R.P.I. Technical Report MP-16

MARS ROVING VEHICLE CONFIGURATION

by

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National Aeronautics and Space
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Grant NGL 33-018-091

August 1970

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ABSTRACT

A simple, single-module unmanned Mars Roving Vehicle (MRV) with flexible metal toroidal hoop-spoked wheels is proposed and analyzed. Concentrating gross weight over the two individually-controlled rear traction wheels facilitates wagon steering and obstacle negotiation, and permits turning and maneuverability within a small area. A remote-controlled model based on similitude has been designed and fabricated to simulate on earth the static and dynamic responses of the full-size vehicle on Mars.

ACKNOWLEDGEMENT

The author would like to thank the National Aeronautics and Space Administration and Mr. Paul Tarver for support of this research, Mr. Jesse Moore of Jet Propulsion Laboratory for his active interest and assistance, Dr. Stephen Yerazumis, project administrator at Rensselaer Polytechnic Institute, for his helpful guidance, and Dr. George Sandor for many hours of invaluable discussion and advice.

1. INTRODUCTION

The wheel, man's most celebrated invention, will undoubtedly find its way to the moon during this new decade, on both astronaut-driven and remote-controlled vehicles. More surprisingly, before the end of the 1970's, a man-made vehicle may be logging miles on Mars! NASA's plans for landing an instrument package on the Red Planet in 1975 may pave the way for sending an unmanned rover there to snoop around in 1979.

Starting in September, 1969, research was initiated to design an unmanned roving vehicle for the surface exploration of Mars. Three simultaneous approaches were attempted. First, a thorough study was made of the Lunar Roving Vehicle (LRV) designs being developed for NASA by several corporations. This survey made apparent the many problems associated with development of a lightweight, high reliability, extremely versatile vehicle; it also helped prevent any duplication of effort. Secondly, many alternative schemes to a wheeled vehicle were considered, with subsequent analysis and optimization of the most promising designs. Thirdly, accumulation of all available environmental data on the Martian surface and atmosphere was begun to help define the design limitations for the vehicle.

2. MRV CONFIGURATION

2.1 LRV Designs

While several of the LRV designs proposed to NASA by various companies are well developed, featuring many creative and unique ideas, they all have certain characteristics in common. Battery-powered electric motors mounted in each wheel provide the vehicle propulsion system. The unmanned, or dual-mode (manned/unmanned) configurations consist of six- and eight-wheeled, segmented vehicles: two or three elastically coupled modules forming a caterpillar type vehicle. (See Figure 1). The primary advantages of such a design are its ability to conform to the terrain, the reduction of peak power requirements during obstacle negotiation, and its stability. The major disadvantages associated with this approach are its large turning radius and thus limited maneuverability, the loss of thrust that occurs if one or more wheels loses traction during obstacle negotiation, and the increased complexity and associated loss of reliability of the segmented configuration. For these reasons, a unified configuration was sought with greater maneuverability and less complexity.

2.2 Dragster Configuration

Attempting to adapt several earth-use vehicles to the demanding specifications of a Mars roving vehicle (MRV) led to the configuration which is now the basis for our MRV. Two major restrictions for the exploration vehicle are that it be lightweight and achieve good traction. Optimizing these parameters results in a maximum-acceleration vehicle: the "dragster"! This high performance earth machine concentrates its weight over the rear traction wheels, achieving the maximum normal force over its drive wheels, while maintaining the minimum vehicle mass. Increasing the wheel span to improve side slope and turning stability, and customizing certain other features leads to the MRV configuration of Figure 2.

The two rear wheels are individually driven by hub-mounted electric motors; the lighter, unpowered front wheels are used for steering. The all-metal wheels are flexible to provide a large footprint for traction, and cushion the vehicle's instrument package from high-frequency disturbances.

2.3 Comparative Analysis of MRV

While the use of two driven wheels, instead of the segmented vehicles' six appears to reduce the mission reliability in case of failure of a single wheel drive, there are several advantages. The weight thus saved can provide proportionately more powerful, more sophisticated and thus higher reliability electric motors in each wheel hub. Since the two drive wheels support 80% of the vehicle weight, the maximum traction produced by the two larger motors and wheels can be nearly equal to that of the six drive wheels in the LRV's. The front steering beam is articulated laterally to constantly maintain the two drive wheels of the MRV in contact with the surface; however, while the LRV segmentation maximizes the surface contact of all six wheels, one or more wheels can lose contact during obstacle negotiation, at the time when maximum traction is required.

The overall dimensions of the LRV's would have to be reduced or the vehicle structural weight increased for application on Mars, where the acceleration of gravity is more than twice as large as on the moon. Maintaining similar vehicle weights, the simpler dragster configuration permits larger wheels; since both vehicles are limited to crevasse type obstacles with no greater width than the vehicle's wheel diameter, the MRV can negotiate wider crevasses. The larger MRV wheels, limited to steps less than their radius, allow the MRV to match the segmented LRV's unique push-pull step climbing capability. The front wheels are pushed over obstacles as shown in Figure 3. The force, F, of the vehicle pushing the wheel must be such that the vertical component of the reaction force, R, exceeds the weight, W, supported by the wheel. The rear wheels must engage their cleats, and apply torque greater than the couple formed by the reaction force, R, and the supported weight, W.

The enlarged wheels provide a smoother ride at higher speed and reduce total power requirements by reducing the number of small indentations the wheels must drop into and climb out of. The larger wheels also increase the ground clearance of the vehicle's frame.

Several other advantages are incurred with the adaptation of this configuration. The unitized payload reduces vehicle weight by requiring a single support frame, eliminating segment couplings and communication links between segments. The compact form facilitates stowage in and deployment from the landing craft. A disadvantage of this feature is the additional insulation and cooling apparatus necessary to dissipate generated heat from closely packed components. However, consolidating most components would simplify protection of the payload from the hostile Martian surroundings (radiation, heat, dust, etc.).

The lightened load on the front section of the vehicle facilitates steering, and allows the front wheels to serve as a mechanical obstacle-detection system. The 360° wagon steering system, used in conjunction with the separate drives of the rear wheels, allows the vehicle to turn about the midpoint of the rear wheel span, an important maneuverability feature. (See Figures 4.b, and 5). When turning as shown in Figure 4.a., the ratio of the right wheel speed to the left wheel speed must equal A:B. Thus, in the case shown in Figure 4.b., this ratio is -1. This steering system eliminates scuffing, permitting the wheels to be easily turned when the vehicle is at rest, as well as when moving. This helps prevent the wheels from becoming wedged when on rough terrain. A single yoke and and bearing system is provided at the central steering hub.

Having the same tread width and diameter as the rear wheels, the lighter front wheels can detect and measure obstacles for the advancing vehicle. Should the front wheels encounter an unobserved non-negotiable step or crevasse, for instance, the weighted rear traction wheels could easily withdraw the light forward section and the vehicle could proceed along an alternate path. Since the front wheels are extended the maximum distance from the vehicle's center of gravity, their transmission of vibration and shock to the payload is minimized, thus simplifying the front end suspension system. Cleat-mounted penetration sensors would allow the lighter front wheels to detect a surface too soft to support the heavier rear section.

The rear-mounted payload has suggested a unique maneuver which only this rover can perform. By permitting the light-weight forward structure to pivot, the rear section of the vehicle can be tilted to any desired angle, over a range of 75^{o}. This operation can be used to shift the center of gravity behind the rear wheels causing the vehicle to tip back onto a rear-mounted swivel wheel, as shown in Figures 6 and 7. The front section may now be extended upward improving the three-wheel stability, illustrated in Figures 6 and 8. With the front section thus raised above any nearby obstacles the vehicle can rotate completely around in an extremely confined area, a circle of radius equal to half the rear wheel span, allowing it to find a less dangerous route. (See Figure 4.c). The rear wheel swivel bearing mount allows the individually driven traction wheels to maneuver the tilted vehicle in a straight line as well as turning it. Returning the vehicle to its normal four-wheel mode requires the following operation: lower the front section to bring the front wheels close to the surface, tilt the vehicle forward using the hinged swivel wheel strut as a jack until the CG is again ahead of the rear wheels, and finally extend the front section to the normal position.

The pivoted vehicle body also permits the vehicle to maintain a level payload over a specified range of fore- and aft-slopes, as shown in figures 9.a. and 9.b. This feature increases stability on steady up-grades and improves traction for braking on down-grades. Figure 9.c. illustrates side-slope stability. If desired a single pivot can be added to the rear suspension to permit leveling of the payload on small side-slopes as well, reducing payload orientation restrictions. This would require the vehicle body to be sloped on the underside to maintain a constant ground clearance. (See Figure 9.d).

The location of the center of gravity of the MRV is quite critical to its operation. The design is based on the dragster configuration, and therefore must concentrate its weight over the rear drive wheels to provide the maximum traction. However, to retain the necessary margin of stability for climbing steps (see Figure 3) the center of gravity (CG_T) of the MRV must be forward of the rear wheel axis by a distance of at least one wheel radius, as shown by A in Figure 10.a. This scale below the vehicle represents the percentage of weight carried by the rear traction wheels. If the CG_T were located at more than 85%, the size of the step which can be negotiated safely would be diminished.

The center of gravity must also meet the restrictions imposed by the tilt-back maneuver. The weight must be distributed in such a way that the center of gravity of the entire vehicle, except for the rear wheels and the outer section of the drive motors fixed to them, (CG_{bf}) will be directly over the rear wheel axis when the vehicle body is tilted to a prescribed angle. There are three factors which complicate the determination of the CG_{bf}. First, as the vehicle body tilts back shifting more weight over the rear wheels, the wheel deflection increases, changing the angle of the vehicle body slightly. Also the tilting of the body loads the horizontal deflection springs as cantilevers, and relieves the load on the vertical deflection springs, shifting the vehicle body closer to the rear wheel axis. And thirdly, the tilt-back maneuver changes the vehicle configuration causing the CG_{bf} to change position slightly (5b). The dashed lines in Figure 10.a. show the position of the surface and rear wheels with respect to the vehicle body and the shifted CG_{bf}, during the tilt-back maneuver.

Having thus specified the locations of the CG_T and CG_{bf}, and knowing the proximity of the CG_f, the center of gravity of the vehicle body, CG_b, may be determined. Twenty-five degree planes, which maximize ground clearance on slopes, form the lower bounds on the vehicle body space allocation. Completing the parallelogram about the CG_b provides an approximate body configuration, assuming a constant weight density in the plane of Figure 10.a. Thus, the upper boundary of the vehicle body is not a strict limit provided the center of gravity location is maintained. It seems logical that the heavier elements to be carried within the vehicle body would be mounted low to balance the lighter but elevated navigation and communication antennae and cameras.

The diagram (Figure 10.a) also illustrates the range through which the MRV can be tilted on level ground, without adjusting the body angle, and still remain stable. If the vehicle is just starting to climb the maximum size step obstacle (both rear wheels simultaneously: this is the worst case for stability) the vehicle body could tilt approximately 14° and remain stable (CG_T moving to B). On level ground the body could tilt approximately 45° without tilting back (CG_T moving to C). Of course, the automatic leveling control should prevent the vehicle body from tilting back beyond 5° - 10° at most over gradually changing slopes; and the front suspension should damp out any shock which might cause the body to lurch back.

Stability in the three-wheel mode is shown in Figure 10.b. The dashed lines bound the area of stability over which the CG_{bf} must remain. Should the center of gravity shift ahead of the rear wheels, the vehicle would merely return to the four-wheel mode, the front suspension protecting the vehicle from any shock. However, if the CG_{bf} shifts aft of either of the other two stability bounds, the vehicle could overturn, ending the mission. Therefore, the center of gravity is located as close to the forward stability limit as possible. As the front wheels are lifted from the surface the CG_{bf} shifts from 5b to 5a to 5c, in Figure 10.b, increasing the stability in the three-wheel mode with respect to tipping forward. In the maximum position at 5c, the vehicle can operate on a down-slope of up to 10° without violating the forward stability limit; an effective slope parallel to one of the rear stability limits can be tolerated up to 27°.

3. MRV FLEXIBLE TOROIDAL WHEEL

During the course of design and development of the Mars Roving Vehicle a unique flexible wheel design has been proposed. This all-metal, flexible "toroidal" wheel has certain advantages over heretofore proposed flexible wheels.

The design consists of a flexible metal rim suspended from the hub by means of flexible metal hoops, turned 90° from the plane of the rim. (Figure 11). Flexible joints, parallel to the wheel axle, between the hoop-spokes and the rim, reduce any moments transmitted to the individual hoops, and thus allow the large footprint necessary for traction.

Flexible wheels have been proposed by Bendix Corporation and Chrysler Corporation[3] , consisting of hoop-spokes in the same plane as the wheel rim. (Figure 12). However, this configuration provides less lateral load flexibility, necessary to cushion the vehicle ride over side-slopes, than does the toroidal configuration. The RPI wheel permits more hoop-spokes to fit the geometry of a given wheel size, providing more uniform wheel characteristics, while maintaining an equivalent wheel-torque capacity. Each toroidal spoke carries a smaller load than each of the planar hoop-spokes, and can therefore be thinner. Thus, although there are more spokes in the toroidal wheel, the weight is not increased. A major problem with both planar hoop-spoked wheels and "spiral-spoked" wheels proposed by others (Figure 13) is that rocks and gravel would become wedged at the points where the spokes were attached to the rim; as the wheel was deflected under load, this debris would damage the wheel due to the crushing action of the spokes. Since the hoop expansion of the toroidal wheel is in a different plane from the rim deflection, this problem is greatly reduced.

An alternative design for the toroidal wheel provides hinges in the rim midway between adjacent hoop-spokes. This feature permits the wheel to conform more closely to a rough surface, increasing footprint area and traction. The spring constant of this flexure hinge may be varied in the design, to provide the optimal flexural characteristics for the specific wheel needed.

4. MODELING

4.1 Preliminary Models

To aid in the design of the MRV a small scale model was constructed. Weighted to produce the desired center of gravity, this configuration model was revised several times as the design was being optimized. (Figure 14).

In addition to its value as a design tool, the small model proved helpful in communicating to others the particular characteristics and unique advantages of this MRV. A Martian terrain model was designed and constructed including slopes, steps, and crevasses on the same scale as the model. An 8-mm animated film was then prepared demonstrating the proposed vehicle operation with relation to nine obstacle negotiation situations; the film illustrates the four-wheel mode, tilt-back maneuver, three-wheel mode, and deployment procedures. (Figures 15 and 16).

Several plastic models of the toroidal wheel were constructed to provide empirical data to substantiate the predicted wheel characteristics. Both hinged and solid rim-spoke connectors, and flexible continuous and hinged, segmented rims were built. The rim-spoke hinges were considered necessary to provide a large footprint needed for good traction in soft soil, and to relieve stresses due to moments on the spokes during deflection. The hinged, segmented rim provided an even better footprint but greatly limited the wheel's step-climbing capabilities, an important feature for the MRV; therefore, a flexible continuous rim was chosen.

4.2. MRV Dynamic Simulation Model

To further compare and contrast the MRV with tested LRV designs, a more detailed analysis was necessary. For example, stability and payload acceleration and shock had to be determined for a variety of speeds and terrains to predict accurately the speed and terrain limitations of the MRV on the Martian surface. To provide this data a dynamically scaled model of the MRV was designed and fabricated to simulate here on earth the dynamic response of the actual vehicle on Mars. (Figure 17).

The first step of the model design was the choice of scale. Studying the mathematical relationships for a simple spring-mass system, and the physical laws of motion, scale ratios may be calculated for length, mass, and time, as follows:

Let:

ℓ = linear vehicle dimension
s = linear scale factor, model : full-size MRV
M = mass
V = volume
W = weight
g = gravitational acceleration*
k = spring constant
T = period
t = time
d = distance
v = velocity
a = acceleration

Assume: $S = \dfrac{\ell_e}{\ell_m}$ **

$$\frac{M_e}{M_m} = \frac{V_e}{V_m} = \frac{\ell_e{}^3}{\ell_m{}^3} = \left(\frac{\ell_e}{\ell_m}\right)^3 = s^3$$

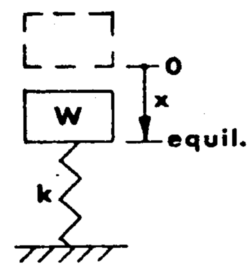
$$\frac{W_e}{W_m} = \frac{M_e\, g_e}{M_m\, g_m} = s^3 \left(\frac{32.2}{12.3}\right) = 2.62\, s^3$$

* g on Mars = 12.3 ft/sec^2.

**Subscript e refers to dynamic model on Earth; subscript m refers to actual MRV on Mars.

For simple spring-mass system:

$$\frac{k_e}{k_m} = \frac{W_e/x_e}{W_m/x_m} = \frac{2.62\ s^3}{s} = 2.62\ s^2$$

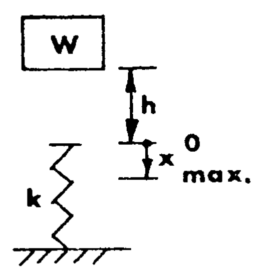


$$\frac{T_e}{T_m} = \frac{\sqrt{M_e/k_e}}{\sqrt{M_m/k_m}} = \sqrt{\frac{s^3}{2.62\ s^2}} = \sqrt{\frac{s}{2.62}}$$

$$\frac{t_e}{t_m} = \frac{T_e}{T_m} = \sqrt{\frac{s}{2.62}}$$

Dynamic checks:

$$\frac{W_e(h_e+x_e)}{W_m(h_m+x_m)} = \frac{\frac{1}{2}\,k_e\ x_e^{\ 2}}{\frac{1}{2}\,k_m\ x_m^{\ 2}} ,$$



$$2.62\ s^3\ (s) = 2.62\ s^2\ (s^2) \quad \checkmark$$

$$\frac{d_e}{d_m} = \frac{v_e\ t_e}{v_m\ t_m} , \quad s = s\sqrt{\frac{2.62}{s}}\sqrt{\frac{s}{2.62}} = s \quad \checkmark$$

$$\frac{d_e}{d_m} = \frac{\frac{1}{2}\,a_e\ t^2{}_e}{\frac{1}{2}\,a_m\ t^2{}_m} , \quad s = s\left(\frac{2.62}{s}\right)\left(\frac{s}{2.62}\right) = s \quad \checkmark$$

The linear scale was chosen to be 1.84, yielding a model size small enough for indoor operation and testing and large enough to permit fabrication. (See Figure 18). The 6.21 pound model, 33-inches long, simulates the actual 1000 pound (earth weight) MRV which measures 14 feet - 11 inches in length.

Using the weight breakdowns of several proposed LRV's as guides, adjusting for the change in gravity, a detailed weight breakdown estimate for the MRV was tabulated. Applying the weight scale factor to these values, weights were assigned to the major elements of the model. This assured the correct weight distribution as well as the location of the center of gravity, both necessary for correct dynamic simulation.

One of the most difficult problems to arise from the model construction was providing traction motors light and small enough to be mounted in the wheel hubs, yet powerful enough to provide the torques necessary to simulate the obstacle negotiation capabilities of the MRV. This problem was solved by using drive motors which provided the desired power, and mounting them on the MRV chassis, where the weight and space limitations were less strict; flexible shafts were used to transmit torque to the wheels, thus achieving the same effect and weight distribution as the hub-mounted motors in the full size MRV. (Figure 19). The motors thus simulate the weight of the power, communications and science payload of the actual MRV. Two other motors are mounted on the chassis; one to control the wagon steering by means of a zero-backlash cable system, and the other to operate the tilt-back and leveling mechanism for the vehicle body.

The suspension components for the model were designed in such a way that they could be interchanged with other elements to vary the suspension characteristics during dynamic testing. Separate spring-tempered steel leaf springs were installed for horizontal and vertical deflections of all four wheels. (See Figure 20). The spring loaded tilt-back system provides additional flexibility, allowing the heavy vehicle body to rock forward due to a head-on collision, reverse acceleration, or vertical jolt to either front or rear wheels. Shock dampers are added to the rear vertical deflections springs and to the vehicle tilt-back system.

A computer program was written using Castigliano's energy method to determine the deflected hoop-spoke spring constants. Graphically deflecting the wheel to attain the desired footprint, the cantilever and compressive deflections were determined. Using these and known equilibrium wheel loads as inputs to the computer program, yielded the necessary dimensions of the hoop-spokes.

The wheel hoop-spokes and rims were constructed of spring-tempered steel; the hinges were constructed of untempered steel. The wheel tread was made from ridged rubber sheet and was designed to be easily replaced by various other wheel cleat bands, which might prove more effective during testing. (Figure 21).

The vehicle scale prohibited an on-board power supply; therefore, it was convenient to control as well as power the vehicle through an umbilical cable. All four motors can be individually controlled. Mercury switches on the vehicle can be activated to automatically level the vehicle chassis on slopes.

5. CLOSURE

A comprehensive testing program is in the planning stages. A dynamic analysis will be developed and compared with the test results from the dynamic model. This will aid optimization of the wheel and suspension designs and vehicle structural design. Also, the dynamic environment of the instrument package to be carried by the vehicle will be determined, thus specifying requirements such as the shock resistance of science components.

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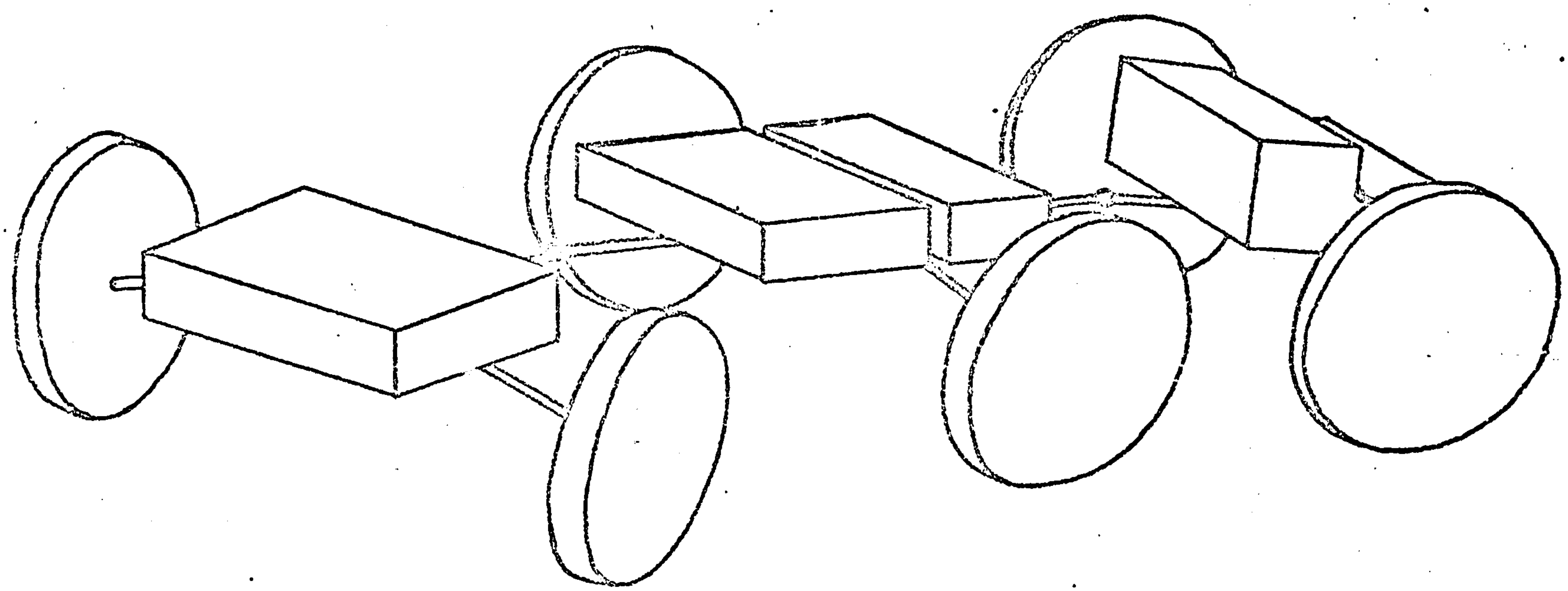
4. Sandor, G.N., and Rayfield, W.P., Dragster on Mars", ASME Newsletter, Hudson-Mohawk Section, January-February, 1970.

FIGURE 1: TYPICAL THREE-MODULE, SEGMENTED LUNAR ROVING VEHICLE CONFIGURATION



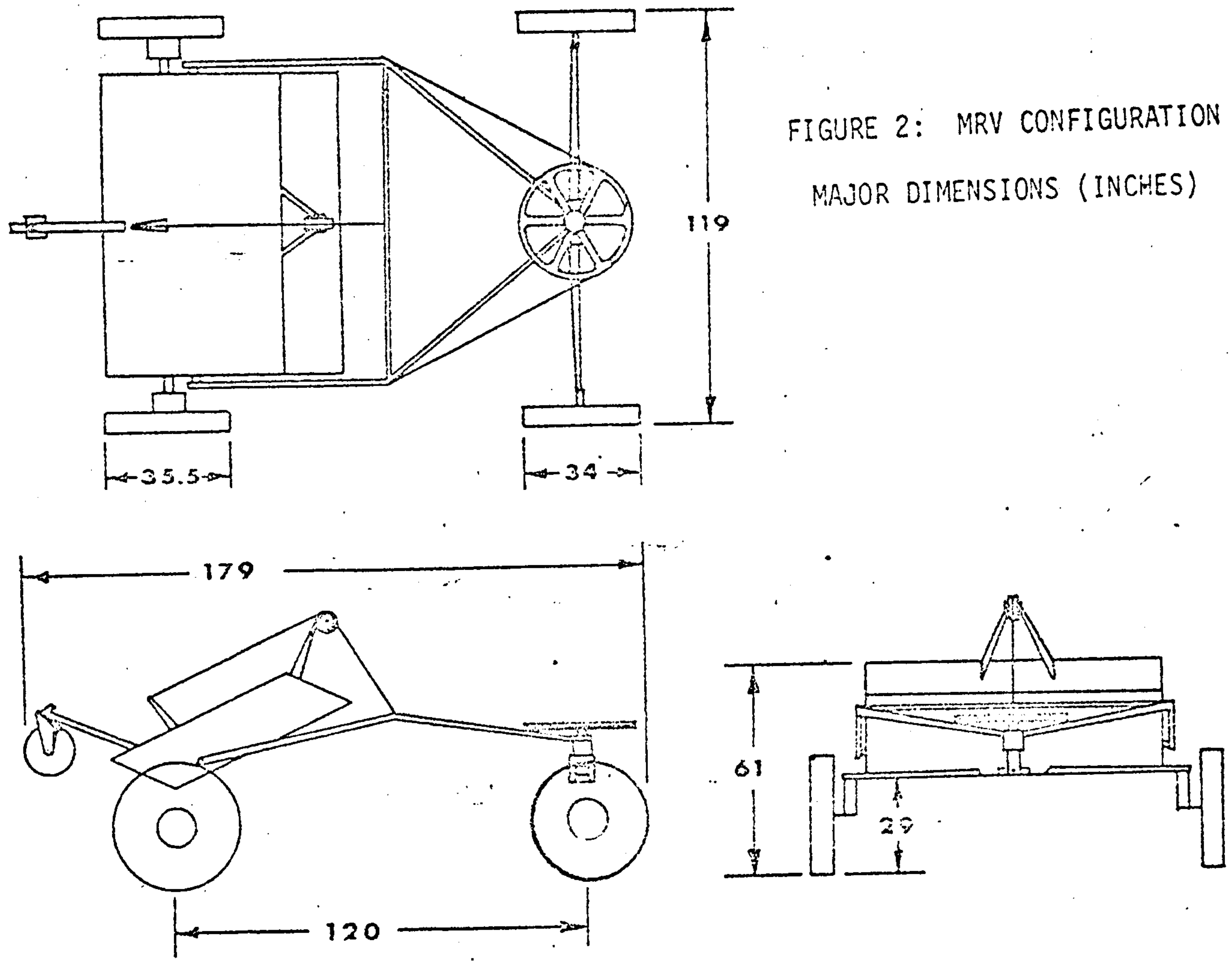
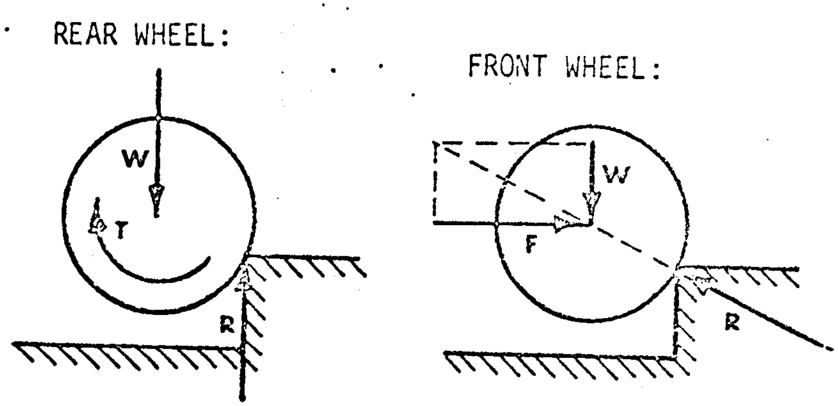


FIGURE 2: MRV CONFIGURATION

MAJOR DIMENSIONS (INCHES)

FIGURE 3: STEP AND CREVASSE OBSTACLE NEGOTIATION



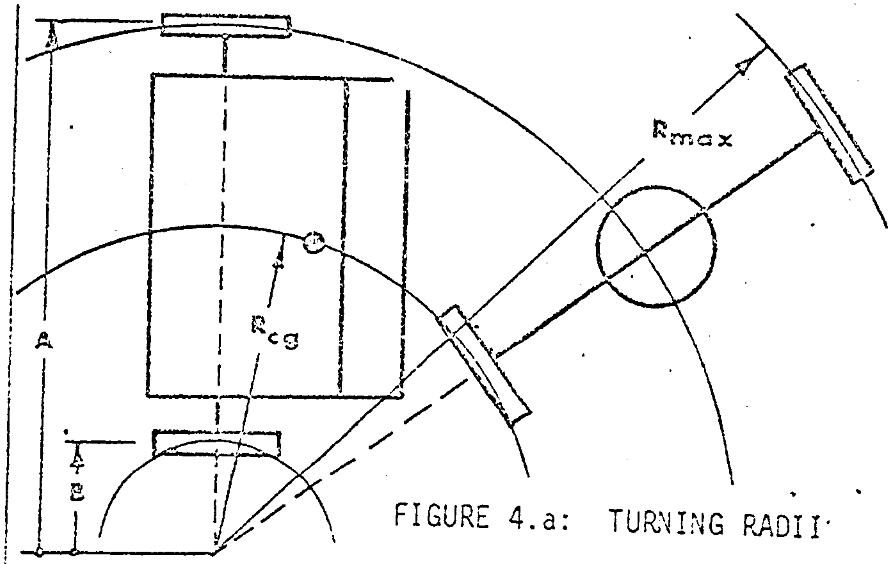


FIGURE 4.a: TURNING RADII

FIGURE 4.b

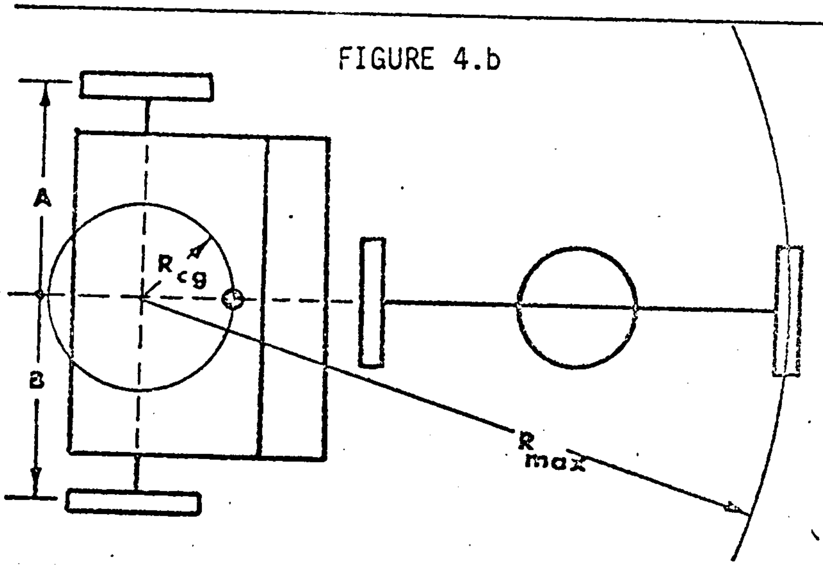
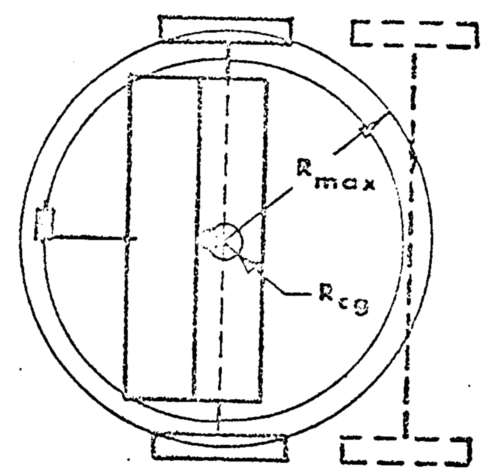


FIGURE 4.c



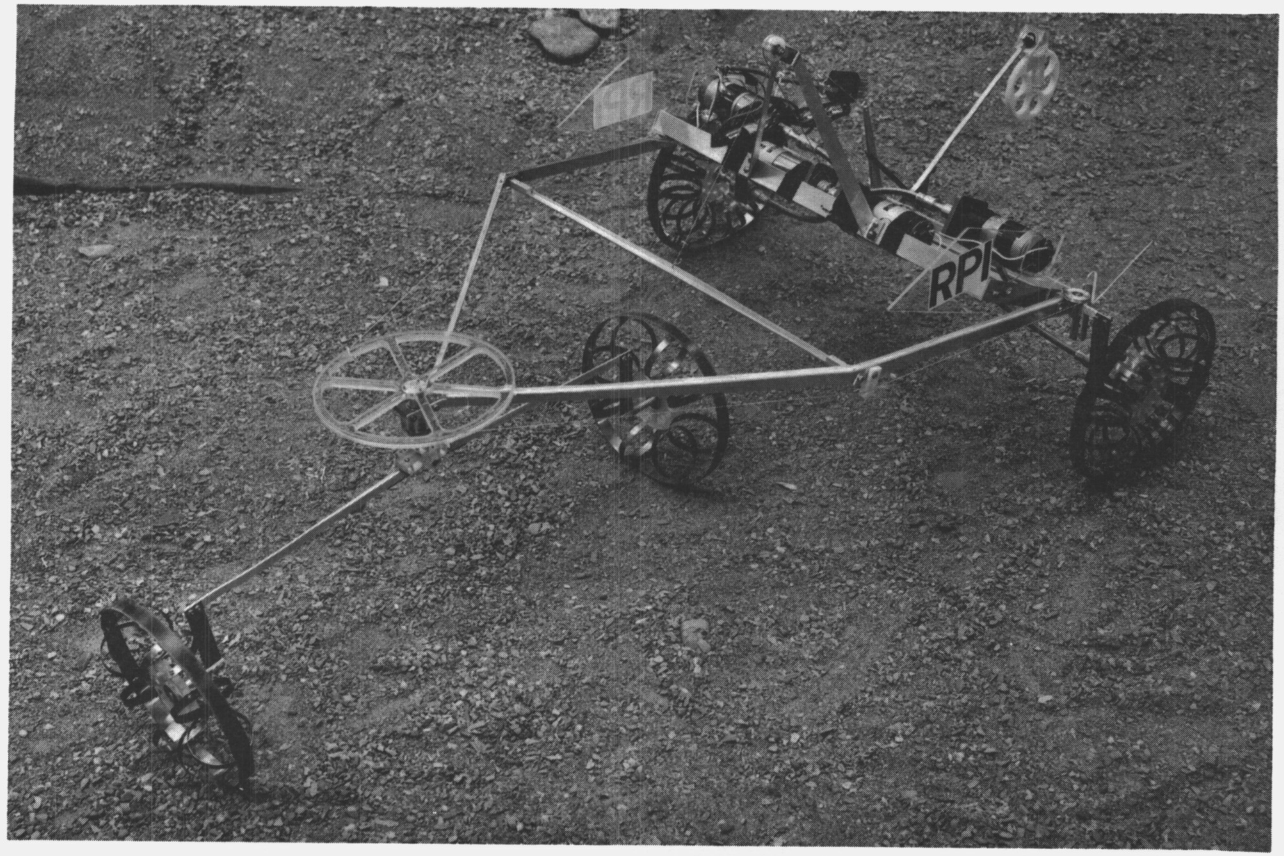
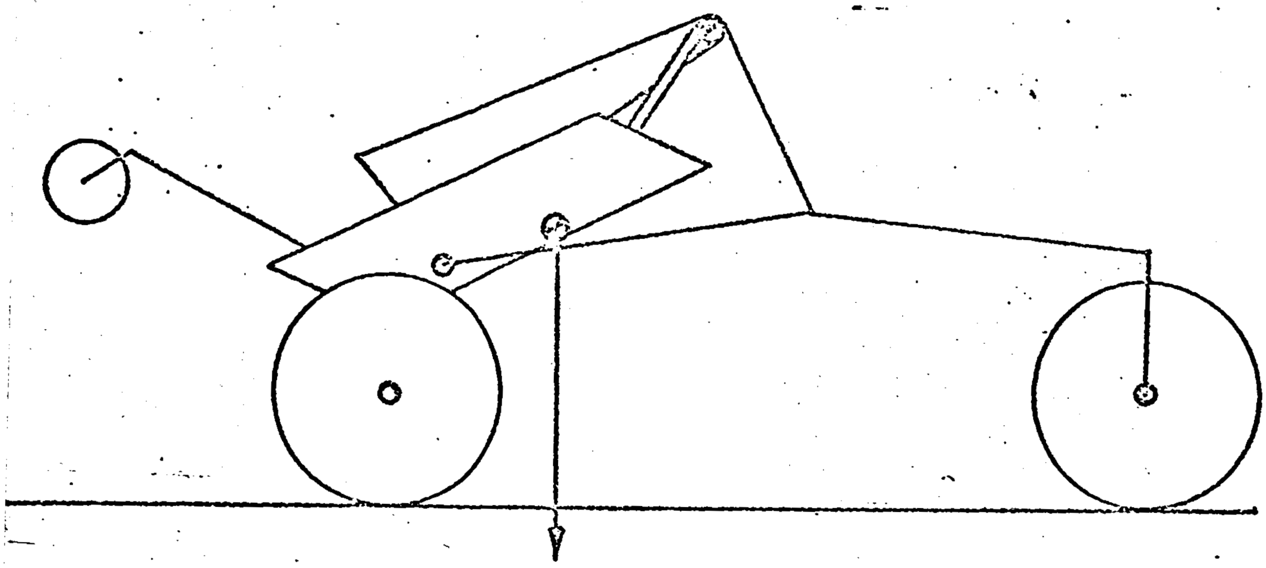
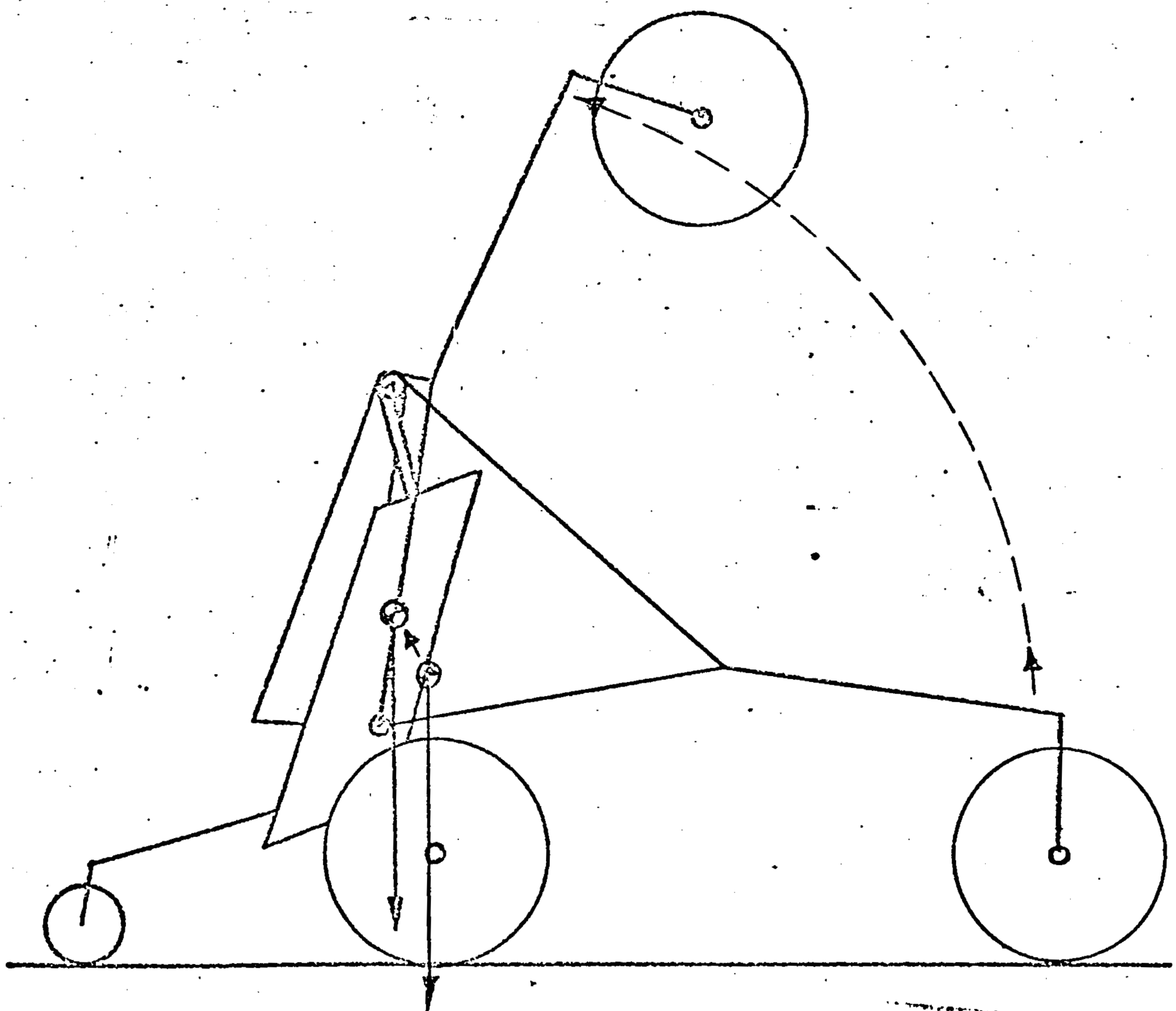


FIGURE 5: AFT-LOCATED CENTER OF GRAVITY FACILITATES WAGON STEERING. IN POSITION SHOWN, VEHICLE CAN TURN AROUND IN CLOSE CIRCLE BY DRIVING TRACTION WHEELS IN OPPOSITE DIRECTIONS.

FIGURE 6: MRV TILT-BACK MANEUVER (CG SHIFTS AS PIVOTS) FORWARD STRUCTURE





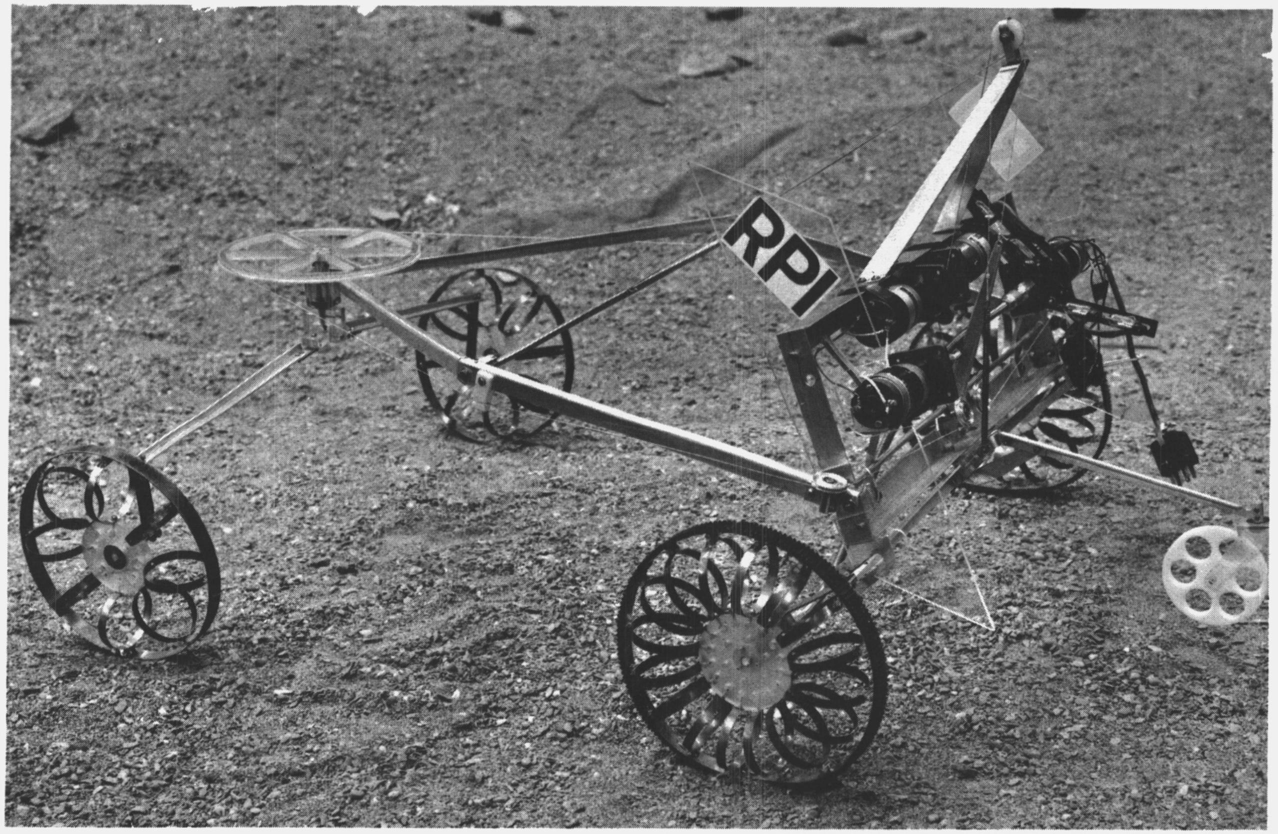


FIGURE 7: CG SHIFTED BY PIVOTED FORWARD STRUCTURE TRANSFERS LOAD FROM FRONT WHEELS TO AFT SWIVEL WHEEL, ALLOWING TILT-BACK MANEUVER. TAIL WHEEL SUPPORT ARM IS PIVOTED AT VEHICLE FRAME TO SERVE AS JACK TO SHIFT CG AND RETURN TO FOUR-WHEEL MODE.

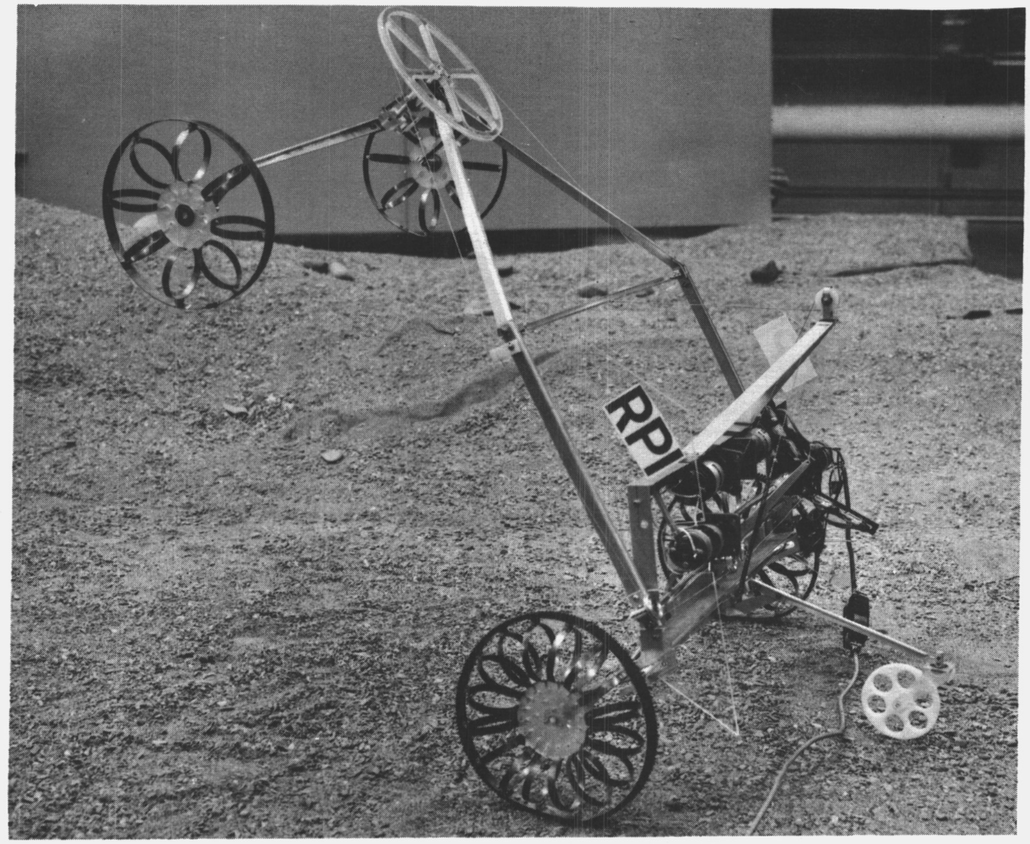


FIGURE 8: TO IMPROVE STABILITY AND CLEAR NEARBY OBSTACLES, THE FORWARD STRUCTURE MAY BE RAISED TO DESIRED LEVEL.

FIGURE 9: MRV SLOPE CAPABILITIES

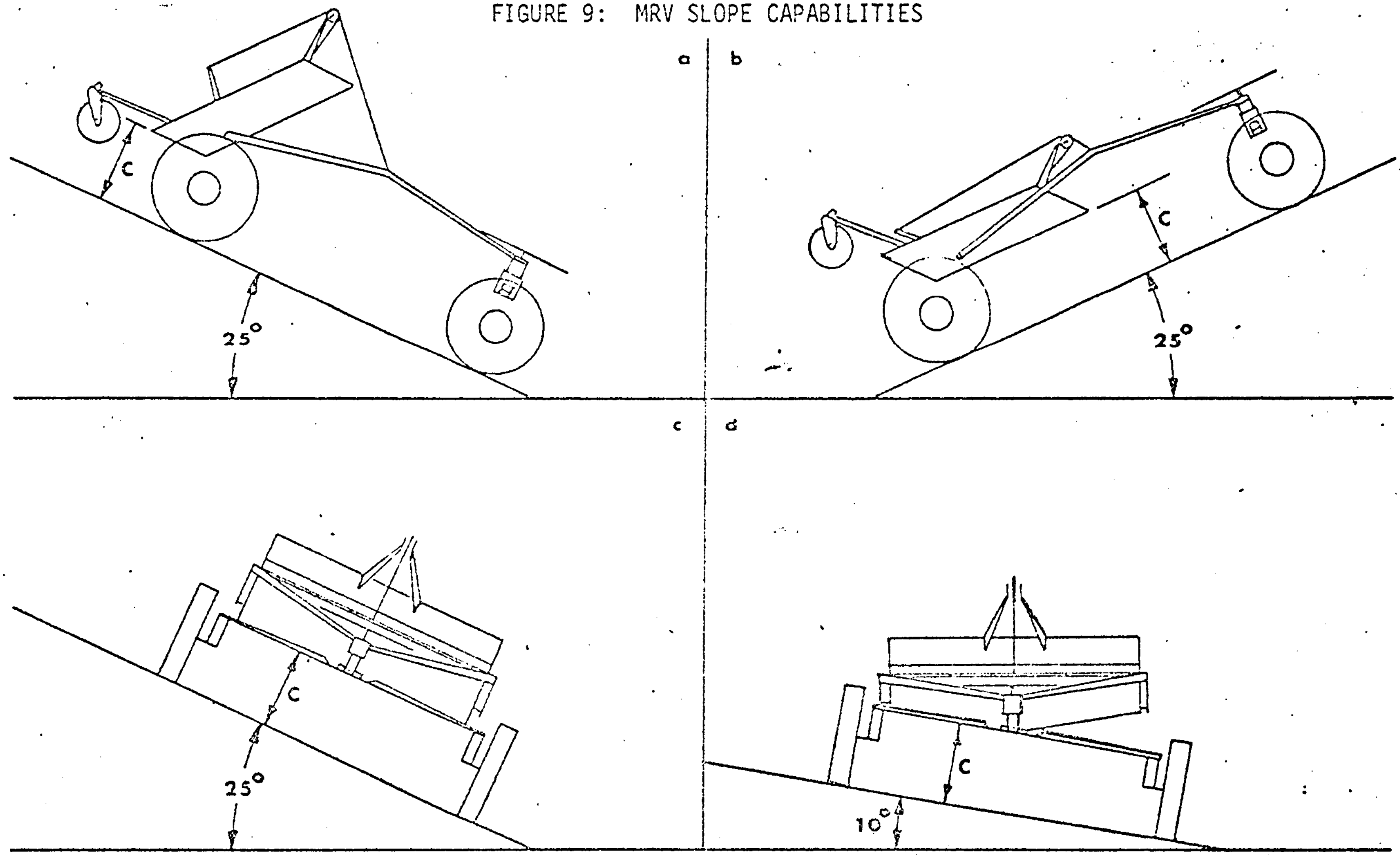
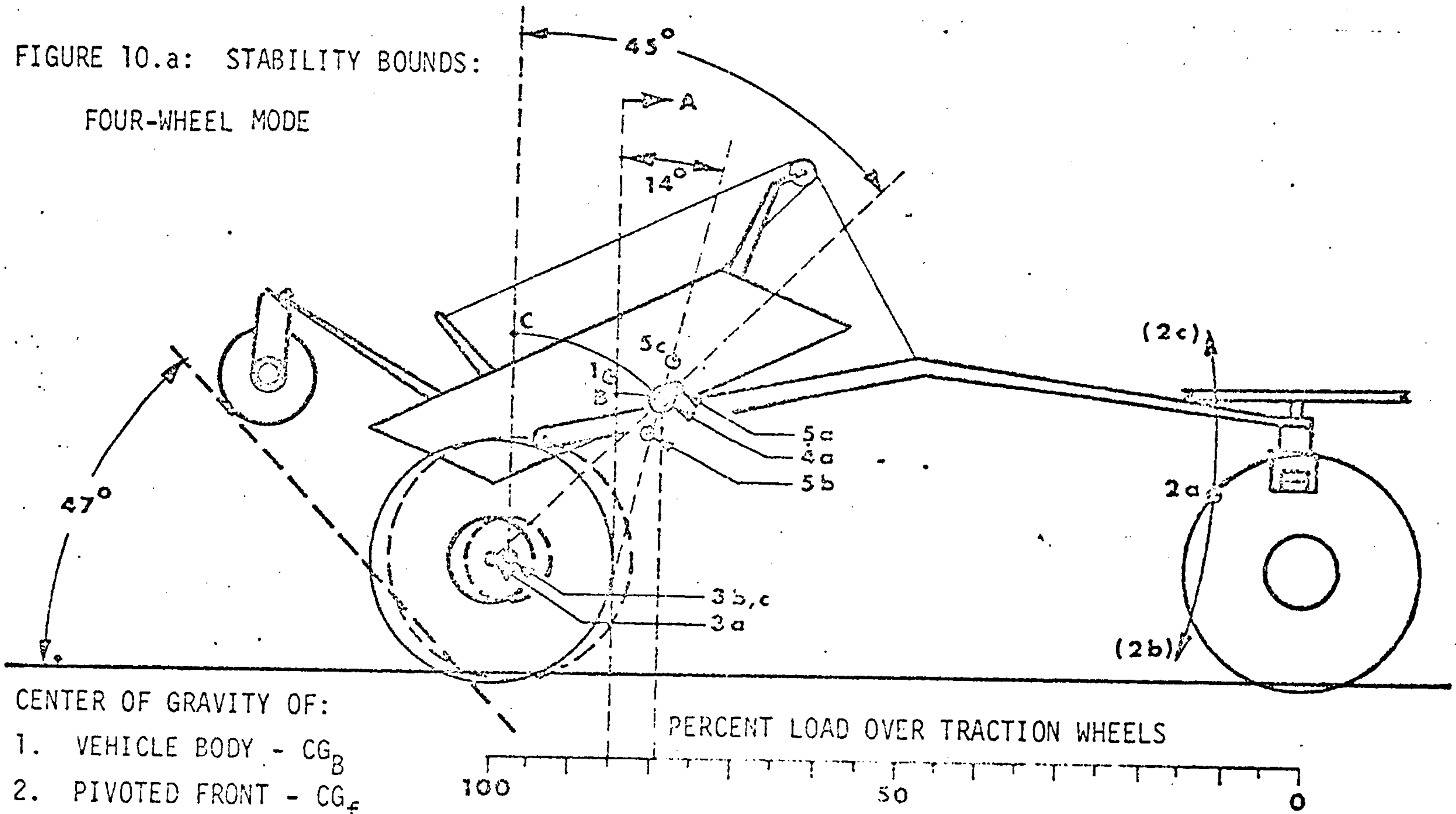


FIGURE 10.a: STABILITY BOUNDS:

FOUR-WHEEL MODE



CENTER OF GRAVITY OF:

1. VEHICLE BODY - CG_B
2. PIVOTED FRONT - CG_f
3. REAR WHEELS
4. TOTAL VEHICLE - CG_T
5. BODY AND FRONT - CG_{bf}

CG POSITIONS:

a: FOUR-WHEEL MODE AS SHOWN

b: THREE-WHEEL MODE - FRONT WHEELS ON SURFACE

c: " " " " " RAISED

FIGURE 10.b: STABILITY BOUNDS: THREE-WHEEL MODE

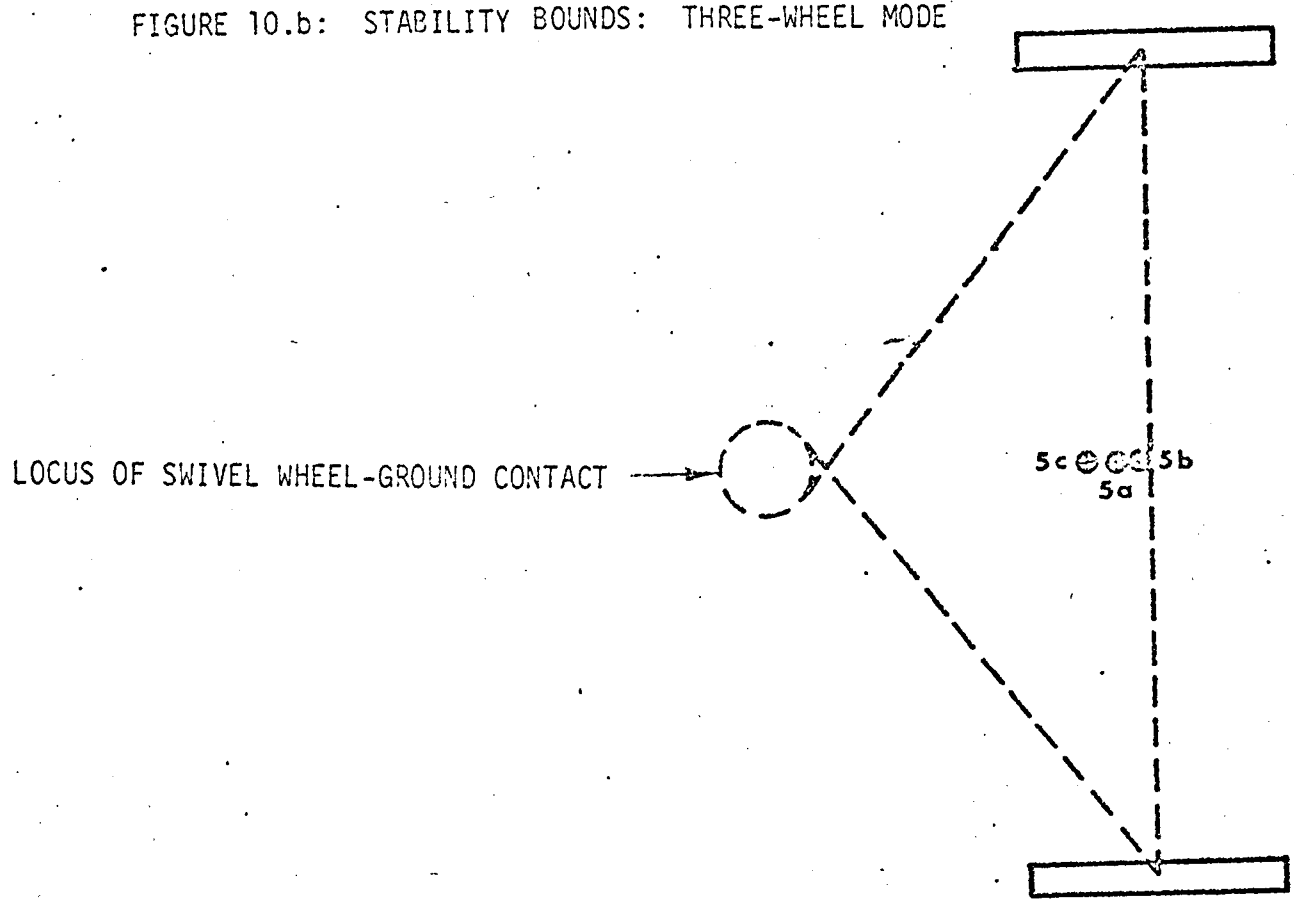


FIGURE 11: TOROIDAL HOOP-SPOKED WHEEL (EIGHT HOOP-SPOKES SHOWN FOR CLARITY; SCALE SHOWN PERMITS SIXTEEN.)

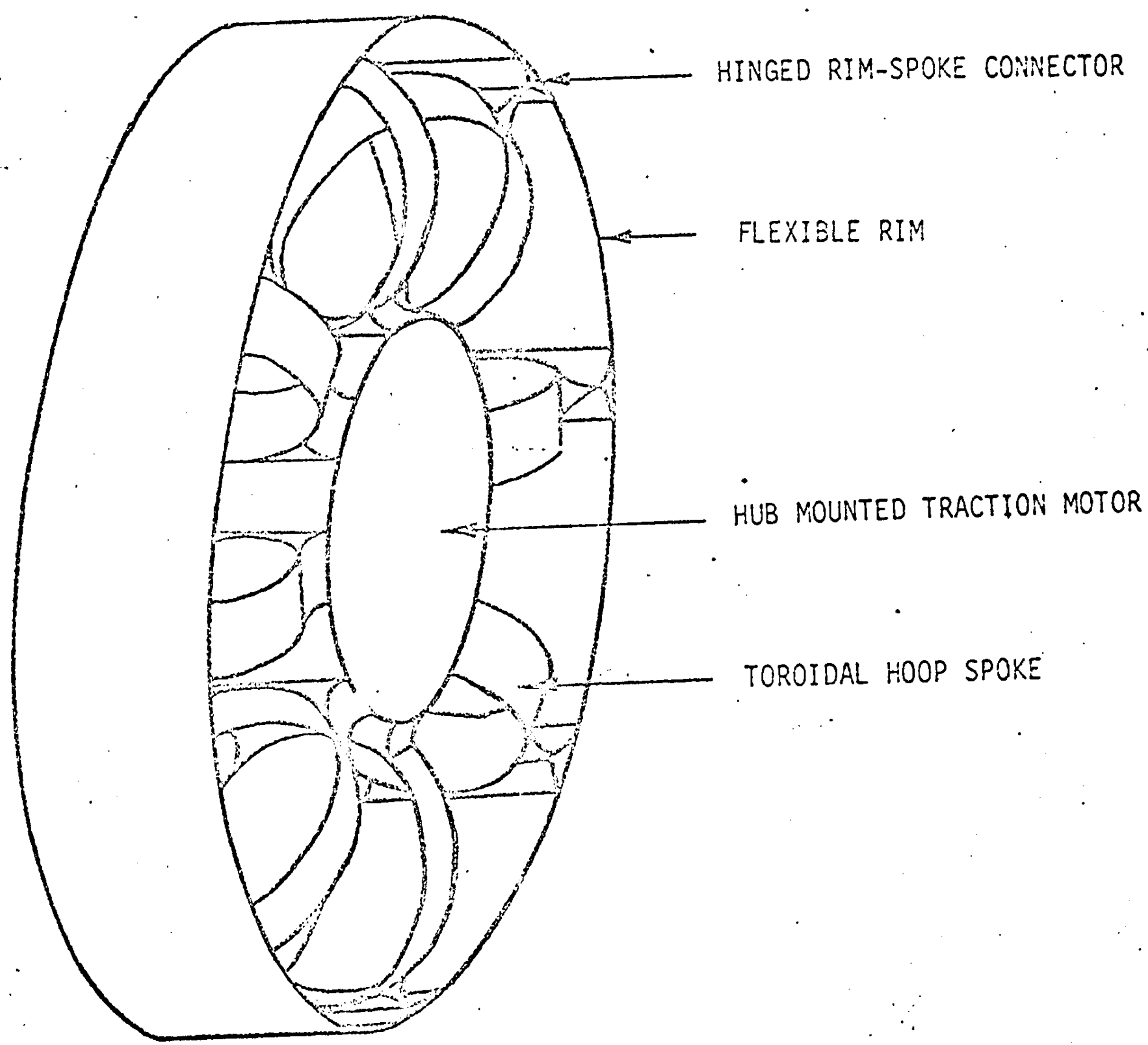


FIGURE 12: TYPICAL PLANAR HOOP-SPOKED WHEEL

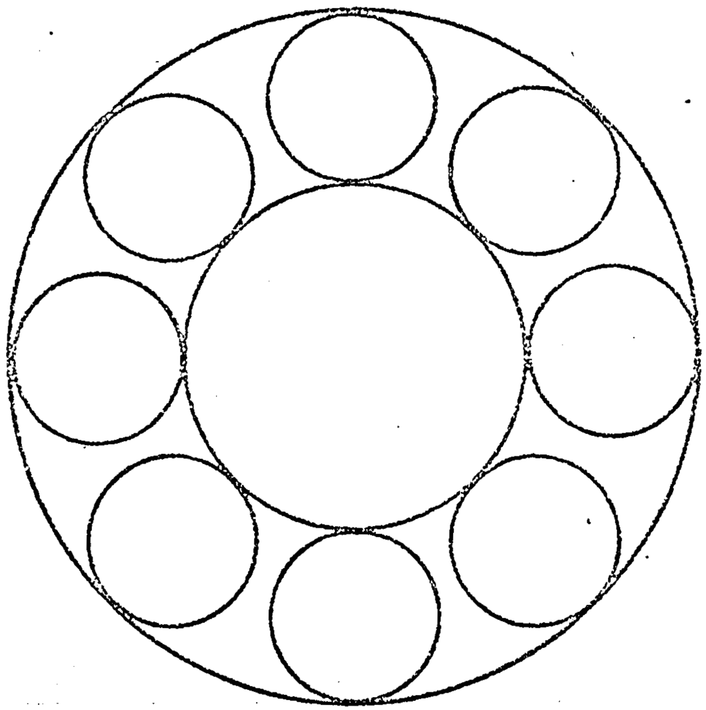
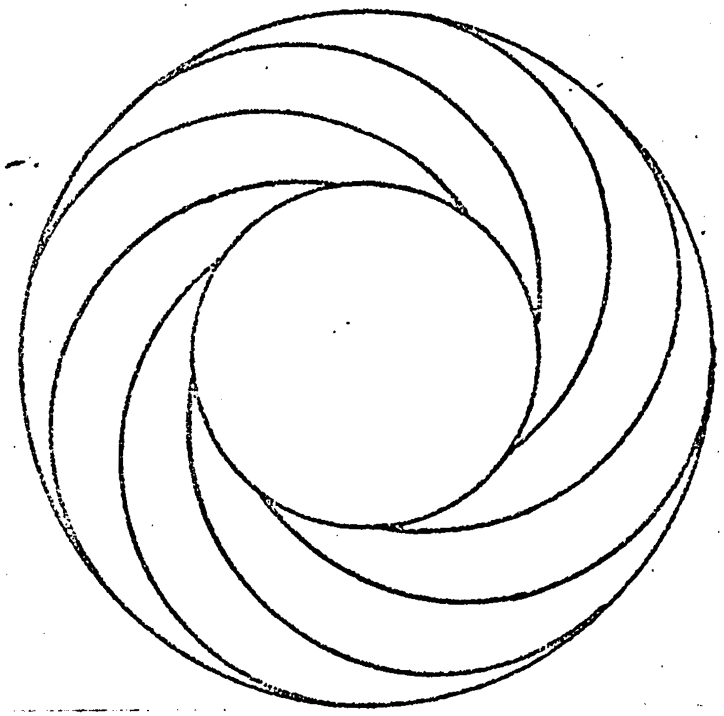


FIGURE 13: TYPICAL SPIRAL-SPOKED WHEEL



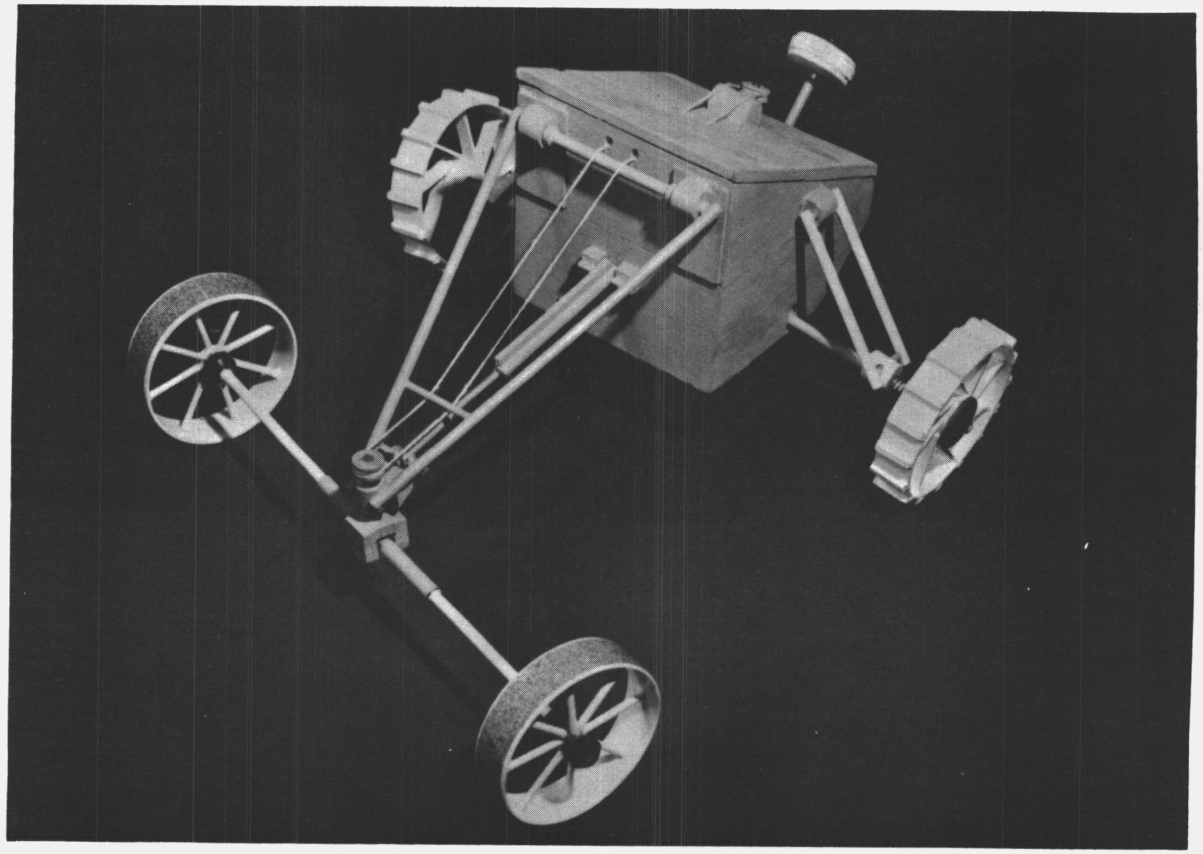


FIGURE 14: EARLY CONFIGURATION MODEL OF MRV. LENGTH = 14".

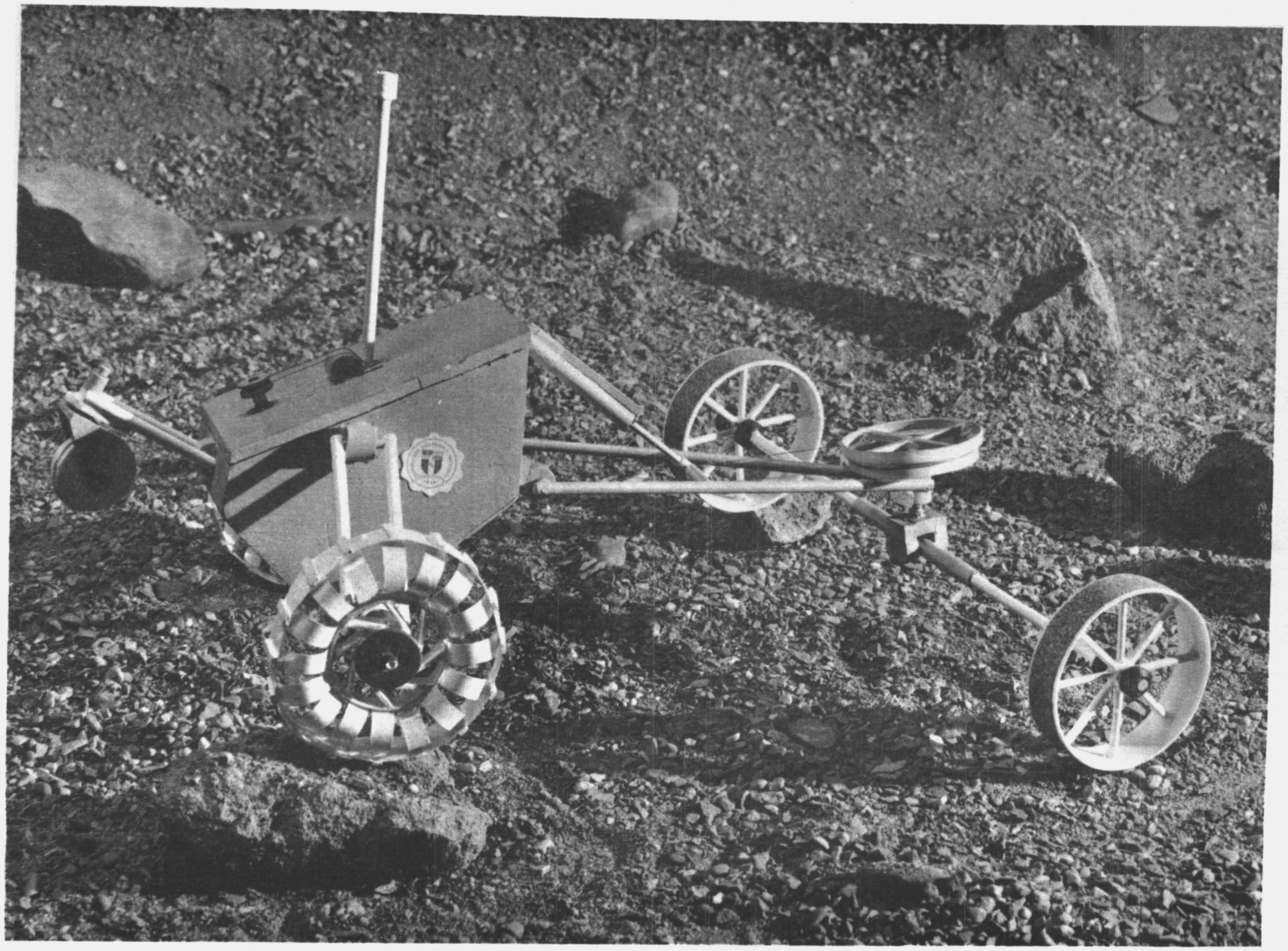


FIGURE 15: MRV CONFIGURATION MODEL ON SCALED MARTIAN TERRAIN, MODEL LENGTH - 14". CONSTRUCTED FOR DESIGN REFINEMENT AND ANIMATED FILM OF OBSTACLE NEGOTIATION CAPABILITIES.

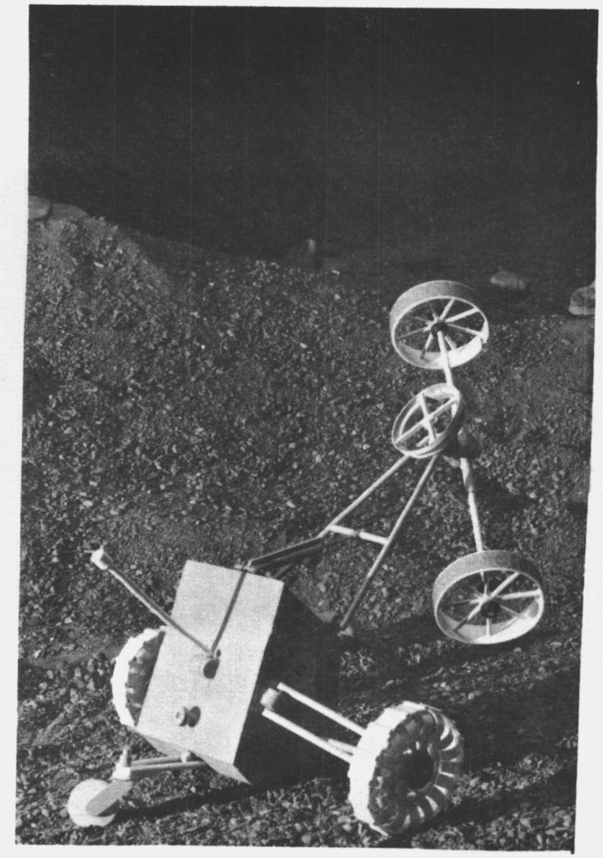


FIGURE 16: MRV CONFIGURATION MODEL IN THREE-WHEEL MODE. MANEUVER ALLOWS TURNING WITHIN VEHICLE DIMENSIONS, EXTRICATION OF OBSTACLE DETECTING FRONT WHEELS FROM OBSTACLES WHICH CANNOT BE NEGOTIATED IN THE FOUR-WHEEL MODE.

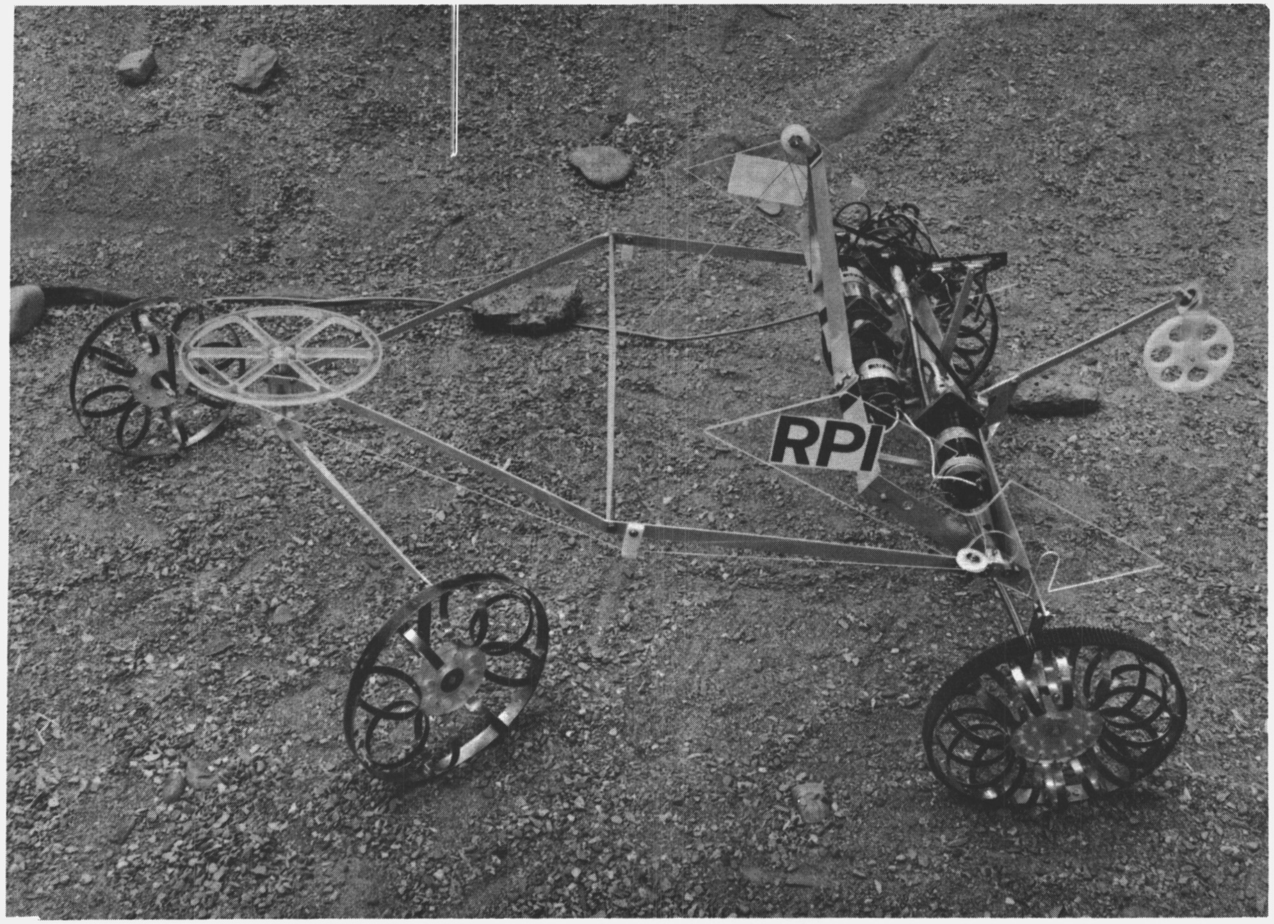
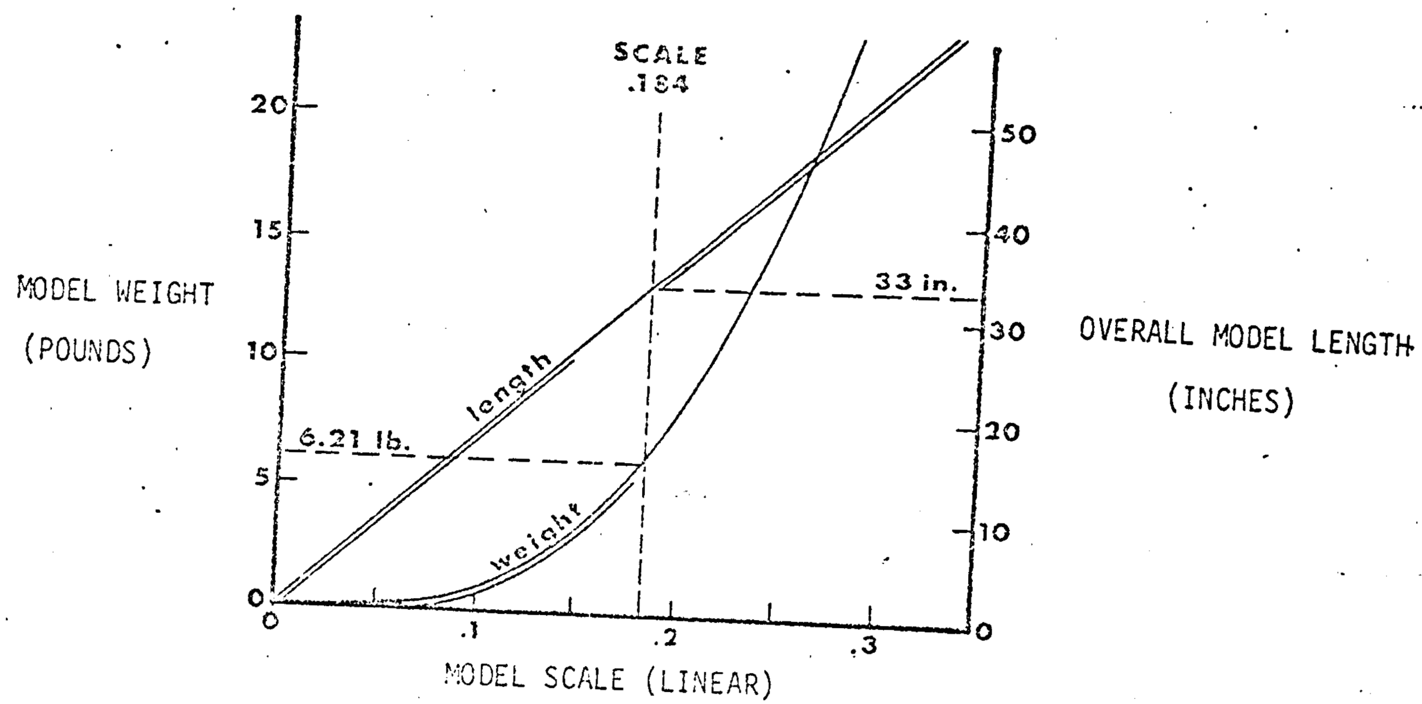


FIGURE 17: MRV DYNAMIC SIMULATION MODEL, LENGTH = 33". SIMULATES IN SCALE, HERE ON EARTH, THE MANEUVERS AND DYNAMIC RESPONSE OF THE FULL SIZE VEHICLE (LENGTH = 179") ON MARS. PLEXIGLAS SIDE PANELS SUGGEST SHAPE OF ACTUAL VEHICLE BODY, ENCLOSED FROM THE HOSTILE ENVIRONMENT. REMOTE-CONTROLLED MOTORS OPERATE LIGHT-WEIGHT CABLE TRANSMISSION SYSTEM FOR STEERING, TILT-BACK AND LEVELING MANEUVERS.

FIGURE 18: OPTIMUM MODEL SCALE



WEIGHT - MODEL TOO LIGHT TO FABRICATE

LENGTH - MODEL TOO SMALL TO FABRICATE

LENGTH - MODEL TOO LARGE FOR INDOOR TESTING

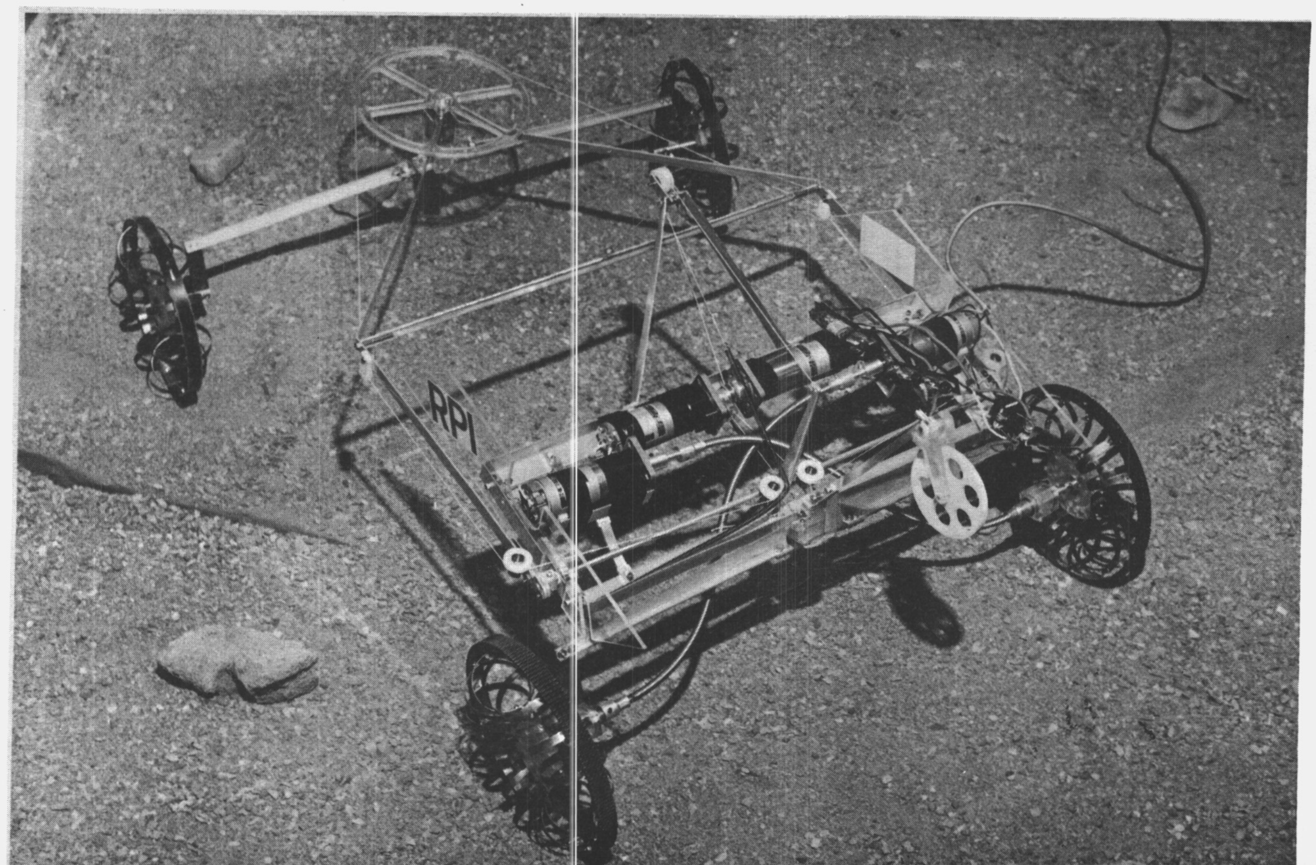
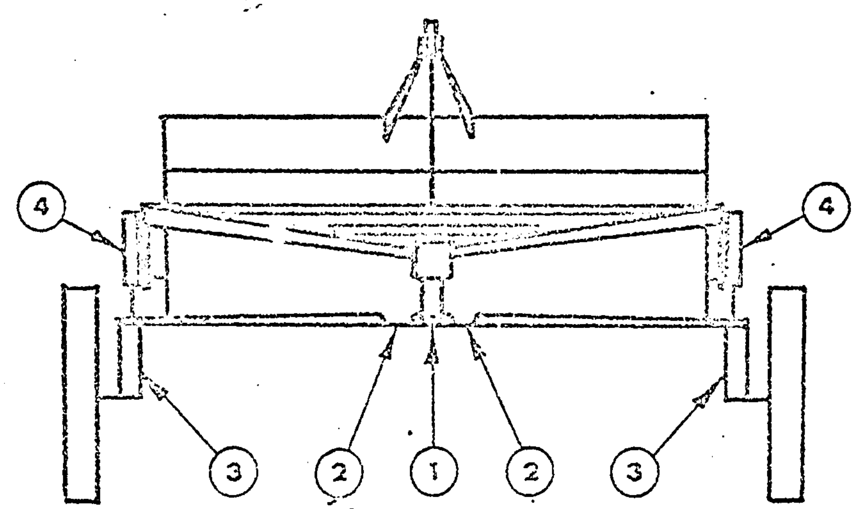


FIGURE 19: INDIVIDUALLY CONTROLLED TRACTION DRIVE MOTORS OF THE DYNAMIC MODEL TRANSMIT POWER TO REAR WHEELS THROUGH FLEXIBLE SHAFTS; MOTORS ARE MOUNTED WITHIN VEHICLE BODY TO ACHIEVE SAME WEIGHT DISTRIBUTION AS ACTUAL MRV WHICH WILL MOUNT DRIVE MOTORS IN REAR WHEEL HUBS.

FIGURE 20: SUSPENSION ELEMENTS FOR MRV DYNAMIC SIMULATION MODEL



1. PIVOT FOR LATERAL ARTICULATION OF FRONT WHEEL SUPPORT BEAM
2. VERTICAL DEFLECTION SPRINGS (FRONT AND REAR)
3. HORIZONTAL (IN THE FORE & AFT DIRECTIONS) DEFLECTION SPRINGS (FRONT AND REAR)
4. VERTICAL SHOCK ABSORBERS (REAR ONLY)
5. BODY TILT SPRING AND SHOCK ABSORBER (NOT SHOWN)

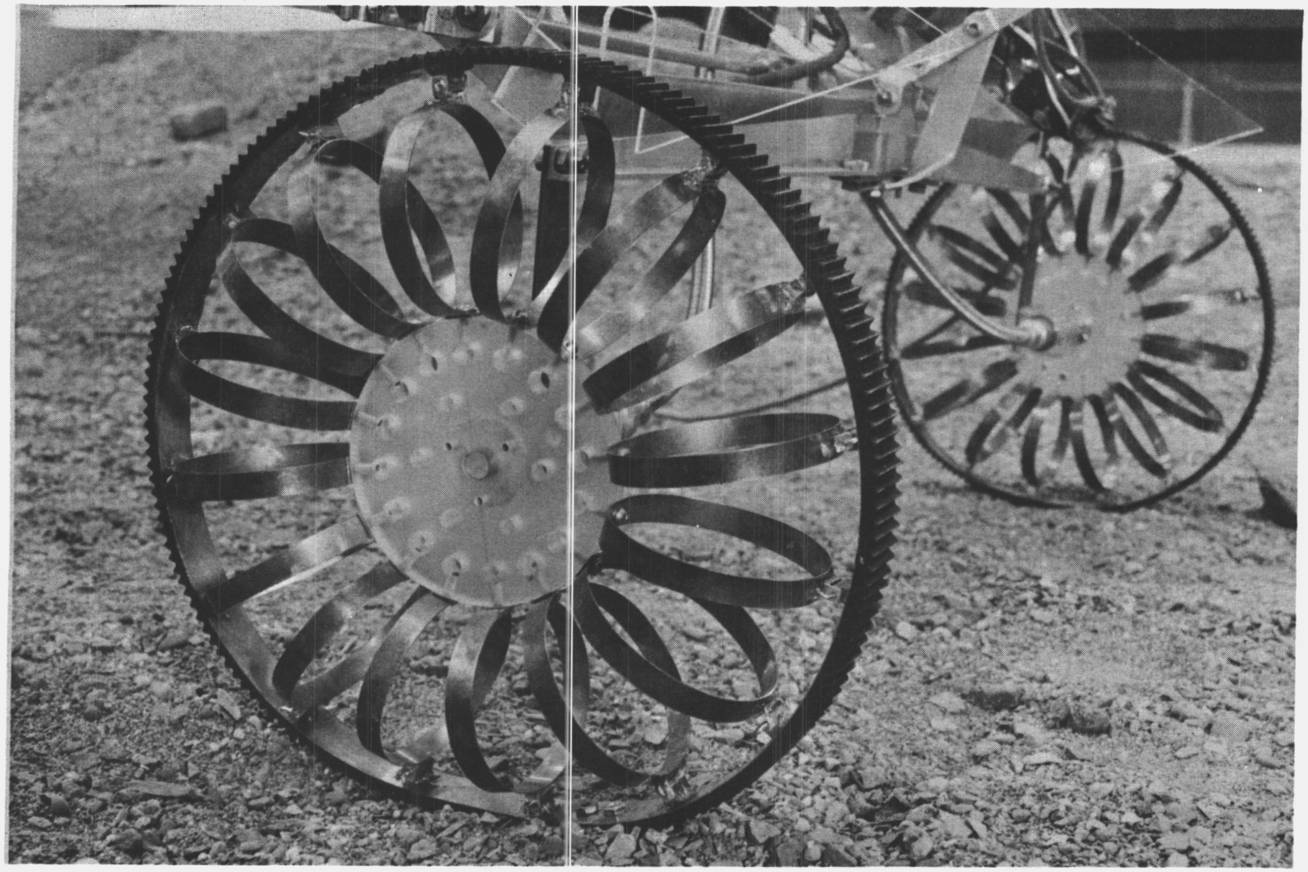


FIGURE 21: FLEXIBLE TOROIDAL WHEEL MODEL FOR MRV DYNAMIC SIMULATION MODEL. CONSTRUCTED FROM SPRING-TEMPERED STEEL THE HOOP-SPOKES AND RIM ARE JOINED WITH SMALL HINGES WHICH ALLOW A LARGE FOOTPRINT AND RELIEVE CERTAIN STRESSES.