PHYS6701 Design Report 1

Monique Cockram and Ryan Husband

August 2020

1 Executive Summary

TorPeDO is a Torsion Pendulum Dual Oscillator designed to measure gravitational tidal forces. To assist in deriving meaning from TorPeDO's measurements, a wheel of rotating masses has been devised to generate a calibration signal for TorPeDO. The following document reviews the design of a Newtonian force calibrator for TorPeDO. This review includes an analysis of the project's purpose to extend TorPeDO's function, the calibrator's design as a weighted wheel simulating Newtonian forces induced by rotating point masses, the wheel's rotation mechanism by a DC servomotor, timing belt and Hall sensor for speed control as well as details of the project requirements, timeline and work breakdown. The prototype is still in the design stage at the time of release of this report, but the ideas demonstrated are the solid foundations of what is looking to be a successful project.

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.

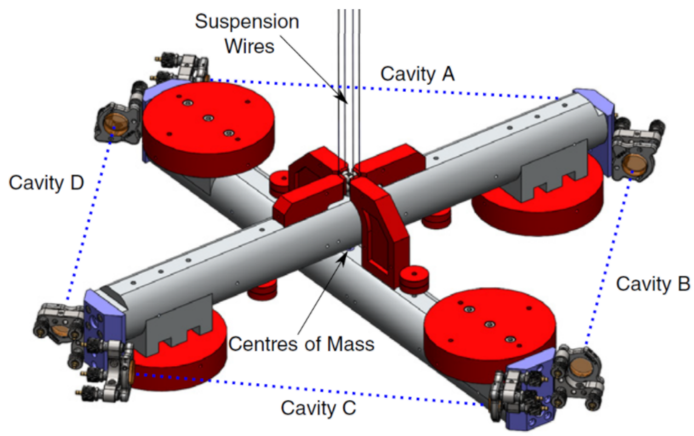

Figure 1: Schematic of TorPeDO, where the red cylinders are dense masses simulating point masses in free space [1].

Like any successful measuring instrument, TorPeDO requires a measurement standard to derive meaning from its data [2]. 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.

3 Technical Design Details

3.1 Overall Design

TorPeDO consists of two suspended crossbeams which are free to rotate about the same axis in the same plane (i.e. the suspension wires and the plane of each cavity as seen in Figure 1). Gravitational tidal forces accelerate the end masses on each arm of TorPeDO, inducing an differential rotation between TorPeDO's arms which is measured by the change in each Fabry-Perot cavity length [1]. The ideal calibration signal for a device reliant on oscillations for measurement would consist of a single frequency; a sinusoid [2][3]. Similar calibration prototypes constructed at the advanced LIGO detector suggest the best mechanism for inducing a sinusoidal gravitational signal is a wheel of fixed rotating masses [4]. The wheel prototyped at LIGO, depicted in Figure 2, was thus the basis for the design of TorPeDO's Newtonian force calibrator.

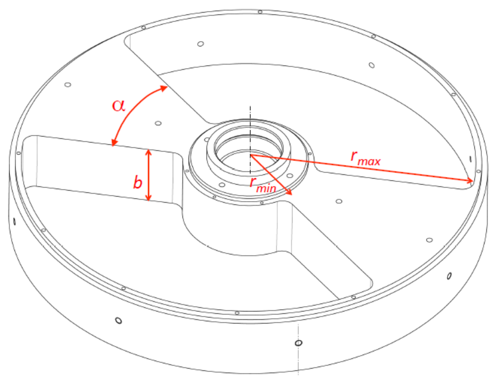

Figure 2: Schematic of Newtonian force calibrator prototype used on the advanced LIGO detector, constructed from aluminium [4].

The prototype of Figure 2 was used on LIGO's mirrors to infer a sinusoidal calibration signal in LIGO's interferometry measurements. This wheel was unique in that it simulated the effect of rotating masses on LIGO's measurements, allowing for ease of calibration as the gravitational force induced by the wheel on LIGO was well defined and simple to calculate.

3.2 Specific Components

3.2.1 The Wheel Design

The Newtonian force calibrator for TorPeDO was therefore going be an echo and improvement on the design of Figure 2. These improvements include:

- Replicating Newtonian force generated by point masses. LIGO's prototype utilised infilled sectors of a ring as their masses as seen in Figure 2, where these masses were approximated as 'point-like' resulting in a range of approximate affects on LIGO [4]. TorPeDO's calibration device would therefore use smaller volume masses of a higher density material to improve on these approximations;

- Using heavier masses to produce a stronger gravitation signal as the gravitational force between bodies is linearly proportional to their masses. LIGO's prototype masses were approximately $2.06kg$ each where as TorPeDO's calibrator masses are planned to be approximately $5kg$ each; and

- Allowing the masses to be replaceable, allow flexibility in generation of specific calibration signal.

Implementing these improvements upon LIGO's prototype and making some further adjustments, the first design of TorPeDO's Newtonian force calibrator was developed as shown in Figure 3.

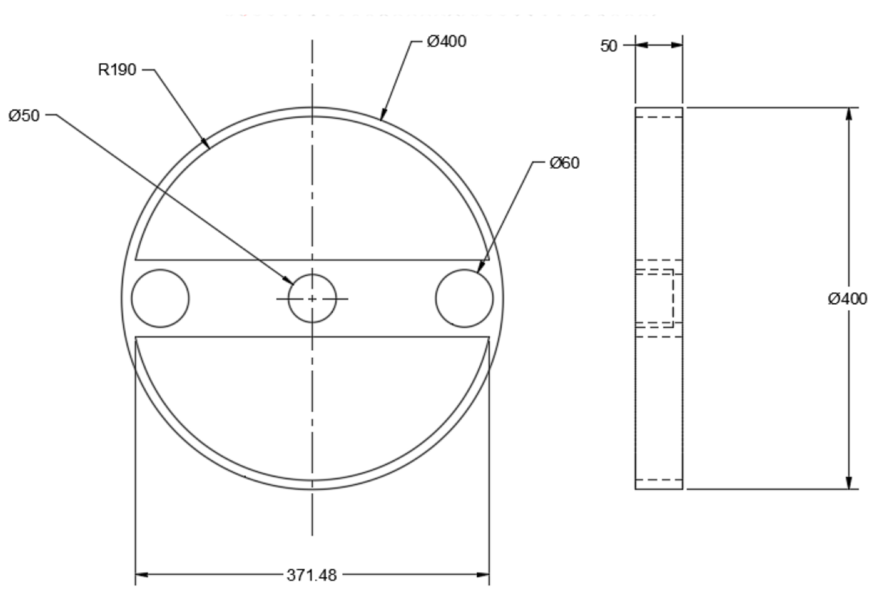

Figure 3: First Newtonian force calibrator design for TorPeDO. Note that the dimensions shown are approximations as this is a proof of concept design.

The wheel body demonstrated in Figure 3 is constructed of aluminium as this is the most light weight, sturdy and available metal. The wheel consists of placeholder holes for the weights, to be constructed of steel as this is a readily available metal of higher density than aluminium. The body also echo's the ring design of LIGO's prototype wheel [4] and consists of an axle hole at its center.

3.2.2 The Rotation Mechanism

The key aspects of the rotation mechanism fit together as seen in Figure 4. 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.

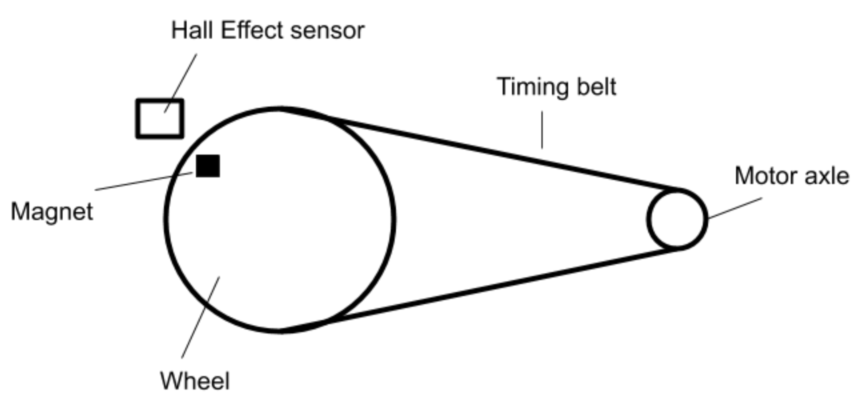

Figure 4: A rough diagram of the components of the mechanism of rotation.

The motor will be a DC servomotor, as these have the most precise speed and position control out of all the options under consideration. In addition, the client suggested a $24V$ motor as the best choice, and there will be a need to get significant power sources in order to rotate the mass of the wheel. From a quick calculation using our current estimations of dimensions of the wheel, the amount of torque the motor could need is about $18Nm$, which is achievable with many of the motors available. In terms of the rotation speed measurement, we will use a

Hall Effect sensor to monitor and control the speed of the motor using a feedback loop, which will be in the computer control system that will be developed. This will be done using either an Arduino or Raspberry Pi, depending on what best fits the final choice of motor and sensor. As a result, a sensor with digital output will be best for this application. This feedback loop will take the current speed of the wheel and try and minimise its difference compared to the chosen speed of rotation. The output signal will therefore be proportional to the change in the motor needed to maintain a constant rotation speed. A possible improvement to Figure 4 is to use multiple magnets and Hall Effect sensors around the circumference of the wheel in order to maximise the accuracy thought frequent monitoring of the speed. This will ensure the rotation is as constant as is achievable for this project, and thus optimising the gravity force signal that TorPeDO reads and is calibrated with.

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 multiple Hall Effect sensors around the circumference of the wheel, this will be be maximised for this version of the project.
Other specifications from the client included a rotation speed of $1 - 10Hz$, which will be implemented and tested once construction has commenced. In addition, the rotating masses were suggested to be greater than $1kg$, thus two $5kg$ masses were chosen in order to be a significant size as compared with that of TorPeDO, which uses has $3kg$ masses on each are as seen in Figure 1.

5 Revised Timeline

Figure 5 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.

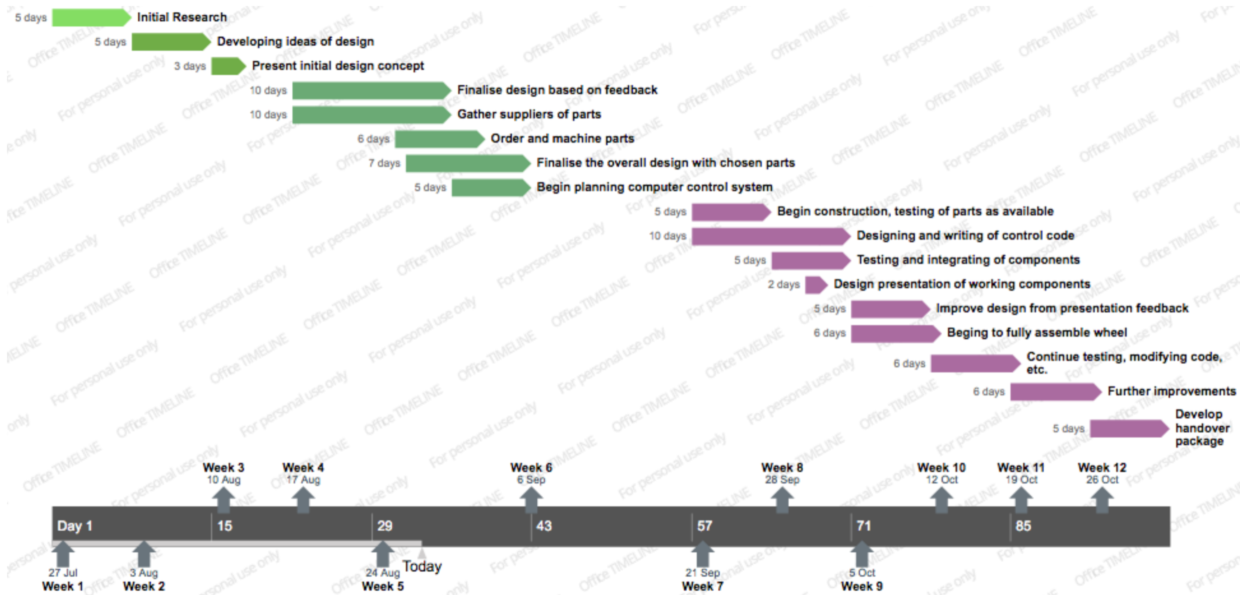

Figure 5: An outline of the current proposed timeline for the project.

5.1 Work Breakdown

At the current progression of this project, 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. This may change for future work however, as the periods of time when the wheel is being machined and ordered parts are being delivered may result in both team persons working on the same part of the project simultaneously. Examples of the tasks where this could be done include programming the computer control of the wheel with the Arduino or Raspberri Pi or simulating the measurement data TorPeDO will generate once the wheel is constructed and ready for testing to verify its performance.

6 Conclusion

At present, a draft design of the rotation mechanism and wheel construction for 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 Hall effect sensor 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] D. J. McManus, "Dual torsion pendulum sensor for measurement of terrestrial gravitational forces," PhD thesis, The Australian National University, Canberra, ACT, Jun. 2019.

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

[3] MAtthew D. Schwartz, *Matthew d. schwartz lectures on oscillator analysis*, `http://users.physics.harvard.edu/~schwartz/15cFiles/15c-2015-Schwartz.pdf`, 2015.

[4] D. Estevez, B. Lieunard, F. Marion, B. Mours, L. Rolland, and D. Verkindt, "First tests of a newtonian calibrator on an interferometric gravitational wave detector," Jun. 2018.