ALiCE II: Locomotion for a Line-Crawling Robot Designed for Manitoba Hydro

Dan Lockery
James F. Peters, Supervisor
$\{$*dlockery,jfpeters*$\}$*@ee.umanitoba.ca*

University of Manitoba
Computational Intelligence Laboratory
ENGR E3-576 Engineering & Information Technology Complex
75A Chancellor's Circle
Winnipeg, Manitoba R3T 5V6
Tel.: 204.474.9603
Fax.: 204.261.4639

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Abstract

The is the second of a series of research reports that were begun in 2005, and are now being completed in preparation for the completion of the first phase of the ALiCE II project. This report focuses on locomotion of the line-crawling robot affectionately named ALiCE II. ALiCE II is an acronym for Autonomous Line-Crawling Equipment II, a second generation version of a new family of autonomous line-crawling robotic devices using swarm intelligence system engineering design principles introduced during the past 3 years. ALiCE II represents the combined efforts of Maciej Borkowski, Dan Lockery, Christopher Henry (alpha order) with some help from Peter Schilling during the summer of 2005. The main architect of ALiCE II has been Dan Lockery. ALiCE I was a single line-crawling robot designed by Vitaliy Degetyarov in 1999 as part of his M.Sc. project, which was also funded by Manitoba Hydro. ALiCE II is the focus of Dan Lockery's M.Sc. research project.

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1 Introduction

This report provides a brief outline of the recommended change in the locomotion drive for the ALiCE II project. We have gone through several revisions to date, but with the overall weight increasing more than planned, another revision is required. This report follows a brief discussion of the problems encountered, the new approach to solving the problem and finally the recommendations for dc motors.

2 Motor Drive Problems

The dc motor drive of the line crawler robot has gone through a couple of stages of evolution as my experience has progressed and the shape of the robot has solidified over time. Initially, we started with small dc motors provided from Gleason Research along with the handyboard kit. These original motors were provided without any specifications and other than a stamp on the side of the motor which stated it was in fact a Johnson motor, shown in figure 1.

Figure 1: Original dc motor

After sending emails to the supplier as well as Johnson Motors, I was unable to find out any more about the original dc motor. Without knowing the specifications, I began using the original motor as a starting point for the physical design as the main drive for the line grip. Preliminary tests were done with the line grip alone. The original motor was able to turn the wheels easily in one direction but seemed to struggle with the other direction. Since the weight of the overall structure was an unknown at that point, it was difficult to know whether to replace the first dc motor immediately.

The first tests of the structure when using the original dc motor demonstrated quickly that our motor was unable to supply the necessary torque that we needed. The main reason for this is that the dc motor is quite small which implies that it will likely have minimal output torque and since it does not take advantage of a geared output shaft the speed is significantly faster than what we desired (in the order of 1000's of rpms when we would be happier with 60rpm or less).

Once the structure of Alice started to take shape and we had a better idea of what the mass was going to be, a second motor was specified and ordered. This time, we switched to an even smaller motor than before, although with the addition of a gearhead and a gear reduction ratio of almost 300, the output speed and torque improved dramatically. Figure 2 shows the replacement Sanyo motor installed in the line crawler grip.

Figure 2: Second Generation Sanyo Motor Drive

After learning from the drawbacks involved in using the first motor provided with the handyboard, specifications were calculated for the second generation of dc motor drives. As mentioned above, the gear reduction ratio was quite significant, providing much larger continuous torque values at the output shaft. In addition to the improved torque capabilities, the speed of the output shaft was reduced to around 60rpm. The output torque was specified for approximately 20oz-in, this was calculated to be sufficient to drive the mass of the line crawler up 15 degree inclines. However, there was still one area that I missed when addressing the needs of our dc motor drive. The efficiency of dc motors as well as gearheads are not perfect. As a result, the associated effects needed to be taken into account for both when specifying torque and speed. I neglected to include the efficiency effect of the gear head, although there was enough strength at no load, once the shaft was loaded with the drive train, the motor was no longer able to drive the weight of Alice even with a reduced weight payload due to the efficiency of both motor and gear train together.

In order to solve the problem of the dc motor drive once and for all, a more detailed look into the attributes of the motor as well as the overall weight of the structure and how the angle of inclination will affect Alice all was revisited. The next section of the report includes a more in depth look at these calculations and where extra care was placed in the design to ensure more power is available than what we need since it is better to be capable of driving a larger payload than having to worry about repeatedly dropping weight.

3 DC Motor Specification

Some of the previous decisions made regarding drive power needed to be revised when specifying a new set of dc motors. To ensure success in selecting a drive motor, several options were assessed that fit the new specifications (three). Each of the options selected is equally able to drive the gear train. This section discusses the choices made in generating the model for the line crawler drive requirements.

I was originally concerned with the model that I was using for estimating the required specifications for a dc motor based on previous results. Some time was spent revisiting how to specify dc motors from different sources, only to discover that the model I had originally used was correct. A few changes were needed in my decisions for the variables to ensure proper selection of a new motor for each option. The variables that I selected were the angle of inclination that Alice will climb along the sky wire as well as the coefficient of friction for the wheels (rubber lined) rolling. Since the previous motor was not up to the job I decided to beef up my estimates since it is better to overshoot a little and have a stronger motor as it will be able to provide locomotion. Also, I took into account the speed, torque and efficiency of both the motor and the gear train.

The next step is to look at the model for estimating the requirements of a dc motor drive. Figure 3 shows a simple model of how the line crawler is treated. Included are V (velocity), F_{app}(Force applied), r (wheel radius), F_n (normal force), mg (acceleration due to gravity), F_w (weight causing the line crawler to slip down the line), and F_f (Frictional force).

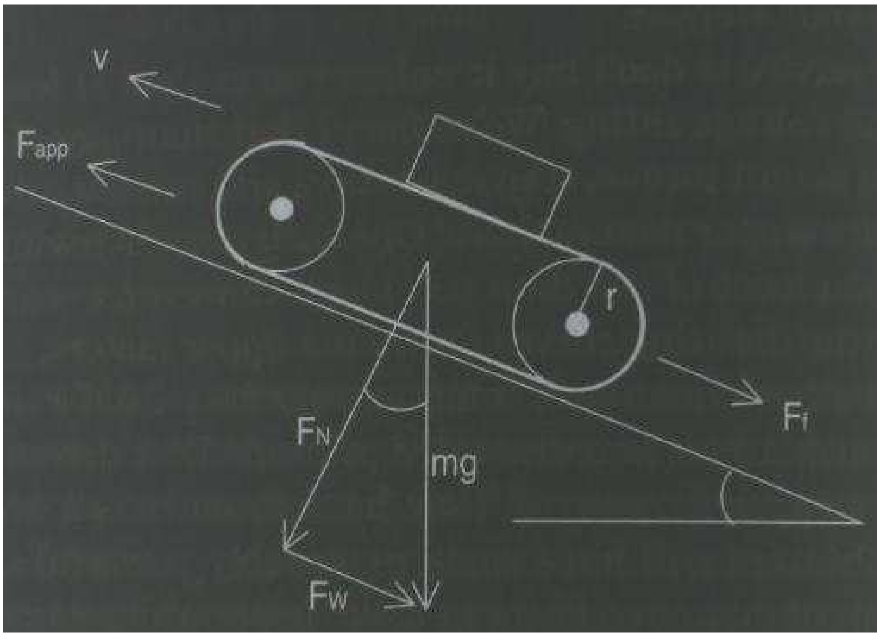

Figure 3: Robot force model [1]

The applied force to move the robot (F_{app}) is shown in (1), containing two parts, the frictional force and the weight causing the robot to slip on the line (due to the incline of the sky wire).

$$F_{app} = F_f + F_w \tag{1}$$

The individual equations for these two force components are shown in (2) and (3) [1].

$$F_f = \mu \cdot mg \cdot cos(\theta) \tag{2}$$

$$F_w = mg \cdot sin(\theta) \tag{3}$$

The angle θ refers to the angle of inclination of the sky wire for the line crawler. The term μ in the frictional force equation is referred to as the coefficient of friction [1]. This coefficient is generally a small value from 0 to 1 [1]. To approximate the conditions that we will be facing, I had originally estimated the value of θ as 15 degrees but after examining the sky wire during the summer months and noting the large inclines, I decided to set θ at 45 degrees. Also, the coefficient of friction was originally estimated to be 0.4, a reasonably conservative value considering the wheels roll fairly smoothly on the sky wire. However, I decided to change the value of μ to 0.9 since the rubber wheels do present a fair bit of friction to avoid slippage on the sky wire. The value for g (acceleration due to gravity) is 9.8 m/s^2, and the estimated mass of one completed pair of robots is approximately 3.6kg. Next, the values were generated to provide an idea of exactly what the torque and velocity of our locomotion system will operate at.

F_w corresponds to 24.95 $kg \cdot m/s^2$ and F_f came out to 22.45 $kg \cdot m/s^2$. As a result, the total F_{app} comes out to 47.4 $kg \cdot m/s^2$. At this point, the power and angular velocity can be derived, providing a clear picture of the speed as well as the torque that a motor drive will require to power the line crawler. Equation (4) shows the relationship of the applied force to the velocity and in turn the power required from the motor, and (5) demonstrates how the angular velocity ω relates [1].

$$P = F_{app} \cdot velocity \tag{4}$$

$$\omega = velocity/radius \tag{5}$$

The radius (r) is a known quantity, 6mm is the inner radius of the wheels (including rubber) that will come into contact with the sky-wire when the line crawler is traveling. The remainder of the elements in each of these equations are all unknowns. One of the design decisions made for the line crawler is to keep the velocity low since it will avoid a host of problems (including smashing into other bots or moving too quickly in critical situations). I decided to select an angular velocity of approximately 2π radians/s. The velocity from (5), provides a velocity of 3.77cm/s. Substituting this value into (4), the required power is 1.787 Watts. Using one final equation, we can estimate the required torque of the motor needed to generate our power requirements [1].

$$T = P/\omega \tag{6}$$

The torque provided by (6) that is required to power the line crawler robot up 45 degree inclines with the maximum amount of weight is approximately 0.28441N·m. Converted to imperial units (commonly found when sourcing parts from the US), the value is 40.27 oz-in.

Through re-calculating and analyzing the model again, I found one critical error from the previous model I was using. The angle θ in (2) and (3) are not meant to be the same, unless that angle is in fact 45 degrees (which it happens to be this time). The angle in (2) is meant to be from the horizontal axis whilst the angle in (3) is meant to be from the vertical axis. I missed this fact during the previous set of specifications. As a result, the two values for cos and sin were not the same and I actually wound up improperly estimating the friction force (F_f). This can have dramatic effects such as not having enough power to overcome the friction force implying that Alice would not move.

With the new model for dc motor selection completed, the next step is to move into specifying a commercial model (or models) that will satisfy these requirements.

4 Commercial Motor Options

In this section of the report, Included is a discussion of the space constraints as well as several locomotion options that were included to provide a dc motor drive for the next version of Alice.

4.1 Space Constraints

One of the problems with selecting a dc motor drive for the line grip is that we have limited space available to us. Keeping this constraint in mind, I put together some rough sketches to help visualize what we have available and how we could expand the chassis to accommodate larger motors. The current dimensions are discussed briefly followed by a plan for modifying the line grip to fit in larger motors.

The current dimensions for the line grip are small relative to the size of dc motors that provide the power and torque that we need to drive the Alice structure. The reason for the small dimensions are that the original line grip was built with the intent of keeping a minimalist design for weight and space. The important dimensions to note are seen in figure 4, total width of the compartment, as well as space for gear housings to hang below and the height at which the shaft interfaces to the power train.

The current space available, without modifications is approximately 4.6cm in length and about 1cm in depth below the drive shaft. In addition to that, any sort of gear box can hang below the motor support platform to a width of about 1.1cm at present. After spending a little bit of time examining the structural integrity of the upper grip, I arrived at the conclusion that the maximum amount of space available to us would be approximately 2.2cm in width for a gear box to sit below the platform and the motor shaft can be longer if it fits into the bore of the driving gear as there is space in the next compartment that is unused. The depth of 1cm is difficult to modify as this will change the shape and size of the line grip and how it connects together. However, it can still be modified a small amount to accommodate varied locations of a drive shaft. Should we need to modify it beyond this, the backbone will need some changes to shift the upper and lower grip chassis modules so that they still meet at the same place.

Keeping these space constraints in mind, the next step was to come up with some suitable options for a replacement dc motor.

4.2 DC Motor Options

In order to select some options for the locomotion drive onboard Alice II, I spent a bit of time sifting through commercially available products to get an idea of what was available. In the end I found three different options that will suit our needs equally but through different means of arriving at the same goal. The first option is a parallel shaft dc motor that fulfills the torque, speed and power requirements. The second option is a parallel offset shaft dc motor, meeting those same requirements. The final option is a parallel shaft dc motor that meets half the required torque and double the speed required, the savings in space of a smaller motor is countered by adding a smaller drive gear in the power train to improve the output torque and speed to values more appropriate for our needs.

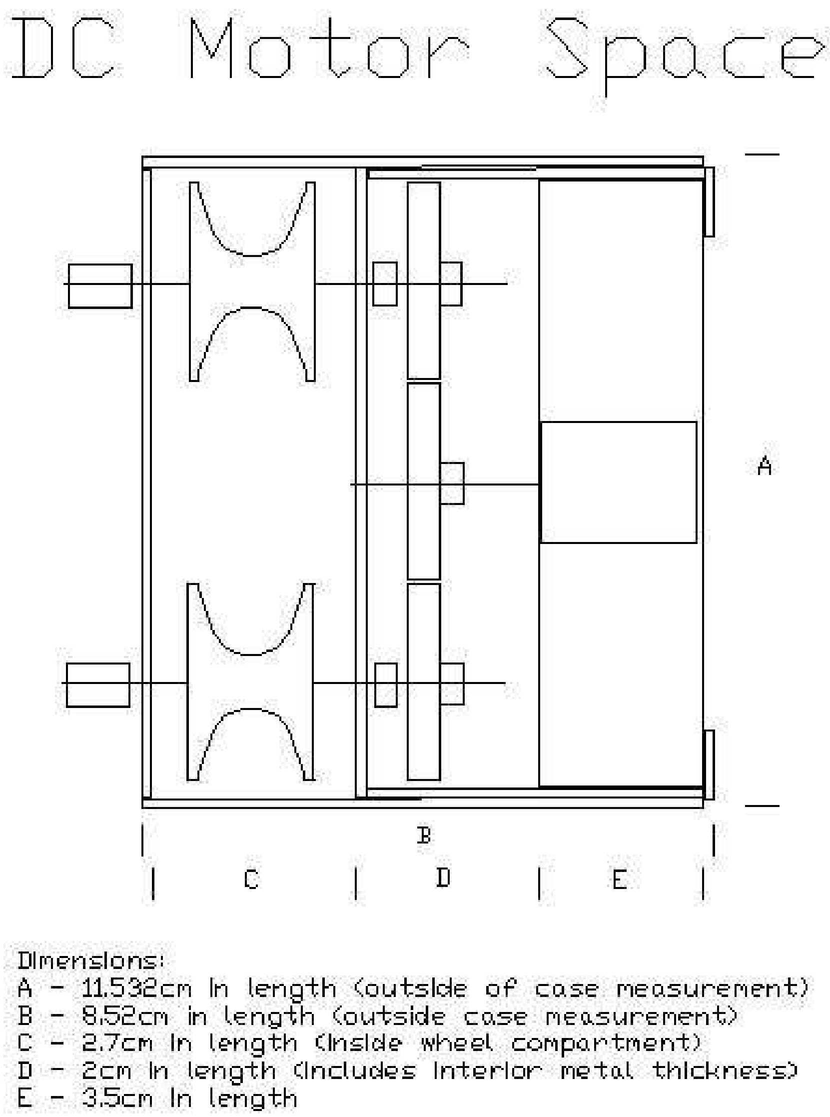

Figure 4: Space available for dc motor

4.2.1 Option 1: Parallel Shaft DC Motor

The essential attributes for this option are that the torque, power and speed are selected (including the efficiency effects) to meet our needs. The space available to us was not as big of a concern in my selection of this motor drive, although some effort was made to keep the size as small as possible.

I managed to find a suitable candidate for the parallel shaft dc gear motor at MicroMo Electronics [2]. My selection is a dc micromotor and gearhead combination. The model is the 'Series 2230 006S'. This is a 6 volt motor which will fit in nicely with our current power supply avoiding having to make any immediate changes. The efficiency of this motor is 82% and it weighs approximately 50 grams. The maximum torque is 2.5mNm and the output shaft speed is 8,000rpm. In addition to those specifications, the shaft is 1.1cm from the base of the motor which implies that it will mate almost perfectly with the current gear train (minor modifications will be required). Obviously, with the torque and speed listed we will need the gearhead to bring the output attributes closer to what we need. The 38/3 gearhead extends the length of the motor to 5.84cm which is outside the available space we have (this can be altered as previously discussed). The advantages of adding the gear head are significant since the output torque increases to 1200mNm or 169oz-in. The efficiency of the gear train is approximately 53% with the reduction ratio of 689:1 and the associated weight of the gearhead is 92 grams. The total weight of the motor and gear head is 142 grams which is less than what I was allowing for motor weight (approximately 300 grams). The only extra problem introduced by the gear head is that the output shaft sits slightly higher (around 1.2cm above the base of the motor). This will require some modifications on the part of the upper and lower grips to mate the shaft with the gear train. When the efficiency of the motor and gearhead are taken into account, the output torque available at the shaft is 73.45oz-in at maximum. Since we will will likely be operating the motor at less than optimal efficiency this allows us a healthy amount of room to move on the efficiency curve without losing the ability to drive the line crawler.

Option 1 appears to be a suitable candidate for driving Alice II along the sky wire with several modifications to the physical structure. In addition to these modifications, the output shaft of the gearhead has several options as well. The original gear train that we have been using has a bore size of 3.175mm, however there are larger size bore holes available from PIC design. As a result, to simplify one aspect of the integration of the new dc motors, it may be in our best interests to move to a larger bore size for the driving gear. The follower gears can remain with the current 3.175mm bore since that is the size of the shafting for driving the wheels.

4.2.2 Option 2: Offset Parallel Shaft DC Motor

The next option is to move to an offset shaft so that we can attempt to fit the gearbox into the upper grip from a different perspective. This poses a new problem, since the gearbox can be quite large, and the dc motor may be quite small. As a result, the centre of mass and how the motor is attached to the grip will require some mounting blocks to secure it. This motor was selected based on the same requirements as the previous parallel shaft motor with the only exception related to the spacing.

After scanning numerous sites for manufacturers or distributors that provide offset shaft dc gear motors, I encountered a promising solution from Merkle-Korff Industries [3]. The size was immediately appealing as it will fit into the compartment space we have available with some minor modifications (we will need to cut down the platform size). The model in question is the D47 Plastic Series DC gear motor. There are both 6 and 12V options with torque rated up to 40in-lbs which corresponds to 640oz-in (much more than we need) and speeds up to 25rpm which is also acceptable. The efficiency and motor characteristics were not provided on the supplier's website and were estimated based on my experience with other dc motors of similar size and parameters.

There is another motor that I found in the 'in-stock' section from Merkle-Korff that is fairly similar in characteristics as well. The second possibility for the second option is as follows: The motor is an offset parallel shaft dc gear motor. The model is the 8152, the output shaft operates at 25rpm and it is a 12V motor (implying we would need a new power supply design). The output shaft operates at 15in-lbs, or 240oz-in. The output shaft is quite large (5/16 of an inch or 8mm) making it unappealing. However, should there be an alternate option for shaft sizing as there are with some motor manufacturers, then this would be a viable alternative.

So long as they are readily available, I think that it would be better to select the D47 offset shaft motor since it provides an excess of the performance parameters we need and it comes in the correct shaft sizing and power supply requirements also.

4.2.3 Option 3: Reduced Performance DC Motor w/ Boosted Power Train

The last option that I am suggesting as a locomotion drive replacement is to use a motor that does not quite meet our specifications for torque and speed but we can instead gear down the main drive train to match what we need. The efficiency of a power train is not significantly reduced when only a small gear ratio is used. When looking at commercially available dc motors, I found that the offset shaft motors were more difficult to locate, therefore my recommendation is for a parallel shaft dc motor.

The most important motor characteristics for this option are the torque, which can be approximately cut in a half to two thirds from the previous value and the speed which can now be approximately doubled or tripled. As a result, motors that provide around 25oz-in of torque and speeds of around 120rpm should fit our needs. Greater torque or lower speeds will suffice, but they are also associated with larger gear heads and more weight so they were not as much a factor in my decision.

My suggestion for option 3 is to make use of a motor from Micro Drives [4]. The motor that I think meets our needs most closely is one of their dc gearmotor series, model number MD3636 + MD35C. This is the dc motor and the gear head pair. The dc motor model is the MD3636 A006V which is the 6V version of this motor. The efficiency of the motor is 70% and the gearhead selected has an efficiency of 59%. Together they provide an overall efficiency of 41.3%. The output torque is rated to 588mNm or 83.3245oz-in. Taking the efficiency into account this provides 34.413oz-in at the output shaft, leaving us some room to operate below max efficiency. Since we will be operating with a gear ratio of approximately 3:1 in the power train, this will bring the overall output torque to an acceptable level for driving Alice up inclines. The weight of the dc motor is 65g, unfortunately I was unable to obtain the gear head weight although I would estimate it to be anywhere from about 50-100g. The output shaft for the dc motor operates at about 5800rpm and with the addition of the gear reduction (241:1) the speed will be reduced to about 24rpm. The overall length of the gear head and the motor is 52.5mm not including the output shaft (an extra 21mm). This implies that there will need to be modifications to the compartment to fit the motor into the space available. In addition to that, the shaft is slightly higher than the 1cm available so we will have to alter the depth of the compartment as well (by 1.5mm).

The dc motor and gear head combination specified for the third option should be able to supply enough torque and have an appropriate output speed to meet our needs once again. Making use of a 3:1 gear reduction ratio in the main power train will help us improve the torque and speed whilst employing a smaller gear head/motor combination.

5 Gears

In addition to the motors that we are ordering, I think that it is important to replace the driving gear in the power train to accommodate the new shaft diameters. This eliminates the need for using a coupling device to mate the two different shaft dimensions (this would reduce the amount of space needed for the motor interface as well). My suggestion is to switch to an aluminum gear as well to help reduce some of the extra weight introduced with the new dc motor options. In addition to the new drive gear, we will need smaller gears for the third option as well. Three small gears are needed, one driver and two followers to interface with the larger gears (they will need to be 1/3 the size, hence the approximate 3:1 ratio). The gears for the power train can be ordered from PIC design [5]. The next section of the report includes all of the part numbers and specifications in one place out of convenience for ordering.

6 Parts

Gears: (from PIC Design [5])

- Aluminum drive gear replacement with larger bore size:
PIC-Design part number: G4-65 Qty required: 2
- Aluminum follower gear replacement
PIC-Design part number: G62-65 Qty required: 4
- Reduced size drive gear and followers
PIC-Design part number: G4-20 Qty required: 2 (drive)
PIC-Design part number: G62-20 Qty required: 4 (follower)

Motors:

Option 1:
- DC Micromotor + gear head (from MicroMo Electronics [2])
- DC motor part number: series 2230 006S (6V)
- Gear head part number: 38/3 (for the dc motor above)

Option 2:
- Plastic series DC Gearmotor (from Merkle-Korff [3])
- DC motor part number: D47
- options: 6V model
- shaft selection: 0.25 inch, Flat-Type-F

Option 3:
- DC Gearmotor (from Micro-Drives [4])
- DC Gearmotor series part number: MD3626 + MD35C
- the dc motor required is the MD3626 A006V (6V model)
- the gear reduction ratio for the gear head selected: 241:1

7 Conclusion

With the options presented and specified above, we will be able to overcome the problem of lacking enough torque to drive Alice up and down the inclines that she will encounter on the sky wire. Each option presented has a different set of pros and cons associated with it, but all of them can operate as a locomotion drive in Alice's environment. As a result, I'm confident that whichever option we select will be successful.

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[2] MicroMo Electronics: Micro Motors Supplier: *MicroMo Electronics*
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[4] Micro Drives: Motor Supplier *Micro Drives*
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[5] PIC Design: Gear Supplier *PIC Design*
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