3D DYNOSCAN PROGRESS REPORT

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Executive Summary

3D Scanners are an expedient solution to obtain a 3D 360° CAD model from physical objects, such as turbine blades or other small turbine engine components. Imperial College's Dynamics group requires a solution that can obtain a 3D 360° CAD model with a resolution of 0.5 mm within a £1000 budget. As most commercial solutions were too expensive or incompatible with the objects that the Dynamics group wanted to test, a DIY solution was developed.

The mechanical aspect of this project mainly consists of a turntable connected to a belt-pulley transmission. A mechanical turntable deflection test was conducted on the turntable, to validate previous calculations on the turntable's structural integrity, and revealed that a 20 kg load at the turntable edge caused a 5 mm elastic deflection compared to the calculated value of 0.55 mm. This could have been attributed to the shaft tilting due to leeway in the tolerancing.

An electrical test was also performed to determine the turntable's rotational accuracy when loaded and unloaded. While centrally loaded, the turntable completed rotations ranging between 85 – 90° with consistency, regardless of load. It further revealed that a 100 N load placed eccentrically at the edge of the turntable caused the motor to stall and unable to complete a revolution. This suggests a lack of torque provided by the motor due to increased friction between the bearing and bearing housing, which will be rectified by increasing the transmission ratio from 1:1 to 4:1.

Lastly, a scanning test was performed to verify the validity of open source code. A single 3D point cloud and subsequently a single 3D mesh was obtained, albeit with low resolution due to limitations in projector quality. This test suggested that using a project with higher resolution and shorter focal length will increase the 3D point cloud density. Consequently, a higher resolution 1280x720p AAXA P300 Neo Pico projector and 15 Megapixels Logitech C920 webcam have been ordered.

1 Introduction

Imperial College London's department of Vibrations' work involves the analysis of small engine components such as turbine blades. Such analysis is done computationally and requires an accurate 3D representation of the actual engine component. While old engineering drawings are available, it is a time-consuming and error-prone process to manually recreate models using Computer Aided Design (CAD).

Therefore, a solution is required to scan similar objects and create a complete 3D model with a resolution of less than 0.5 mm and cost less than £2000 (initial budget of £1000 with potentially an additional £1000 available for purchasing a scanning device). Furthermore, the objects can weigh up to 20 kg and have a maximum length and height of 500 mm and 300 mm respectively. The full list of product requirements can be found in the updated Quality Plan document.

A study of existing 3D scanning solutions was conducted. Relevant products that are below the stipulated budget of £2000 pounds and meet the required resolution requirements are shown in Table 1 below.

Table 1 - Analysis of commercial solutions with resolutions lower than 0.5 mm and cheaper than £2000

Product Name	Resolution (mm)	Price (£)	Weight and Max Scanning Dimensions	Remarks
Eora 3D Scanner [1]	0.10	455	2.2 kg Ø 300 mm	Maximum turntable load of 5 kg Proprietary software Requires smartphone camera Still in Kickstarter status, no complete product Scanner can be used without turntable
Matter and Form [2]	0.10	570	1.71 kg 250 x Ø 180 mm	Maximum turntable load of 3 kg Proprietary software Incompatible without built in turntable
EinScan-SE 3D Scanner [3]	0.17-0.20	1400	4.9 kg 700x700x700 mm	Scanner can be used without turntable 4-60 second total scan time Proprietary software

While some products such as the EORA 3D or the Matter and Form scanner are well below budget and can achieve the resolution demands, other requirements such as the maximum load or scanning dimensions are not met. Wholesale commercial solutions are thus unsuited, and a custom solution must be designed and made.

2 Work Done

2.1 Design Choices

Given that scanning and model reconstruction is the central aspect of this project, the scanning method was first considered before other mechanical aspects, like object support and positioning. Initially, adapting existing commercial scanners to fit with the project requirements was considered, such as using the EinScan-SE with a custom-built turntable. The arguments for and against such an approach are laid out below in Table 2.

Table 2: Evaluation of commercial and self-made scanning devices

Commercial	Self-Made
Adaptable scanners with the required resolution of below 0.5 mm were above the budget of £1000	Budget can be better managed with total control over components
Simplifies the software aspect Allows better workflow Focus on the mechanical aspect of positioning and image acquisition	Requires more focus on software given the group's inexperience in this aspect
Does not easily allow for future improvements on scan resolution and process, given a fixed commercial product	Easier to design a modular approach

At the same time, different approaches to self-made 3D scanners were investigated, with the main methods detailed below in Table 3, and a comparison between these methods shown in Table 4.

Table 3: Description of various scanning methods considered

Scanning Method	Description	Mechanical Requirements
1D Laser Scanner	A 1D distance sensor is used to measure the distance from a rotating object at a known frequency to get a depth profile of an object. By incrementing the sensor vertically after each rotation, a complete 3D model can be obtained	Requires the object to be rotated about a vertical axis, and the sensor to be periodically moved linearly up and down.
1D Laser Triangulation	Similar to the 1D laser scanner, with a laser triangulation sensor used instead. This has the benefit of greater distance resolution via the use of optical triangulation.	Similar mechanical requirements as the 1D laser scanner
2D laser Triangulation	Instead of a point light projected onto the object, a line is projected, giving a linear profile at all points at one time. The 3D depth profile of a surface is quickly obtained by moving the object or sensor normal to the projected line	Requires movement of either the object or sensor
Structured Light Scanner	A series of patterns are projected onto the object's surface, from which digital image processing by an adjacent camera allows reconstruction of the depth profile	The object and scanner must be stationary during capture, but multiple captures at different positions are required to obtain a full model

From the survey of both commercial and self-made methods, it is apparent that fusing a commercial scanner with a custom rig is prohibitively expensive. Likewise, while laser triangulation sensors have an attractive depth resolution and ease of implementation, their hefty costs make them an unsuitable approach. Using a simple laser depth sensor would also take too long in order to achieve the 0.5 mm resolution required. The most attractive approach is thus the Structured Light Scanning (SLS) method, which is what the team decided to proceed with.

Table 4: Evaluation of various scanning methods

1D Distance Sensor	1D or 2D Laser Triangulation Sensors	Structured Light Scanning
Relatively simpler to reconstruct point cloud given a known revolution rate and sensor capture frequency rate	Very precise depth resolution of $\pm 20 - 50\ \mu m$	Cheaper components, better control over budget Commonly used components total to about £400 maximum
Poor sensor depth accuracy ($\pm 5\ mm$ for a £200 laser) [3]	Sensors exceed budget (1D - £2,750 2D – £8,430) [4]	Resolution depends on the quality of the products used
Estimated 10+ hours to scan an object at the required <0.5 mm resolution given a set capture frequency rate	Requires precise control to obtain known turning and linear movement rates	Relatively simple mechanical setup
Requires precise control to obtain known turning and linear movement rates		Relatively more complicated to implement, no simple open source software available

One issue with the SLS method is that 3D model resolution cannot be accurately estimated before proceeding, and as such, different sources and past projects have been consulted.

Based on this choice, the mechanical requirements for the project are as such:

- Projector to project patterns and a camera to capture them. The mount for both the projector and camera should allow for variation in distance and pitch from the object
- The object to be scanned has to be automatically repositioned after each scan to allow for complete digital reconstruction
- Lighting conditions should be controllable, given that a projector's output is sensitive to the ambient lighting conditions

3 Design Iterations

On the mechanical aspect, we identified the need for automatic object repositioning as the primary objective and decided to have the object rotating with a stationary scanning platform. This decision will be further elaborated in Section 2.3.1 where the physical demands of structured light scanning are considered.

As seen in Figure 1, a turntable is used as a platform to rotate the scanned object, with a bevel gear transmission setup. A turntable bearing at the bottom of the turntable provides support, along with a thrust bearing at the bottom of the vertical shaft.

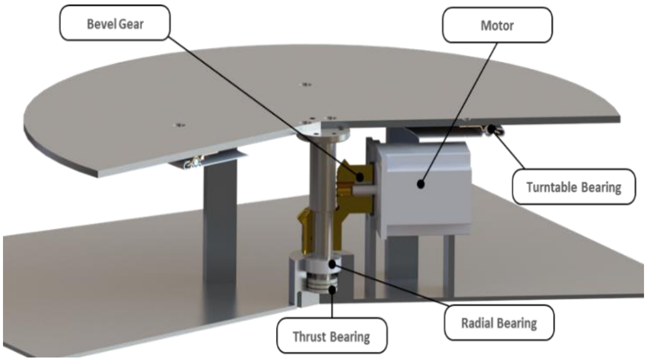

Figure 1: Cross section of bevel gear transmission assembly

After initial evaluation and tutor feedback, there were concerns raised regarding bevel gear backlash when starting and stopping the motor. Furthermore, at a height of 120 mm, the design is not very compact. The usage of a thrust bearing is also not ideal, given that a significant radial load will come from the turning of gears.

While the next iteration kept the general idea of a turntable, the transmission method was changed, using a pulley and timing belt instead. More specifically, the reduced backlash timing belt selection from HPC was selected with the constant starting and stopping in mind. By shifting the motor out of the turntable, the overall height was reduced to 89 mm. The thrust bearings were replaced with radial bearings that could handle a dynamic axial load of 1.43 kN, thus accounting for the radial and axial loads it would be subjected to.

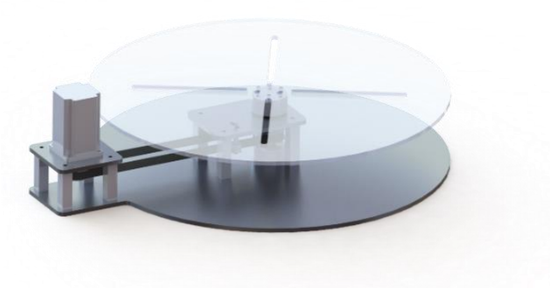

Figure 2: Render of belt-pulley turntable transmission assembly with a transparent turntable for clarity

A stepper motor was chosen to drive the load, as positional control is obtained by specifying the number of steps to turn, and angular velocity controlled by varying the delay between each step. This has an advantage over a DC motor which usually requires at least proportional feedback and a more involved control setup with a rotary encoder to achieve the same results.

The motor used is the RS Pro 535-0445 stepper motor with a holding torque of 1.89 Nm and step angle of $1.8°$. This torque is higher than the calculated torque of 0.51 Nm to overcome the friction in the bearings in the worst-case scenario where the 20 kg mass is placed at the edge of the turntable. The torque needed to overcome inertia is significantly lower, approximately 0.12 Nm, which means that the motor should have been sufficiently capable of rotating the object during scanning.

Figure 3: Overall setup

The overall setup is shown in Figure 3. A tripod mount was used to hold the camera and the projector, allowing for variable height, distance, and yaw of projector-camera configurations. Aluminum profiles were used to form the frame of the box, with acrylic sheets fitting in between the slots of the profiles. These sheets could be appropriately tinted to adjust the ambient light conditions while scanning. The separation of turntable with scanner isolates the potential vibrations from the motor that could potentially affect the positioning and the calibration of the camera and projector.

After another review and feedback, the box was deemed too bulky with wasted space, while the large base plate and acrylic sheets served to unnecessarily increase the weight of the whole assembly.

3.1 Prototype Testing

3.1.1 Structured Light Scanning

Concurrent to the prior designs, a Structured Light Scan was attempted in order to better understand the process, ascertain exact physical requirements, determine the veracity of resources used, and to formulate a specific action plan for further improvement and testing.

Consisting of camera-projector calibration and then the actual scanning, a Dr. Q HI-04 projector of resolution 1280x786 and a OnePlus 6T camera with resolution 4608x3456 was used. The calibration method and code are provided by Moreno and Taubin [5] in their paper, along with the object reconstruction code.

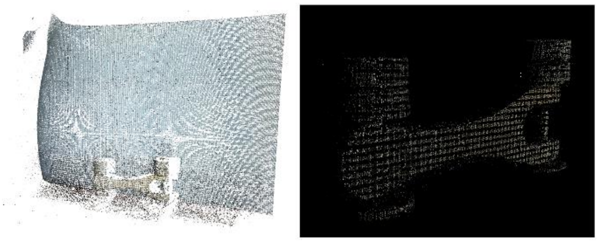

Figure 4: Point clouds obtained from a scanned toy car before and after post-processing

Through the implementation of a SLS scan, we have found that the sources for code and methods used are reliable. Also, the action plan has been updated to better account for the complexity involved, which is reflected in the Gantt chart shown in Section 4.1 below.

Through this testing, it was found that while it was possible to streamline the calibration process, movement of the projector and camera would render current calibration parameters invalid, thus keeping them stationary would be ideal from a usability standpoint. The projector should have a short focal length and small screen size, such that the object takes up the largest proportion of the projected space possible for a more detailed point cloud, better illustrated in Figure 4 above. It must be noted that camera focal and exposure settings must be constant throughout the whole process.

3.1.2 Turntable

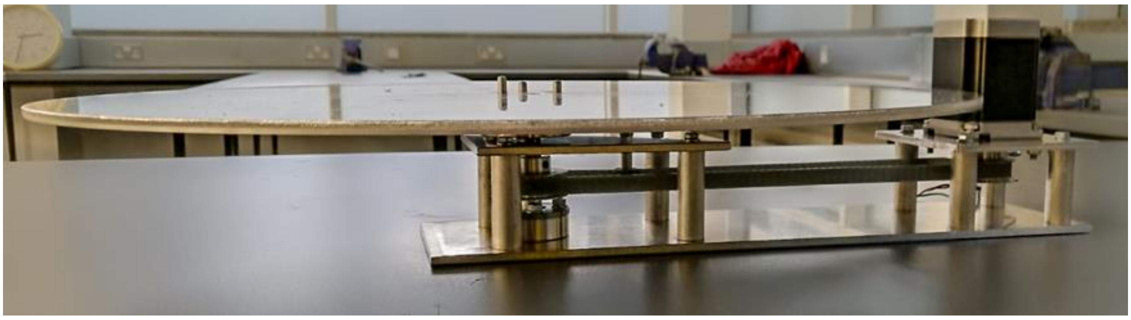

Figure 5: Completed belt-pulley turntable transmission prototype

The above turntable was manufactured and assembled based on the model in Figure 2. This was to ensure that this design could indeed handle the stipulated max loads and test the control and response of the motor under loaded conditions. Also, any preliminary issues with this design could be picked up early on and rectified.

3.1.2.1 Structural Test

The purpose of a structural test was to investigate the possibility of failure and yield by determining the end deflection of the turntable when varying loads are placed 125 mm from the center of the turntable. The empirical results are then compared with analytical calculations and a Finite Element Analysis (FEA) simulation for further validation.

The turntable was loaded with weights varying from 50 N to 200 N, with a dial gauge set up to measure the deflection near the edge of the table. This deflection is then recorded for each weight.

After unloading of all weights, the dial gauge was observed to return to 0, indicating that the turntable did not yield or plastically deform. The variation of deflection with load was observed to be approximately linear, with a maximum deflection of about 5 mm at the edge when a 200 N load was placed. This is significantly greater than the analytical calculation of 0.55 mm, possibly due to the inaccurate assumption made in treating the turntable as a cantilever. FEA analysis gives an end deflection of 1.23 mm instead, which is more in line with the experimental result.

The greater deflection may also be a result of the tilting of the shaft due to some leeway in the tolerance. However, the deflection is still acceptable as there is no plastic deformation of the turntable and the scanning software can correct any positional errors caused by the tilting.

It was also noted after the test that the turntable shaft was made from aluminum instead of steel, due to a manufacturing error. This is likely to have a noticeable effect on deflection, given that aluminum has a Young's modulus about one third of steel.

3.1.2.2 Electrical Test

There is a need to investigate the accuracy of the turntable's rotating angle with varying loads and loading positions, in order to determine the extent of slip of the motor and adjust the control scheme accordingly. In this test, the predefined desired rotating angle is 90°, and the angular change, settling time, and overshoot is measured for varying loads.

A sticker with a cross mark is placed 180mm from the centre of the turntable and a video is taken as the turntable turns with various loads on it. From the video, the path of the marker is recorded, and the angle of rotation performed by turntable is computed. The settling time is also determined by analysing the data using MATLAB. The experiment is repeated with increasing loads of up to 200N placed in the centre of the turntable and with the same loads placed 180mm from the centre. The corresponding angles of rotation and settling times are obtained.

The angle of rotation when the turntable is loaded centrally varies from 87° to 95° with the average rotation angles of different loads keeping within $\pm$ 1°. There is also a small variation of angle of rotation performed across different loads which suggests no correlation between the angle achieved and the loading of the turntable. This is consistent with the results from when the turntable is eccentrically loaded. The variance of 10% for the rotation angle is acceptable as precise angular change is not required for Structured Light Scanning since the software can correct for positional errors. Therefore, motor slip is negligible and there is no need for additional controls for the turntable.

An average settling time of 11.02 s with standard variation of 0.12 s is achieved. This gives a good estimate of how long scans will take depending on the number of positions needed and the number of pictures taken per position.

One issue encountered was that the turntable was unable to make complete reliable 90° rotations when loads of greater than 100 N was placed eccentrically. It was found that incomplete rotations were more prevalent in certain start positions. This was largely due to the turntable having a more significant tilt in certain positions when it is eccentrically loaded, perhaps due to leeway in tolerances during manufacturing. This tilt resulted in more friction experienced by the bearings and the housing. As such, more torque is required to overcome the frictional torque. To increase torque, various methods, including changing to a higher transmission ratio, changing to a more powerful motor and changing to self-aligning bearings, were explored.

3.2 Current Design

From the results of the prototype testing, we updated our design to the current version as shown in Figure 6. First, to counteract the slip, we changed the transmission ratio 1:1 to 4:1, on the assumption that the torque scales linearly with weight. Based on the torque requirements from

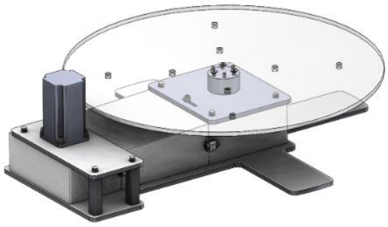
Figure 6: Final turntable assembly

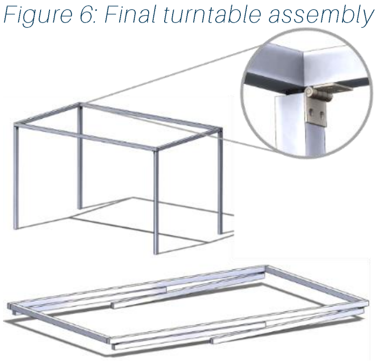
Figure 7: Frame in open and closed configuration for operation and storage

the eccentric loading, this fourfold increase in torque would be able to move a 20 kg load placed away from the centre. The base plate has also been reduced in area to save weight.

The frame has also been modified, utilising a hinge as shown in Figure 7 to transform it into a compact configuration. Acrylic sheets from the previous design have been removed and instead a fabric 'tent' of similar shape to the frame will be used, saving both weight and space.

A transmission cover was also designed to be 3D printed, but after meeting with the manufacturing technicians, the cost (>£200) of printing such a cover was found to be too expensive and alternative methods of protecting the transmission must be considered.

4 Design Review

The design review for our group was conducted on the 24th of January 2020 at 1500 hours in the Rolls Royce meeting room, City and Guilds Building room 560. The attendees for the review are:

- Dr. Salles: Research Fellow in Rolls-Royce Vibration UTC and direct supervisor of Dynoscan 3D
- Dr. Cinosi: Subject Matter Expert (SME) in computing and mathematical modelling
- Dr. Muscutt: Dynamics group lab technician

During the review, Dr. Muscutt mentioned that some components like fan blades might require an excess of 20-50 scans to properly capture the geometry, and that rotational symmetry might pose an issue during the reconstruction process. This must be considered during mechanical setup, such as marking a distinct feature on one side of a symmetrical object.

Dr. Cinosi emphasized the need for more focus on the software aspect, given that a bulk of our work in the autumn term was on the mechanical transmission and scanning environment. His feedback, along with the SLS prototype findings, have led to a more detailed Gantt chart and action plan with a greater proportion of future tasks focused on software. This will be elaborated on in Section 4.

5 Discussion

5.1 Overview of Progress

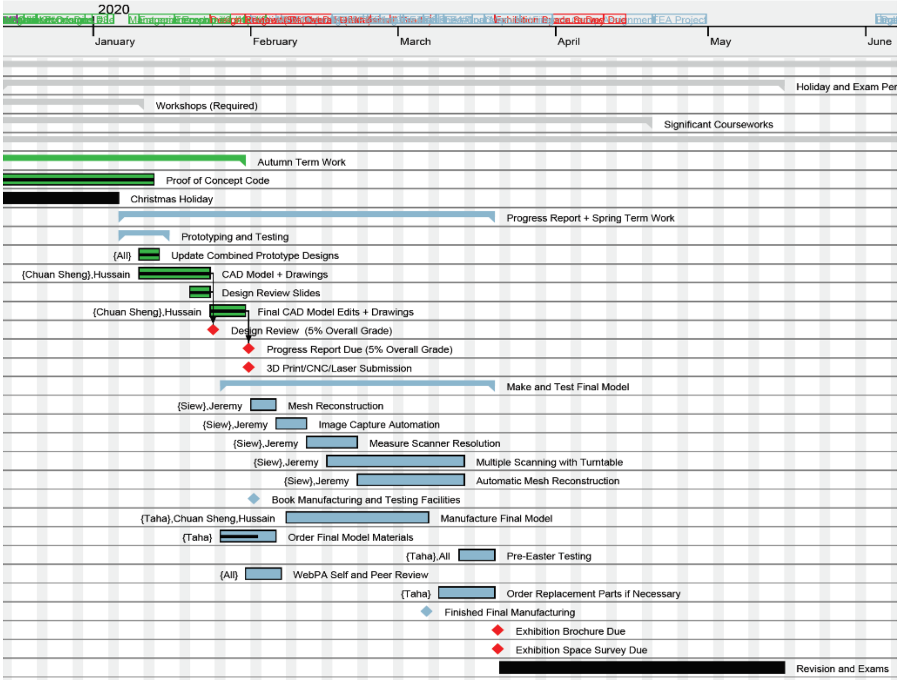

Figure 8: Updated Gantt chart (Condensed) V4 forecasting Spring Term work accurate as of 28/01/2020

As of 30th January 2020, the project is on track to meet the projected key milestones according to V4 of the Gantt chart. The team decided to front load the design of the mechanical aspect of the project to the Autumn term in order to produce and test a transmission prototype for the turntable prior to the Design Review early in Spring Term.

While the initial design phase had a slow start due to the difficulty in selecting a method of scanning, this slip in the schedule was accommodated by the slack factored into the coursework breaks. The time taken to manufacture and assemble the transmission prototype was underestimated due to a few unexpected closures of the STW (Student Teaching Workshop). While manufacturing was completed by the last week of Autumn term, the assembly was only completed one week into the Christmas holidays.

Due to the team front loading the mechanical design of the transmission prototype, progress on the software aspect of the project was delayed, with the intention of creating a proof of concept 3D model before the Christmas holidays. As a result, extra work had to be done over the holidays and the first week of Spring Term prior to the Design Review.

While most of the procured items have next-day delivery services, slack has been introduced between ordering the materials and the beginning of manufacturing to account for any unforeseen procurement delays. The project had to undergo a few modifications after Design Review regarding increasing the transmission ratio to 4:1 and the redesign of the transmission cover. This delayed the procurement of the new transmission components and CNC/Laser cutting submissions by a week. This slip can be absorbed by the seven-day gap between "Pre-Easter Testing" and "Manufacture Final Model".

The significant barriers to progress lie mostly on the software side as it is difficult to precisely predict the exact time required for each step. Compared to the previous versions of the Gantt chart, the scope of the software development has now been subdivided into five distinct parts. According to the PDS and based on tutor feedback from Design Review, the scope of the project does not need to include "Automatic Mesh Reconstruction" but will be pursued if time allows. The most obvious solution to overcome this barrier is to assign more resources to developing and implementing the software.

After reviewing the PDS and the prototype test results, there is no need to change any of the initially stipulated requirements and they are achievable with the latest adjustments to the design.

5.2 Identification of Risks

Based on the results from the prototype testing, the risks affecting project progress have been re-evaluated shown below in Table 5.

Table 5: Condensed project management risk assessment and mitigation matrix

	Identified Risk	Severity	After Evaluation
Software	Prototyping is not completed on time Likelihood - 6	Can delay designs (i.e. clamping, external structure) based on the results from the software prototype. Impact - 7	Ensure that enough time is left to complete prototyping software. New Occurrence - 4
Testing	Turntable breaks upon loading. Likelihood - 3	Might need to reorder parts and re-manufacture the entire turntable transmission, thereby significantly affecting budget and timeline. Impact - 8	Ensure that the design, stress calculations and engineering drawings are all validated by a supervisor. Account for testing and budget slack to ensure any resulting damages can be fixed. New Occurrence - 2
	Parts fail to arrive on time. Likelihood - 5	Can delay manufacturing progress significantly. Impact - 7	Ensure alternate suppliers exists that can deliver parts on time. Plan for component delays and ensure that this time can be replaced with other aspects of the project. New occurrence - 2
Procurement	Insufficient funds available to meet any additional project requirements Likelihood – 4	Can seriously affect the progress of the project and an explanation will have to be given to the supervisors as to why the budget was not planned properly. Impact - 8	Ensure that budget allocation is done sensibly and have reserves left over for any last-minute expenditures. New occurrence - 3
	Wrong part manufactured	Incorrect parts will delay assembly. May result in extra expenditure as new	Ensure that the engineering drawings are checked by separate members of

Likelihood - 6	raw materials will have to be ordered.	the group with a clear manufacturing plan set.
	Impact - 6	New occurrence - 2

6 Conclusion

Preliminary mechanical and electrical testing of the transmission prototype suggest that increasing the transmission ratio will improve the turntable's performance in rotating eccentric loads greater than 100 N. While other minor readjustments to the prototype need to be made to accommodate the larger transmission ratio, most of the overall prototype will remain untouched, thus eliminating the need to re-manufacture the turntable assembly. The manufacturing of the device frame and tripod mount is not a complex task and is independent of the turntable assembly's progress. Therefore, it can be carried out concurrently to save time. Having identified the software aspect as the main barriers to progress and considering the relative lack of progress on this portion of the project, more resources need to be allocated to ensuring that the code can generate a complete 3D meshes from the point clouds obtained from scanning. This is to ensure that both the software and hardware can ideally be tested in conjunction prior to Easter holidays. Despite these changes to the allocation of resources and time, pre-allocated slack ensures that the project is on track and ready to proceed onto the manufacturing and testing of the final product.

7 References

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