PHYS6701 Design Report 2

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1 Executive Summary

This document outlines the final design of the first iteration of a Newtonian Force Calibrator for the TorPeDO system. An introduction on the purpose of such a product is provided, before the details of the design is discussed. In particular, the wheel design is justified, a description of the rotation mechanism's use of pulleys and timing belts is provided, and the securing structure for the whole calibrator is outlined. The client's requirements for this project are also revisited, as well as an update on the budget, timeline, and work breakdown. This design review also outlines the next stages of this project of construction and testing.

2 Introduction

The Center of Gravitational Physics (OzGrav) at the Australian National University uses a range of devices sensitive to gravitational tidal forces to conduct experiments. These gravity sensitive devices are constantly under the influence of gravitational disturbances from sources such as local traffic and the moon, invoking uncertainty in experimental data. To mitigate these external gravitational influence on experiments, OzGrav constructed a Torsion Pendulum Dual Oscillator (TorPeDO), as depicted in Figure 1. TorPeDO can accurately measure gravitational tidal forces, such that the local gravity over the time each experiment is conducted can be recorded and used in the analysis of the experiment's result to uncover any influence from unwanted gravitational sources.

Like any successful measuring instrument, TorPeDO requires a measurement standard to derive meaning from its data [1]. In its current form, TorPeDO relies on past measurement data for a relative comparison to derive inference from current data. A better inference method for TorPeDO would utilise a well defined baseline signal for universal comparison from each measurement TorPeDO conducts. The purpose of this project is to develop a prototype device to generate this reference signal for TorPeDO's measurements; a Newtonian force calibrator (NCal).

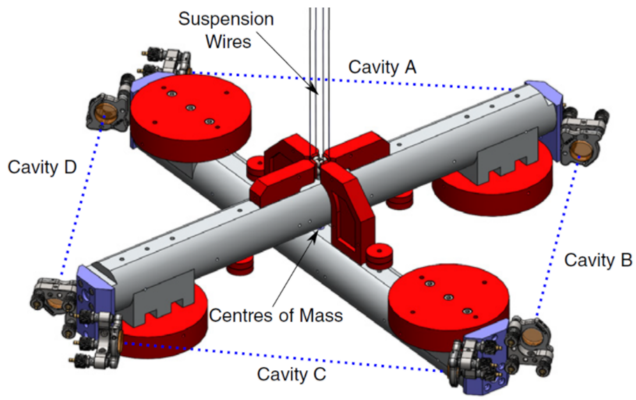

Figure 1: Schematic of TorPeDO, where the red cylinders are dense masses simulating point masses in free space [2].

The initial design review of this project consisted of preliminary compositions for the rotation mechanism and wheel construction. This initial review focused on the wheel as an echo of the Newtonian force calibrator prototype developed by LIGO[3], where the initial design is demonstrated in Figure 2. The key improvements on this wheel architecture compared to that of LIGO included the use of more appropriately shaped, weighted and interchangeable ‘point-like’ masses. Another key focus of the initial review was the rotation mechanics and their utilisation of a DC servomotor attached to a timing belt wrapped about the wheel’s axle. The rotation speed would be monitored with a Hall effect sensor which would produce an error feedback signal to the motor for accurate rotation control. The client’s requirements, revised the timeline of project goals and discussions of the past and future breakdowns of work between group members was also covered.

This document addresses the changes made and additions to the initial TorPeDO NCal prototype design as well as reflecting the current state of the project and required future work.

3 Technical Design Details

The physical design of the NCal prototype is a growth of the idea presented in Figure 2. Not only does the design consist of the wheel and rotation mechanisms themselves, but also an axle, a means of attaching the axle to the wheel, an outer casing for the wheel and masses, a means to hold the wheel in place along a fixed rotating axis within said casing and an improved system for speed measurement.

3.1 Specific Components

3.1.1 The Wheel and Mass Positioning Architecture

The wheel’s new design consists of a more realistic approach to the desired theoretical model for making the NCal signal, alongside features to implement other components of the prototype. The initial and final designs for the wheel body are demonstrated in Figure 2.

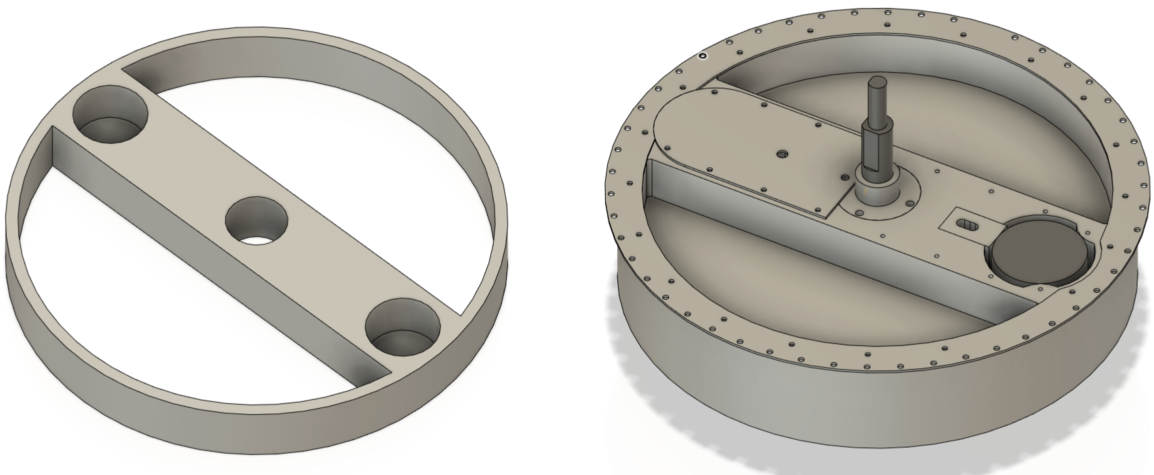

Figure 2: The initial (left) and final (right) designs of the wheel. Note the final design also demonstrates the axle attachment with the collar, as well as the mass positioning mechanism and chopper wheel attachment. There is also only one weight lid showing to demonstrate their purpose.

As discussed in the initial design report, the initial design of the wheel body was based upon the design of LIGO's wheel [3]. The updates applied to develop the current wheel shown in Figure 2 include:

- Implementing a three-point contact mechanism for the masses. Another prototype of LIGO's NCal consisted of weight holes [4] as echoed in the initial NCal design for TorPeDO. To secure the masses in this manner however, LIGO had to heat the holes on their wheel such that they would expand and contract around the masses when inserted. To ease the method of adding weights to the wheel, a three-point stability mechanism was used instead as shown in Figure 2. The weights would first be inserted into the hole, after which a smaller slanted weight holder piece would be inserted into the wheel against the weight, acting as the third point of contact between the wheel and weight. This would also allow adjustment of the weight positions such that they can be located exactly 30cm apart as desired;

- Increasing the wheel's diameter from 400mm to 420mm. This was required to make room for the larger hole sizes for the three-point weight positioning system.

- Increasing the wheel's thickness to 90mm and changing the weight's masses to 3kg. these changes were required to keep the wheel's size within the client's requirements and to keep the overall prototype at a reasonable weight;

- Adding the appropriate screw holes for the axle, weight lid and chopper wheel attachment mechanisms. A collar is applied over the axle to fit tightly into a socket onto the wheel where the angle between the axle and wheel plane can be adjusted to as close to 90° as possible to minimise gyration. The chopper wheel is applied to the wheel body for speed measurement via the photogate. Furthermore, the weight lids are added to ensure the masses are both vertically and horizontally secure within the wheel's body; and

- Applying an infill material layer to the wheel in the gaps between the bows and the center frame. This was implemented as a result of the project supervisor highlighting a concern with potential structural resonances on the bows from the rotational motion. A series of simulations were conducted to determine the best wheel design that would keep the structural resonances as far from the rotational frequency as possible. A 10mm infill in the center plane of the wheel was found to be the most appropriate wheel architecture.

3.1.2 The Securing Structure, Base Plate and Outer Casing

With the wheel's design set, a mechanism to hold the wheel in place was required. To do this, a base plate and securing structure components were developed as demonstrated in Figure 3, a design inspired by that used by LIGO's NCal prototype [4]. Both the base plate and securing structure consist of 25mm thick aluminium. Each component of the securing structure is separated into blocks to simplify machining. The center of both the base place and securing structure lid consist of four M12 screw holes where flange bearings will be placed. These flange bearings will attach to either end of the wheel's axle to fix its rotation axis in space as shown in Figure 4. The other screw holes on the securing structure lid consist of six M8 screws to attach to the walls and a number of M6 screws to mount the motor to the structure. The base plate utilises the three-point contact mechanism from the wheel's architecture to ensure the entire NCal will sit flat on a surface when used to ensure the wheel rotates in the horizontal plane. The base plate is attached to the securing structure via six M8 screws, and consists of an additional twenty M6 screw holes for application of an outer casing demonstrated in Figure 5.

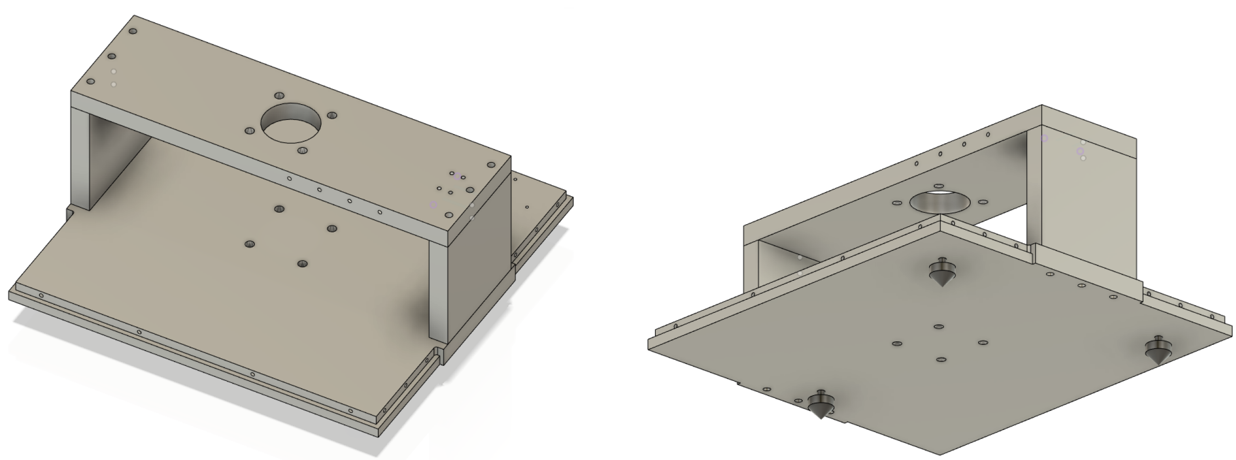

Figure 3: The securing structure and base plate prototype designs.

3.1.3 The Rotation Mechanism and Speed Control

The key aspects of the rotation mechanism fit together as seen in Figure 4, and specific part numbers are found in Table 1. The key features include a timing belt, which is used to reduce resonances and minimise slippage and gyrations, both of which are important for smooth and stable rotations. A belt width of 16mm was chosen for a combination of strength and stability, and the availability of pulleys that fit the other requirements of this design. Additionally, pulleys (not shown in Figure 4) of slightly different diameters (63.85mm and 47.95mm) will be added to the top of the wheel and motor axles respectively, to further reduce resonances from amplification by their respective rotations and to simplify future changes to the rotation mechanism should they be required.

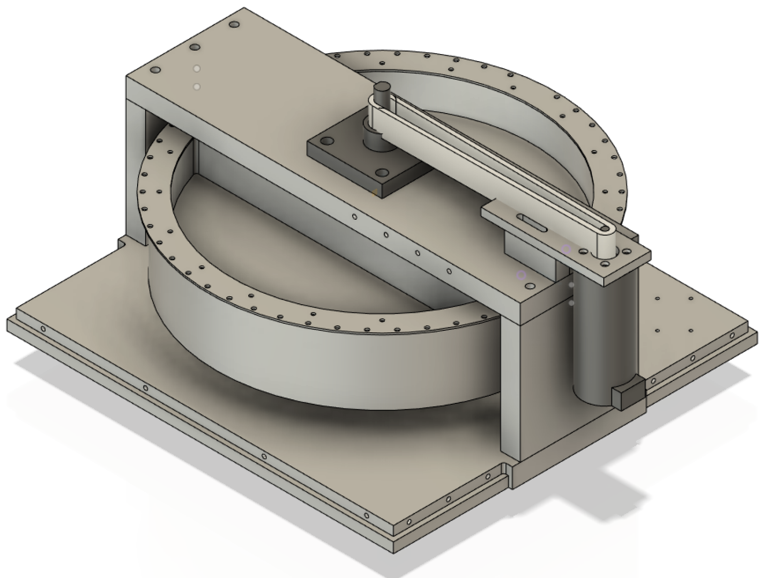

Figure 4: The wheel secured to the outer structure via the axle and flange bearings, fixed in the plane of rotation.

The motor used is a 180W DC servomotor as seen in Figure 4, as these have the most precise speed and position control out of all the options under consideration. The motor mount consists of a 10mm aluminium plate with slotted holes, attached to the securing structure lid through a spacer plate. The 10mm thick aluminium plate uses this thickness to reduce motor vibrations on the timing belt. The slotted holes of the motor mount and spacer plate are required to add horizontal tension to the timing belt and ensure the wheel and motor axles are aligned vertically respectively. The chosen motor also has a built in encoder, which can be used for monitoring of the rotation speed of the wheel.
Another means of monitoring the rotation speed comes in the form of a photogate, as seen implemented in the prototype in Figure 5. The photogate will be implemented to control the speed of the motor using a feedback loop, which will be in the computer control system under development. The computer control system consists of a Teensy 3.5 microprocessor development board, which will use the signal from the photogate due to the integrated optical chopper wheel as seen in Figure 4 and 2, to determine the rotation speed of the wheel. This will ensure the rotation is as constant as possible, thus optimising the stability of the NCal signal induced upon TorPeDO.

3.1.4 Overall Design

The assembled components of the NCal prototype are demonstrated in Figure 5. Notably, the outer casing applied to each side of the exposed wheel. The outer casing is constructed from 6mm thick aluminium plates held together by M4 screws and is required for safety reasons as a heavy spinning wheel can be dangerous if care is not taken around the device. Furthermore, the photogate is applied to the roof of one of the outer casings. The roof for this outer casing in particular consists of a square slotted hole, such that the photogate can be attached to a small aluminium plate, situated on the slotted hole and slid into place such that the optical axis of the photogate is secured over the holes of the chopper wheel.

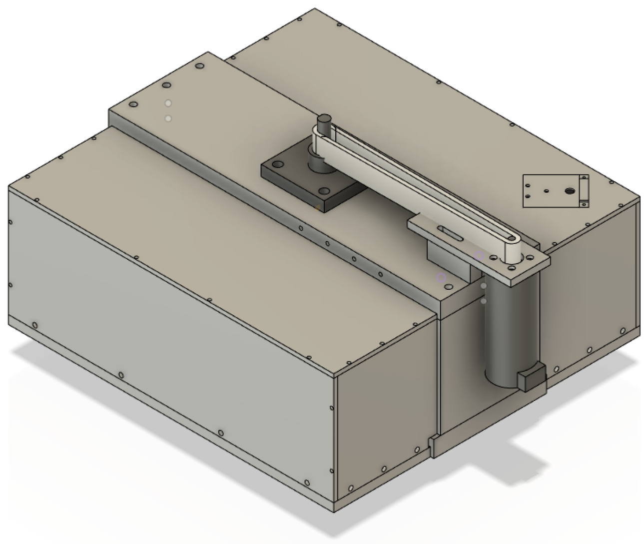

Figure 5: The final NCal prototype design for TorPeDO, with outer casing and photogate applied.

4 Requirements Review

The most important and overarching client requirement is to maximise the stability of the Newtonian force calibrator. This will be achieved in a number of ways, but with the current design in particular the timing belt will assist in achieving this. The design of the wheel will also be made as balanced and symmetrical as possible in order to minimise gyrations.
The calibrator also needs to be of a reasonable size to work within the allocated lab space around TorPeDO. In response to this, this initial wheel design from Figure 3 is 40cm in diameter, allowing plenty of leeway to move around in the spaces that are at a minimum about 50cm wide. Pending further discussions and refinements, this can be easily changed in future versions of the design.
Additionally, there needs to be accurate measurement and control of the rotation speed in order to obtain the desired gravity signal from the calibrator. By using a chopper wheel with 49 holes around the circumference of the wheel, this large number of measurements made by the photogate in a single rotation will thus maximise the accuracy of measurements.

Safety is also an important requirement from the client, so the development of a strong casing in this design is a key factor. In addition, the three-point contact mechanism on the base plate increases stability thus safety of the calibrator.
Other specifications from the client included a rotation speed of $1 - 10Hz$, which will be implemented in the control code and tested once construction has commenced. In addition, the rotating masses were suggested to be greater than $1kg$, thus two $3kg$ masses were chosen in this version of the design. This was reduced from the $5kg$ of the previous design review, as the total mass of the wheel needed to be reduced for greater ease of transportation.

5 Revised Budget and Timeline

5.1 Budget

For the current iteration of the design, the components needed to be purchased have been finalised, excluding the machining of the wheel mechanism, so current total spending can be outlined in Table 1.

Component	**Supplier**	**Item Code**	**Cost ($)**
Servomotor Kit	Ocean Controls	CNC-116	654.50
Teensy 3.5 Board	Core Electronics	DEV-14055	54.04
Bearings x2	RS Components	750-8775	17.51 ea
Timing Belt	RS Components	474-6277	44.64
Pulley	RS Components	745-725	34.43
Pulley	RS Components	745-719	32.81
Photogate	RS Components	219-2296	52.97
		Total	908.41

Table 1: Outline of the current spending of the project.

5.2 Timeline

Figure 6 outlines the ideal progression of this project as it stands currently. It is expected that the duration of each of the tasks will vary, however following this will assist the project in reaching completion.

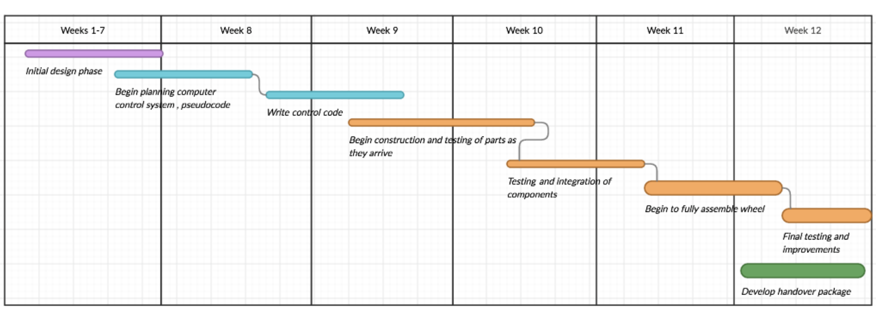

Figure 6: An outline of the current proposed timeline for the project.

5.3 Work Breakdown

Previously, the work has been split into design of the wheel and the design of the rotation mechanism such that these tasks have been divided up on a per person basis and with the occasional collaboration. For future work, the time during the machining of the components and the ordered parts being delivered will require both persons to collaborate on the same part of the project. The tasks which will utilise this collaboration include programming the computer's speed measurement and stability control of the wheel with the Arduino or by constructing a simulation which reflects the calibration data TorPeDO will generate once the prototype is complete and functional, to assist in verifcation of the prototype's performance.

6 Conclusion

At present, a final design of the first iteration of a Newtonian force calibrator has been produced. The wheel is an echo of the Newtonian force calibrator prototype developed by LIGO as well as an improvement in properties including the use of more appropriately shaped, weighted and interchangeable 'point-like' masses. The rotation mechanics will utilise a DC servomotor attached to a timing belt wrapped about the wheel's axle. The rotation speed will be monitored with a photogate which will produce an error feedback signal to the motor for accurate rotation control. This document also reviewed the client's requirements, revised the timeline of project goals and discussed the past and future breakdowns of work between group members.

References

[1] M. Lombardi, "An introduction to frequency calibration - part i," *Cal Lab: International Journal of Metrology*, vol. 3, pp. 17–28, Jan. 1996.

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