Two options were considered for the selection of the brakes. The first was to use an Electroid bi-stable brake, model BSB-3, which can provide 0.28 nm of holding torque. This brake is unique in that it does not require constant excitation to remain released. To operate the brake, an electrical pulse, 24 VDC at 2.1 A for 100 ms is applied. For a typical motion, the brake will be released then re-engaged, resulting in a total energy expenditure of 10 J.

Another option is to use a fail-safe brake, a Binder 86 621 A04. This brake requires 8 W of power to release. Comparison of the two brakes shows that if a motion last for more than 1.25 seconds, using the bi-stable brake will result in a less energy consumption. Using the optimal cycle times, using a combination of fail-safe and bi-stable brakes yields 132 J per cycle, where using fail-safe brakes only requires 116 J per cycle. This lower energy per cycle is due to the very short cycle times of the brakes. For the majority of robotic applications, the bi-stable brake will yield lower energy expenditure.

## 5 Summary

Careful design of a robot drivetrain is essential for optimal performance. To achieve the goals of a planetary exploration mission, the robot drivetrain must operate efficiently, reliably and incorporate redundancy. The design procedure outlined was used to develop a drivetrain, using mostly available components, that results in a system efficiency greater than 65% of electrical power to mechanical output. These techniques are generic and can be applied to the drivetrain of other systems.

## 6 Acknowledgments

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| | | Load condition | | | |
|---|---|---|---|---|---|
| **variable** | **units** | **horizontal, low speed** | **horizontal, high speed** | **vertical, low speed** | **vertical, high speed** |
| Gearing ratio (theoretical) | N | 108.400 | 17.179 | 108.400 | 17.179 |
| Load torque (theoretical) | N m | 5.560000 | 1.250000 | 9.530000 | 0.880000 |
| Load speed | r/s | 9.300000 | 41.300000 | 5.500000 | 59.300000 |
| *(Motor torque)* | *oz in* | *7.262878* | *10.303229* | *12.448782* | *7.253473* |
| *(Motor speed)* | *rpm* | *9626.5378* | *6774.9776* | *5693.1138* | *9727.7524* |
| Efficiency | % | 87.05 | 84.73 | 81.61 | 87.06 |
| Gearing ratio (actual) | N | 108.90 | 17.431 | 108.90 | 17.431 |
| Load torque (actual) | N m | 5.560000 | 0.793000 | 9.530000 | 0.714000 |
| Load speed | r/s | 9.300000 | 41.300000 | 5.500000 | 59.300000 |
| *(Motor torque)* | *oz in* | *7.262878* | *6.536368* | *12.448782* | *5.885204* |
| *(Motor speed)* | *rpm* | *9671.2411* | *6874.5415* | *5719.5512* | *9870.7097* |
| Efficiency | % | 87.04 | 86.32 | 81.71 | 86.51 |
| Temperature rise | C | 31.55 | 21.28 | 48.11 | 27.07 |

**Table 4.4-2 Motor efficiency for the four motion types**

The calculated temperature rises assume 100% duty cycle. When the actual duty cycles are taken into consideration, this motor yields acceptable results given the initial criteria, Section 4.4.1. The cycle time weighted efficiency of the motor is 86.8%. In addition, the least efficient motion is the vertical body lift, and this is perfectly acceptable as this motion occurs the least frequently.

### 4.4.4 Brake sizing

Although back-driving the brakes from the output shaft is highly unlikely, the possibility of back-driving one brake through the differential stage of the gear box while the other motor is operational presents a likely scenario. Consider first the case when the high speed motor is operational. This occurs when the legs are being lifted/lowered or the y-frame is being moved. From Table 4.4-1, the latter case requires greater output torque, 1.43 Nm. The required braking torque is found to be

$$\tau_{brake} > \tau_s = \frac{1}{\alpha}\tau_r = \frac{1}{\alpha}\frac{\tau_{load}}{N} = 0.014\text{Nm} , \tag{4.4-3}$$

where $\alpha$ is defined in Table 4.3-1 and $N$ is the overall gear ratio from Section 4.4.3.

Now consider the case where the low speed motor is operational. This occurs when the body is being lifted/lowered or the body is being moved. From other documentation, the former case requires greater output torque, 9.53 Nm. (This value is a steady state value and does not include accelerating the body. However, body lifts are very slow and the additional force due to acceleration is less than 4% of the steady state force. Incorporating the additional spur gear pair, $N_1 = 129/95$, the required brake torque is given by

$$\tau_{brake} > \tau_c = \frac{1+\alpha}{\alpha}N_1\tau_r = \frac{1+\alpha}{\alpha}N_1\frac{\tau_{load}}{N} = 0.591\text{Nm} . \tag{4.4-4}$$

Using the same equation, the brake torque required to move the body is 0.392 Nm.

To determine the gear ratio with the highest efficiency, calculate

$$\frac{\partial e}{\partial N} = 0 = (2k_T^2\tau_d\omega^2 + 2\Omega\tau_d^2\omega^2)\,N^4 + (k_T^2\tau_f\omega + 2\Omega\tau_d\tau_f\omega)\,N^3 - 2\Omega\tau\tau_f N - 2\Omega\tau^2 \qquad 4.4\text{-}2$$

and solve for *N*. Applying the Routh stability criterion to Equation 4.4-2 shows that there is only one positive root, and it must necessarily be real. This solution can be solved for in closed form or numerically.

Since the motion that consumes the most power is the body move, the load conditions for that motion are the ones to be used in Equation 4.4-2 to determine the low speed gear ratio. It must also be recognized that the gear ratio developed is a theoretical ratio in the sense that it may not be achievable given the constraints on gear design from the manufacturer. However, small changes in the ratio will not have an appreciable impact on efficiency.

To determine the high speed gear ratio, Equation 4.4-2 is used with both high speed motion requirements. The two resulting gear ratios are duty-cycle weighted to yield the high speed ratio. The low speed ratio divided by the high speed ratio yields the difference in ratios. This approach maximizes the efficiencies of the motions used for walking at the cost of the body lift motion.

### 4.4.3 Actual implementations

The following sections show the results of these calculations applied to an actual motor. The required variables are determined from the motor data sheets, then the theoretical optimal gearing ratios are determined, the ratio between the gear ratios is selected found. These values are used to determine motor efficiencies for the four types of motions. As a final step, actual gear ratios (based on manufacturers' constraints) are used to determine actual system performance.

The motor selected is a Pittman 4111 with winding 2. This motor is a brushless DC servo motor. It is a square motor, 40 mm x 40 mm x 67.8 mm and has a mass of 380 gr. The optimal difference between the ratios is 6.31:1. The parameters for this motor are $k_T = 0.0314\text{Nm}$, $\tau_f = 0.0013\text{Nm}$, $\tau_d = 2.6 \times 10^{-6}\text{Nm}$ and $\Omega = 1.21\text{Ohms}$. The temperature rise per watt is 4.1°C. The calculations used in Table 4.4-2 show that the motor operates between 25 and 35 VDC and draws between 1.5 and 3 Amps.

In theory, any combination of gear sizes can be used to construct a planetary gear. The particular manufacturer for the Daedalus gearbox, CGI Incorporated, uses a small number of sun gears (12, 18, 24, 30, 36, 42, 48 and 54 teeth) matched with a single ring gear (108 teeth) to produce a wide variety of possible gear ratios. To control costs, only standard gear ratios were considered for the Daedalus project. This resulted in the following selection of gearing: the differential stage sun, 30 teeth; the output stage sun gears, 24 teeth; gear H, 129 teeth and gear C, 95 teeth. This yields actual overall gear ratios of 108.90:1 for the low speed motions and 17.43:1 for the high speed motions.

Table 4.4-2 appears to contain an error: the efficiency of the vertical low speed motion increases when the gearing ratio is changed from the theoretical value to the actual value. Since the gearing ratio was selected without taking the vertical, low speed motion into account, the initially chosen ratio is non-optimal for this motion. When the ratio is changed to the actual value, there is a 50% chance that the efficiency will improve, depending on whether the actual ratio is closer to the optimal value for this motion or not. Thus, the increase in efficiency is not an error, but merely fortuitous chance.

## 4.4 Drivetrain component specification

### 4.4.1 Motor requirements

To develop the motor requirements, the non-accelerated portion of the motions will be considered. This is done because these periods dominate the walking cycle. Table 4.4-1 shows the required speed and force for each of the four types, not phases, of motion. These types are lifting/lowering the legs, moving the y-frame, lifting the body and moving the body. The first two types of motions (referred to as high speed motions) are assumed to use one of the gearing ratios and the second two types of motions (referred to as low-speed motions) use the other gearing ratio. For lifting/lowering the legs and moving the y-frame motions, there are two forces shown. The italicized force is that force which yields the same power expenditure as the body move for the specified speed. The speed for the body lift is chosen to yield the same power as a body move. Choosing pinion gears 0.625 in radius for vertical motions and 0.375 in radius for the horizontal motions, allows rewriting the requirements in Table 4.4-1 as torques and angular velocities.

| | **high speed motions** | **low speed motions** |
|---|---|---|
| **vertical motors** | f = 75 (*92*) N [$\tau$ = 0.88 Nm (124 oz in)]<br>v = 0.565 m/s [$\omega$= 59.3 r/s (566 rpm)] | f = 1000 N [$\tau$ = 9.53 Nm (1349 oz in)]<br>v = 0.052 m/s [$\omega$ = 5.5 r/s (52 rpm)] |
| **horizontal motors** | f = 50 (*79*) N [$\tau$ = 1.25 Nm (177 oz in)]<br>v = 0.656 m/s [$\omega$ = 41.3 r/s (395 rpm)] | f = 350 N [$\tau$ = 5.56 Nm (787 oz in)]<br>v = 0.148 m/s [$\omega$ = 9.3 r/s (89 rpm)] |

**Table 4.4-1 Force/torque and speed requirements**

In addition to the speed/torque requirements, the motors should also meet the following requirements: be as small and light as possible, not require more than 48 VDC, not require more than 7 A during normal operation, limit temperature rise during normal operating conditions to 35$^{o}$C, must not have an integral fan or require one for cooling and the cost of the motors and required amplifiers must be “reasonable”.

### 4.4.2 Optimal gear ratio selection

Motors have an operating point, speed and torque for a constant voltage, at which they are most efficient. For DC servo motors, this point is typically close to the no-load speed of the motor. The purpose of gearing is to change the required output conditions to the motors optimal operating conditions, if possible. For this robot, however, it is not possible to have optimal performance for all loading conditions because of the disparity between the high speed and low speed motions. However, by determining the optimal gearing ratios for three of the phases, the overall system performance can be optimized.

For a first order approximation, a motor can be defined by four parameters: torque sensitivity ($k_T$), static friction torque ($\tau_f$), viscous damping ($\tau_d$) and coil resistance ($\Omega$). Back EMF ($k_e$) is the same as torque sensitivity. Equation 4.4-1 shows the current required for a given load torque ($\tau$) at a given angular velocity ($\omega$) with a gear ratio of (*N*), the required voltage and the motor’s percent efficiency. Gearing efficiency can be added to Equation 4.4-1 by dividing the load torque by the gearing efficiency.

$$i = \left(\frac{\tau}{N} + \tau_f + \tau_d \omega N\right) / K_T \qquad V = i\Omega + K_e \omega N \qquad e = \frac{\tau\omega}{Vi} \tag{4.4-1}$$

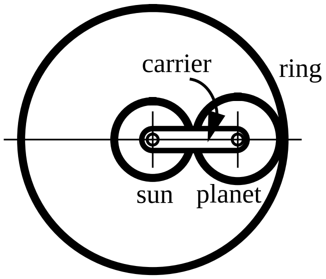

**Figure 4.3-1 Planetary gear**

The gearbox designed for Daedalus has “two” components. The first is a differential that is used to generate the difference in gear ratios required for the two modes of operation. The second component is speed reducer. Planetary gearing was chosen for both components because actual implementations of this gear arrangement yield compact gear boxes with high ratios, high torque carrying capability and high efficiencies. The layout of a planetary gear stage is shown in Figure 4.3-1.

There are three ways to achieve the differential gearing for the first stage of the gearbox. The first is to use a clutch that selectively engages different gear ratios. The second is to use two motors and to selectively brake one or the other. The second approach was used because it provides redundancy in the case of the failure of a motor. Using this approach a motor/gearbox package was developed that produces the required outputs whose mass is less than 3.0 kg. Figure 4.3-2 shows a schematic layout of the gearbox design. For high speed operation, the brake attached to the low speed motor is engaged and for low speed motion the brake attached to the high speed motor is engaged.

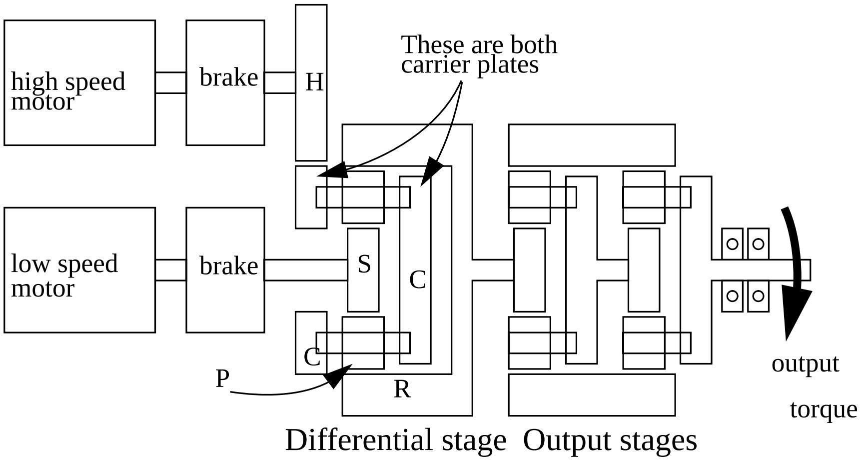

**Figure 4.3-2 Gearbox schematic**

The speed ratios (the speed of the input divided by the speed of the output) for the two combinations of inputs, outputs and fixed gears used in the differential stage of the Daedalus gearbox are shown in Table 4.3-1, with $\alpha = N_{ring}/N_{sun}$, and $N_{ring}$ and $N_{sun}$ the number of teeth on the ring and sun gear respectively. (The torque ratios are simply the inverses of the speed ratios, neglecting frictional losses.):

| Input Gear | Fixed gear | Output gear | Speed ratio |
|---|---|---|---|
| sun | carrier | ring | $-\alpha$ |
| carrier | sun | ring | $\alpha/(1+\alpha)$ |

**Table 4.3-1 Speed ratios**

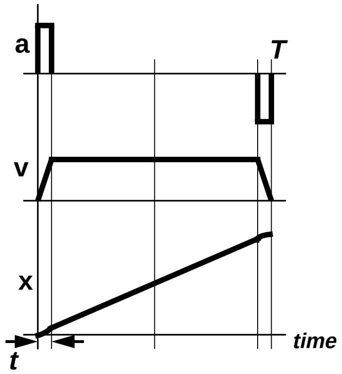

**Figure 4.2-1 Kinematic Profile, Trapezoidal Velocity**

phase times and acceleration times for each of the six phases of motion. Other possible optimization criteria include minimum average power or minimum total energy. The minimum maximum power criterium was chosen because the typical space-rated power sources are power limited, not energy limited and to simplify the actuator motor/gearbox design.

The three primary components of power expenditure of a moving body are inertial power, gravitational power and frictional power. There are other sources of power expenditure, such as aerodynamic drag and rover/terrain interactions, but these effects are not considered. A non-regenerative system is assumed, thus the inertial and gravitational energies are not conserved. Using these assumption, the minimum maximum power expended to walk 5 m/min is found to be approximately 60 W, see Figure 4.2-2. It is important to note that this figure does not show the power expenditure for a body lift maneuver. Since lifting the body should only happen occasionally, the actuators are sized for the nominal walking cycle, and are geared to provide the higher torque required to lift the body. This will yield a slow body lift, assuming constant power, but this should have little impact on the overall mission.

## 4.3 Gearbox configuration

Because of the wide range of required force/speed, a two-speed gearbox will be used. This gearbox will provide two motion regimes, a high-speed/low-torque mode and a low-speed/high-torque mode. This is done so that the motors can be run at optimal efficiency in all motion phases. An alternative was to use a motor larger than necessary with a single gearing ratio to provide all required motion profiles. This approach was not studied because of the lower efficiency of the system. This is primarily due to the need to provide the high torque, thus having a substantial margin for the low torque motions.

**Figure 4.2-2 Speed, force and power profiles**

# 3 Configuration

## 3.1 Daedalus configuration

Daedalus is pictured Figure 3-1. Daedalus belongs to a class of walking robots called frame walkers. Frame walkers are typically considered to be the simplest walking machines capable of negotiating rugged terrain [Bar91].

Daedalus is comprised of two frames, the body frame and the y-frame, each of which has three legs. The rover moves in the following manner: the legs on one frame are lifted, this frame is moved relative to the other, then its legs are set down. Then the legs on the other frame are lifted, the second frame moves with respect to the first, then its legs are set down. This cycle of six motion describes a complete walking cycle.

## 3.2 Daedalus kinematic capabilities

Daedalus has a design mass of 200 kg. This mass is divided approximately equally among the four major subsystems: locomotion, power, computing and sensing, and scientific instrumentation. Daedalus stands between 1.5 - 2.5 m tall and is designed for a nominal walking speed of 5 m/min.

The greatest longitudinal slope Daedalus can traverse is approximately 30 degrees. The greatest transverse slope traversable is in excess of 40 degrees. Daedalus is capable of traversing its maximum longitudinal and transverse slopes simultaneously.

Daedalus can negotiate steps of greater than 1 m in height if two conditions are met: the terrain at the edge of the step is solid and able to support the loads placed upon it and that the region above the step that is approximately 1.75 m deep.

The widest ditch than can be crossed is 0.6 m wide. To perform this maneuver, several shortened steps are required. Like step climbing, ditch crossing also requires that the material along the edge of the ditch can support the applied loads

# 4 Daedalus Actuator Subassembly

## 4.1 Vertical and horizontal translational motions

The Daedalus configuration requires prismatic joints for its vertical and horizontal motions. A prismatic joint is comprised of a two basic parts: a moving element and a stationary element. The moving element is typically comprised of a strength member, bearing member and force transmission member and the stationary element is typically comprised of motor and bearing.

To reduce the total leg mass and overall complexity, Daedalus integrates the strength and bearing members into a single component. To properly size these elements, equations describing the most probable failure mode are used. The gear rack, for power transmission, is bolted directly to the leg, and the leg assembly is driven by a gear motor with an output pinion.

## 4.2 Motion profile

To determine the sizes for the motor and gear train, certain assumptions about the robot's nominal walking cycle are needed, including its nominal speed and motion profile. For the APEX mission, a nominal speed of 5 m/min is desired and a trapezoidal velocity profile employed, Figure 4.2-1.

To minimize the maximum required locomotion power, the cycle time, determined from nominal speed, and the joint displacements are used to determine appropriate

This paper focuses on the actuator design, including motor selection and gearbox ratio selection. These components must be carefully chosen if the goals of extended autonomy are to be achieved. This paper first presents an overview of the proposed missions and the Daedalus robot, then describes, in detail, the actuator sub-system.

## 2 Mission Overview

The Daedalus configuration is designed to accommodate two missions, an extended duration lunar mission and a long duration Earth mission. The purpose of the Earth mission is to develop a system capable of performing long-duration, autonomous planetary exploration. Development for the Earth mission has commenced. Although the Daedalus robot itself is not space-qualified, only those component systems that are potentially space qualifiable are utilized.

Earth-based missions serve as analogs for lunar missions by simulating the operating conditions, terrains and interactions. Daedalus will be tested in the south-western US desert because the extreme ruggedness of the terrain is similar to that found on the moon. Candidate sites include Death Valley, CA, Kelso, CA and Cinder Lake, AZ. The goal of the earth mission is a multi-day, multi-kilometer, autonomous traverse of a region while performing selected scientific experiments. During this mission, every effort will be taken to simulate the actual conditions that would exist for a lunar mission, such as data rates, interactions with the robot, etc.

Lunar mission goals include the exploration of the lunar surface, performing lunar surface scientific experiments, site certification for follow-on missions and exploration of interesting formations such as volcanic vents, impact craters and lava tubes. Unless the lunar rover has the capability of storing large amounts of energy, or unless it possesses radioactive heat sources, the longest mission will last one lunar day (14 terran days) since the cold night temperature may damage certain system components. During the course of this mission, the rover is expected to cover upwards of 100 km over a variety of terrains.

**Figure 3-1 Daedalus**

# Drivetrain Design, Incorporating Redundancy, for an Autonomous Walking Robot

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## Abstract:

An often overlooked, though critical, component of a mobile robot is the drivetrain. To achieve the ambitious programmatic goals of an extra-terrestrial, planetary robotic explorer, a rover's drivetrain must be both highly efficient and robust. This paper describes the design of the drivetrain for the Daedalus robot. This drivetrain uses a maximally efficient gearing ratio and redundant components to achieve the stated goals of efficiency and reliability.

## 1 Introduction

Carnegie Mellon University's Autonomous Planetary Exploration Program (APEX) is currently building the Daedalus robot; a system capable of performing extended autonomous planetary exploration missions. Extended autonomy is an important capability because the initial exploration of the moon, Mars and other solid bodies within the solar system will probably be carried out by autonomous robotic systems. There are a number of reasons for this - the most important of which are the high cost of placing a man in space, the high risk associated with human exploration and communication delays that make teleoperation infeasible.

The Daedalus robot represents an evolutionary approach to robot design and incorporates key features from a number of predecessor systems, such as the CMU Ambler, the Martin Marietta frame-walker and others. Among other features, Daedalus combines the Ambler-derived orthogonal-leg design and the Martin walking-beam concept. Using technologies previously proven, on Earth, ensures that the required goals of reliability, terrainability and space relevance will be achieved.

In the course of developing Daedalus, a number of issues were highlighted and resolved. These issues include the ability to space-qualify the robotic system, to design a power and mass efficient robot for carrying out scientific experiments, to economically deliver the robotic system on-board a commercial launch vehicle, to develop robust software capable of functioning for periods of weeks, to develop a system capable of stand-alone exploration missions and to enable planetary exploration by providing a general framework for autonomous mission planning.

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