MANCHESTER 1824
The University of Manchester

Department of Electrical and Electronic Engineering

Embedded Systems Project 2020-21

DESIGN REPORT #1

Title: Mechanical Considerations for the Buggy

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1. Introduction

This report details information obtained through experiments, to obtain values of K_T and K_E, providing a method to determine the ideal gearbox ratio for the buggy [2]. This report examines the minimum force, and thus the required torque to drive the buggy up a slope of angle 18° [1], which is the maximum angle required. These measurements are required to ensure the motor always runs at a sufficient voltage to keep the buggy moving.

A gearbox allows the buggy to increase or decrease the output torque and hence the motor speed [2]. This provides a higher output torque for a lower input current, allowing the system to be more efficient and less power consuming, hence reducing running costs of the system and hence allowing the current limit to be maintained [2].

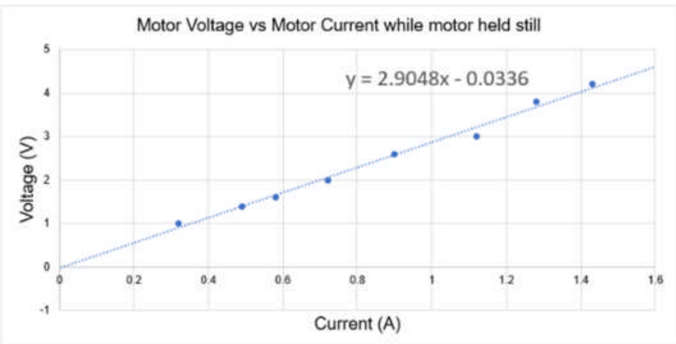
The motor speed and torque will be controlled by the motor drive board using switches to turn the motor on and off using PWM, controlling the voltage and hence the current, torque and speed [2]. The motor drive board will use the bipolar switch configuration to allow regenerative braking, allowing the motor to run in reverse [2].

2. Motor characterisation

The motor is the core of the buggy providing the required driving force to move the buggy. A DC motor is used, so when it is operating, the direction of the current (I) cannot change [2]. The gears and rubber wheels are driven by the motor; therefore, they are connected in series with the axle of the motor. In the experiment, the buggy overcame frictional forces (N) on a flat surface and on a slope [2]. When the buggy is climbing the slope, the main drag force is caused by the component of weight (mg) parallel to the slope, therefore, the motor needs to provide enough mechanical energy to ensure that enough driving force F_{pull} is supplied [2]. The revolution speed of buggy ω, also depends on the DC motor. There is a torque on the armature T_1 which is inversely proportional to the revolution speed of the motor; hence the torque will affect the speed of buggy directly. Furthermore, K (the motor system constant) is a property of the motor, so it cannot be changed. T_1 can be measured and changed by altering the magnitude of I supplied to it, and hence estimate the value of K_T. The value of power (P) that the motor will produce when stalled can be determined. From Graph 1, the approximate value of voltage (E) at 1.28 A, was 3.8 V.

$$P = EI \quad (1)$$

so, the power dissipated would be 4.86 W from equation 1.



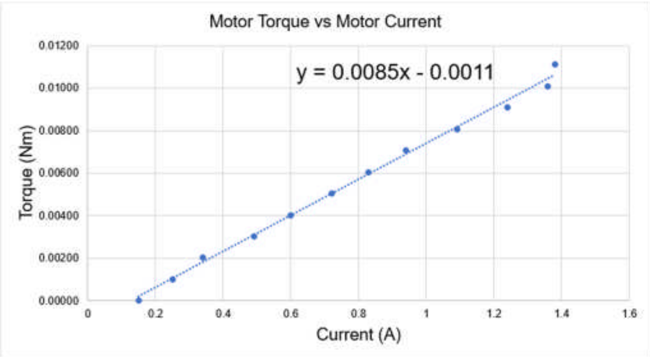
Graph 1 - A graph displaying the voltage- current characteristics of the motor when held still while the motor is held still

Experimental values of E for different values of I were plotted as shown in Graph 1, giving the relationship:

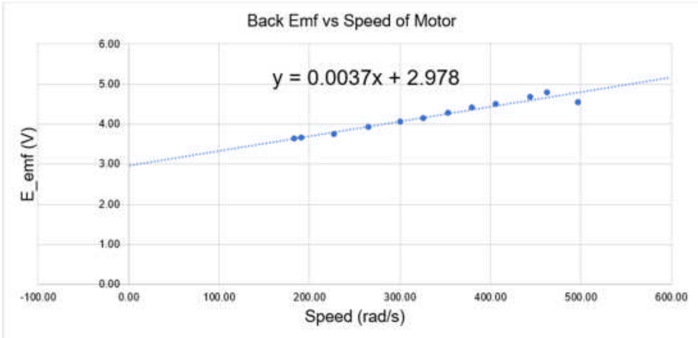
$$E = RI + V_b \quad (2)$$

where R is the armature resistance and V_b is the offset voltage

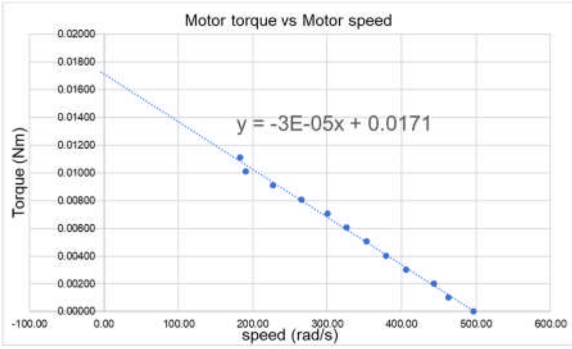
From Graph 1, it can be observed that E is directly proportional to I. The values of R and V_b were determined from Graph 1, which are 2.90 Ω (gradient) and -0.0336 V = -33.6 mV (y-intercept), respectively.



Graph 2 - Relationship between motor torque and motor current while the motor is running



Graph 3 - Relationship between motor back emf and motor speed while the motor is running



Graph 4 - Relationship between motor torque and motor speed when the motor is running

There are two graphs (Graph 2 and Graph 3) illustrating the relationships T-I and E-ω for the motor while running. As shown in equation 3, T is directly proportional to I:

$$T = K_T I \quad (3)$$

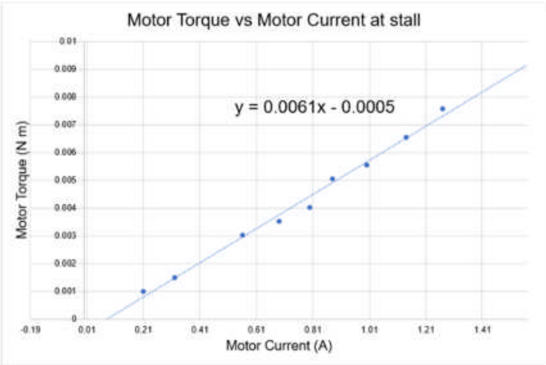
where K_T is the motor torque constant.

The value of K_T (from the gradient of Graph 2) was found to be 0.0085 N m A^{-1} = 8.5 mN m A^{-1}, with a maximum stall torque of 0.0171 N m = 17.1 mN m (y-intercept of Graph 4). Graph 3 shows the linear relationship between E and ω, as expected from equation 4:

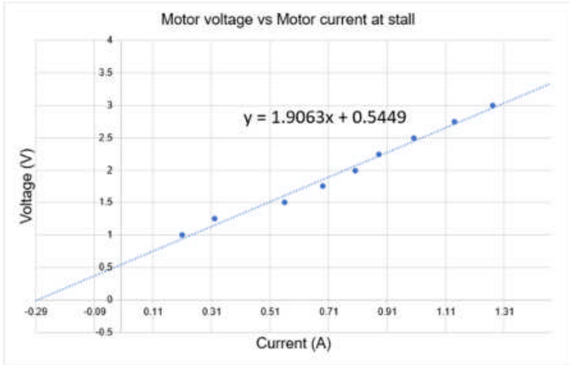
$$E = K_E \omega \quad (4)$$

where K_E is the motor back EMF constant

Therefore, as E increases, ω will also increase. From the gradient of Graph 3 K_E was found to be 0.0037 NmA^{-1}= 3.7 mN m A^{-1}. Theoretically, the values of K_T and K_E should be equal, but in reality, experimental error will occur. When the motor rotates quickly I decreases, and hence T is also reduced. The current was reduced due to back EMF which lead to error. As K_E and K_T are very close, this supports the claim from section 1.



Graph 5 – Relationship between motor torque and motor current at stall



Graph 6 – Relationship between motor volage and motor current at stall

The experiment was repeated under high torque, and the values of K_T, R and V_b were obtained from the graphs. Just as with the measurements undertaken with constant voltage, with the motor running, K_T was determined by calculation of the gradient (Graph 5), which gave a value of 0.0061 N m A^{-1}=6.1 mN m A^{-1}. This is a smaller value than the previous K_T value determined. This is because these measurements were taken at stall, rather than when the motor is moving. The first value of K_T calculated from Graph 2 seems to be more relevant for this experiment. The values of R and V_b from Graph 6 were found to be 1.91 Ω and 0.54 V, respectively. The measurements at stall are only relevant when the buggy is braking and the motor is stopped.

In the experiment, there are some external factors that will affect the outcomes. A perfect motor is frictionless, therefore having no mechanical load torque and no brush drop; the voltage applied to the motor coils is perfectly balanced by the back emf voltage, reducing the current to zero [2]. At this point, the motor will not be producing any torque and the motor will be turning as its maximum possible speed. When motor is running, the temperature of motor will be high, because the work efficiency cannot reach 100%, some electric power will be transferred to heat, affecting the performance of the buggy. If the motor becomes very hot in one test, the accuracy of subsequent tests will be affected. Also, there is a safety issue where people cannot directly touch the motor by hand, due to the surface of motor being very hot at high currents. Hence, gloves need to be worn and the motor should be allowed to cool down.

3. Load measurements

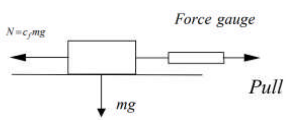


Figure 1 Forces exerted on the buggy on a flat surface [2]

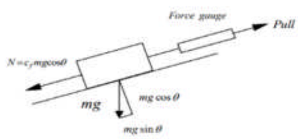


Figure 2 –Forces exerted on the buggy up a slope of angle θ [2]

For the buggy to move, a force must be applied in order to overcome the frictional forces, where the minimum force on flat is seen in equation 5 (forces on flat are illustrated in figure 1) [2].

$$N = c_f mg \quad (5)$$

where c_f is the coefficient of friction.

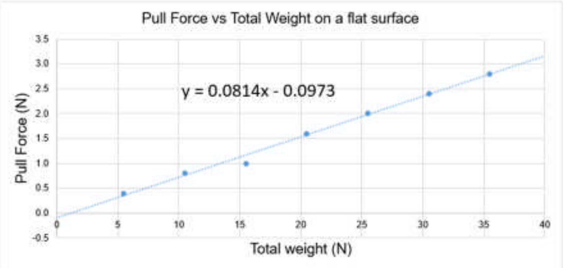
At standstill, F_{pull} is required to overcome static friction. If the force applied is lower than the static friction, the buggy will not move from standstill. At high ω, a force will be required to overcome drag and viscous friction. Furthermore, to make the buggy accelerate, an additional force is required [2]. Finally, for the sloping part of the track (as observed in figure 2), the force is required to overcome the parallel component of the weight. The total minimum force required by the buggy to ascend the slope is given by equation 6 [2]:

$$F = mg\sin\theta + c_f mg\cos\theta \quad (6)$$

Once the force required to drive the buggy is determined, the necessary torque can be calculated using equation 7 [2]:

$$T = F_{pull} r \quad (7)$$

where r is the radius of the wheel/motor shaft



Graph 7 – Relationship between the pull force on a flat surface with the total weight of the buggy

c_f was determined by calculating the gradient (Graph 7), which gave a value of 0.0814 = 8.14×10^{-2}. c_f depends on the material of the surface, not the angle, so it will not change when the buggy is going up an inclined surface [2].

To estimate the forces required to drive the buggy on a flat surface, the pull has to overcome only the frictional force of the buggy as seen in Figure 1 [2].

The total mass of the buggy with the test chassis was calculated [2]:

m = 70 g (MC board) + 38 g (breakout board) + 53 g (motor drive board) + 265 g (battery pack) + 2(133 g + 95 g) (motors and wheels) + 119 g (castor wheel) + 30 g (ball castor) +560 g (test chassis) = 1665 g = 1.665 kg

The c_f calculated in Graph 7 was used to work out the minimum force required to move the buggy on a flat surface using Equation 5:

$$F_{pull} \geq (0.0814 \times 1.665 \times 9.8) = 1.33\ \text{N}$$

To calculate the minimum force required to go up the slope, the angle of the slope as well as the parallel component of weight must be taken into consideration. The minimum force was calculated using equation 7 [2]:

$$F = mg(c_f\cos\theta + \sin\theta) \quad (8)$$

Substituting known values, the minimum force was determined:

$$F = (1.665 \times 9.81)\left(8.14 \times 10^{-2}\cos 18 + \sin 18\right) = 6.31\ \text{N}$$

The force per wheel on the slope is 3.16 N as there are two wheels.
Using the wheel radius as 40 mm, and the values of the required force (obtained previously), the required torque can be calculated.
The torque required per wheel to move the buggy from stationary (on a flat surface) was calculated as follows:

$$T = Fr = 40 \times 10^{-3} \times 1.3279 = 0.0531\ \text{N m} = 53.1\ \text{mN m}$$

The torque required per wheel to move the buggy from stationary (on the slope) was calculated as follows:

$$T = Fr = 40\times10^{-3}\times3.156 = 0.126\ \text{Nm} = 126\ \text{mN m}$$

The assumed mass of the buggy the sum of the parts, though the mass of some parts may be inaccurate. It is also assumed that both wheels have a radius of exactly 40 mm [1]. Furthermore, the surface of the test track may differ from that of the assessment track. If the surface material was to differ, then the coefficient of friction would differ, and would introduce a slight measurement error. The required force needed for the buggy to ascend the slope has been determined, fulfilling the aims outlined in section 1.

4. Gear ratio selection

From the previous experiments and results, it can be observed that the higher the current or K_T, the higher the torque [2]. However, K_T will be unchangeable for the actual experiment as the following parameters cannot change: the diameter of the motor shaft/wheel, the magnetic fields of the motor and the length of wire in the motor [2]. Also, the current cannot be increased in the experiment due to the motor being current limited to 1.4 A [2]. This means that an alternative method of increasing the torque for the experiment is required. To solve this issue, a gearbox will be used to increases the torque in proportion to the ratio of the number of gear teeth, as per equation 9 [2]:

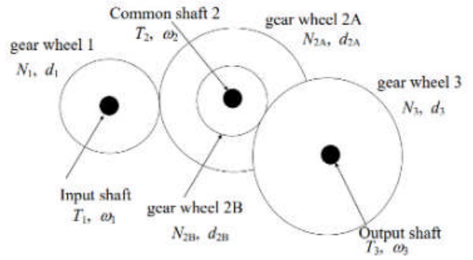


Figure 3 – A simple representation of the gears in our buggy

$$T_3=T_1\frac{N_3N_{2A}}{N_{2B}N_1} \quad (9)$$

where T_3 is the output torque, T_1 is the input torque and N_1, N_{2A}, N_{2B} and N_3 are the number of gear teeth on the respective gear (as shown in Figure 3).

This equation is based on the fact that a centre shaft is used which shares two gears of different size (as shown in figure 3) which will be used to increase the torque on the output [2]. The torque of the 1st gear wheel comes from the motor and is increased through gear 2A. The torque on gear 2A and hence gear 2B is given by equation 10 [2]:

$$T_2=T_1\frac{N_{2A}}{N_1} \quad (10)$$

where T_2 is the torque on the intermediate gear shaft

Similarly, the torque on gear shaft 3 is calculated as per equation 11:

$$T_3=T_2\frac{N_3}{N_{2B}} \quad (11)$$

Then substituting Equation 10 into Equation 11 gives Equation 9. This describes a perfect gearbox, however, in reality gearboxes lose power [2] and hence torque will be reduced due to the gearbox not being ideal. This can be seen in equation 12:

$$T_3=\eta T_1\frac{N_3N_{2A}}{N_{2B}N_1} \quad (12)$$

where η is the efficiency constant.

A typical value of η for a gearbox that has been well constructed is 0.85 [2] for 1 gear stage and hence 0.85^2 for 2 gear stages, as per equation 13:

$$T_3 = 0.85^2 T_1 \frac{N_3 N_{2A}}{N_{2B} N_1} \quad (13)$$

However, this causes a compromise on the speed ω_3 of the output as $\omega \propto \frac{1}{T}$ (shown in Graph 4); therefore, a compromise is needed between output torque and output speed. The proposed plan is to supply the required torque plus a little extra to compensate for a small margin of error and by doing so would allow for a higher ω_{max}.

The value for I of the motor on a slope needed without a gearbox was calculated using equation 14:

$$I = \frac{T}{K_T} \quad (14)$$

From section 2, K_T = 8.5 mN m A^{-1}, and the value of T can be calculated using Equation 7.The radius of the wheel is 40 mm on the output, as seen from section 3, and the radius of the motor shaft is 5.05 mm. Substituting Equations 7 and Equation 8 into Equation 13, gives equation 14:

$$I = \frac{\left(mg(c_f \cos\theta + \sin\theta)\right)r}{K_T} \quad (15)$$

From Section 3, c_f was calculated to be 0.0814 and that the total mass of the buggy with the test chassis is 1.665 kg. As can be seen from section 3, the required torque is 0.126 Nm for a mass of 1.665 kg.

Substituting all of the values into Equation 15, it can be observed that the current for a single motor is given by (the force is divided by two as it is distributed over both motors/wheels):

$$I_{motor} = \frac{3.156 \times \frac{0.0101}{2}}{0.0085} = 1.88 \text{ A}$$

From this, the motor torque T_m was calculated at 1.88 A and hence at the required 1.2 A (a little less than the limit of 1.4 A to prevent exceeding the current limit):

$$T_{m \text{ at } 2.250 \text{ A}} = 3.156 \times \frac{0.0101}{2} = 0.01594 \text{ Nm} = 15.94 \text{ mN m}$$

$$T_{m \text{ at } 1.2 \text{ A}} = 0.01594 \times \frac{1.2}{1.88} = 0.0102 \text{ Nm} = 10.20 \text{ mN m}$$

To obtain the value of voltage required up a slope, the values for E, I and V_b are substituted into Equation 1:

$$V = 1.2 \times 1.9063 - 0.0336 = 2.254 \text{ V}$$

This means that the gear ratio needed is $\frac{T_{wheel}}{T_{m \text{ at } 1.4 \text{ A}}} = \frac{0.1261}{0.0102} = 12.3627$. This means that only the 3rd gearbox can be chosen. The 1st gearbox would not supply the required torque, with a ratio of $0.85^2 \frac{48 \cdot 48}{12 \cdot 16} = 8.67$ and the 2nd gearbox also would not supply sufficient torque at 1.2 A with a gear ratio of $0.85^2 \frac{48 \cdot 50}{10 \cdot 16} = 10.84$. So, the only gearbox that supplies enough torque at 1.2 A is gearbox 3, which has a gear ratio of $0.85^2 \frac{60 \cdot 50}{10 \cdot 16} = 13.55$. All the measurements are based on the test chassis and it is likely that the actual chassis will be heavier.

To obtain the position of the intermediate shaft, the Pitch Circle Diameter for each gear needs to be calculated first using equation 16:

$$PCD = No\ .of\ teeth \times MOD \quad (16)$$

where PCD is the pitch centre diameter and MOD is the module of the gears (which in this case is 0.5 mm [2])

The PCD then used to calculate the centre distance between two meshes using equation 17:

$$centre\ distance = PCD(A)+PCD(B)2+0.1\ mm \quad (17)$$

Using Equation 16 the PCDs of the gears for the 3rd gearbox were:

Motor gear's PCD = 16×0.5 = 8 mm

Intermediate (A) gear's PCD = 50×0.5 = 25 mm

Intermediate (B) gear's PCD =10×0.5 = 5 mm

Drive Gear's PCD = 60×0.5 = 30 mm

Equation 17 was used to calculate the centre distance between gear 1 and gear 2A and the centre distance between gear 2B and gear 3:

$$\text{Centre distance between the motor and intermediate shafts} = \frac{8+25}{2}+0.1=16.6\text{ mm}$$

$$\text{Centre distance between the intermediate and drive shafts} = \frac{5+30}{2}+0.1=17.6\text{ mm}$$

The centre distance between the motor and the drive shafts has a fixed centre distance of 31.1 mm [1]

To obtain the coordinate of the centre shaft trigonometry and vector calculations were used, assuming the origin is at the motor shaft. First, the angle between the line connecting the motor shaft (b) and the wheel shaft (c) and the line connecting the motor shaft to the intermediate shaft was calculated using the cosine rule:

$$\theta = \cos^{-1}\frac{b^2+c^2-a^2}{2bc} \quad (18)$$

where a, b and c are the lengths of the sides of the triangle and θ is the angle between sides b and c.

$$b \cdot c = bc\ \cos\theta \ (19)$$

Here, point A, point B and θ are (31.1,0), $(b_x,0)$ and 25.36 ° respectively. This gives an x –coordinate of 15.0mm. Then to obtain the y-coordinate equation 20 is used:

$$\sin\alpha = \frac{d}{c}\ (20)$$

where d is the perpendicular height of the triangle

Using Equation 20 the y – coordinate of 7.1 mm was calculated; hence the coordinate of the intermediate shaft is (15.0, 7.1).

The value of maximum output speed was calculated using equation 21:

$$\omega_3=\omega_1\frac{N_{2B}N_1}{N_3N_{2A}} \quad (21)$$

where ω_1 is the speed on the motor shaft and ω_2 is the speed on the wheel shaft.

This was derived similarly to Equation 10, bearing in mind $\frac{\omega_1}{\omega_3}=\frac{T_3}{T_1}$.

$$v = \omega r \quad (22)$$

ω_1 is the motor maximum speed and was calculated using Equation 3 with the maximum required voltage and K_E.

The expected maximum speed up the ramp was calculated as follows:

$$\omega_1=\frac{2.25}{0.0037}=609.19 \text{ rad s}^{-1}$$

$$\omega_3 = 609.19\times\frac{10\times16}{60\times50}=32.49 \text{ rad s}^{-1}$$

By dividing the value of the expected speed up the slope by $\cos 18°$, this gave an approximate value for the expected maximum speed on a flat surface is.32.49 rad s^{-1}

5. Summary

In conclusion, throughout this report, the results obtained thorough the experiments were used in order to obtain K_T and K_E, the minimum force and torque required to move up an inclined slope of 18° ,and the gear ratio required by the gearbox.

Using the graphs plotted it can be observed that, K_T = 0.0085 N m A^{-1} and K_E = 0.0037 N m A^{-1}. In theory, the values of K_T and K_E should be the same, however, due to the back EMF and experimental error, there is a slight difference in the values. The results were also used to calculate the minimum torque required to make the buggy move from stationary (5.42×10^{-3} Nm) and the torque required to ascend the inclined slope (0.126 Nm).

The 3rd gearbox was chosen because the required gear ratio that was calculated was 12.36. The 1st gearbox did not have a sufficient gear ratio (8.67) and the 2nd gearbox would be unable to enough torque at 1.2 A with a gear ratio of 10.84. This leaves the 3rd gearbox to be the most optimal option. A current of 1.2 A was used instead of 1.4 A because reaching the current limit of 1.4 A would be risky. Also, the weight of the actual chassis may differ from the weight of the test chassis.

6. References

[1] L. Marsh. Procedures Handbook. (2020 Winter). EEEN21000 Embedded Systems Project. University of Manchester. United Kingdom

[2] L. Marsh. Technical Handbook. (2020 Winter). EEEN21000 Embedded Systems Project. University of Manchester. United Kingdom