.

Department of Electrical and Electronic Engineering

Embedded Systems Project 2022-23

DESIGN REPORT #1

Title: Motor Characterisation

Group Number: 04

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Contents

1. Introduction

This report serves the Embedded Systems project that aims to build a buggy capable of autonomously navigating through a path with a maximum 18° slope by following a white line. This design report is concerned with the motor characterisation aspect of the project.

The main objective of this design report is to determine the necessary torque required to move the buggy on an inclined plane of an 18° slope and, if necessary, choose the optimal gear ratio that can supply the buggy with minimum necessary torque, thus the highest top speed.

Motors will convert the electrical energy supplied by the batteries to mechanical energy in order to move the buggy. Using the inputs from the sensors on the buggy (line sensors, wheel encoders), the microcontroller, Nucleo-F401RE, will send 3 signals to the motor drive board: PWM signal for the speed of the motor, a digital signal for the direction, a digital signal for the mode [4]. Then the motor drive board will supply the needed voltage and current to the motors.

The design report consists of two lab experiments:

- Load measurements in which the necessary force to move the buggy is measured.
- Motor characterisation in which the necessary measurements are made to identify the torque (related to the current) and speed (related to the back EMF) the motor can produce under different circumstances (stalled, moving, low current, high current) which will make it possible to calculate the motor constant K.

It is expected that the motors will not be able to produce enough torque to overcome the reactive forces of the inclined plane thus a gear ratio will be needed. “A gear ratio can increase the output torque or output speed of a mechanism, but not both” [2]. If the data shows that the motor lacks the required torque, a gearbox will be used to increase the torque by sacrificing the top speed.

2. Motor characterisation

Characterising the motor is the basis and the core of the lab. For this project's objectives, Armature Resistance (R), Brush Voltage (V_b) Estimation, K_E and K_T estimations are necessary to overcome friction force and gravitational force with the help of a gearbox.

Before starting with the motor characterisation, maximum current and voltage need to be stated. There are two main constraints for the maximum voltage and current.

- High current, i.e., $1.4\ A$, and high voltage can cause a rise in the temperature of the motor. High temperature could permanently damage the motor.
- The resistance of the motor is inversely proportional to the current thus it limits

the current [2].

To start with motor characterisation, armature resistance and brush voltage are required.

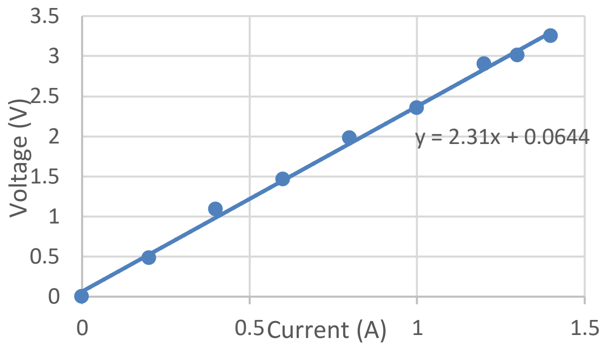
Armature resistance and brush voltage can be estimated by measured voltage and current with the Multimeter.

$$I = \frac{V - V_b - K_E * \omega}{R} \qquad (1)$$

as when the motor is stalled the angular speed $\omega = 0\ rad/s$. So

$$I = \frac{V - V_b}{R}$$

$$V = I\ R + V_b \quad (2)$$



Graph 1 – Voltage against Current for armature resistance

According to Graph 1, the gradient is the armature resistance $2.31\ \Omega$ and the y-intercept is the brush voltage, $V_b = 0.0644\ V$.

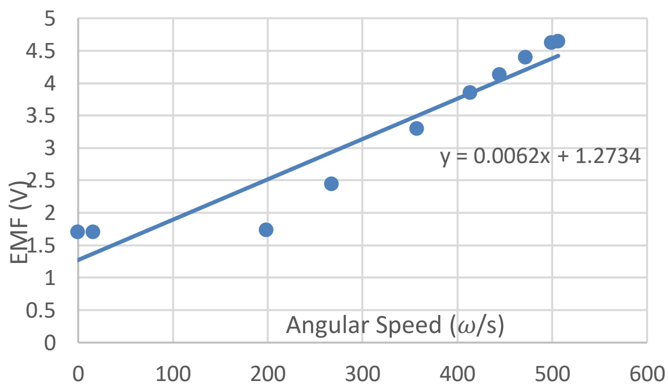
When the motor is rotating,

$$V = E_{emf} + I\ R + V_b = K_E\ \omega + I\ R + V_b \quad (3)$$

$$In\ (3),\ V_b\ is\ the\ brush\ voltage, R\ is\ armature\ resis\tan c\ e$$

$$K_E\ \ is\ the\ back\ emf\ cons\tan t\ ,\ \omega\ is\ angular\ speed,\ V\ is\ the\ voltage\ \sup p\ ly$$

$$and\ I\ is\ the\ current\ through\ the\ motor.$$

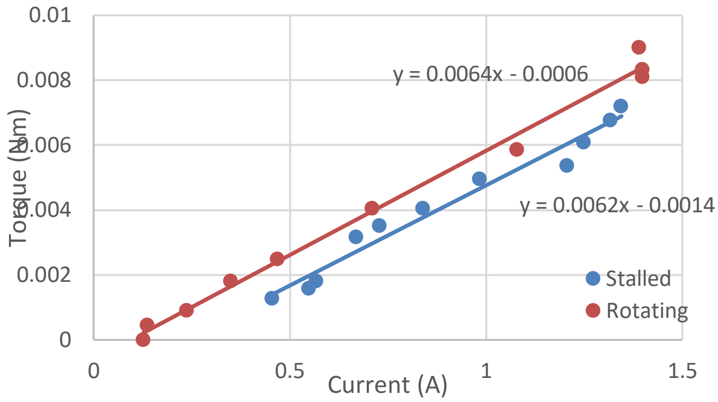


Graph 2 – EMF against Angular Speed

According to the Graph 2, the gradient is K_E $(B\ l\ d)$ $(0.0062\ V/(rad/s))$.

Equation $T = B\ I\ l\ d = K_T\ I$ (4)

Torque constant K_T can be used to instead flux density B, wire length l and diameter of the shaft d which are constants. Torque is a measure of the force that can cause an object to rotate about an axis.



Graph 3 – Torque against Current

$$T = Fr \quad (5)$$

while there are two force gauge acting on the motor, so

$$T\ =\ (F1 - F2) \cdot \left(\frac{d}{2}\right) \quad (6)$$

When the motor is rotating, the gradient of Graph 3 is K_T $(0.0064V/(rad/s))$.

K_E 0.0062 V/(rad/s) is similar asK_T 0.0064 V/(rad/s), so K_T is approximated as equal to K_E.

When the motor is stalled, the gradient of Graph 3 is K_T $(0.0062\ V/(rad/s))$. As

$$K_T = B\ d\ l \quad (7)$$

and flux density, diameter and wire length are constants [2], they will not be changed by the status of motor rotating or stalled. K_T for stalled motor is $0.0062\ V/(rad/s)$ which is equal to K_T for rotating $(0.0064\ V/(rad/s))$. Hence K_T and K_E are equal and they are constants.

Comment on measurement accuracy

- Measurement on the Multimeter and tachometer are not stable thus making it hard to read.
- There is human error (parallax error) while reading measurements on force gauges.
- The string which connects with gauges may “catch” the axle and then slip again – causing the readings to jump in the measured torsion.
- High motor temperature can result in inaccurate measured data.
- For using two gauges to stall motor, it is hard to find the most appropriate forces

that allow the motor to stop, most time forces are much more than that current and voltage to stop motor.

- Resistance in PSU leads that affected the readings.

3. Load measurements

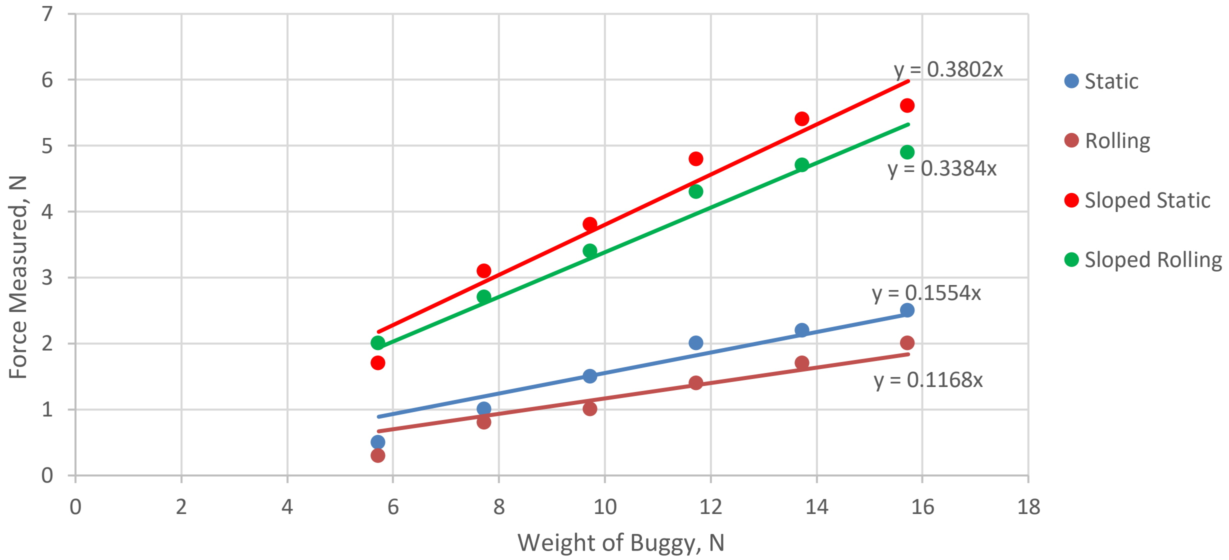
This part of the laboratory is concerned with measuring the force needed to move an example buggy on a flat surface; this allows you to estimate the required force to climb or descend any slopes on the track and estimate the coefficient of friction of the track.

The test chassis was loaded with several different values of slotted weight from below our expected weight to over the expected weight of our buggy.

The chassis weighed at $0.584\ kg$. This variable is considered while estimating the weight of the buggy, which was estimated to be roughly $15\ N$.

The chassis is dragged around the track, and the greatest force recorded at the start is used to calculate static friction. The chassis is then dragged over the flat track at a constant pace, and the steady force observed is utilised to calculate rolling friction. This procedure was repeated for the sloped part of the track.

The data is tabulated then plotted into a graph to estimate the coefficient of static friction and coefficient of rolling friction:



Graph 4 – Force Measured against Weight of Buggy

A best fit line is drawn for all the graphs, with their intercepts set at 0. This is because of the directly proportional relationship of force and weight on flat surfaces. Using the gradients as coefficient of friction,

$$At\ 0^{\circ},\ F = C_f mgcos\theta \qquad (8)$$

$$At\ 18^{\circ},\ F = C_f mgcos\theta + mgsin\theta \qquad (9)$$

$In\ (8)\ and\ (9), F\ is\ force\ needed\ to\ drive\ buggy,\ C_f\ is\ coefficient\ of\ friction,$
$m\ is\ mass\ of\ buggy, \theta\ is\ angle\ of\ slope, and\ g\ is\ gravitational\ acceleration.$

For static friction, the calculated value is F = 2.331 N at 0° and F = 6.852 N at 18°.

For rolling friction, the values are F = 1.752 N at 0° and F = 6.302 N at 18°.

$$T = F\mathrm{r} \qquad (10)$$

$In\ (10),\ T\ is\ torque\ on\ tyre, F\ is\ force\ on\ tyre, and\ r\ is\ radius\ of\ tyre.$

Since the buggy will be driven by two motors, only one tyre is taken into consideration. Hence, the force will be divided by two. Then, the buggy will need to overcome the maximum force, which is the static friction at the slope. The maximum force measured on the slope was 5.6 N, which is smaller compared to the calculated value. We will therefore use the larger value to accommodate more room for weight.

$$T = \frac{6.852}{2}\ N * \frac{0.0776}{2}\ m$$
$$= 0.133\ Nm \qquad (11)$$

4. Gear ratio selection

Without the help of gearbox system, the motor itself will need to overcome the force N ($6.302\ N$).
Using the equations (10) and (4), the current required is:

$$I = \frac{T_1}{K_T} = \frac{F/_2 * r}{K_T} = 22.167\ A$$

Assuming that m (12) is 1.500 *Kg*, g (12) is 9.81 m/s^2 and c_f (12) is $0.1168\ N$.

The current required by the motors to overcome the force N is bigger than the maximum current supported by the motor. A gear box is the solution to this problem. To select a gearbox, constants K_T and K_E are required from the motor characterisation and C_f from load measurements. This project has three different gearboxes from which to choose from and each of them has different gear ratio.

Selection Number	Pinion Gear (motor shaft only)	Intermediate Gear Two common gears on one shaft	Gear on final drive
1	16 tooth	48/12 press fit gears (orange*)	48 tooth
2	16 tooth	50/10 press fit gears (orange)	48 tooth
3	16 tooth	50/10 press fit gears (red)	60 tooth

Table 1 – Available gear combinations from Procedural Handbook

For the heat race, the buggy needs to climb up a slope that can have an angle of up to 18°.

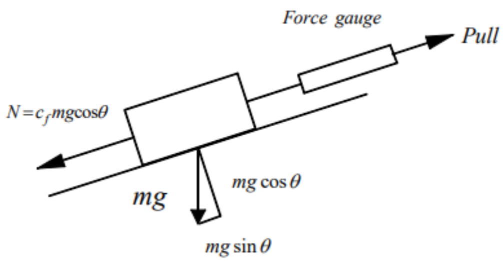


Figure 1 – Load on sloped surface

To climb the slope of this angle, the buggy needs to overcome this force:

$$N = c_f mgcos(\theta) + mg\sin(\theta) \qquad (12)$$

c_f is constant of friction estimated from load measurements.
m is weight of the buggy.
g is constant of gravity.
θ is angle of the slope.

The force applied from the tires of the buggy should be greater than $6.302\ N$.
The following calculations are using rolling coefficient on Flat and Slope.

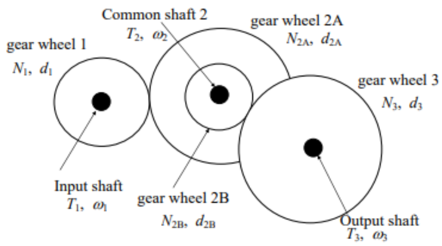


Figure 2 – Gearbox position

Form Figure 2, $T = T_3$

$$\frac{N_1}{N_2} = \frac{d_1}{d_2} = \frac{\omega_1}{\omega_2} \qquad (13)$$

T_3 can described as:

$$T_3 = \eta T_1 \frac{N_3 N_{2A}}{N_1 N_{2B}} \qquad (14)$$

Where N_x is number of teeth of the gear ratio and *x* is the gear wheel.
η is efficiency ratio. In this case $\eta = 0.7225$.
T_1 is the torque applied by the motor on the first gear.

Using (11) for the first gear box, T_1 is:

$$T_1 = \eta \frac{T_3}{\frac{N_3 N_{2A}}{N_1 N_{2B}}} = 0.7225 \frac{0.133}{12} = 0.008\ N$$

Assuming that $K_T = 0.006$, I can be calculated (4)

$$I = \frac{T_1}{K_T} = \frac{0.008}{0.006} = 1.333\ A$$

Following the same procedure as above, the second gear box requires $I > 1.068\ A$.
The third gear box requires the $I > 0.854\ A$.
The second gearbox was selected for the following reasons:

- With m of the buggy not defined, the first gear box requires higher current to climb the slope than the other gearboxes. Thus, the first gearbox was excluded.
- The third gearbox has the highest gear ratio, hence limiting the speed of the buggy.
- The second gearbox has a good balance of gear ratio that can deliver close to ideal torque and speed required for the project.

The second gearbox intermediate position can be determined with the following equation:

$$center\ distance = \frac{PCD(1)+PCD(2)}{2} + 0.1\ mm \qquad (15)$$

Where PCD is defined as:

$$PCD = No.of teeth * MOD \qquad (16)$$

MOD is $0.5\ mm$ for all gears.
Using the equation (15), we can determine the position of the intermediate as (x, y) coordinate with $(0, 0)$ being the centre of the first gear and the centre of the intermediate gear is on the *x* axis:

$$center\ distance = \frac{16 * 0.5\ mm + 48 * 0.5\ mm}{2} + 0.1\ mm = 16.1\ mm$$

Hence the coordinated of the intermediate gear are $(16.1, 0)$. The coordinate unit is in millimetres.

The maximum speed for the second gearbox can be calculated by supplying maximum voltage: $V = 9\ V$.
Next step is to calculate ω_1:

$$\omega_1 = \frac{V - V_b}{K_E} - \frac{T_1 R}{K_T K_E} = 1046.894\ {}^{rad}/_{s}$$

ω_3 can be derived from equation (13):

$$\omega_3 = \omega_1 \frac{N_{2B} N_1}{N_3 N_{2A}} = 1046.894\ {}^{rad}/_{s} * 0.0667 = 69.828\ {}^{rad}/_{s}$$

Linear velocity (v) of the buggy on the slope with 18° will be:

$$v = r\omega_3 = 0.0388\ m * 69.828\ {}^{rad}/_{s} = 2.709\ {}^{m}/_{s}$$

Linear velocity (v) of the buggy on the flat will be:

$$v = r\omega_3 = 0.0388\, m * 84.661\ {}^{rad}/_{s} = 3.285\ {}^{m}/_{s}$$

5. Summary

This report described how the motor system can be characterised by a single value (termed K) that will determine proposed balance of top speed and acceleration.[3] A fast motor has a small K, whereas a high torque motor has a large K [3]. The motor we were given a motor with not enough torque to propel the buggy up the slope, but by changing the value of K by incorporating the use of a gearbox. A typical efficiency for a well-built buggy gearbox is 85% per gear stage; we used a two-stage gearbox, so the efficiency from input shaft (gear wheel 1) to output shaft (gear wheel 3) is 72.25%.

In an ideal situation, the torque constant, K_T, and the back emf constant, K_E, are equal. The law of conservation of energy can be used to demonstrate this:

electrical power in = mechanical power out + motor electrical loss [1]

The difference in percentages between K_E and K_T is around 2%. The motor heated up during the experiment, causing a loss of energy to the surrounding environment, which is thermal energy. K_E is more confident value to use in our calculation. Due to the motor connected with power supply directly, using the K_E value in gearbox calculation is more accurate than using the K_T value.

The average percentage error for Power Supply Unit is 9.51%. Vernier Calliper has an average percentage error of 1.01% when measuring the diameter of the motor shaft and 0.52% when measuring the diameter of the wheel. The percentage error for measuring motor speed with an optical tachometer is around 3.70%. The percentage error for measuring force with Force Gauge is around 10%. The value is very precise since it did not exceed the 20% error limit range.

The main source of heat generation within the motor is motor winding resistance. Current must be forced through the windings for an electric motor to generate torque. Electrical overload caused by an excessive voltage supply or overwork by drawing more current will result in overheating. As the motor works harder or under unusual load, it generates heat, which can lead to motor failure.

These losses are attributed to the effort required to overcome the drag associated with rotating the rotor or armature of the motor. Brush friction in a DC motor is an example of friction loss [5].

We have decided on Gearbox Selection 2 with 16 teeth at the pinion gear, 50/10 press fit gears at the intermediate gear, and 48 teeth at the final drive gear. By choosing this gearbox, it could produce a reasonable amount of torque and generated intermediate speed.

6. References

[1] D. Collins, “FAQ: What's the difference between torque constant, back EMF constant, and motor constant?,” Motion Control Tips. [Online]. Available: https://www.motioncontroltips.com/faq-difference-between-torque-back-emf-motor-constant/. [Accessed: 22-Oct-2022].

[2] N. Delson, “Gear ratios,” *MAE3*. [Online]. Available: http://mae3.eng.ucsd.edu/machine-design/gear-ratios. [Accessed: 23-Oct-2022].

[3] P. Millett, “Using Current Regulation in DC Motor Drivers,” *MPS*. [Online]. Available: https://www.monolithicpower.com/en/using-current-regulation-in-dc-motor-drivers. [Accessed: 28-Oct-2022].

[4] “Technical Handbook 2022-2023.” University of Manchester Department of Electrical and Electronic Engineering, Manchester.’

[5] TeddyG, “Understanding Electric Motor Efficiency Losses: Groschopp Blog,” Groschopp, 24-Mar-2015. [Online]. Available: https://www.groschopp.com/efficiency-and-losses-in-electric-motors/. [Accessed: 25-Oct-2022].