MECHANICAL DESIGN OF A STANDARDIZED GROUND MOBILE PLATFORM

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Abstract

The paper summarizes the mechanical design of a Standardized Ground Mobile Platform (SGMP) with special attention on the development of a novel type of passive suspension. The suspension mechanism consists of two planar closed kinematic chains on each side of the rover. The design considered here was simpler than existing passive suspension mechanisms in the sense that the number of links and joints have been significantly reduced, without compromising the climbing capability of the rover.

Background

The first planetary exploration rovers, Lunakhod 1 and 2, each visited the moon to gather information and send pictures of the terrain. In 1996, NASA's Jet Propulsion Lab and the California Institute of Technology designed new rovers with identical structures; they were named Sojourner and Marie-Curie and weighed about 10.5kg. [1], [2]. The Rocky 7 design and dimensions are similar to Sojourner. As wheeled robots evolved, the mobility system changed from two-wheel steering systems to Ackerman type [3]. Rough-terrain mobility can be increased by shifting the center of gravity. A good example of this is the NASA Sample Return Rover (SRR), which was designed for missions on Mars and has an active suspension system with variable angles between linkages [4]. Shrimp is a six-wheeled rover, designed by the Swiss Federal Institute of Technology. It has one front four-bar linkage to climb over obstacles up to twice its wheel diameter without stability problems. The middle four wheels have parallelogram bogie, which balances the wheels' reaction forces during climbing [5]. Mars Exploration rovers were designed on the basis of Sojourner. Each of them is about 1.6 meters in length and weighs 174kg. The mobility system uses a rocker-bogie suspension and four-wheel steering [6]. Tao et al. [7] presented the design of a six-wheeled robotic rover with passive/active suspension for uneven terrain. The rover suspension consists of two articulated frames, each with three degrees of freedom (DOF) and where each joint of the suspension can rotate passively or be driven by a motor. Singh et al. [8] aimed to design a suspension mechanism which would utilize the advantages of both passive-suspension and active-suspension rovers. As future space exploration, rescue and other missions include the principle of reducing costs, new, more flexible rover designs will be needed. This need provides a number of highly motivational educational and research opportunities for design, development, and testing of new small-form–factor, ground-based robots.

Concept of Operation

The overall goal that was set for the multidisciplinary development team was two-fold. Electronically, the system had to be manageable from a remote location and be capable of adding/upgrading sensor and control technologies through a slice-based architecture. Mechanically, the system had to be low cost, small, compact, highly maneuverable, and be able to be fabricated and maintained with a minimum investment in tools/materials. An overview of the concept of operation of SGMP is shown in Figure 1. As the figure indicates, the system architecture is Internet–based, thus allowing for monitoring and control of the robot from anywhere that an Internet connection could be secured. The heart of the system is the MySQL Server. This resource accepts route-planning inputs from a Base Station as well as collects geographical positioning and other sensory information from the robot. Route planning information is downloaded from the server to the robot, while information sent from the robot to the server can be transferred to a Base Station that requests this information. The server can also record route generation and tracking data for later playback and analysis.

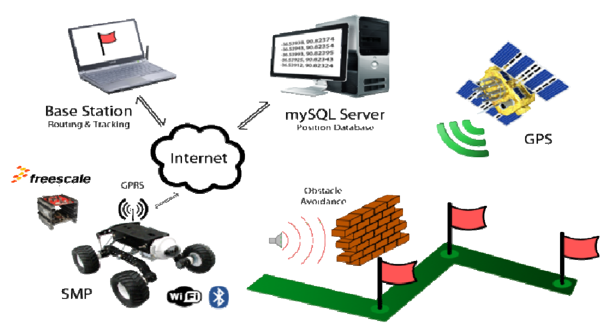


Figure 1. SGMP Concept of Operation

The SGMP robot has the ability to connect to the server via a wireless Wide Area Networking link using GPRS. In addition to the GPRS communications, the robot can use either Bluetooth or wireless Local Area Networking to communicate locally. The robot uses ultrasonic detection for collision avoidance and has both GPS and AHRS to assist in path following. The mobile platform uses a Freescale Tower architecture to provide the on-board, slice-based command, control, and communications functions. The hardware/ software infrastructure of the vehicle is based on subsumption architecture, which is a way of decomposing a complex behavior into "simple" modules [9]. The robot was intended to operate in an urban-type environment with the ability to avoid large obstacles and negotiate uneven terrain.

Mechanical Design of a Novel Articulated Suspension

The mechanical design for the SGMP was developed with the main goal of improving the size, maneuverability, and suspension of existing Surface Mobility Platforms (SGMP) [10]. In four-wheel-drive vehicles, obstacle limit is generally half of the wheel diameter [1]. It is possible to pass over this height by pushing the driving wheel to the obstacle, which is called climbing. For this condition, the contact point of the wheel and obstacle is at the same height as the wheel center. Although obstacle geometries can vary, the most difficult geometry which can be climbed by a wheeled vehicle is a stair-type rectangular obstacle. For that condition, climbing motion consist of two sub-motions. The first is a vertical motion, which causes a horizontal reaction force on the wheel center. The vertical motion instant center is at infinity. The second sub-motion is a soft rotation about a point located at the top of an obstacle, with an instant center of rotation at that point. Tests show that the Mars rover is able to overcome about 1.5 times the height of its wheel diameter. This limitation forces scientists to improve their current designs.

Climbing over an obstacle is a critical problem when wheel forces in the opposite direction of motion produce a moment about a pivot joint to rotate the bogie [3]. If the surface friction of an obstacle is not enough to climb, the obstacle force on the wheel can reach high values. A solution for this problem is the use of a linear-motion suspension where obstacle reaction force cannot create any moment.

Based on all of these factors, the challenge in this current study was to design a suspension which would: 1) be simple in structure, 2) allow for a near to straight line motion of the center of the wheel in order to decrease overturn moment, 3) have a climbing capacity of about two times the wheel diameter, and 4) have the ability to maintain equal force and maintain equal load distribution on all wheels. Therefore, the goal of this kinematic synthesis was to calculate the design parameters for the linkage suspension that accounts for the physical contact of the wheel with an obstacle in the workspace during motion. For the synthesis, the authors defined a start and an end position and used velocity and acceleration task specifications defined in the two positions, which are directly derived from the geometry of the problem [11] and are compatible with contact and curvature constraints of the wheels with obstacles in the environment. After the task was specified, the dimensions of the chain, which would satisfy the task specifications, were calculated. A four-bar linkage was synthesized to obtain the desired approximate straight-line motion of the wheel center. The suspension on each side of the platform was constructed by connecting two four-bar linkages symmetrically. Figure 2 shows two of the five designs that best fit the requirements [11]. Tests were performed to assure that each suspension moved smoothly throughout the task.

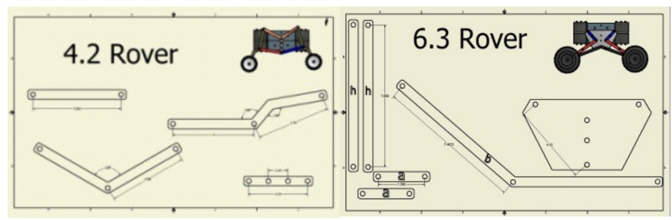
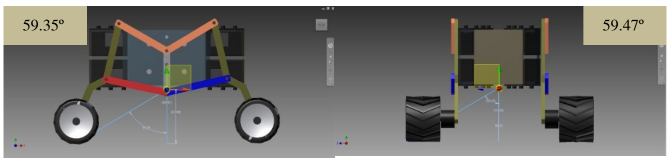


Figure 2. Linkage Type and Link Lengths for Each Design

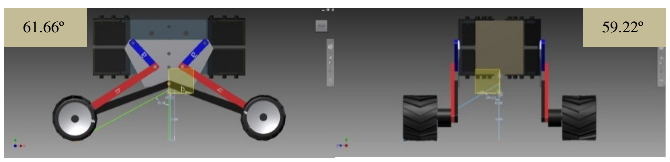
Because the proposed bogie design was to be symmetrical, reaction forces of the front and rear wheels were identical. During operation on rough terrain, if the robot can maintain its balance at all times, even when frozen position, it can be said that the robot has static stability. Physically, the boundary for stability criteria is related with a polygon, which consists of contact points between the ground and the wheels [12]. If the projection of the center of gravity on the ground plane stays inside of the stability area at all times during operation, the robot is considered to be stable. The stability of the robot can be defined by using the gravitational stability margin [13].

The maximum slope of the terrain that the robot can climb is called gradeability, The maximum downhill and cross-hill gradeability can be easily calculated and are functions of the projection of the center of gravity on the slope and its distance to the wheels. Since the center of gravity is sufficiently low for all design models, the coefficient of friction of the wheels would be the next limiting factor when traversing a sloped surface. For that reason, hollow rubber wheels were chosen. Each rubber wheel was mounted on a plastic hub and was additionally secured by an adhesive along the circumference of the hub. The wheels were non-pressurized and could deform and return to their shape, providing uniform, low-maintenance traction. A diameter of 3 inches was chosen for the wheels. Wheel width contributes to traction as a factor of the ground surface area displacing the normal force on each wheel. In challenging environments such as sand, wider wheels aid in preventing the unit from sinking into the shifting soil.

Development concepts for each rover design had an approximate size of 14”x14”x14” and a weight of 14 pounds for the five different suspension designs. The two top designs are shown in Figure 3. They were tested using three primary criteria: 1) obstacle climbing ability of the suspension; 2) linear motion capacity of the suspension; and, 3) platform-suspension system stability in climbing slopes. These criteria are described below.



a) Design Model 4.2



b) Design Model 6.3

Figure 3. Center of Gravity for the Top Two Designs

Obstacle Climbing Ability and Linear Motion Capacity of Suspension

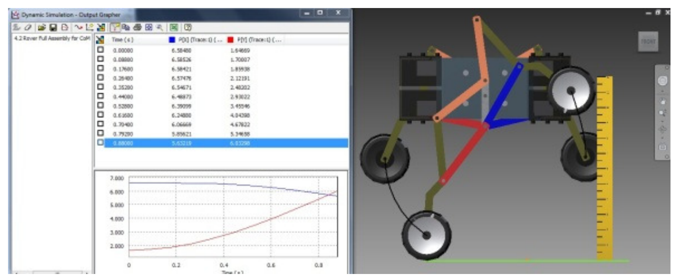
In order to quantify the desired linear motion of each of the linkage systems, the maximum displacement of the wheel center in the *x* direction was calculated. The displacement of the value for the *y* direction gave insight into the maximum height of an object that the platform could overcome. Design 4.2, shown on the left in Figure 4, meets and exceeds the goal of 1.5 times the wheel diameter climbing height, while minimally diverging in the *x* direction late in its path.

The trajectory of the center of the wheel of design 6.3 (Figure 4 to the right) follows a circular path proportional to the length of input crank *b* and its travel is restricted by output crank *a* and coupler *h*. These yield semi-vertical travel within the range of actuation, increasing in linearity as the length of *b* link increases.

Center of Gravity and System Stability

The maximum slope, or gradeability, was broken into two perspectives (see Figure 3). Design 4.2 (Figure 3a), has a wheel base well outside of the body, resulting in a good gradeability. The center of mass is higher than some of the other designs, but only a few degrees of the cross-hill gradeability is traded for the greater ground clearance. While design model 6.3 (Figure 3b) seems to have respectable gradeability and cross-hill gradeability, there is a fundamental stability issue with the geometry. Since the linkage system would be pivoting about the center fastening point, there would be a need for a secondary set of linkages in order to add stability.

a)



b)

Figure 4. Climbing Ability of the Top Two Designs

Design model 4.2 was chosen as the best overall design based on its climbing capacity of about 3 times the wheel diameter, and its linear ratio of 0.1. The linear ratio indicates the ratio of *x_max* displacement over the total *y* displacement from the ground, which is close to a straight line for this design. Even though the linkages were sized to accommodate this height, the center of mass was maintained low enough to offer a forward climbing angle (gradeability) of 59.35º, (Figure 5, right) and a cross-hill gradeability of 59.47º, (Figure 5, left).

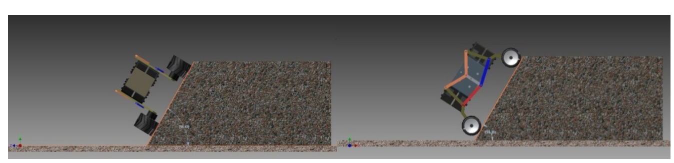


Figure 5. Gradeability for Design 4.2

The kinematic analysis of the suspension uses the idealization that the links do not flex during movement and can be considered as rigid. The constraint equation (1) of a general four-bar linkage can be used for deriving the output angle Y as a function of a known input angle Q (see Figure 6). The constraint equation is obtained from the requirement that the coupler link maintains a constant distance between the moving pivots of the input and output cranks [14]:

$$C: \quad (B - A)\ (B - A) - h^2 = 0 \qquad (1)$$

where

$$\mathbf{A} = \begin{Bmatrix} a\cos\theta \\ a\sin\theta \end{Bmatrix} \text{ and } \mathbf{B} = \begin{Bmatrix} g \\ 0 \end{Bmatrix} + \begin{Bmatrix} b\cos\psi \\ b\sin\psi \end{Bmatrix}$$

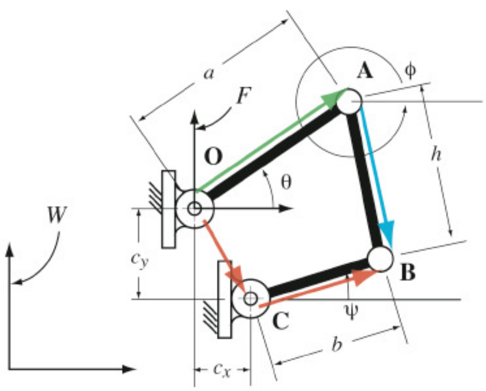


Figure 6. Four-Bar Linkage Configuration

Differentiation of this constraint yields the speed ratio of the linkage, which defines its mechanical advantage in a particular configuration. For a given input angle and a known value of the output angle, the position loop equations are solved to determine the coupler angle:

$$\phi = \arctan\left(\frac{b\sin\psi - a\sin\theta}{g + b\cos\psi - a\cos\theta}\right).$$

The first derivative of the loop equations of the four-bar linkage defines the velocity loop equations, which are used to compute the angular velocities of the output crank and coupler link. It was assumed that the input crank of Design 4.2. would move with a constant velocity of 1deg/s. The locations of the fixed pivots **O** and **C** and moving pivots **A** and **B** with respect to a fixed frame W, as well as the link lengths, were obtained to be **a** = 4, **b** = 4.5, **h** = 3.85. The offsets were cx = 0 and cy = -3 (see again Figure 6). The results from the kinematic analysis for different input crank angles Q, in the range of 30° to 90°, are given in Table 1.

Table 1. Results from the Kinematic Analysis

Q° In. angle	Y° Out. angle	F° Coupler angle	• Q(deg/s) in. vel.	• Y (deg/s) out. vel.
30	16.09	-77	14.33	-37.36
40	24.44	-74.4	16.15	-29.15
50	32.45	-71.4	18.48	-19.16
60	40.04	-67.9	21.35	-7.41
70	47.16	-63.9	24.75	5.76
80	53.75	-59.2	28.60	19.57
90	59.76	-53.9	32.74	32.74

Figure 7 shows the SGMP undergoing a number of tests. The chassis and suspension were primarily constructed from 6061 Aluminum, which was chosen for its light weight and availability in various extruded profiles. Each piece was drilled manually using a Bridgeport vertical mill, which had been fitted with a digital x and y readout. In order to couple each motor to the legs, a two-piece adapter was modeled in 3D and then printed in ABS plastic, using a Stratasys FDM 200MC rapid prototyping machine. This method was also used to create the module, which holds each level of circuit boards.

Figure 7. The Standardized Ground Mobile Platform (SGMP)

Conclusions

The mechanical design of the Standardized Ground Mobile Platform (SGMP) was discussed with special attention on the development of a novel type passive suspension mechanism. Different designs were analyzed based on a number of system requirements. The advantages of the final design are its linear motion, ability to overcome obstacle capacities, stability in climbing either uphill or downhill, as well as compact size and low cost. The platform employs an open-electronics hardware and software architecture. The working prototype of the new design was discussed and presented.

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