| PET-G | 0.22 |
| PET | 0.25 |
| Nylon | 0.26 |
| ABS | 0.35 |
| PLA | 0.38 to 0.45 |
| PC | 0.38 to 0.5 |
| I180-PF | 0.17 |

**Table 2.5.2 : Friction Coefficient Comparison**

(3D Printing Filament Properties | GitHub, 2017)

(iglidur® I180-PF, filament for 3D printing | IGUS, 2021)

I.T Maries (2020) investigated the tribological properties of different 3D printing filaments and determined that PETG had the lowest friction coefficient with a medium wear percentage, while Z-GLASS displayed a high coefficient of friction with a low wear percentage. It is worth noting that Z-GLASS is 80% PETG, 8-12% Fibreglass filings, 0-8% additives and colourants (Zortrax 2021). It can also be seen that ABS+ has a higher friction coefficient and higher wear compared to PLA and PETG (Nedic et al 2019).

In reviewing the literature it was difficult to find reliable and comparable data on materials, especially with regards to wear properties. The two images below show a comparison between different material under two different loading scenarios. We are looking specifically at the ABS versus the iglidur I180 filaments. It is clear that there is a marked difference in wear between the I180 to that of the ABS (IGUS 2021).

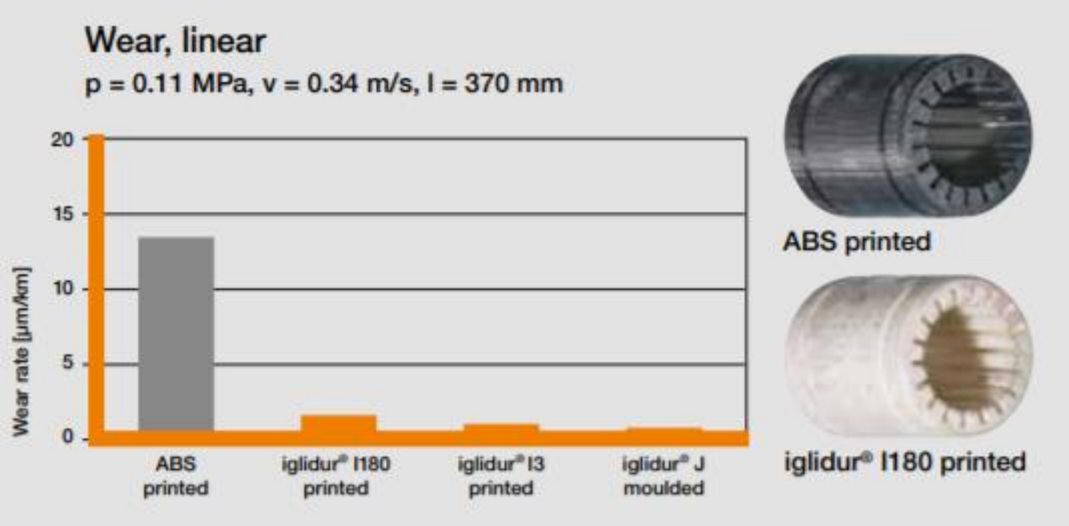


**Figure 2.5.1 : Linear Wear Comparison**
(3D Printing Brochure | iglidur, 2021)

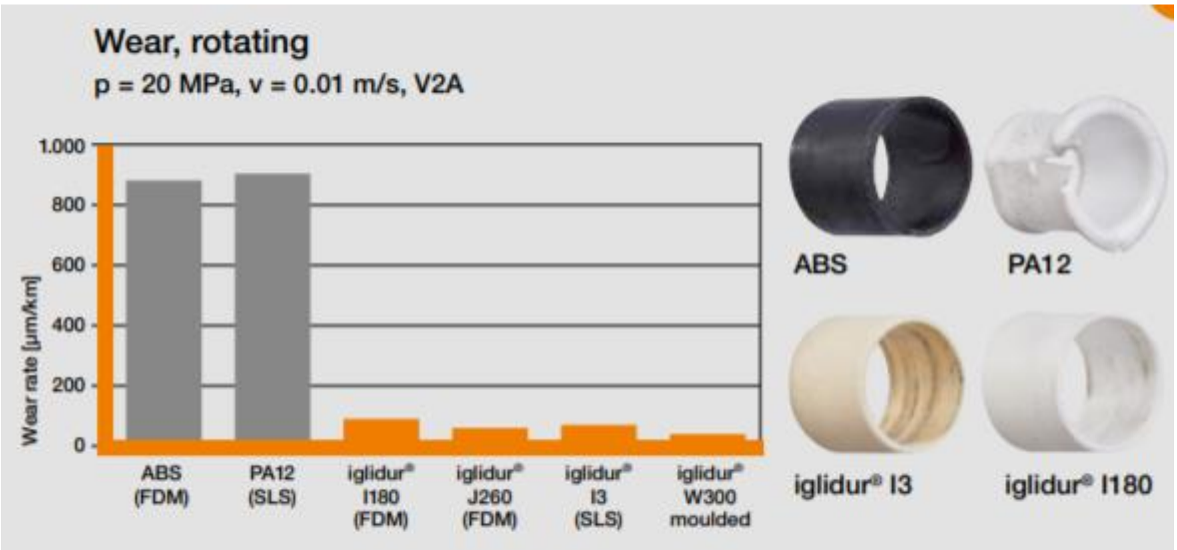


**Figure 2.5.2 : Rotating Wear Comparison**
(3D Printing Brochure, iglidur, 2021)

Iglidur (a plastics manufacturer) offer a range of tribo-filaments, the main disadvantage is that many of them require a high temperature 3D printer with a bed temperature of 160-200°C and a nozzle temperature of 350-365°C. This requires a high-end printer with an experienced user (iglidur 2021). Alternatively, they have a self-lubricating filament, with high abrasion resistance, designed for dynamic plain bearing applications up to 100°C.  Like

ABS filaments, this material requires good ventilation of the room and a nozzle temperature of 250-260°C. The nozzle temperature puts it outside of the realm of most desktop FDM printers, although many printers can be upgraded to extrude filament >240°C (iglidur 2021).

Based on the information available, the iglidur I180-PF filament will be utilised due to its high wear properties and high strength. Additionally, it has a lower flexural strength than the other materials, allowing greater material flexibility when positioned in the drive. PETG will also be selected as a cheaper alternative. Additionally, PETG produces no odour, is strong yet flexible and is recyclable (Tractus 3D 2021). It will also be a suitable material to test the meshing of the rollers as the material costs are much less than the I180-PF filament. If time and materials permit, there is a possibility of using ABS or ASA filaments as they too are cost effective with reasonable strength and wear properties.

## 2.6. Conclusion

Based on the requirements for a low cost, digitally produced, high reduction drive with zero backlash, the friction drive will be the chosen reduction drive for this project. Material selection will include a minimum of two materials, one of which being the iglidur I180-PF and the other a more cost effective such as PETG. This will allow for a comparison between a tribo-filament and a cheaper, more accessible filament.

# Chapter 3 - Design and Evaluation of the Reduction Drive

## 3.1. Evaluating Reduction Drive Performance

A literature review has been conducted to evaluate the current technologies, designs, and materials of reduction drives to develop the background knowledge required to adequately undertake this project. A review has also been conducted to determine applied loads and material properties required to ascertain suitable material selection. As the Archimedes drive is relatively new there was limited information available about its design and suitable testing. Due to a gap in the literature the methodology has been something of a work in progress and has developed as the project progressed.

The drive's performance will be evaluated by testing the backlash, accuracy, repeatability, and torque. The drive's performance will be evaluated by means of physically examining the movement in the reduction drive by attaching a digital bevel gauge to the output of the drive. The reduction drive will be driven through a set range of rotations and then returned to its starting position. The difference between the starting position and the final position will indicate the precision of the system. These tests will be run multiple times to ensure the results are consistent.

The bevel gauge that will be used for the testing is an iGaging AngleCube which has a maximum tilt range of 90° with a maximum accuracy of 0.2°. Noting the maximum tilt angle, this will need to be considered and allowed for in any rotations greater than 90°. i.e., if the angle finder shows 85° but it has rotated past the 90° mark, then the angle of rotation will be 90+(90-85) = 95°. Additionally, maximum output torque will be measured. Maximum torque will occur when the gearbox fails to provide constant output motion, when the drive slips or ultimately fails. This will be performed by affixing an arm with a mass attached to the output of the gearbox and measuring the torque the drive can output before failure or slippage between the rollers and the rotating annulus.

## 3.2. Material Selection for Reduction Drive

Ultimately, the material selection became a more time-consuming element of the project than initially anticipated. Through the literature review, the iglidur I180-PF material was determined to be the most appropriate filament for the project. However, as the iglidur filament is quite expensive, all prototyping was done utilising PETG, with the intention to only use an engineering filament once the design was finalised. Some experimentation was also conducted with Thermoplastic Polyurethane (TPU) filament. Due to procurement issues the final prototype was not developed enough to warrant purchasing the more expensive iglidur I180-PF filament.

It was determined that FDM printing would be the method of printing employed (discussed further below). However, one challenging aspect of FDM printing which has been highlighted through the research is that there are several factors which influence print quality including: material manufacturer, colour, the 3D printing or 'slicing' software used and the 3D printer itself, making fault finding and fine tuning quite difficult. These issues were not revealed by the literature and created challenges in the development of the prototype. Ultimately, this meant developing the prototype took longer than expected.

The very first prototype was printed using PLA, this was due to a delay in the shipping of the PETG. Initial prototypes printed reasonably well, although the print times were quite high. After some refinement of the design, the reduction drive size was reduced. This reduction in size was two-fold, it resulted in a more compact drive as well as reducing print times and material usage. This is important because a more compact drive will have greater applications in the robotics industry. The reduction in print times was particularly beneficial, at the project level, given several prints were required to develop the prototype.

Once the PETG arrived, it was promptly loaded into the printer and a few test prints were conducted. Being new to 3D printing, it took a little while to fine tune the settings as there were several issues with poor print quality. The biggest issue, apart from aesthetics, was layer adhesion. Poor layer adhesion meant there were gaps in between layer lines which caused the part to be brittle. Some further fine tuning of settings such as speed, nozzle temperature, extrusion ratio and turning the part cooling fan off, resulted in much better prints, although still not perfect. Ultimately, despite that fine tuning, issues remained.

The current issues are due to either: the nozzle temperature not being high enough (the maximum nozzle temperate of the Creator Pro 2 is 240°C) or potential quality issues with the filament itself. Once the PETG prints improved, it was observed that the dimensional accuracy had decreased due to the higher extrusion rate of the filament. As dimensional accuracy was critical to this project, the extrusion ratio was decreased resulting in a part accuracy of 0mm to -0.2mm which is well within the general tolerances for FDM 3D printing and worked well for press fit items such as the bearings. It was observed that with the part cooling fan off, the extrusion ratio became less of an issue. Additionally slowing the print down to around 30mm/sec produced aesthetically better-looking prints. All components which required dimensional accuracy were printed at these slower speeds and a 0.18mm layer height, while housings and mounts were printed at 60mm/sec with a 0.3mm layer height.

The Thermoplastic Polyurethane (TPU) filament which was used encountered similar issues to the PETG filament. Increasing the nozzle temperature and decreasing the speed improved the print quality to a point it was suitable for prototyping. The reasoning for trialling the TPU filament is discussed further in section 3.5. The below figure demonstrates the issues encountered when printing the TPU:

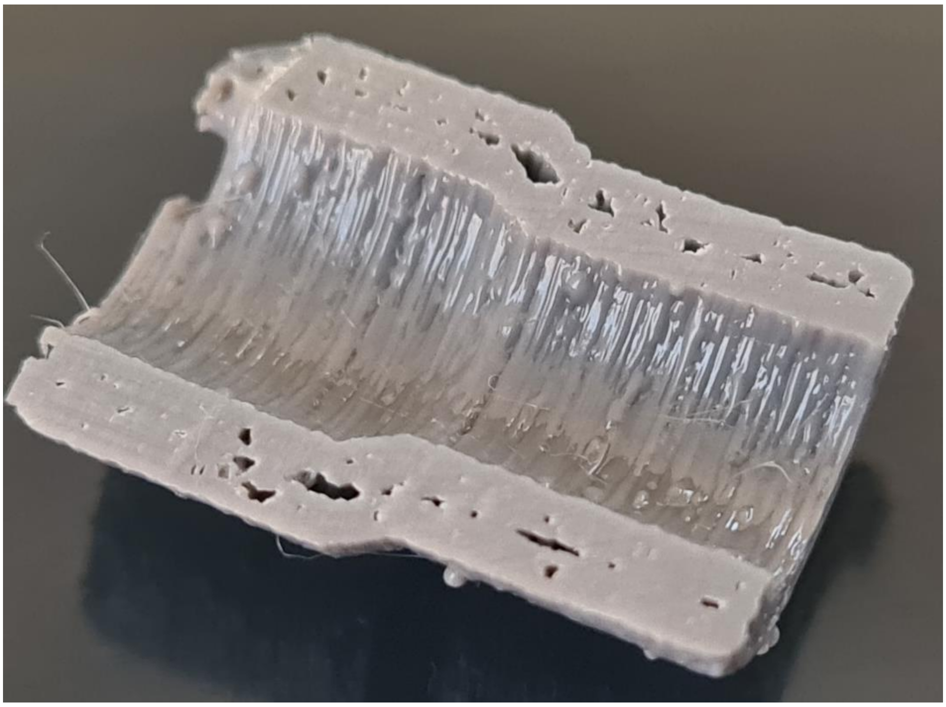

**Figure 3.2.1 : TPU Roller Cut in Half. Showing the Layer Lined and Internal Structure/Infill**

## 3.3. Digital Fabrication Methods for Reduction Drive Manufacture

The concept of digital fabrication is to decrease the manufacturing costs associated with reduction drives whilst also allowing for custom sizing and modifications, including end effectors and mounts, to suit unique industrial, research or education purposes. As discussed in the literature review, there are several types of digital manufacturing methods available. FDM was ultimately selected for this project. One of the key reasons for selecting FDM printing was due to the accessibility of 3D FDM printers, with several manufacturers on the market bringing the purchase price and filament prices down due to economies of scale. While other options such as SLA printing, which is more accurate and provides a better finish, come with an increased cost (due to the purchase price, maintenance and post-processing costs) which made that form of 3D printing less desirable due to low-cost being a primary focus of the project.

As discussed above in section 3.2, FDM printing is not as straightforward as initially believed. It required a reasonable amount of fine tuning and tinkering in order to calibrate the printer for the various materials used. Whilst the final prints are not ‘perfect’ they are more than suitable for prototyping due to the high strength exhibited by the parts. A further point to note with 3D FDM printing are the several different 3D printing or ‘slicing’ software packages that are available. This software turns a solid model into lines of code the printer can use to lay the filament. For those familiar with CNC machining, it is a very similar process, albeit FDM printing is additive while machining is subtractive. Most of the mainstream FDM printer manufacturers have developed their own slicing software, although with some slight differences. Unfortunately, the FlashForge printer purchased for the project requires the FlashForge slicing software to operate, which somewhat limits the potential customisation of printing parameters.

## 3.4. Resource Requirements

Resources were required for both the design phase and then the testing phase of the project. The project was particularly resource intensive in the design phase. There were challenges associated with obtaining resources for the design phase as well as for the testing phase. Preliminary designs were sketched on paper, then turned into an Autodesk Inventor model utilising a student licence and were printed by a personal Flashforge Creator Pro 2 FDM printer. The material that was required and used has been discussed in detail at 3.2, and the digital fabrication method has been discussed at 3.3.

For the purposes of testing the drive, this project utilised the ODrive D6374 dual shaft motor paired with an AMT-102 encoder which was run off the ODrive V3.6 motor control board. This allowed for precision motor control with 8192 available steps, these units were borrowed from the University. Minor material and equipment such as cabling, fuses, crimps and screws are required to complete the wiring and for final drive assembly. Those items were not procured until the final design was completed. The bevel gauge that was used is an iGaging AngleCube.

The below figure is the 3D printer purchased for the project:

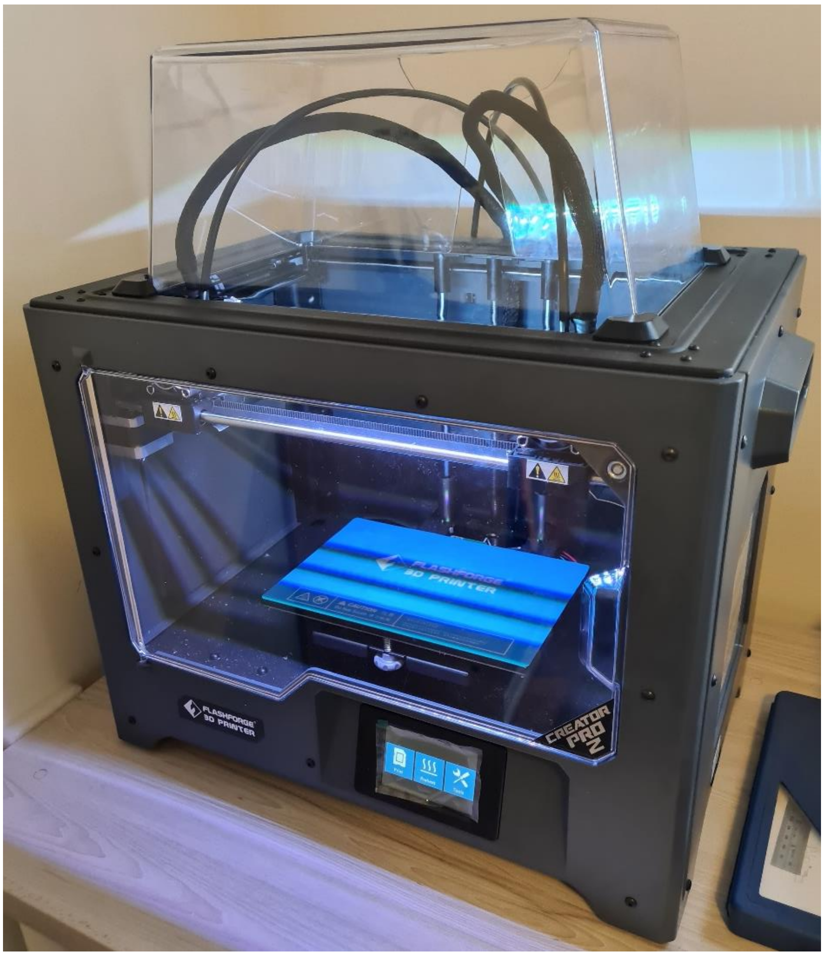


**Figure 3.4.1 : Flashforge Creator Pro 2 – FDM 3D Printer**

The below figure is the prototype set up with the motor and motor driver for the purposes of testing:

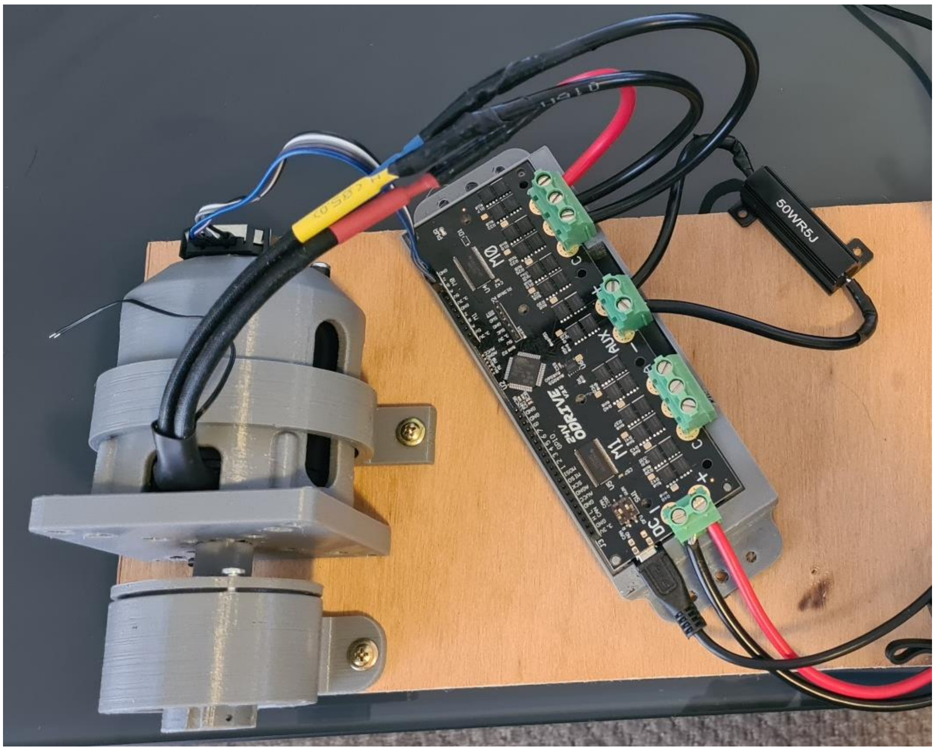


**Figure 3.4.2 : Completed Prototype with Motor and Motor Driver**

## 3.5. Design Iterations

As foreshadowed above, there were many design iterations due to challenges with the filament, the 3D printing process and the design of the drive. Preliminary manual testing was conducted at each stage of the design process in order to develop the most effective prototype. The preliminary design was based on one of the patent designs of the Archimedes Drive by Jack Schorsch (Compound Planetary Friction Drive, United States Patent, 2018). As you can see from the below figures, the design involves an idling sun wheel surrounded by hollow planet wheels and two annulus rings.

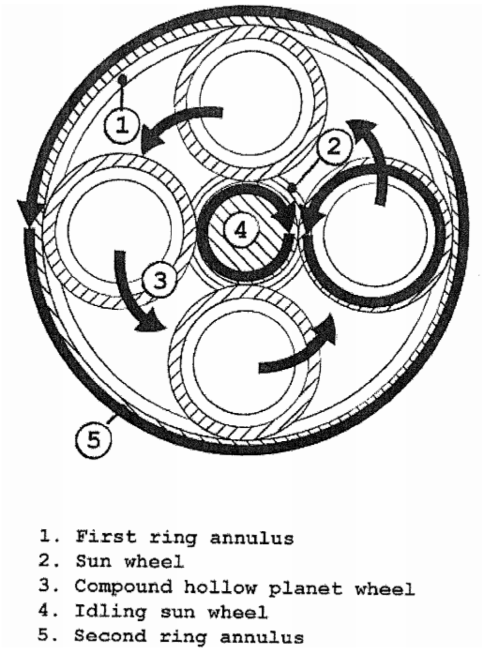


**Figure 3.5.1 : Archimedes Drive Patent Layout**
(Compound Planetary Friction Drive, United States Patent, 2018)

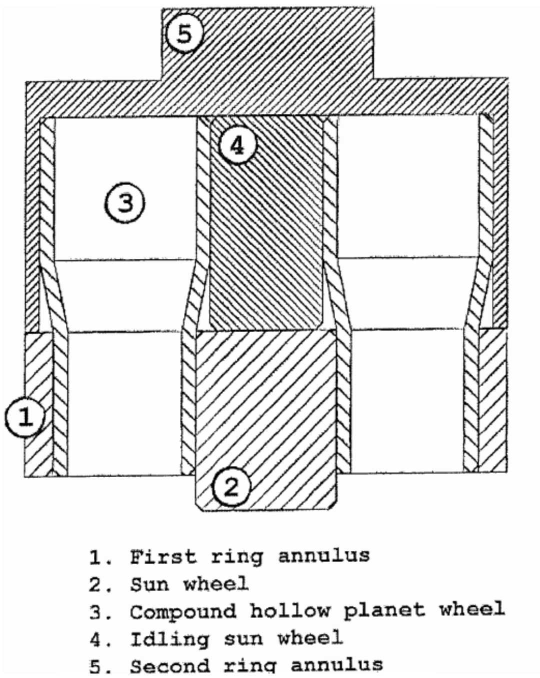


**Figure 3.5.2 : Archimedes Drive Patent Layout - Section**
(Compound Planetary Friction Drive, United States Patent, 2018)

As discussed above, the intention was to design a compact reduction drive. The first iteration of the design was problematic due to trying to make it too compact but also too large. As a result of trying to make the drive compact, the first design iteration consisted of rollers which had a sharp change in diameter. This change in diameter resulted in a shoulder which created high friction points as it brushed against a similarly shaped sun gear. As a result of trying to make the drive too large, when the drive components were imported into the slicing software, it was soon apparent the print time was going to be over 10 hours due to the size.

Accordingly, it was decided to scale the model down in the slicing software to reduce print time. The layout was scaled to 50% and print time was brought down to approximately 4 hours. Unfortunately, the tolerances and material thicknesses were not considered, causing the wall thickness of the rollers to be much too thin which resulted in an unusable drive. As discussed above, the first iteration was printed in PLA.  The below figures show the first iteration:

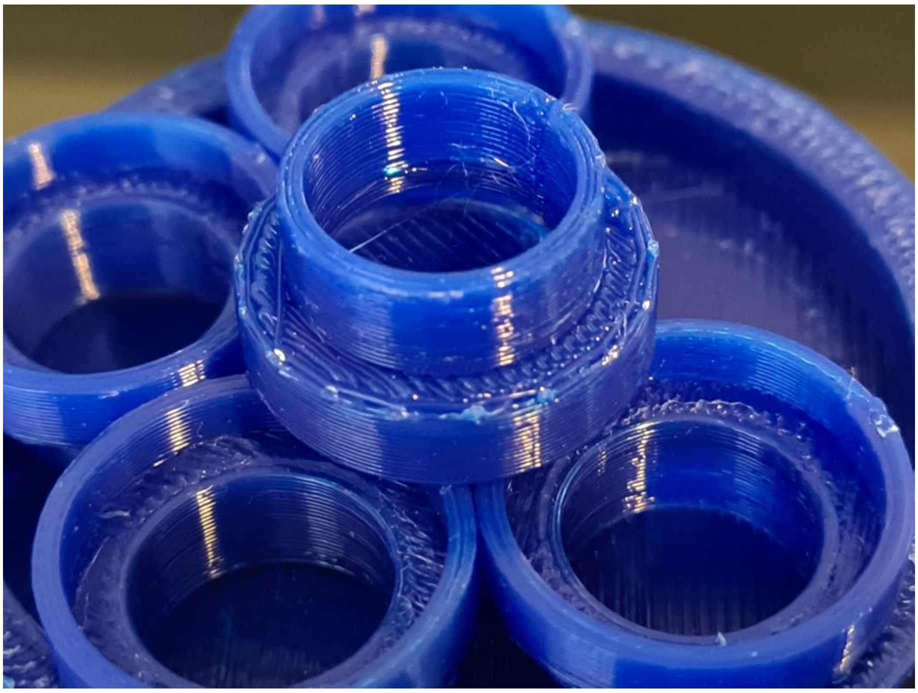

**Figure 3.5.3 : First Iteration of Planet Rollers using PLA**

**Figure 3.5.4 : First Iteration of Planet Rollers and Sun Gear**

The drive was then printed without any scaling, which produced a proof-of-concept drive. Notable issues were high starting torque, the drive was not backdrivable and there was minimal torque output due to the rollers slipping. There was also a minor issue with this print (see figure 3.5.7) when the edge lifted off the bed due to the bed temperature being too low. That issue was resolved by the component being reprinted with a higher bed temperature.

**Figure 3.5.5 : Large Scale Proof-of-Concept Design printed in PLA**

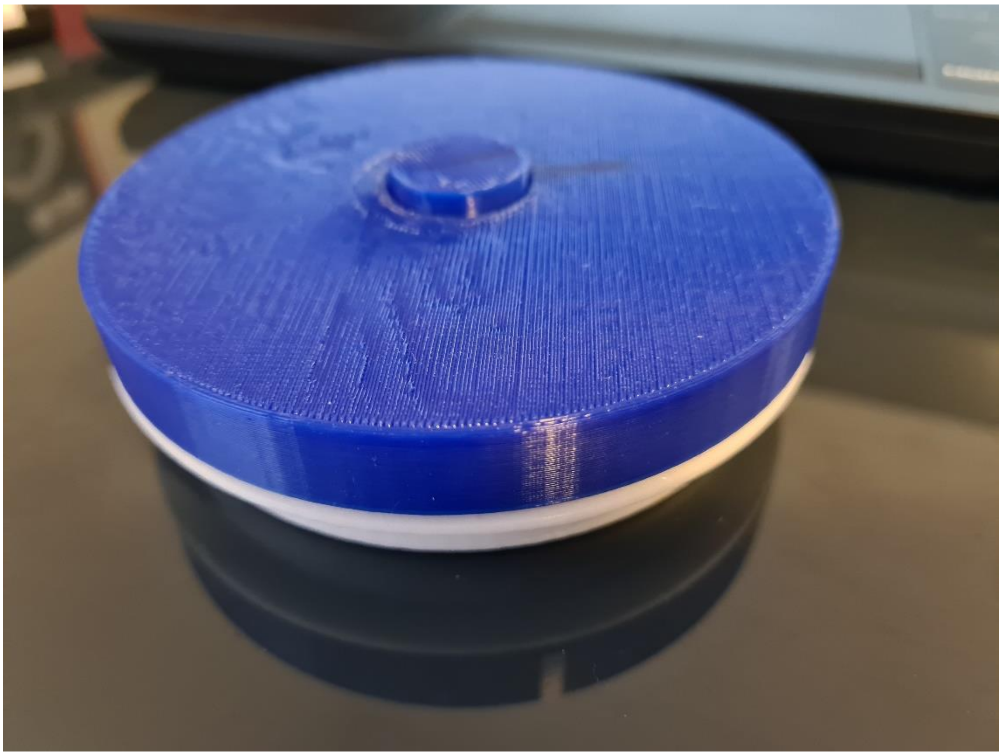

**Figure 3.5.6 : Proof-of-Concept Drive Printed in PLA**

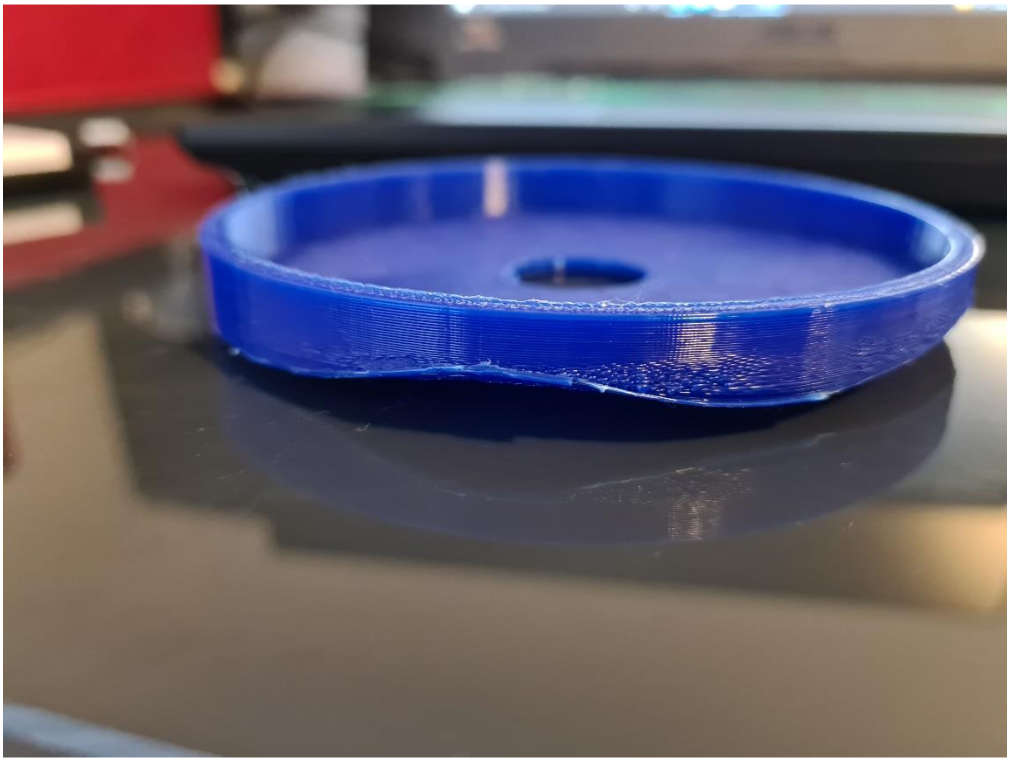

**Figure 3.5.7 : Failed Print – Edge Lifted off Bed**

The next iteration involved a redesign of the drive to more closely follow the patent design which included reducing the overall size of the drive and removing the sharp change in diameter. Additionally, the roller size and wall thickness were reduced to help lower the torque required to turn the input roller. This change in size resulted in not enough normal force between the rollers, resulting in high slippage and accordingly was not providing any output torque.

The fourth iteration further developed the previous design with thicker rollers and was printed in Polyethylene Terephthalate Glycol (PETG) filament. Numerous printing issues such as bed adhesion, poor layer adhesion and dimensional inconsistencies were encountered. This required a considerable amount of time to finetune the slicing software and the model to achieve accurate prints.

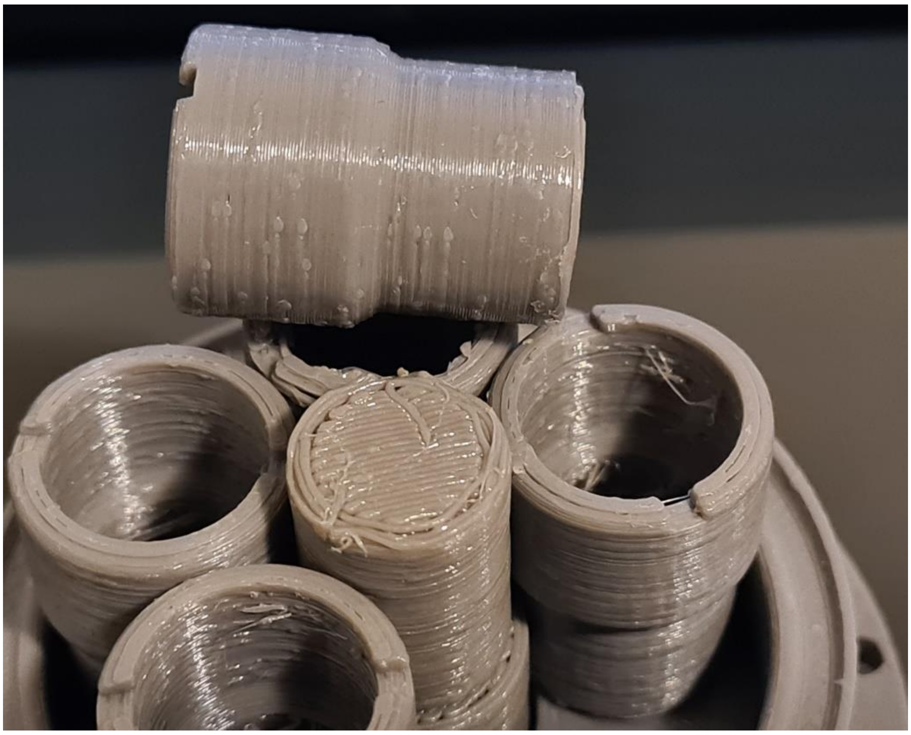

**Figure 3.5.8 : Fourth Iteration using PETG. Note Poor Stringing and Layer Quality**

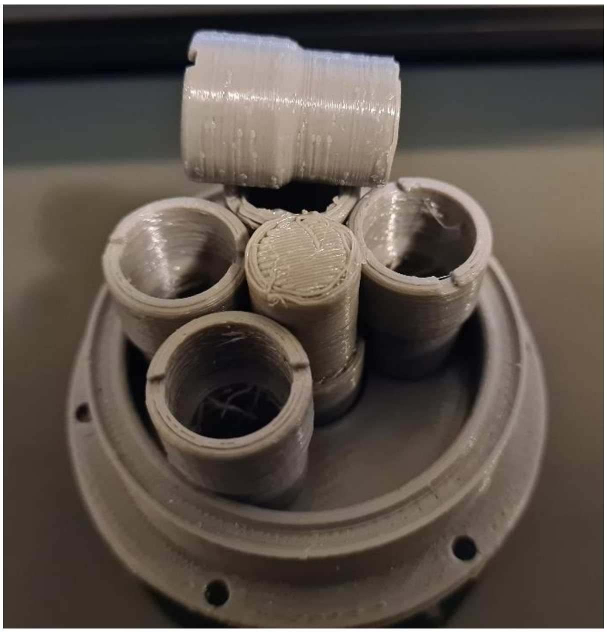

**Figure 3.5.9 : Fourth Iteration Showing Grounded Annulus**

The dimensional accuracy was primarily configured utilising the sun roller as the base line. After several amendments to the slicing software and many test prints, the PETG filament was printed at a speed of 30mm/sec, 0.18mm layer height, a nozzle temperature of 230°C and a bed temperature of 70°C. Which achieved an accuracy of 0mm to -0.2mm from the modelled size.

During preliminary testing it was observed that the rollers were slipping with only minimal load applied. However, increasing the roller diameter to increase the force applied between the input shaft and the rollers caused the drive to bind. After some investigating it was decided to trial some Thermoplastic Polyurethane (TPU) filament with a Shore hardness of 95A. Due to the high elasticity of TPU, the outside diameter and the wall thickness of the rollers were increased. This resulted in a nominal increase of torque output and minimal backlash, allowing for the prototype to be carried forward into the evaluation phase of the project.

**Figure 3.5.10 : Updated Roller 3D Printed in TPU**

Throughout the design process the friction drive prototype was nominally tested to determine suitability to progress by turning the input shaft by hand as well as utilising a drill and later the Odrive motor, to check for correct operation of the drive including a gauge on the torque output. Several failures occurred during these tests. Due to a government mandated lockdown, all retail stores were shut down and parcel deliveries were severely hampered. Due to this, suitable bearings were not able to be procured. To save time and to continue prototyping, the bearings were not installed. This resulted in the input shaft becoming friction welded to the grounded annulus (as shown in the figure below).

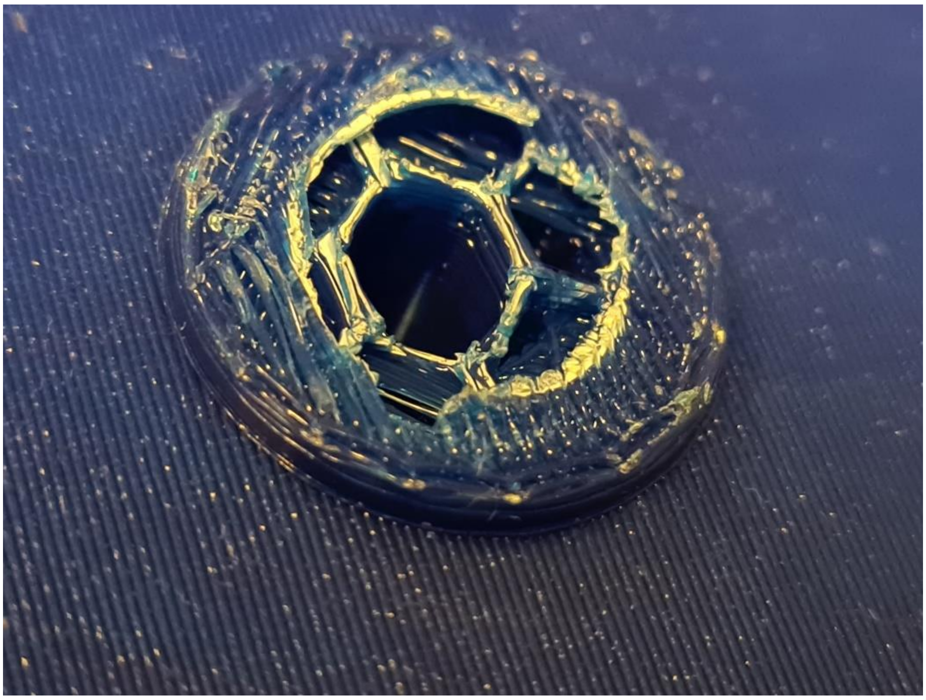

**Figure 3.5.11 : Friction Welded Input Shaft to Grounded Annulus**

Another failure while testing occurred when assessing the drive slipping while a load was applied. This resulted in melted and deformed rollers (shown in the figure below), which also damaged the grounded annulus (beneficially the damage to this was minor).

**Figure 3.5.12 : Damaged TPU Roller Resulting from a Slipping Input Shaft**

## 3.6. Final Prototype Design

This final iteration was amended in the CAD assembly to confirm suitable tolerances were achieved before being fully 3D printed and assembled (complete with bearings). The image below (Figure 3.6.1) shows a section cut through the centre of the reduction drive revealing the internal components. The final prototype featured:

- 5 off TPU rollers
- 1 off PETG input shaft
- 1 off PETG idler sun gear

- 1 off PETG grounded annulus
- 1 off PETG rotating annulus
- 1 off top PETG cover and mount

A bearing was placed on the exterior of the input shaft as it mated with the grounded annulus and another bearing was placed on the idler sun gear as it mated with the rotating annulus. Due to the size, off the shelf thrust bearings were not suitable, so ball bearings were placed between the grounded and rotating annulus and between the cover and mount and the rotating annulus. As the ball bearing grooves were modelled and 3D printed, there were some artifacts and excess material in the grooves which required minimal post processing with a fine tipped grinding point on a Dremel.

During the prototyping process, the input shaft was modelled with a hole to suit a 6mm Hex bit which was placed in a drill for the input for testing. This shaft was later modified to suit the motor output shaft by enlarging the hole and inserting a recess for a nut to fit inside which when a grub screw was screwed in it clamped onto the motor shaft. This highlights how versatile a 3D printer can be as it allows for relatively quick, custom designs to suit the required application.

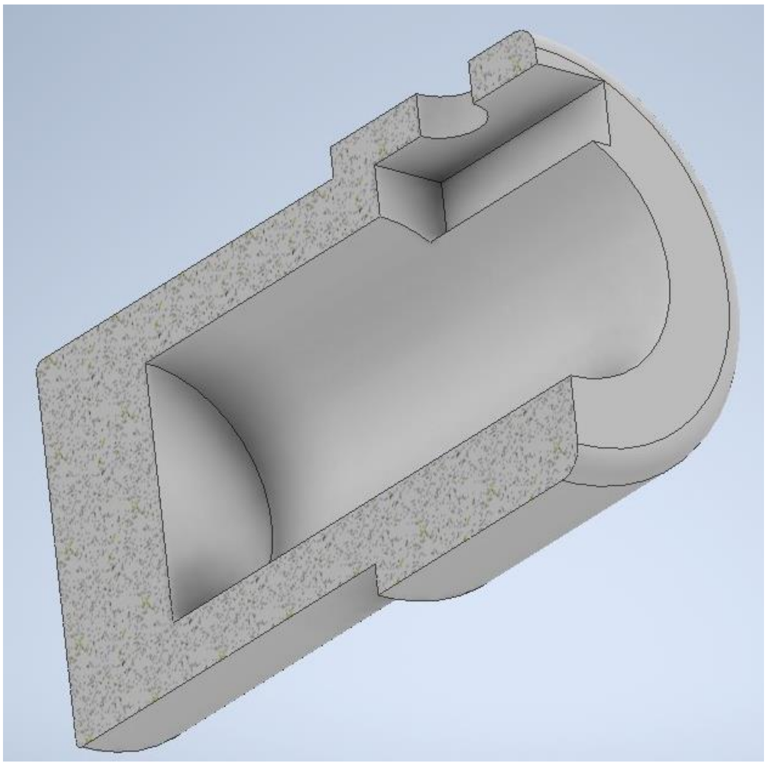

**Figure 3.6.1 : CAD Model of Input Shaft**

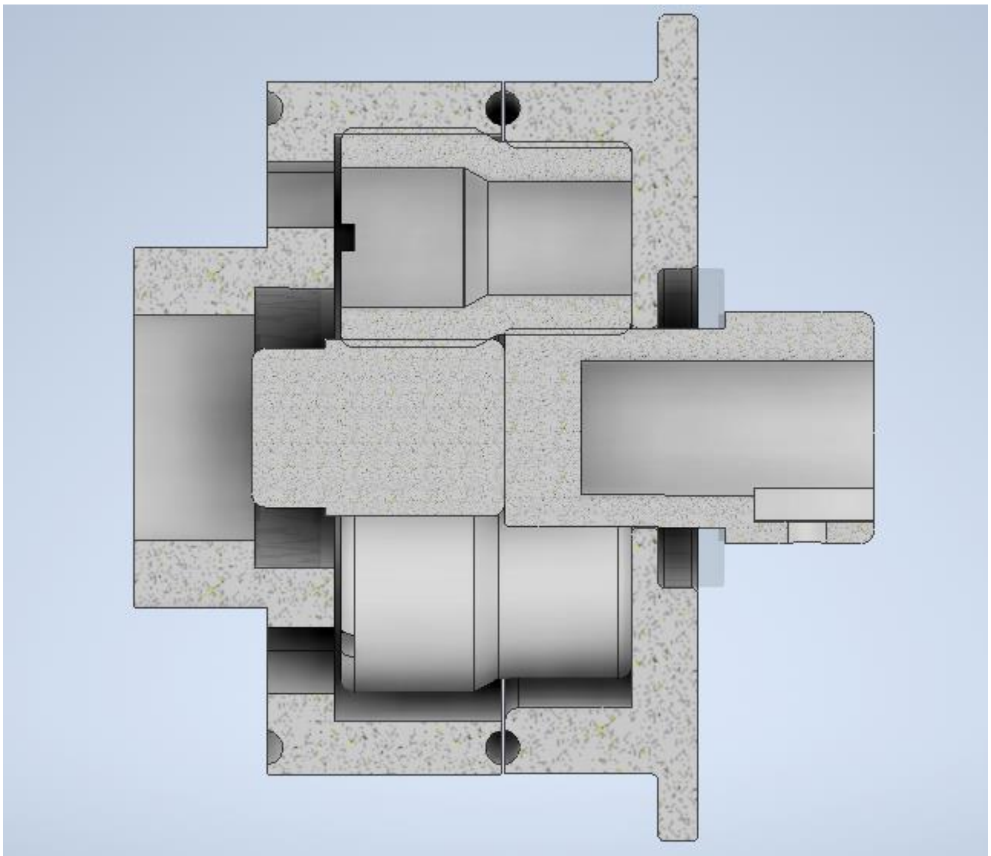

**Figure 3.6.2 : CAD Model of Assembled Prototype**

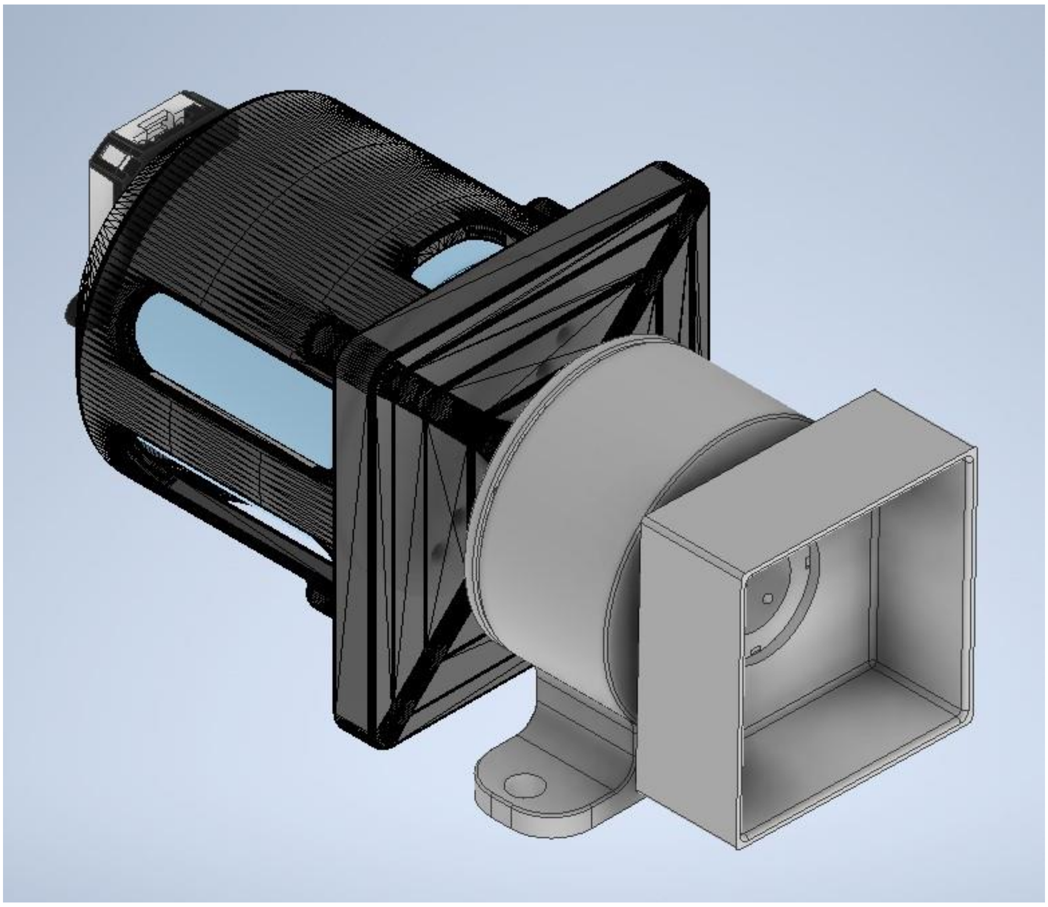

**Figure 3.6.3 : CAD Modelled Prototype including Motor, Encoder and Angle Finder Housing**

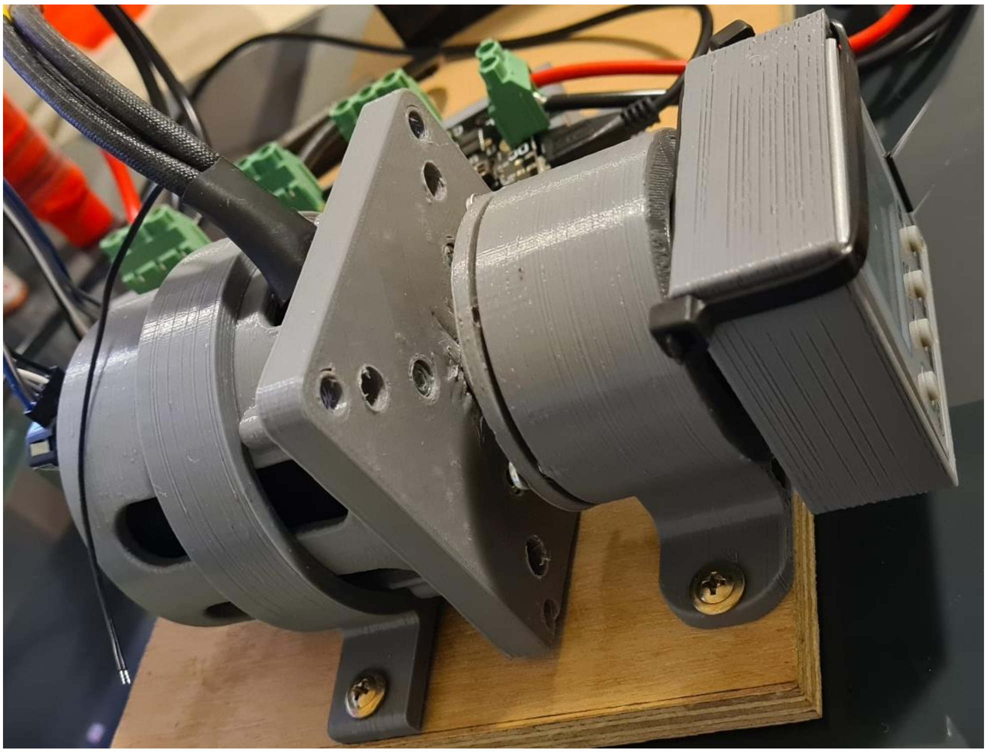

**Figure 3.6.4 : Actual Prototype including Motor, Encoder and Angle Finder Housing**

## 3.7. Prototype Costs

One of the key objectives with this research project was to design, manufacture and build a low-cost reduction drive. The main manufacturing costs have been substantially reduced by utilising digital design and manufacturing of the prototype. The prototype weighs approximately 130grams based on the density of PETG being approximately 1.22g/cm$^3$. With the average cost of PETG around $30 per 1kg spool, the material cost is approximately $4.55. Each roller weighs approximately 4grams, TPU has a similar density to PETG at 1.21 g/cm$^3$, resulting in approximately $0.82 for the 5 rollers.

Bearings were sourced off eBay and were $14.85 delivered for two sealed bearings and 100 ball bearings. In terms of print time, an allowance of $1 per hour of print time is reasonable and allows for some maintenance costs. Noting the print times were not recorded, if all parts were to be printed there would be around 15 hours of printing, so a nominal $15 has been allowed for. To cover any miscellaneous costs such as electricity, additional maintenance and upkeep of the work area an allowance of $5 has been incorporated. This brings the approximate cost of the drive to $45 in total.

As ball bearings are quite fiddly to place into the housing by hand any further design reiterations should incorporate two needle thrust washers, which are around $15 each. That brings the final cost closer to $75. It is worth noting that these prices are online retail prices, including freight and weights, and prices have been rounded up where required. As a budget price of $75, this is considerably cheaper than the currently available alternatives. Additionally, many of the component prices will come down significantly if purchased in bulk.

In summary the budgeted cost is as follows:

| Component | Mass (g) | $/kg | $/gram | Cost ($) |
|---|---|---|---|---|
| Reduction Drive - PETG | 130 | 35 | 0.035 | 4.55 |
| Rollers - TPU (5 off) | 20 | 41 | 0.041 | 0.82 |
| Bearings | | | | 44.85 |
| Fastener | | | | 5 |
| Print Costs | | | | 15 |
| Misc. | | | | 5 |
| | | | Total | 75.22 |

**Table 3.7.1 : Budget Costing Summary**

# Chapter 4 - Results

This analysis was conducted under the following conditions:

- Motor controller supply voltage of 12.689 volts
- Motor limited to a maximum rotational velocity of 5 revolutions per second
- Current limited to 10 amps
- The prototype reduction drive has a reduction ratio of approximately 30:1 as assembled and experimentally measured
- The angle finder was reset to zero after each run

The precision and the torque output of the reduction drive were tested, bearing in mind the main goal (aside from low-cost) was to develop a reduction drive with zero backlash.

## 4.1. Precision of Reduction Drive

The precision of the drive was evaluated by setting the motor to rotate a desired number of revolutions and then returning to the starting point. Eight evaluations were conducted to determine the precision of the drive, these were from one revolution through to thirty revolutions. It is worth noting that there is no play or backlash which is evident in the drive when applying a moment to the output drive. This is due to the drive utilising smooth rollers, instead of geared teeth.

The first test was rotating the motor one full revolution, which resulted in an average output rotation of 9.38° and an average of 0.13° as the output returned to the starting point.

| **Test 1: 1 Revolution of Input** | | | |
|---|---|---|---|
| | Start Angle (°) | Position Angle (°) | Finish Angle (°) |
| Run 1 | 0 | 9.40 | 0.20 |
| Run 2 | 0 | 9.40 | 0.20 |
| Run 3 | 0 | 9.35 | 0.00 |
| Run 4 | 0 | 9.50 | 0.25 |
| Run 5 | 0 | 9.25 | 0.00 |

**Table 4.1.1 : Precision Test 1**

The second test was rotating the motor two full revolutions, which resulted in an average output rotation of 18.52° and an average of 0.27° as the output returned to the starting point.

| **Test 2: 2 Revolutions of Input** | | | |
|---|---|---|---|
| | Start Angle (°) | Position Angle (°) | Finish Angle (°) |
| Run 1 | 0 | 18.30 | 0.15 |
| Run 2 | 0 | 18.45 | 0.20 |
| Run 3 | 0 | 18.50 | 0.25 |
| Run 4 | 0 | 18.70 | 0.40 |
| Run 5 | 0 | 18.65 | 0.35 |

**Table 4.1.2 : Precision Test 2**

The third test was rotated the motor five full revolutions, which resulted in an average output rotation of 47.35° and an average of 1.71° as the output returned to the starting point.

| **Test 3: 5 Revolutions of Input** | | | |
|---|---|---|---|
| | | | |
| | Start Angle (°) | Position Angle (°) | Finish Angle (°) |
| Run 1 | 0 | 47.25 | 1.35 |
| Run 2 | 0 | 47.15 | 1.25 |
| Run 3 | 0 | 47.65 | 2.05 |
| Run 4 | 0 | 47.15 | 1.60 |
| Run 5 | 0 | 47.55 | 2.30 |

**Table 4.1.3 : Precision Test 3**

The fourth test rotated the motor ten full revolutions, which resulted in an average output rotation of 86.84° and an average of 3.03° as the output returned to the starting point.

| Test 4: 10 Revolutions of Input | | | |
|---|---|---|---|
| | Start Angle (°) | Position Angle (°) | Finish Angle (°) |
| Run 1 | 0 | 86.70 | 3.00 |
| Run 2 | 0 | 86.80 | 2.65 |
| Run 3 | 0 | 84.35 | 5.35 |
| Run 4 | 0 | 89.50 | 0.75 |
| Run 5 | 0 | 86.85 | 3.40 |

**Table 4.1.4 : Precision Test 4**

The fifth test rotated the motor fifteen full revolutions, which resulted in an average output rotation of 140.37° and an average of 4.26° as the output returned to the starting point.

| Test 5: 15 Revolutions of Input | | | |
|---|---|---|---|
| | Start Angle (°) | Rotation Angle (°) | Finish Angle (°) |
| Run 1 | 0 | 141.70 | 5.10 |
| Run 2 | 0 | 140.35 | 4.55 |
| Run 3 | 0 | 139.75 | 3.85 |
| Run 4 | 0 | 140.40 | 4.15 |
| Run 5 | 0 | 139.65 | 3.65 |

**Table 4.1.5 : Precision Test 5**

The sixth test rotated the motor twenty full revolutions, which resulted in an average output rotation of 185.72° and an average of 5.30° as the output returned to the starting point.

| **Test 6: 20 Revolutions of Input** | | | |
|---|---|---|---|
| | Start Angle (°) | Rotation Angle (°) | Finish Angle (°) |
| Run 1 | 0 | 184.20 | 4.20 |
| Run 2 | 0 | 186.05 | 5.80 |
| Run 3 | 0 | 186.35 | 5.85 |
| Run 4 | 0 | 186.25 | 5.25 |
| Run 5 | 0 | 186.50 | 5.40 |

**Table 4.1.6 : Precision Test 6**

The seventh test rotated the motor twenty-five full revolutions, which resulted in an average output rotation of 233.69° and an average of 5.33° as the output returned to the starting point.

| **Test: 25 Revolutions of Input** | | | |
|---|---|---|---|
| | Start Angle (°) | Rotation Angle (°) | Finish Angle (°) |
| Run 1 | 0 | 235.50 | 4.80 |
| Run 2 | 0 | 232.80 | 5.35 |
| Run 3 | 0 | 232.90 | 4.90 |
| Run 4 | 0 | 233.45 | 5.55 |
| Run 5 | 0 | 233.80 | 6.05 |

**Table 4.1.7 : Precision Test 7**

Finally, the eighth test rotated the motor 30 full revolutions, which resulted in an average output rotation of 278.22° and an average of 4.88° as the output returned to the starting point.

| **Test 8: 30 Revolutions of Input** | | | |
|---|---|---|---|
| | Start Angle (°) | Rotation Angle (°) | Finish Angle (°) |
| Run 1 | 0 | 278.80 | 5.30 |
| Run 2 | 0 | 277.80 | 4.60 |
| Run 3 | 0 | 279.10 | 5.45 |
| Run 4 | 0 | 278.05 | 4.75 |
| Run 5 | 0 | 277.35 | 4.30 |

**Table 4.1.8 : Precision Test 8**

The collated results show a very consistent range of motion, generally within ±1.5° of the median value, but with a substantial difference between the starting angle and the finishing angle. Considering there does not appear to be any play in the drive, and noting the error was less prominent on the earlier tests which did not have a high rotation count of the motor, this inaccuracy must be a result of the input shaft spinning against the rollers. If time permitted the acceleration could be reduced in the motor controller leading to slow movement of the end effector (unnecessarily slow movement is undesirable), and this change may result in greater accuracy of the drive. The inaccuracies could also be reduced by increasing the reduction ratio, although there will still be the issue of the drive slipping.

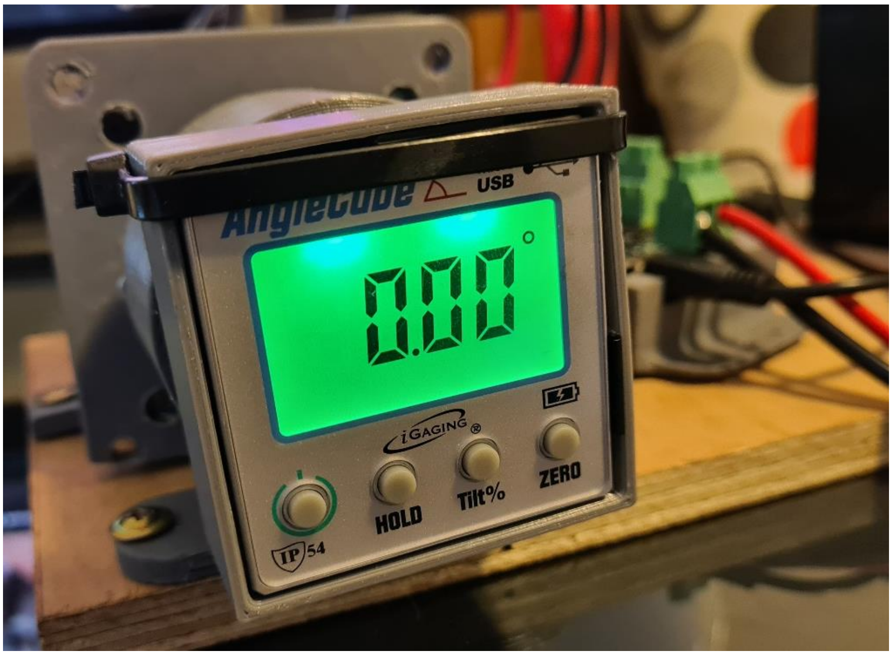


**Figure 4.1.1 : Angle Finder Attached to a Custom End Effector**

## 4.2. Torque Output of Reduction Drive

To measure the maximum torque that the drive can move, a weight (water bottle) was attached to the arm. The maximum mass the friction drive could move was 182grams using a 100mm long arm. The following equation was used to calculate the torque:

$$M = F_w \times d$$

$$M = m \times g \times d$$

$$M = 0.182 \times 9.81 \times 0.1$$

$$M = 0.1785\text{Nm}$$

This is a very low torque output and was purely due to the input shaft slipping against the rollers. One way to increase the torque output is to increase the coefficient of friction between all rotating components.

**Figure 4.2.1 : Torque Test - Utilising Empty Water Bottle**

# Chapter 5 - Discussion and Conclusion

## 5.1. Achievement of Project Specification

Throughout the project, the project aims and direction slightly changed from the initial evaluation of a low-cost strain wave reduction drive, to designing and evaluating a substantially different reduction drive (the friction drive) which had minimal information available. However, the general ethos of this research project has remained unaffected. Ultimately, the project's main goal to design, develop and evaluate a low-cost reduction drive for use in mechatronics, was achieved.

1. The literature and existing designs of several of the main styles of reduction drives were evaluated by carefully considering the literature to determine and understand the mechanical properties of these drives. The information was utilised to evaluate the different reduction drives in order to ensure the most appropriate drive was carried forward through to prototyping
2. Research was conducted into the costs of several reduction drives. It was noted that some prices had reduced over the past few years. The purpose of this research project was to design, develop and evaluate low-cost drives for prototyping and education where high torque outputs are not necessarily required but low-cost is highly regarded
3. The required loads vary depending on application, with many being very low and others quite high such as in many of the 'Robo Dog' units. As this drive was intended for research and education, high torque output was not a stipulated requirement but was evaluated in the results section
4. 3D FDM printing was investigated and determined to be suitable for manufacturing of this low-cost reduction drive
5. Several methods of 3D printing and materials were investigated. Several materials were deemed suitable for the intended application
6. The Archimedes drive was designed utilising 3D CAD software
7. The Archimedes drive was 3D FDM printed using a Flashforge Creator Pro 2 printer
8. A test procedure and a test rig were built to allow for evaluation of the reduction drive
9. The 3D printed reduction drive was evaluated with key points being backlash, precision and torque output. Unfortunately, the wear was not evaluated due to time constraints

## 9.1. Further Work and Recommendations

Given the project involved the design and evaluation of a reduction drive about which little information is available (the friction drive) it started from a low knowledge base, and accordingly, there are several areas of potential further work. Areas of further work include further prototyping to reduce the slipping of the rollers, further evaluation including of the starting torque of the drive, scaling the reduction drive up to better fit the testing motor, evaluation of the wear of the drive, further research into the kinematics of the drive, and peer review of the prototype design.

Further development of the prototype can be done to reduce the slipping of the rollers between the input shaft and the rollers and the rotating annulus. Reducing the slipping will increase the precision of the drive. Greater precision will ensure greater toque can be transmitted to the end effector. This could be achieved by using different materials for the rollers such as a more elastic or 'rubbery' material such as a TPU with a 'Shore A' hardness of less than 85 or an equivalent Thermoplastic Elastomer (TPE) filament. Such a filament will have more flexibility and potentially provide a greater coefficient of friction between the rolling surfaces. Alternatively, a coating could be used, but the likelihood of the coating failing is high due to the flexible nature of the material and compressive forces applied to the rollers. A coating which shows potential is a rubberised coating Bully Liner, which is available through most automotive retail stores.

Unfortunately, due to procurement issues resulting in limited time to complete this project the level of evaluation was not as detailed as initially intended. One aspect which was not able to be completed was to calculate the motor starting torque or current required to start the drive. It was observed, however, that when turning the drive by hand a 'reasonable' amount of torque was required. As such, it would be beneficial to determine what this value is and how it can be reduced. The reduction drive could also be scaled up to suit the ODrive D6374 motor as it is a physically large motor. Increasing the size of the drive, particularly the rollers, should allow for greater torque transmission. The increase in size, combined with a better mounting system (to alleviate any motor shaft to reduction drive misalignment as well as removing any play or vibration from the current mounts) will also result in a more compact footprint. The measurement of the torque output could also be better determined through the control channels on the Odrive board, ensuring a more accurate result.

Wear was another aspect which was not able to be adequately tested. Wear is generally not a significant factor in prototyping but should be considered. Particularly, due to the nature of FDM printing and the materials used it would be worthwhile to conduct an in-use wear test to help determine the expected life of the drive. This could be done by applying a load to the drive and running it for say 10,000 rotations, reversing it for say 10,000 rotations and measuring the wear before, during and after.

Further research could also be conducted into the kinematics of the reduction drive to calculate the required forces and tolerancing required. This would potentially allow for a more analytical design noting FDM filaments often do not have any material property specifications making it difficult to accurately determine the loads and elastic deformation FDM printed parts can withstand. It also may allow for a cost-effective design utilising materials such as metal alloys instead of FDM printing. This would result in a more accurate drive with potentially higher torque outputs at the cost of weight and manufacturing expenses.

Finally, a peer review of the reduction drive design and operation would be highly beneficial. Particularly, if someone had more experience with digital fabrication methods, they may be able to alleviate some of the issues. Further, a peer review could include redesigning the whole drive which may alleviate some or all of the issues which are currently being experienced.

## 9.2. Personal Appraisal

While the project specification was developed to help direct the project in the appropriate direction, it also presented me with many challenges and opportunities to further enhance my knowledge. Through my research and analysis of reduction drives I have greatly expanded my knowledge of what has been accomplished and where and how we can push the boundaries to further our knowledge and to bring that technical knowledge into fruition to solve problems practically and efficiently. It was also rather interesting researching the many variations and combinations of drives available to achieve varied outcomes.

This research also greatly expanded my knowledge on 3D FDM printing. At the start of this project, I was quite naïve when it came to FDM printing, with the ideology that once a part is designed, it is simply printed using any filament you want. Through my research it was evident that FDM printing, while readily accessible, is actually quite difficult to master unless you have a vast knowledge of how FDM printing works, the particular requirements of different materials, understanding of different slicing software and the (endless) customisation of print settings which can be tailored to suit your specific requirements. While most simple or non-functional parts are easily printed with minimal print setting changes, to ensure appropriate dimensional accuracy and strength, several factors must be considered as discussed above in sections 3.2 and 3.3. Additionally, however minor, one must also consider FDM printing requirements when designing and modelling parts to ensure efficient use of material (minimising support material) and to ensure parts are printed in a manner that will not introduce any failure points or modes.

One of the most rewarding parts of any project is to observe the progress of an idea which has been developed from a simple sketch to a 3D model and finally to a fully functioning prototype. While the level of evaluation and prototype development was hindered by global procurement issues due to a worldwide pandemic it was still rewarding to get this far, and hopefully, someone else will pursue this and further develop this prototype.

## 9.3. Conclusion

In conclusion, this project, as intended, has achieved the aims of designing, digitally fabricating and evaluating a low-cost reduction drive. While the reduction drive is not perfect (it does not have a huge torque output and lacks some precision) the concept of a no backlash drive has been proven through the development of this friction drive.

This digitally fabricated reduction drive is a proof-of-concept approach to reducing the cost of robotics particularly in the fields of research and education. With some further work, there is ample reason and opportunity for this type of drive to be widely utilised in mechatronics. That development will allow more time and money to be applied to other areas of research, innovation and education. The final reduction drive prototype provides a solid foundation to allow for rapid prototyping and further research.

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# Appendix A - Project Specification

**ENG4111/4112 Research Project**

**Project Specification**

**For:** Shaun Gooneratne

**Title:** 3D Printed Strain Wave Gearing for Low-Cost Robotics Application

**Major:** Engineering - Mechanical

**Supervisor:** Craig Lobsey

**Enrollment:** ENG4111 – EXT S1, 2021

ENG4112 – EXT S2, 2021

**Project Aim:** To design, develop and evaluate low-cost strain wave gearing for use in mechatronics.

**Programme: Version 1, 14 March 2021**

1. Evaluate literature and existing designs of strain wave gearing to have a thorough understanding of the mechanical properties of these gearboxes.
2. Conduct research into current costs of strain wave gearing and investigate areas where reductions can be made.
3. Determine loads/torque required from the gear set.
4. Evaluate/confirm the suitability of 3D printing as a fabrication method.
5. Conduct research into 3D printing processes and 3D printing materials to determine suitable design methodology and material selection.
6. Design strain wave gear set.
7. 3D print gear set.
8. Design a test process to evaluate gear set performance. Primary evaluation criteria are strength and wear.
9. Evaluate performance of 3D printed gear set.

*If time and resources permit:*

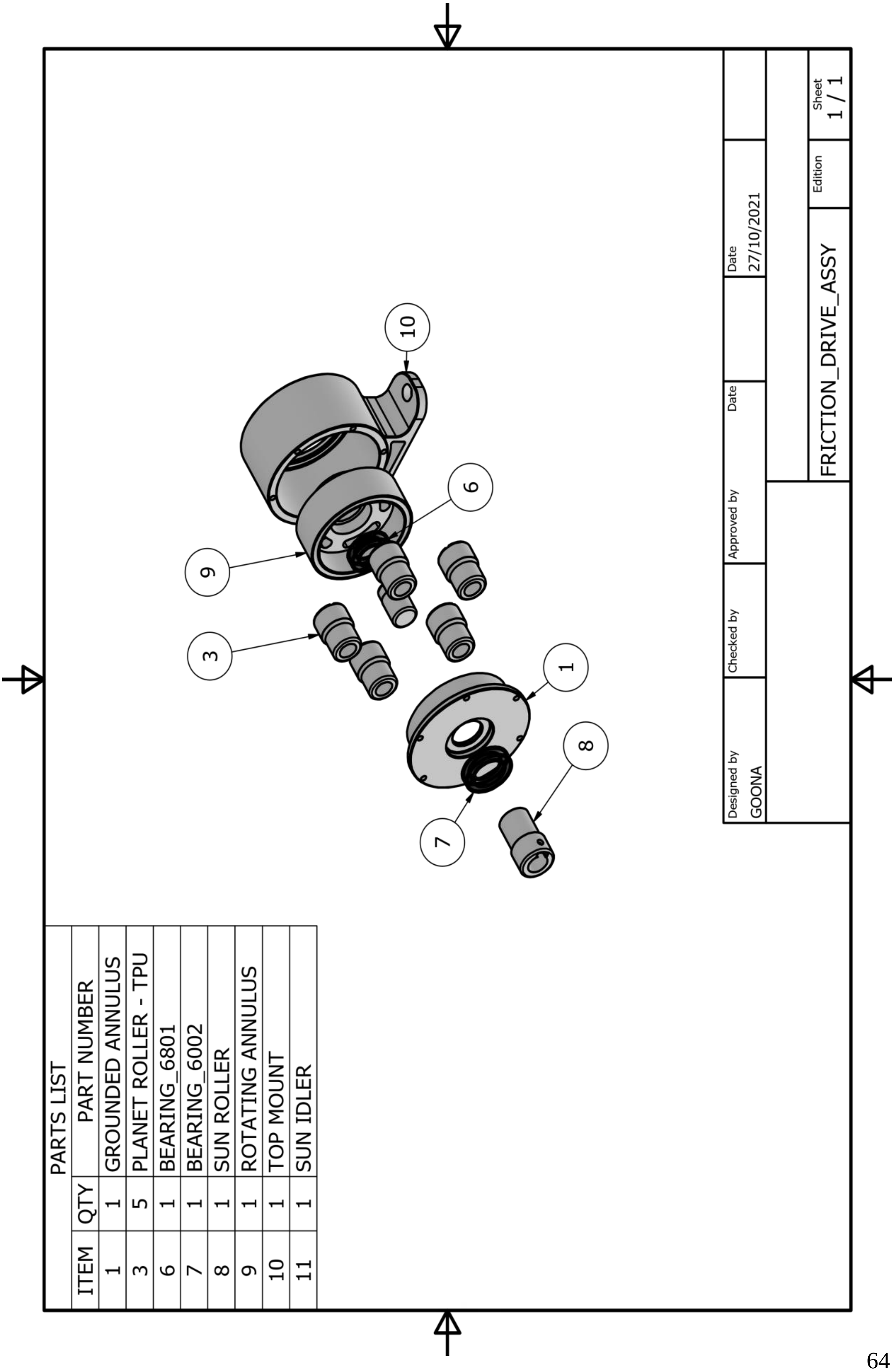
1. Evaluate different materials for suitability/cost/strength/wear comparison.

# Appendix B - Risk Assessment

| Step 1 (cont) | Step 2 | Step 2a | Step 2b | Step 3 | | | Step 4 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Hazards***: From step 1 or more if identified | ***The Risk:*** What can happen if exposed to the hazard without existing controls in place? | ***Consequence:*** What is the harm that can be caused by the hazard without existing controls in place? | ***Existing Controls:*** What are the existing controls that are already in place? | ***Risk Assessment:*** Consequence x Probability = Risk Level | | | ***Additional controls:*** Enter additional controls if required to reduce the risk level | ***Risk assessment with additional controls:*** | | | |
| | | | | **Probability** | **Risk Level** | **ALARP? Yes/no** | | **Consequence** | **Probability** | **Risk Level** | **ALARP? Yes/no** |
| **Example** | | | | | | | | | | | |
| Working in temperatures over 35º C | Heat stress/heat stroke/exhaustion leading to serious personal injury/death | catastrophic | Regular breaks, chilled water available, loose clothing, fatigue management policy. | possible | high | No | temporary shade shelters, essential tasks only, close supervision, buddy system | catastrophic | unlikely | mod | Yes |
| Chemical Fumes | Potential long term effects from repeated exposure. Short term irritation of airways | Moderate | Nil | Possible | High | No | Provide exhaust sytem | Moderate | Unlikely | Moderate | Yes |
| Hot end of 3D printer | Burn | Moderate | Nil | Possible | High | No | Ensure signage<br>Cover over hot end<br>Allow hot end to cool | Moderate | Unlikely | Moderate | Yes |
| Injury from hand tools | Cut/Stab | Moderate | Nil | Possible | High | No | Use tools appropriately, ensure adequate training has been provided | Minor | Unlikely | Low | Yes |
| Electrocution | Burns, internal injuries, death | Moderate | Nil | Possible | High | No | Ensure all power is appropriately fused and all connections are secure.<br>Ensure lowest volatge is being used i.e. 12/24V, NO 240V | Moderate | Unlikely | Moderate | Yes |
| Injury from runaway/out of control drive | Cuts<br>Broken bones | Moderate | Nil | Possible | Low | No | Emergency power off | Moderate | Unlikely | Moderate | Yes |
| Pinch Points | Cuts<br>Broken Bones | Moderate | Nil | Possible | Low | No | Ensure body parts are away from moving equipment<br>Provide covers, if possible | Moderate | Unlikely | Moderate | Yes |
| Laser | Eye injury | Moderate | Nil | Possible | Low | No | Use only class 1 lasers<br>Do not look/point laser into eyes | Moderate | Unlikely | Moderate | Yes |

# Appendix C – Friction Drive Drawings

## C1 – Friction Drive Exploded View



## C2 – Friction Drive Assembly