Vertical movement system

Overview:

The function of the vertical movement system was to raise and lower the 1kg mass through a height of 1m. There were two parts to this system: a pulley system to reduce the force required to lift the mass and a gear configuration to multiply the torque of the motor. The design processes included: concept generation, embodiment & prototyping and final prototyping.

Concept Generation:

Pulley System:

A simple pulley system (shown in Figure 1) was chosen to be employed in order to decrease the force and torque required by the motor to lift the mass. To decide which pulley ratio to use, pugh matrices and control convergence (see Tables 1 and 2) were utilized to compare the systems based on force multiplication, complexity and space.

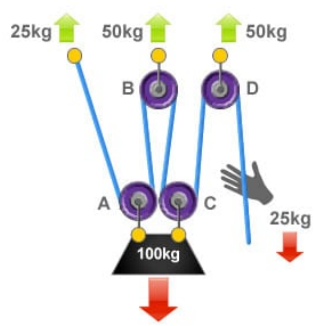


Figure 1: A 1:4 pulley system

Table 1: a Pugh matrix comparing pulley ratios

	1:1 Pulley system (datum)	1:2	1:3	1:4
Force multiplication	0	+	+	+
Complexity	0	-	-	-

Space	0	-	-	-
Total	0	-1	-1	-1

Table 2: a Pugh matrix for controlled convergence to further decide the best system

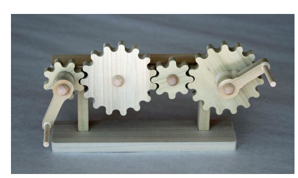
	1:3 System (Datum)	1:2	1:4
Force multiplication	0	-	+
Complexity	0	+	-
Space	0	+	-
Total	0	1	-1

The pugh matrices gave us the result that the simpler pulley systems were better than more complex ones. However, using engineering judgment, we believed that the matrices did not give enough weight to the force multiplication criteria as lifting the 1kg mass was the 1st performance requirement in the PDS and was prioritized as a must requirement whereas space and complexity are just wish requirements. A 1:5 pulley system was chosen as we believed the increase in leverage from higher ratios compared to the relatively small increase in complexity and space was worth it.

Gears:

The various possible lego gear configurations were put in Table 3. Lego gears were favored over laser cutting/ 3D printing custom gears because they are made with high precision so they mesh perfectly together and they are modular so it was easy to replace gears in order to try out different gear ratios and configurations.

Table 3: shows different gear configurations that could be used

Gear Type	Bevel	Worm	Simple gear train
Image			

he gear ratio chosen was 12:40 as it was the greatest ratio possible for a simple lego gear train. The purpose was to increase the torque from the motor to ensure that there was enough force to lift the mass (1st performance requirement in the PDS).

Embodiment and Prototyping:

Gear configuration:

CAD was used to virtually prototype possible gear configurations to see the space it would take up. By the end of the prototyping stage, 2 configurations were created that would be suitable. Figure 5a where bevel gears would be used to increase compactness or Figure 5b where a simpler gear train would transmit power.

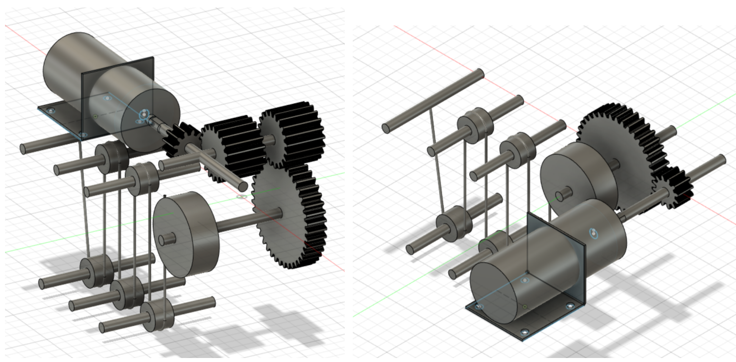


Figure 5: (a) left configuration including bevel gears, (b) right configuration including a simple gear train

After generating these 2 design configurations, a pugh matrix was used to decide the best configuration for use in the final prototype.

Pugh matrix 3: Final configuration comparison

	Bevel gear configuration	Gear train configuration
Complexity	0	+
Width	0	-
Speed	0	0
Total	0	0

The result of the Pugh matrix was a draw so engineering judgment was used to decide which of the criteria was more important. The width of the system was chosen as the most important because of the constraints created by the horizontal distance between the rails and the size of the cart.

Initial Calculations:

The torque required by the motor was calculated to be 0.147 Ncm which was 70x less than the maximum rated torque output of the motor so the motor should definitely be able to lift the mass. See appendix for more detail.

Final Prototyping:

Everything was assembled during this phase. The virtual prototyping was translated into physical prototyping as shown in Figure 8. The overall design wasn't changed however small adjustments were made. During the final prototyping, there were issues with the precise geometry of the gear train - gears kept falling off. To solve this, the axles were replaced with longer ones and bushes were added to stop the gears from shifting. Another adjustment that was made was the addition of circular laser-cut discs to prevent the pulley string from slipping off the spool

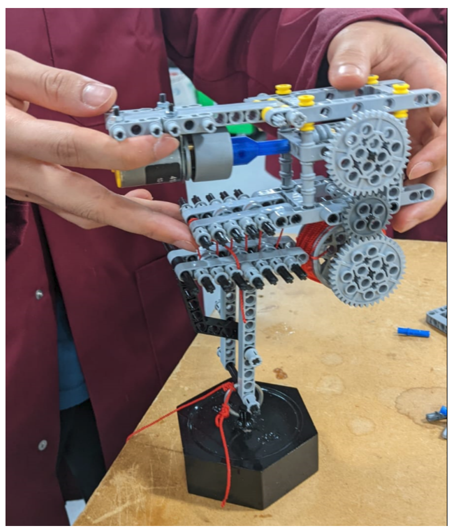


Figure 8: Side View of vertical movement system

Energy Analysis:

The mechanical power of the system when raising the 1kg mass 1m was equal to 0.208W. To lower the mass the mechanical power was 0.308W. The corresponding electrical power to raise and lower the mass was 4.8W and 0.84W respectively. In an ideal world, the system should require 0 electrical power to lower the mass however the small power was due to friction and other resistive forces in the system that need to be overcome. The entire system was powered by a 12V power supply which meets the requirement in our PDS.

The efficiency of raising the mass is calculated to be 4.3% and the efficiency of lowering the mass is technically negative as energy was required to decrease the potential energy of the mass.

These efficiencies can be shown on the Torque, speed and power graph below.

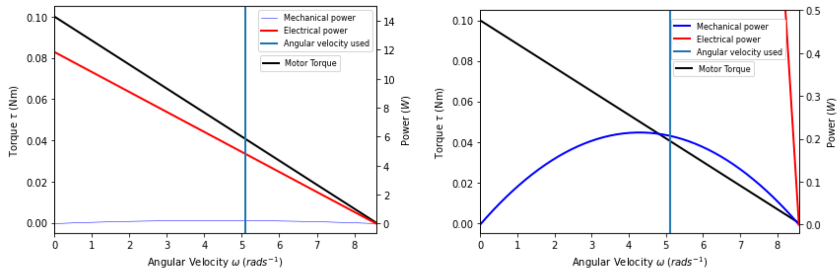


Figure 10: Energy analysis graphs

Even though our angular velocity is greater than half the no-load speed which should result in a relatively higher motor efficiency, however, because the gear ratio not being correctly configured this then resulted in more work required to be done by the motor. This resulted in our final motor speed being 48 rpm and the output torque of the motor at 4 Ncm. These values are way off the we expected during the initial calculations and are largely due to the gear train.

Improvements:

The difficulty of getting bevels gears to work was underestimated - there were many issues with the bevel gears slipping. Also, the bevel gear configuration took up more space than was initially planned because extra gears were needed for power transmission which added unnecessary complexity.

To improve the efficiency of the system more precise gears could be used to reduce friction in the system. Also, the configuration of the gearbox could be improved. When assembling it 2 gears in train were the wrong way round and the ratio was much lower than expected (3:4 instead of 3:10). This would have positive environmental impacts as less energy is wasted so the energy requirement is lower. This is especially useful if a full-scale model was created.

Appendix:

Motor to Lego axle adaptor:

During the design process we realised that there was no apparent way to attach the DC motor to the custom shaped lego axle.

A motor to lego axle adapter was required to connect the motor to the lego gears. Fusion 360 was used to create a CAD model of an adaptor that can be used to attach the 4mm ∅ motor axle to the cross-shaped lego axle as shown in Figure 4.

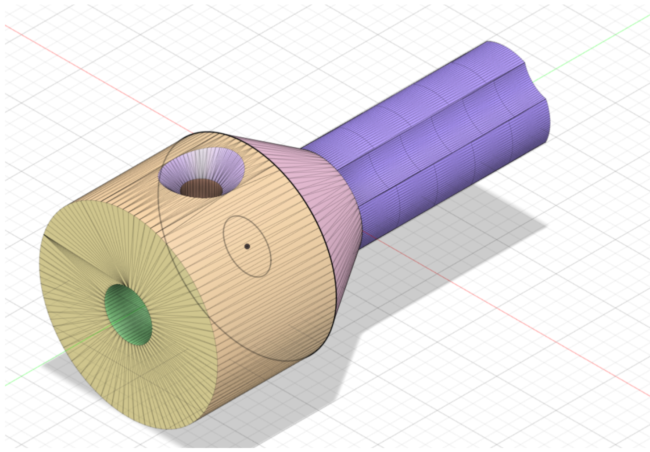


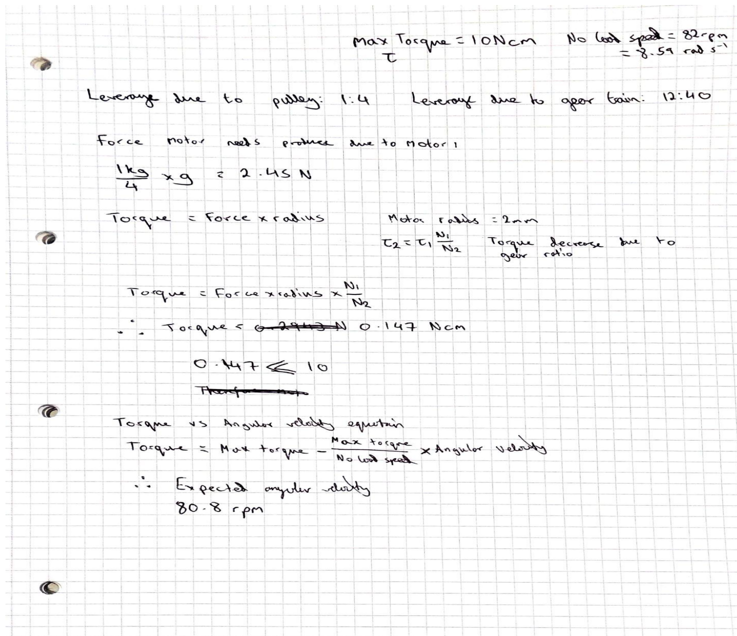
Figure 4: Motor to Lego axle adaptor CAD model

3D printing was a necessary manufacturing process as it was not possible to create the precise adaptor geometry using laser cutting. The adaptor was small and only 2 were required so the material and energy requirements were minimized. 5 adaptors took 1 hour and 18 minutes to print (the 3 extra adaptors were spares) so printing 2 adaptors would take 31 minutes which would hence meet our 1st materials requirement.
After designing and printing the adaptor we conducted a small scale test to ensure it works this is shown in Figure x and a link to a full video here:
https://photos.app.goo.gl/AxQamMKjZ4ztq5T96

Figure x: Small scale test of motor axle adaptor

Calculations:

Figure 7 shows the calculations carried out to ensure our design decisions are mathematically backed before moving onto the final prototyping stage to ensure no time is wasted building a final prototype that will not work.



Max Torque = 10Ncm (τ)   No load speed = 82rpm = 8.59 rad s^{-1}

Leverage due to pulley: 1:4   Leverage due to gear train: 12:40

Force motor needs produce due to motor:

$\frac{1kg}{4} \times g = 2.45 N$

Torque = Force x radius   Motor radius = 2mm

$\tau_2 = \tau_1 \frac{N_1}{N_2}$ Torque decrease due to gear ratio

Torque = Force x radius x $\frac{N_1}{N_2}$

$\therefore$ Torque = 0.147 Ncm

$0.147 \leq 10$

Torque vs Angular velocity equation

Torque = Max torque − $\frac{\text{Max torque}}{\text{No load speed}}$ x Angular velocity

$\therefore$ Expected angular velocity
80.8 rpm

Figure 7: Initial calculations

The torque required by the motor is 0.147 Ncm and the angular velocity should be about 80.8 rpm according to these calculations. This means that the system should work very well as the torque required is about 70x less than the maximum rated torque meaning the motor should be able to function at almost max speed (82 rpm) and losses due to friction between gears and within the pulley system shouldn't prevent the system from functioning. These calculations are based on the fact that the whole system works optimally in our chosen configuration.