Dual-Axis Drive for a Mars Rover

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Abstract

Conventional Mars rover designs incorporate complicated drive systems. In order to reduce weight, complexity and power consumption, it may be beneficial to consolidate the orthogonal functions of wheel-walking and steering into a single drive. The simultaneous operation of both steering and wheel-walking is not required. This paper demonstrates the concept of a dual-axis drive through the design and construction of a scaled prototype. The final design is novel in employing a linear actuator which is eccentric to both axes of motion. A switching and locking mechanism provides transfer between the two different functions at multiple angular positions.

Key Words: Mars Rover, drive train, wheel-walking, linear actuator

1. Introduction

Mars exploration has been a possibility for a relatively short time. Nevertheless, humankind has had over 40 missions to Mars, with an uninspiring success rate of less than 50% [1]. The practice of getting a rover to the surface of Mars is difficult enough; even more difficult is ensuring that the rover will operate as predicted. As extreme demands are placed on the exploration equipment, the reliability of the rover should be of utmost concern. With design goals being of the highest standards possible, the challenge is to optimize existing design and increase mission success. Our client, MDA MacDonald Dettwiller Robotics (MDA herein), seeks to improve standards for flight-ready Mars rovers. One way to achieve this is to simplify chassis design.

1.1 Existing Design

Virtually all Mars rover designs have complicated motion control systems. In many cases the reason for this is to provide the ability to *wheel-walk*, a method of propulsion where the centre of a wheel is propelled forward relative to the rover body by a rotating radius arm. Another reason is to provide all of the wheels the ability to steer independently. One of the most common rover designs has been of the multi-wheel type, where the forward and aft wheels each employ three rotary actuators: one to drive the wheel, one to steer the wheel, and one to provide wheel-walking; while the middle wheels employ two actuators: one to drive and the other to steer the wheel (Fig. 1 illustrates a typical wheel walking system [2]). This traditional setup is straight-forward, but cluttered. For a typical six-wheel rover, this results in up to 15 actuators to provide basic motion. Added to this the associated gear-boxes and control circuitry, which represent a significant amount of weight and complexity of the overall system.

In this traditional design, there is room for improvement. With the goal of reducing complexity, weight, and energy usage, it may be beneficial to consolidate the functions of wheel-walking and steering into a single drive. A mechanism to switch control of either axis is part of this solution. It is thus the objective of the project, described in this paper, to build and test a single prototype drive that has the ability to manipulate two different axes of motion.

1.2 Project Parameters

As set by MDA, the prototype is to demonstrate the following operating specifications: for steering, a range of ±45°, an angular velocity of $15^{\circ}\text{sec}^{-1}$, and a minimum torque of 5 Nm; for wheel walking, a range of ±30° at 5°sec^{-1}

and a minimum of 20 Nm torque. In achieving these tasks, the foremost criteria are lightweight, low power consumption and compactness of mechanism design. As some kind of actuation is necessary to switch between the two functions, the design may use a low power-draw device. The simultaneous operation of both axes need not be considered. The objective is to prove the concept of the dual-axis drive; the final design need not involve space-ready materials or packaging, but should be able to be scaled up for the client's practical applications.

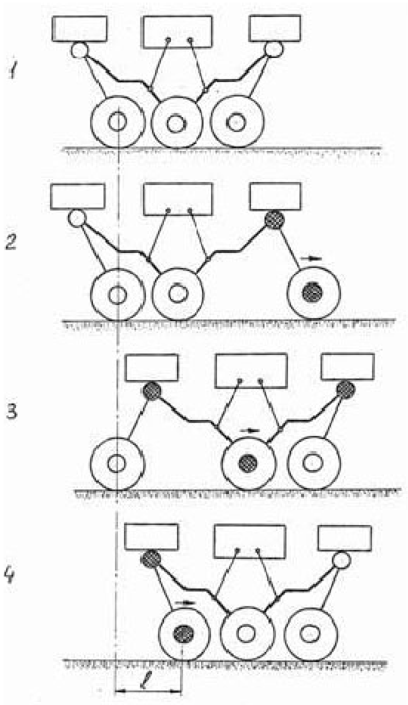


Fig.1. Multi-wheel Mars rover

2. Concept Generation

The project involved an extensive concept-generation phase, and the entire process was of an iterative nature. Initial research was done on different space exploration missions, and a set of general design challenges was assembled to help judge what solutions would be appropriate. The main criteria (in order of importance) were found to be: minimal weight and size, reliability of all critical systems, efficient power utilization and transmission, ability to maneuver in a majority of terrain, and the ability to pack and unpack the system.

2.1 Initial Concepts

During the initial phase of concept generation, two types of concepts emerged: one employed a rotary actuator, the other a linear actuator. The former concept placed a traditional rotary actuator along the axis of walking, and through a set of gears transmitted power to either axis of motion. The linear actuator concept, detailed in Fig.2, used a linear actuator whose line of action is eccentric and nearly perpendicular to both the steering and walking axes. To activate walking, a mechanism would lock the steering axis while the walking axis is free. To activate steering, the same mechanism would lock the walking axis and unlock steering.

Upon evaluation of these concepts, it was decided to pursue development of the linear actuator setup. The reasons for this were threefold: to avoid the high mass associated with a required gear box for a rotary actuator, to get advantages of the inherent efficiency benefits of a linear ball screw versus a rotary actuator, and to provide the functionality of having wheel walking at virtually any steering angle (herein referred to as "*steering above walking*").

2.1.1 Linear vs. Rotary Actuation

While a rotary actuator itself is extremely desirable from a packaging standpoint, its gearbox is not. Small rotary actuators operate at high angular velocities, and the required gearbox significantly increases the dimensions of the actuator assembly as well as decreases the operating efficiency. By comparison, a linear ball-screw actuator (typically above 90% efficiency) does not require a gearbox. Furthermore, given the lack of designs that employ linear actuators, it was the expressed will of the client to explore this option.

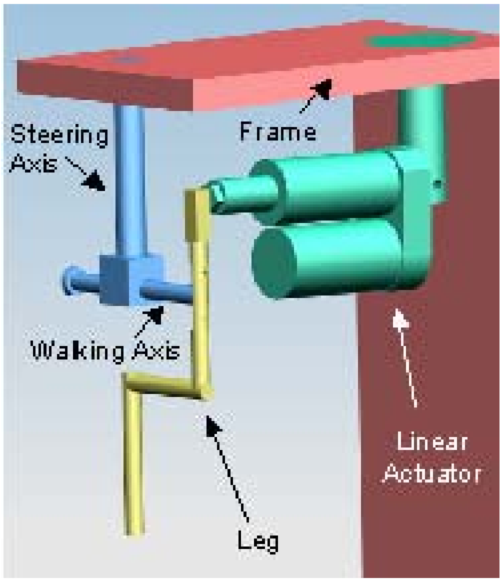


Fig.2. Linear actuator concept

2.1.2 Steering above Walking

Concerning the broader mode of operation, it was deemed more beneficial to have steering functionally independent of walking. This means the leg is steered about the body, but the walking action is done about the steering axis: for virtually any steering orientation, the rover can wheel-walk. Such a setup allows for greater maneuverability and better stability on sloped surfaces, allowing the rover to "crab" diagonally. This is not the case for a conventional rover design, where wheel-walking can only be performed perpendicular to the body.

2.2 Development of Linear Concept

Once linear actuation was chosen, further development efforts focused on the switching mechanism. Though not adequately addressed in the initial concept generation, the switching and locking mechanism unquestionably represents a fundamental component of this design. Its function as a purely transitional device means that it must draw very little power and be useful for a wide range of motion. Our final solution resulted from brainstorming with a host of proposed locking methods: cable disk brakes, electro-magnets, gears, interlocking pins, and friction pads. A set of evaluation criteria was developed to help select the design of the mechanism, where focus was on manufacturability, the ability to resist torque, ease of switching and the simplicity of the device, power consumption, compactness, and the range of available locking positions.

Based on these criteria, a final design for the locking mechanism was conceived: an internal/external gear setup provides the locking for the steering axis, while two indexed plates with pins and holes lock the walking axis. This combination provides an acceptable interval of locking positions and is extremely reliable in terms of strength. Furthermore, the system only requires power during transition between drives. With the concept fully defined, it is necessary to explore the intricacies of the design.

3. Final Design Description

As stated, our solution to the dual-axis drive, shown in Figs.3, employs a linear actuator which is eccentric and nearly orthogonal to both axes of motion. As can be seen, the chosen actuator is relatively oversized; for a space ready system, a more sophisticated and compact model should be designed. The actuator's retracted and extended positions correspond to angular extremities in both steering and walking.

To activate wheel-walking, a switching mechanism locks the steering axis while the walking axis is free. To activate steering, the same mechanism locks the walking axis and unlocks steering. Upon switching, both drives are locked to ensure stability. The mechanism allows for power transmission at multiple angular positions.

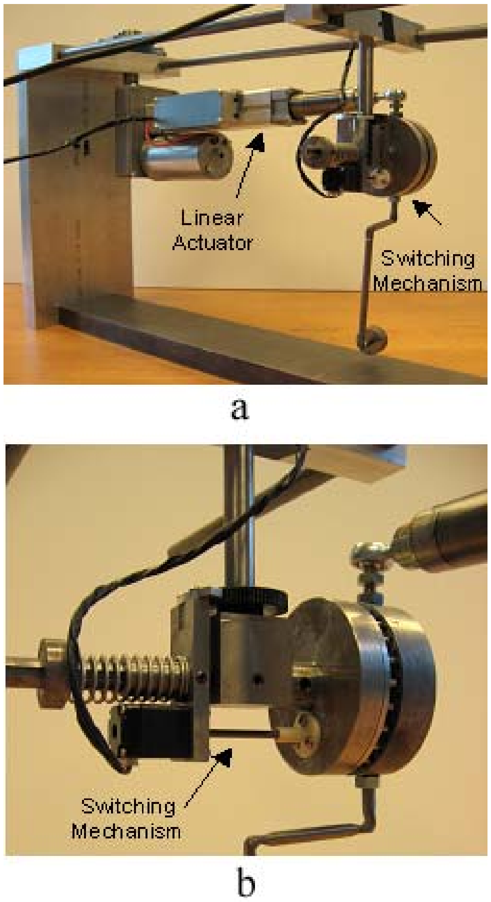


Fig.3. Built prototype: a) General view;
b) Switching/Locking Mechanism

3.1 Main Actuator Subassembly

The main linear actuator powers the steering and walking functions. As can be seen in Fig.3, the distal end of the actuator is connected to the leg subassembly through the use of a ball joint. In order to provide two-axis motion of the leg, the actuator movement is required to have two degrees of freedom with respect to the frame translation and rotation. The rotation is achieved by connecting the proximal end to a pin and clevis. The clevis is in turn connected to a bearing which is attached to the frame.

3.2 Switching Mechanism

The switching mechanism (Fig.4) is the most complicated component in the prototype. It contains the orthogonal axles about which steering (axle A) and wheel-walking (axle C) are performed. An inherent feature of this subassembly is that it provides locking of the dormant axis. Axle A is rigidly attached to the external frame. Connected to this rod is block B to which all other components in this assembly will be directly or indirectly attached. Such that it may rotate freely about the steering axis, block B has an internal bearing. The wheel-walking axis C is set-screwed into block B. The spring along this axis is referred to as the walk-axis spring. Two interlocking plates F contain a set of regularly spaced spring loaded pins that mate with indexed holes. This provides the locking mechanism for walking mode. The outermost plate also contains the ball joint connection, which mates the leg with the actuator. As well, embedded inside this plate is a bearing that allows the leg to freely walk about shaft C. Internal/external gears D and E provide locking for steering.

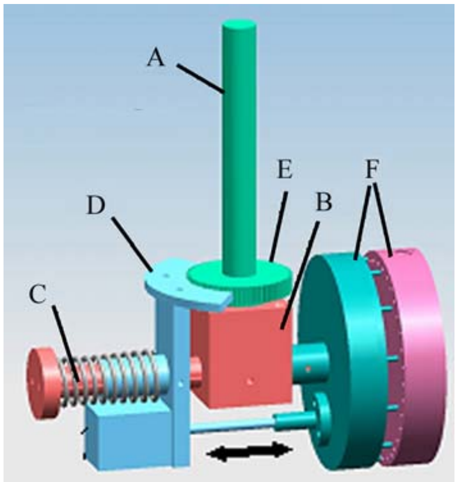


Fig.4. Switching Mechanism

To explain the operation of the locking mechanism, consider Fig.5a, where the pins are engaged and the walking axis is locked (the steering axis is free). Powering the switching actuator, its screw length shortens and the walk-axis spring on shaft C extends from a compressed position allowing the steer-lock gear to move forward, so that it meshes with its external counterpart. All this occurs without the walking-lock moving (Position 2, Fig.5b). Once the internal/external gears are mated, the small actuator continues to shorten, pulls the plate of the walking-lock back and disconnects the pins from the holes (Position 3, Fig.5c).

Concerning the operation of the walking lock, if the two plates are lined up at one of the 5º hole increments, the pin/hole arrangement will engage and locking is achieved. In a case of misalignment, the Main Linear Actuator may have to be adjusted until the holes and pins line up. This can be controlled using knowledge of angular positions (i.e. an angular encoder), and is a small drawback of this design. Once the pins are engaged (Position 2), both locks are engaged to ensure the mechanical stability of the system. The selection of the walk-axis spring, the indexed springs, and the switching actuator are interlinked, as the force exerted by the small linear actuator must be adequate to compress all the springs to their required lengths.

3.2.1 Analysis of walking lock

Referring again to Fig.5c, upon advancement of the switching actuator, plate F slides along the walking axis and its spring loaded pins engage with the complementary holes. There are 24 spring-loaded and indexed pins that fit into the innermost plate (one every 15°), and 36 indexed holes in the outermost plate (one every 10°). This allows for the engagement of 12 pins and holes for every 5 degrees. The remaining 12 pins will be pushed into recessions. It was found that the selected pins each experience a shear stress of 5Mpa, which is well within the shear strength of mild steel of 350MPA.

3.2.2 Analysis of steering lock

At any given orientation, the torque requirements for either axis of motion give the torque requirement for the locking mechanisms. According to the initial requirement, when the steering axis is locked, the mechanism has to withstand the forces associated with a walking torque of 20Nm. The walking lock has to withstand the force involved with a steering torque of 5Nm. Actual torques depend on the radius arms associated with each axis. For the suggested design the lock torques were found to be 22Nm for the steering lock, and 4.6Nm for the walking lock, which is within the acceptable deviation from the specifications.

Locking of the steering axis is provided by sliding the internal gear towards the external gear which is attached to shaft A. It should be noted that internal spur gear teeth may interfere with external ones when the pinion gear is too close in size to its mating internal gear. It was found that for a 20° pressure angle, the difference in tooth numbers (per gear) between the gear and pinion should not be less than 12 [3]. It is also relevant to analyze the contact forces of the two mating gears. Fig.7 shows the top view of this internal-external gear pair.

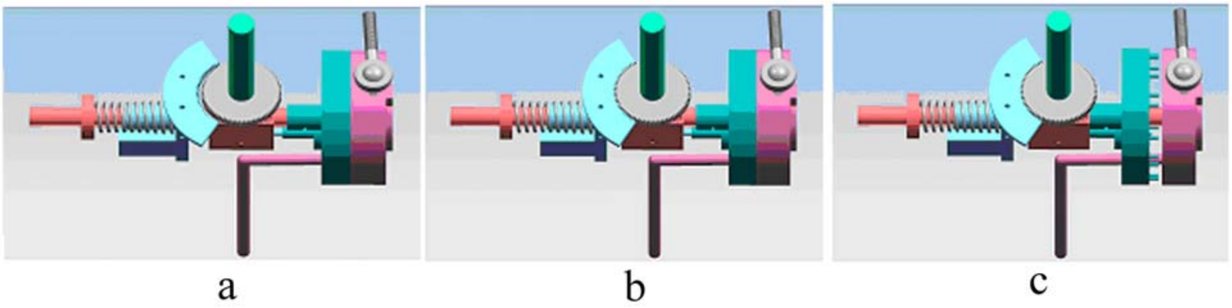


Fig.5. Switching operation steps. **a.** Walking axis locked, steering axis free. **b.** Both axes locked. **c.** Walking axis free, Steering axis locked.

The pressure line profiles are the lines of action of the contact force for each meshed gear-tooth pair. While there are force components in the **X** direction (i.e. along the axis of walking), these components add up to zero and the net exerted force is only in **Y**. This means that choice of the spring used to control the actuation of this locking mechanism along **X** need not concern these contact forces. The **Y** components of these contact forces are not negligible, however. The set-screw-pegs that run along grooves in shaft C (Fig.4) should counter any moment created by these components about the axis of walking. Given that we foresee a maximum of 22Nm about this axis, at 3mm the pegs are deep enough to overcome this counter-moment. It was calculated from the Lewis formula for gear failure, that the max load per tooth for these gears is approximately 160N [4]. The total contact force is roughly 1000N, and that divided by 10 meshed gear teeth gives a failure safety factor of 1.6 [5].

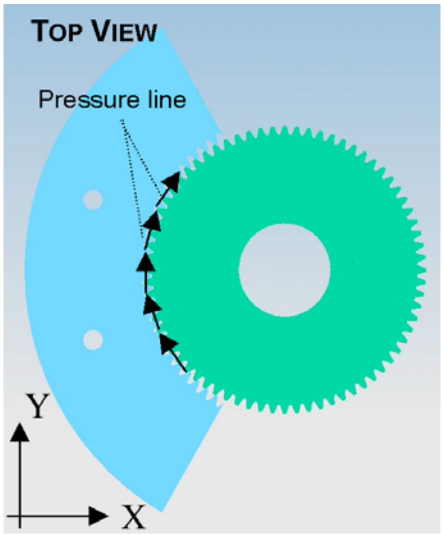


Fig.6. Steering Lock detail

3.3 Leg Subassembly

This subassembly contains the leg of the Mars rover and its connection to the rest of the mechanism. In Fig.7, the annulus at the top of the assembly is the female half of the ball joint connection to the Main Linear Actuator, where axis A-A is the line of action of the actuator. This ball joint was chosen to have a conical movement of over 50°; 30° is required for this application. The entire subassembly rotates about the walking-axis (axis B-B), which connects to the walking-axis shaft through a ball-bearing that is set-screwed inside the circular plate.

It should be noted that the walking and steering axles and bearings also bear the load of the switching mechanism. An analysis with Unigraphics software gave an estimated Martian weight of roughly 5N for the components (excluding the actuator, whose load is taken by a bearing in the frame). Moments created by this weight were assumed to be negligible.

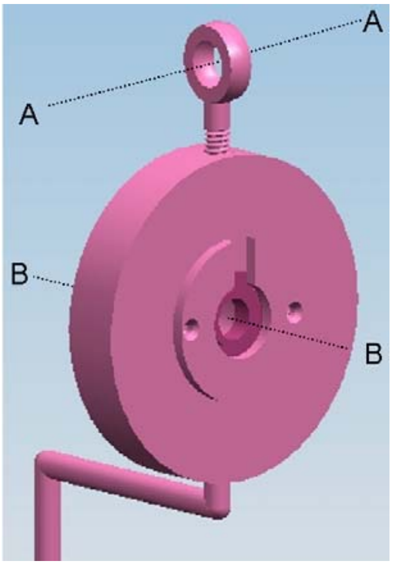


Fig.7. Leg subassembly

4. Kinematics Analysis

In order to prove our concept and satisfy the given performance requirements, an analysis detailing the kinematics characteristics of the design is essential. An initial assumption was made. It was assumed that the client would desire constant angular speed for either steering or walking. Then, the challenge of using linear actuation to produce rotary motion involves relating the linear characteristics of the actuator to the angular movement of the leg. In such a case, the linear speed of the actuator becomes a function of the steering angle, the walking angle, and the geometry of the system. In the following paragraphs, a brief description of the development of these relationships will be outlined. All vector and geometric parameter definitions are given in Fig.8 and Table 1.

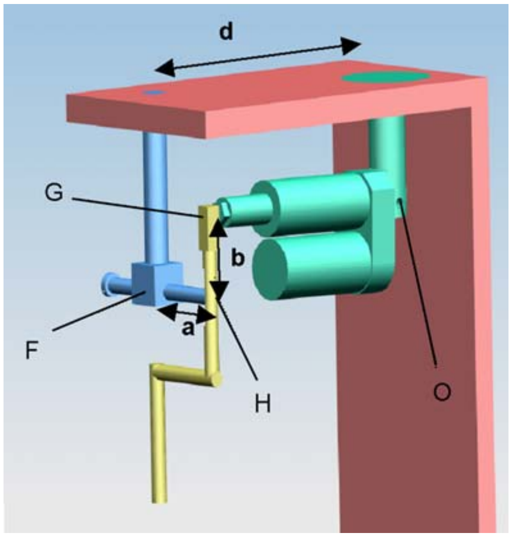


Fig.8. Definition of geometric variables

Table 1

a	Steering radius arm (vector FH)
b	Walking radius arm (vector HG)
d	Displacement between O and G
O	Attachment bet. actuator and rover
F	Attachment bet. steering and walking axes
G	Attachment bet. actuator and leg
H	Attachment bet. walking axis and leg
Θ	The walking angle
Φ	The steering angle
S	Required actuator stroke length
V	General actuator linear speed
V_s	Actuator linear speed in steering
V_w	Actuator linear speed in walking
F	General actuator supply force
F_s	Actuator supply force in steering
F_w	Actuator supply force in walking

The geometric parameters **a, b,** and **d** largely depend on the performance and behaviour of the actuator. Packaging concerns also impose constraints. Specifically, the steering radius arm **a** must be large enough to contain the switching mechanism. Similarly, parameter **d** must accommodate the main actuator housing. We must also understand relations between **a**, **b**, **d**, the collapsed length, and the stroke **S** of the actuator.

In developing the kinematics relations, we must impose a condition on the geometry such that the system will not bind at the extreme ranges of motion. This is satisfied when the actuator line of action has zero pitch at extreme walking positions and zero steering angle. Symbolically, this can be expressed as follows:

$$OG_z\left(\theta = \pm 30^\circ, \phi = 0^\circ\right) = 0$$

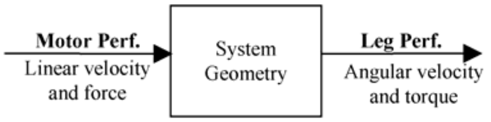
Similarly, for the extreme steering position and zero walking angle, the line of action should have zero yaw.

$$OG_y\left(\theta = 0^\circ, \phi = \pm 45^\circ\right) = 0$$

These two restrictions allow expression of $\overrightarrow{OG}$ solely in terms of the geometric parameters (**a**, **b**, and **d**) and the generalized coordinates (θ, φ), where:

$$\overrightarrow{OG} = \begin{bmatrix} d + a\sin\phi + b\sin\theta\cos\phi \\ a\cos\left(45^\circ\right) - a\cos\phi + b\sin\theta\sin\phi \\ b\cos\left(30^\circ\right) - b\cos\theta \end{bmatrix}$$

This is of particular use since this vector represents the line of action of the actuator. From this, the relevant expressions for angular velocity and torque can be expressed in terms of known quantities. For brevity the detailed development of these equations has been omitted [5]. The resulting equations are presented in Fig.9.



$$\frac{V_w\left\|\overrightarrow{OG}\right\|}{OG_x\left(b\Omega\Psi\right) + OG_y\left(b\Omega\Phi\right)} = \dot{\theta}$$

$$\frac{V_s\left\|\overrightarrow{OG}\right\|}{OG_x\left(a\Omega - b\Theta\Phi\right) + OG_y\left(a\Phi + b\Theta\Psi\right) + OG_z\left(b\Phi\right)} = \dot{\phi}$$

$$\frac{F_s}{\left\|\overrightarrow{OG}\right\|}\left[OG_x\left(-a\Psi + b\Phi\Theta\right) - OG_y\left(a\Phi + b\Psi\Theta\right)\right] = T_s$$

$$\frac{F_w \cdot b}{\left\|\overrightarrow{OG}\right\|}\left[\Theta\left(OG_y\Omega + OG_z\Phi\Theta\right) + \Psi\left(OG_z\Theta\Psi + OG_x\Omega\right)\right] = T_w$$

where cosθ=Ω, cosφ=Ψ, sinθ=Θ, sinφ=Φ

Fig.9. Input/Output relations

With knowledge of these governing kinematics relations, an iterative process was used to select a linear actuator which would satisfy the performance requirements. This was done by incorporating the relations into several Matlab programs to achieve optimal geometric properties and motor performance characteristics. The programs were particularly useful during preliminary design in providing presentation of the systems behavior. The results of the Matlab code are presented in Fig.10.

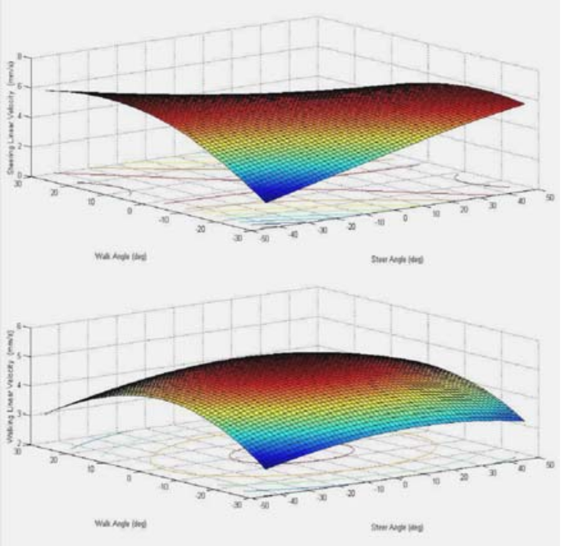


Fig.10. Force surfaces from Matlab code

In Fig.10 the vertical axes are actuator velocity, while the horizontal axes are the walking (left) and the steering (right) angles of the leg. The top chart shows the velocity profile for steering, the bottom for walking. From this figure it can be seen that a) there is a minimum linear velocity that must be met for both modes, and b) the linear velocity varies constantly and is a function of both θ and φ. As the leg is functioning near an angular extremity, the actuator velocity is slowest.

Similar to velocity, graphical results were obtained which verified that the chosen actuator would satisfy the given torque requirements. In Fig.11 the vertical axes are torque, and the horizontal axes are walking (left) and steering (right) angles. From the chosen actuator, there is a maximum available linear force of 800N. It can be seen that the minimum required torque is satisfied at each angular extremity, i.e. at each four corners of the torque surface, where the most force from the actuator is required. More force is required at these extremities because of deviance from an applied perpendicular force at zero angles.

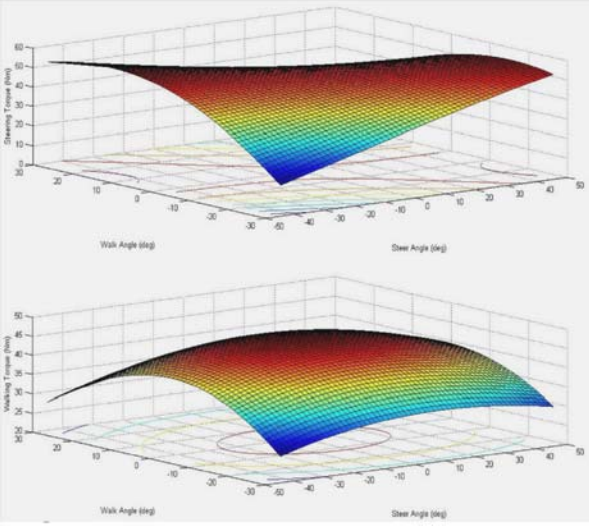


Fig.11. Torque surfaces from Matlab code

This exercise was instrumental in pairing an actuator with appropriate dimensions for our design. Its results are also used as proof of concept when evaluating the project using the given performance criteria.

5. Recommendations/Conclusions

As the objective of this project was to prove the concept of a dual-axis drive, there are a few aspects of our final design upon which further improvement could be made. Namely, the switching and locking mechanism could benefit from a reduction in complexity and mass. In fact, a suitable project would be the optimal design of such a switching mechanism. Furthermore, a space-ready design would need a more sophisticated actuator design. As the conditions of a Mars environment were always considered during the design process, it should be noted that the prototype is envisioned to be well contained in a shielded area above or below the main body. Space would be required for the actuator and leg to move, but given the compactness of the assembly, this wouldn't be a major concern. Finally, to impose constant rotational speed of the steering and walking axes with variable linear actuator speed may present both unreasonable and unnecessary complications to the control system. It should be investigated whether employing constant linear actuator speeds with variable rotational speeds offers a reasonable alternative.

This dual-axis drive concept provides a novel approach towards the evolution of unmanned space vehicles. First, the employment of an optimally- designed linear actuator to provide wheel motion could provide several important advancements. Increased power efficiency would be the main result, and values up to 90% are possible [4]. Where a typical Mars rover needs to use as little energy as possible, this is a significant improvement over current design. Furthermore, weight savings could be achieved by combining two motors into one, as well as by freeing the design of the required gearboxes of rotary actuators. Second, the functionality of "steering over walking" in the design is another significant result of this project. This unique configuration leads to greater maneuverability and stability when overcoming sloped terrain. Any improvement in movement capability is also an improvement in mission success. Both of these points will hopefully provide for significant increases in the future reliability, capability of future rover designs.

6. References

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