Nomad: A Demonstration of the Transforming Chassis

E. Rollins, J. Luntz, A. Foessel, B. Shamah, and W. Whittaker
Robotics Institute
Carnegie Mellon University
Pittsburgh, PA, USA 15213

Abstract

During the Summer of 1997 - Nomad - a planetary-relevant mobile robot, was driven via satellite link for more than 125 miles in the Atacama Desert of Chile by novice operators in North America, demonstrating many technologies relevant to robotic exploration of the planets. An innovative "transforming" chassis was demonstrated which uses a simple linkage to change the footprint of the vehicle from a stowed to a deployed position. This linkage also enables both double Ackerman and point-turn steering. This paper presents details on the design of the transforming chassis including kinematic analysis used in low and high level control.

1 Introduction

Interest in the exploration of the planets and moons of our solar system is growing. Robotic explorers are ideal for long-duration exploration of such harsh and unknown environments. These environments present challenges for communication, sensing, autonomy, power, and locomotion systems. In order to develop robotic explorers qualified for these challenges, it is necessary to first test them in analogous missions on the earth. Harsh environments such as the deserts and polar regions of Earth offer accessible proving grounds for such experiments.

During June and July of 1997 *Nomad*, a lunar rover prototype developed at Carnegie Mellon University, made the longest teleoperated cross-country traverse ever accomplished by a robot - 138 miles through the Atacama Desert in northern Chile. Nomad was driven via satellite for most of its journey by team members and the general public at Pittsburgh's Carnegie Science Center, the University of Chile, NASA Ames Research Center, and even from their own homes through Pittsburgh Public Television using the telephone. This field experiment successfully demonstrated several technologies slated by NASA to be included in future planetary exploration missions. Among these technologies were a new imaging device - the *panospheric camera*, a high-performance antenna pointing device for high bandwidth communication, remote geological investigation, and safeguarded and autonomous modes of driving.

In order to accomplish its journey, Nomad needed a locomotion system capable of tackling the planetary-analog terrain of the Atacama desert while carrying all of the necessary equipment for the rest of the task. The special demands of the terrain combined with geometric constraints on the robot required a new chassis, the motivation, design, and kinematic analysis of which is the focus of this paper.

2 Previous Relevant Rover Designs

In 1970, the unmanned Soviet rover Lunakhod traversed 10km of the Lunar surface, collecting data. Lunakhod, with a fixed wheel base and skid steering, was constructed with eight self-contained electrically powered wheel modules. The idea of self-contained wheel modules has become the standard for planetary-relevant vehicles. Later, the LRV rover also made a lunar excursion, driven by American astronauts. This rover had four-wheel Ackerman steering and was expandable from a stowed position to a deployed position. Astronauts manually unfolded "outriggers" holding the wheel and steering modules, providing a larger, more stable wheelbase than would have fit in the landing module. More recently, JPL's Rocky series of micro-rovers [3, 4], which lead to the production of the Martian rover Sojourner, used four-wheel explicit steering on a six wheel rocker-bogie suspension. The suspension allows the Rocky rovers to tackle large obstacles with relatively smooth body motions. Sandia's rover, Ratler [5], used a four wheel bogie suspension with skid steering.

Nomad combines the concepts of Lunakhod's wheel modules and Ratler and Rocky's bogie suspensions with a new linkage to provide both explicit steering, as used by LRV and Rocky, and an automatic version of LRV expanding wheelbase. Nomad's *transforming chassis* automatically expands the wheelbase from a stowed to a deployed position with the same actuators used for steering.

3 Motivation

Two factors motivated the unique design of the transforming chassis of Nomad, both involving volumetric constraints. The first is a constraint on the overall size of the robot, and the second is a constraint on parts within Nomad.

The design constraint for the size of Nomad was generated from a proposed plan to explore the moon with two large rovers transported by a Saturn V rocket. The payload faring constrains each rover's footprint to 72" × 72".

The Moon's surface is bombarded by a constant shower of micrometeorites. creating a deep, loose layer of fine dust that covers much of the surface. A lunar vehicle's wheels must be sufficiently large to "float" on rather than sink into the soil. In fact, such sinking ended the mission of the Soviet rover Lunakhod. A set of equations was developed by Bekker[2] which empirically represent the behavior of wheels in soils of varying composition. These equations were applied by Apostolopoulos [1] to the problem of Nomad's wheels floating in lunar soil, and determined optimal wheel size of 30" diameter and 18" width, along with parameters such as balancing sinkage, traction, and locomotive power draw. (This analysis will be presented in a future paper by Shamah, et.al.)

Four wheels of this size occupy a significant portion of Nomad's lower volume. This forces other components to be placed higher raising the vehicles center of gravity and reducing its stability. Further volume would be occupied by the wheels as they are rotated by a standard explicit steering mechanism. It is important that as much of this lower volume be used for heavy components to keep a low center of gravity.

This motivated an investigation of alternative steering mechanisms that could steer explicitly without sacrificing internal space by moving the wheels away from the body as they steered. A four bar linkage with this property was developed which had the additional property of producing two positions in which the wheels point straight ahead. For Nomad, the first such position is the original, *stowed* position. The second such position is the *deployed* position about which the wheels are steered. Figure 1 shows this linkage in the stowed and deployed positions. Figure 2 shows the range of steering angles around the deployed position including the point turn position.

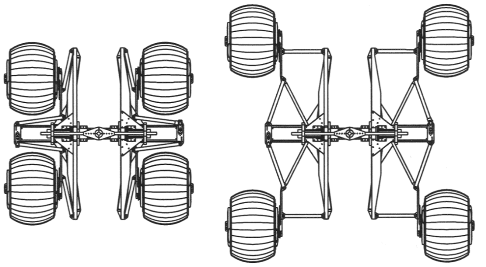

Figure 1: Nomad's transforming chassis in stowed (left) and deployed(right) positions.

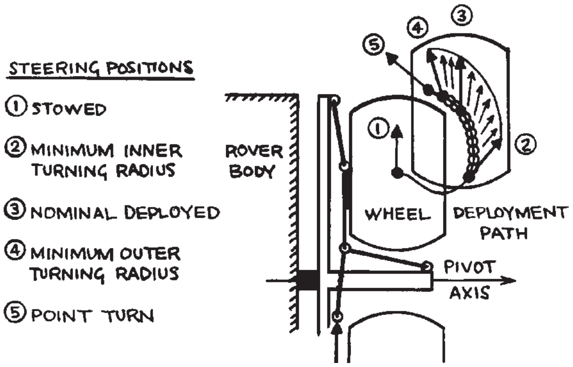

Figure 2: Positions and steering range for Nomad's transforming chassis

Nomad's *transforming chassis* enables explicit steering while keeping a low center of gravity and expanding the footprint of the robot into a deployed position, increasing stability. Nomad can exit a lunar lander by driving straight ahead and using skid-steering in the stowed position until it is clear of lander and can transform into the more stable and mobile deployed position for the remainder of its mission.

4 System Design

The *transforming chassis* along with the *averaging suspension system* and the self contained *wheel modules* make up the locomotion system of Nomad. These systems are described below.

4.1 Wheel Module

Each of Nomad's wheels is a self contained system consisting of a tire, hubs, axle, motor and harmonic drive. All of these components are sealed inside a aluminum tire and are physically independent from the rest of the robot. The tires have grousers to improve traction.

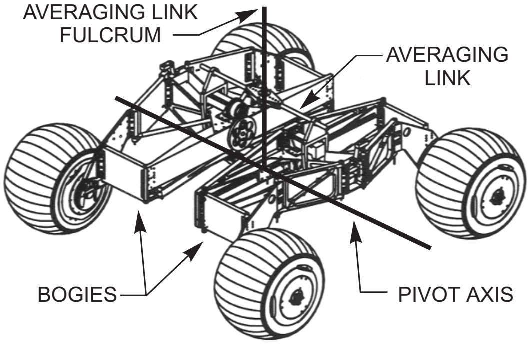

Figure 3: Nomad's averaging system, consisting of bogies and an averaging link

4.2 Averaging System

The averaging system acts as a suspension smoothing the motions of the robot's body relative to the motions of its wheels. The two wheels on each side of the rover are attached through the steering system to a bogie which pitches relative to the body about a central axis (see Figure 3). This allows all four wheels to rest on the ground regardless of the terrain. With the pivot placed in the middle of each bogie, the vertical excursion of the pivot is the average vertical excursion of that bogie's two wheels. A similar averaging is experienced across the rover's body. Therefore the center of the body lifts by an amount equal to the average vertical excursion of all four wheels. The pitch of the body is fixed at the average of the pitches of the two bogies by the averaging link. This pitch, roll, and vertical averaging reducing the effects of rough terrain on the rover body and its components. The following photograph shows the right front wheel perched on a large rock (Figure 4) while the other wheels remain on flat ground.

4.3 Steering System

Nomad can steer by three methods: skid steering, double Ackerman, and point turning. Skid steering is used only to position the robot for deployment, and is considered a backup mode for use in the case that steering motors fail. Point turn mode is best used for reversing direction when progress is blocked. The preferred mode of steering for Nomad is double Ackerman. This is accomplished by two pairs of four-bar linkages - one pair on each of the two bogies. A pushrod is attached to one axis of each output link. These rods are driven by two racks which are pulled in opposite directions by a single pinion placed between the two linkages. The axle of each wheel module is rigidly attached perpendicular to each of the four output links so that the steering angle is equal to the angle of the output links.

Figure 4: Nomad perches on a rock, demonstrating the averaging suspension and the stability-enhancing large footprint

The sizing of the transforming chassis linkage was accomplished by graphical methods with the following goals:

- Accommodate wheels 30" dia. × 18" width
- Enable point turns
- Limit steering actuator loading
- Minimize volume occupied by mechanism
- Limit non-deployed size to 72" × 72"
- Maximize deployed footprint size
- Limit minimum turning radius to no larger than one non-deployed vehicle width

With an overall length limit of 72", accommodating two wheel diameters on the side leaves 12" of space between. To accommodate cabling, support and actuation between the wheels, another 6" is consumed. This leaves 3" each for linkage element behind and in front of wheels. Similarly, accommodating an electric generator in the center of the rover leaves 9" on each side for linkage elements. Turning radius depends both on steering angle and wheel position (see Figure 5). Therefore, minimizing turning radius was an iterative process, requiring the simultaneous consideration of both wheel position and steering angle at the extreme steering position. Similar considerations were

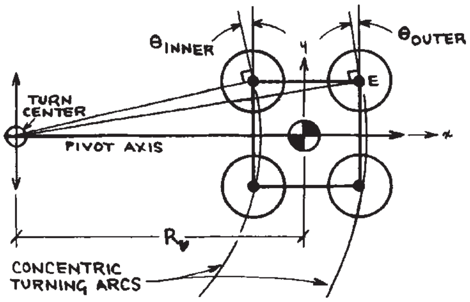

Figure 5: Nomad's turning radius is a function of wheel position and steering angle

necessary to enable point turns. To enable a turning radius of 72", the resulting steering angle of the inner pair of wheels at the extreme position is 33°. To enable a point turn at the other extreme of turning, the resulting angle is 49°.

In the first stages of deployment much of the motion is sideways sliding rather than forward rolling, putting large loads on the steering actuators. In addition, one part of the linkage starts at an angle near a singularity, further increasing loads on the actuators. This situation improves with the increase of this starting angle. However, a large starting angle for this link widens the mechanism in the stowed position, taking up more volume from the body. A balance between these two constraints gives a satisfactory mechanism volume without overloading the steering actuators. Finally, larger links provide a greater deployed footprint, so the links were scaled to be as large as possible while still accommodating the other requirements. The stowed footprint is 72"× 72", while the deployed footprint becomes 96" × 96", greatly improving Nomad's stability.

5 Kinematic Analysis

High-level control algorithms as well as human operators request the center of the robot to steer at a particular turning radius. The turning radius is a function of both the position and steering angle of the wheels. This, combined with the fact that the steering actuators act through a set of linkages, complicates the functional relationship between actuator commands and high-level commands. In order to implement control of Nomad's steering, a kinematic analysis of the linkage is necessary.

First, the case where all wheels lie in a plane is examined, and the relationship between actuator position and turning radius is established. Then, the case where the wheels rest on uneven terrain is considered by projecting the wheels positions into a plane and then calculating the turning radius.

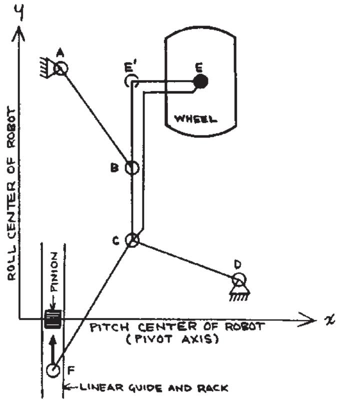

Figure 6: Schematic of one quarter of Nomad's steering system

5.1 2-Dimensional

Following is an analysis of one linkage set. This is mechanically linked to a mirror image linkage on the same side of the rover, and this system is duplicated on the other side. Figure 6 shows a schematic of the links that make up the four bar linkage that steers one wheel. The motion of point F is constrained in the x direction by a linear rail and is actuated by a rack and pinion in the y direction. The linkage is mirrored about the x axis such that this pinion drives both racks. Thus the motion of the two linkages is mechanically linked and the steering angles that are produced are equal. The steering mechanisms on each side of the vehicle are independent, and each must be positioned so that the two turning arcs are concentric, producing double-Ackerman steering. The turning center can also be placed at the center of the vehicle, enabling a point turn.

Turning radius commands from autonomous or user control must be transformed into actuator inputs (motions of point F) and wheel velocities. This is accomplished by calculating the turning radius as a function of the actuator input, computing the appropriate wheel velocity, and using lookup tables to reverse the calculations. The transformation must be done separately for each side of the vehicle since the inner and outer steering radii differ and a single steering radius for the center of the vehicle must be determined.

Using trigonometric relations, wheel position E and steering angle θ (see Figure 5) are computed as follows:

- Given input F_y, fixed position F_x, fixed point D, and link lengths CD and FC, determine position of C from triangle CDF.

- From the position of C, fixed point A, and link lengths AB and BC, find position B from triangle ABC.
- Calculate steering angle, θ, from the relative positions of B and C.
- Using θ, the position of B, and link lengths BE' and $E'E$, determine position E.

Figure 5 shows the relationship between turning radius, wheel position, and steering angle. Equations for calculating the vehicle turning radius R from both the inner (+) and the outer (−) wheel pairs are:

$$R = \frac{E_y}{\tan\theta} \pm E_x$$

When the radius calculated from the outer and inner sides matches the desired vehicle turning radius, the appropriate inner (−) and outer (+) wheel velocities, v are calculated based on the desired vehicle velocity, $v_{vehicle}$.

$$v = \frac{v_{vehicle}}{R}\sqrt{{E_y}^2 + (R \mp E_x)^2}$$

Physical limits of the steering mechanism restrict the Ackerman turning radius to a 72" minimum - one (non-deployed) vehicle width.

5.2 3-Dimensional

The above analysis describes the rover as it functions on flat ground. As it travels over uneven terrain, the system does not exist in a plane and must be considered as three bodies, rotating about the y-axis of the rover. The rover body is considered ground and bogie angle is defined as the angle of rotation of the bogie with respect to the rover body (see Figure 7). Likewise, turning radius is considered in the plane of the body.

The averaging mechanism forces the bogies to have equal and opposite bogie angle ϕ. With steering commands for the rover being given with respect to the global coordinate system, the positions and angle of each wheel must be related to the body coordinate system. Thus the effect of bogie angle ϕ on wheel position E as it is projected into the rover body plane is that of reducing its distance from the pivot axis - E_x remains the same, but E_y is shortened. Furthermore, the wheel centers and the pivot axis are not actually in the same plane but are separated by the vertical distance E_{z_o}. Unlike the symmetric ($\cos\phi$) effect of bogie angle ϕ with E_y on the wheel center location, the effect of bogie angle ϕ with E_{z_o} is to move both projected wheel locations in the same direction ($\sin\phi$) (see figure 7). The adjusted projected position, E' of the wheel center is:

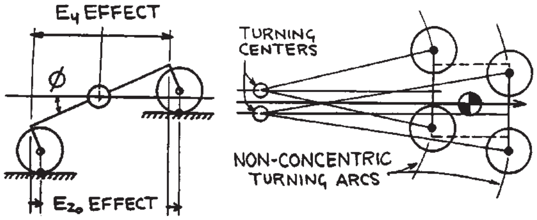

Figure 7: Out-of-plane motions of Nomad's wheels move the turning centers of both pairs of wheels

$$E'_x = E_x \qquad E'_y = E_y\cos\phi + E_{z_o}\sin\phi$$

The calculations above consider E as the position of the center point of the wheels, but the point at which the wheel contacts the ground is relevant to steering. The projection of these points into the body plane is coincident in the planar case, but not necessarily in the 3-dimensional case. Nomad, however, has no way of determining the location of the contact point, so the nominal case is assumed where the wheels contact the ground on a plane parallel to the body plane and tangent to the wheel, regardless of bogie angle. The projection of such a contact point is coincident with the projection of the wheel center, requiring no additional transformation to the position of E.

Since the wheels no longer steer about an axis normal to the body plane, an additional correction factor is necessary to adjust the steering angle, θ:

$$\tan\theta' = \cos\phi\tan\theta$$

The new effective steering center for a pair of wheels lies on a line shifted by the same amount the E'_y was shifted. The radius can be calculated from the 2-D case, using the adjusted wheel positions and steering angles. For the inner (−) and for the outer (+) wheel pairs, the new steering radius is:

$$R' = \frac{E_y + E_{z_o}\tan\phi}{\tan\theta} \pm E_x$$

Also, because the wheel "rolls" sideways on the ground as the bogie angle changes when the wheel is steered, the contact point is no longer at the radius of the wheel. The new contact point is closer to the wheel axis, so the wheel velocity must be adjusted.

Since the contact surface of the tire is spherical, the adjusted wheel velocity is

$$v' = \frac{1}{\cos\phi} v$$

Due to the fact that the projections of the wheel positions are no longer symmetric about the pivot axis but the effective steering angles of the two wheels on each side are still equal, the turning center of each side no longer lies on the pivot axis (see figure 7). Furthermore, the direction in which the turning center is transformed is opposite between the two sides, making it impossible to generate concentric steering arcs. Because of this mismatch, the moving rover wheels slip, making it impossible to accurately predict the true turning center. As a compromise the average turning center could be considered for steering commands (see figure 7), adding a dimension to the lookup table to accommodate adjustments for bogie angle.

At the bogie angle's physical limit of $\phi = 25°$ the difference in the pivot axis and the averaged turning center is fairly small. This leads to an error of less than 10% in the vehicle turning radius. Because of this small error, and the fact that this adjustment would be based on many assumptions about soil mechanics and weight distribution between the wheels, three dimensional effects are ignored.

5.3 Transient Locomotion Control

To maximize driving efficiency and minimize loading on structural members, turning on the fly instead of stopping and turning is desirable. Two factors, however, complicate this implementation. Because of the linkage system, the contact point of the wheel in relation to the body changes for changing turning radii, and the relation between the steering actuator rate and the change in turning radii is non-linear along the actuator range.

When the rover is directed to change its turning radius (the turning radius of its body), the steering linkage on each side must change by different amounts to maintain concentric arcs - the amount the left actuator must travel is different from the right. Further complicating the calculation is the non-linear nature of the four-bar steering linkage. Therefore, to change from one arc to another while maintaining concentricity, the control software implements a transient control that guarantees that at every moment, the instantaneous turning arcs of each side are concentric, avoiding wheel slippage and mechanism stress. This transient steering control is complemented by wheel speed coordination, generating velocities consistent with the rover speed and the turning radius at each side.

To achieve this steering and velocity matching, a feedback control strategy is used to monitor the position of the linkages as they change between steering radii. The desired rover turning radius is compared with the actual values obtained from encoders and the differences are fed back to both controllers. A cross check detects if one side is changing to its target radius faster than the other, and if so, a threshold triggers slowdown routines, keeping each side within 2% of its correct instantaneous turning radius. Combining this radius information with the target rover turn and speed yields the differential velocities required at each wheel. Of note, since the speed of the rover in a turn is roughly the average speed of the outer and inner pairs of wheels, the rover cannot attain maximum speed while turning. In fact, Nomad achieves the maximum design speed only when it is driving straight.

The result of the application of these strategies in locomotion control is the reduction of wheel slippage and mechanism loading, and smooth control through all possible turning radii. The implementation of this complicated strategy is important since Nomad takes about 15 seconds to adjust its steering angle from one extreme to the other.

6 Performance

The primary goal of traversing 125 km under the direction of distant operators, operating through satellite connections was met. Two design flaws prevented a perfect performance from the locomotion system. Rocks occasionally became wedged between the inner hub of the wheel and the wheel-link, causing severe abrasion and in some cases punctures to the hub and damage to bearing seals. The actuation assembly in the wheel modules was not sufficiently fastened and vibrations allowed the assembly to become misaligned. This led to a chain of failures resulting in gear wear and several broken bolts. Even with these events, the rover traversed 138 miles.

The transforming chassis performed extremely well, experienced no failures, and showed no signs of impending trouble. Its wide wheel base provided the extremely stable platform necessary for traversal of the desert environment. Nomad traversed down slopes as steep as 38°, up slopes as steep as 22°, across slopes at 33°, and over discrete obstacles up to 22" high (see figure 4). Although there were some obstacles it could not surmount, nothing short of vertical walls higher than 2 feet were shown to be a problem to the stability of the rover.

7 Conclusions

The in-wheel propulsion was mechanically simple and it placed heavy elements like motors and gearheads low, dropping the center of gravity and increasing stability. The averaging linkage distributed loads among all the wheels and smoothed body angles and excursions, even under extreme conditions. Explicit steering eliminated the side loads, extreme power draw, and most of the slippage common in skid-steered systems. The extremely wide wheelbase Nomad achieves through this transforming chassis gives it stability that belies its stowed size. The extreme slopes and obstacles it encountered in the Atacama were dispatched with confidence by the sprawling locomotion.

The biggest problem with the transforming chassis is its weight. While some weight could have been removed through structural optimizations, the structure needed to be strong enough to withstand the high forces experienced in deployment. When the chassis is deployed and simply performing steering maneuvers, the forces in the mechanism drop by half an order of magnitude. Thus the mechanism must be sized to accommodate the loads that it experiences only during deployment, which only occurs once during a planetary exploration mission.

Since the transformation from compact to deployed position would occur only once during a planetary mission, spring assistance combined with explosive bolt deployment could aid in the initial stages of the motion, reducing the worst case design loads on linkage members and actuators. Further improvement can be gained through reduction of the number of parts and reduction of parts' weight in the form of improvements in materials and optimization of shape for loading conditions. These methods, however, promise only incremental improvements. Revolutionary changes are necessary if this is to be a useful configuration for planetary exploration. Current efforts focus on the development of new linkages that give the same or better performance but do not experience the same side loads during deployment. Parts count reduction, materials improvements, the addition of crab steering mode, more compact mechanisms and thus improved utilization of body volume, deployment expansion in the vertical direction to improve ground clearance and reduce compacted volume, variable averaging amplifying motions in the middle range and truncating motions in the extremes, and the investigation of springs in the suspensions are all targets for research leading to the development of a next generation of Nomad.

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