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ROVER TECHNOLOGY FOR MANNED MARS MISSIONS

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ABSTRACT

A set of Roving vehicle design requirements were postulated by JSC, corresponding to an idealized Mars transport vehicle operational scenario which could serve as a reference for a manned Mars mission. The ability of conventional vehicles to satisfy these requirements were examined. The study indicated that no conventional vehicle could satisfy all of the requirements, as the vehicles are presently configured. Consequently, the requirements have to either be relaxed (as will be proposed in a section of this report) and/or an alternative, less conventional vehicle design will have to be developed. A possible unconventional vehicle design which has received considerable attention for DARPA and the Army is the walker vehicle. The design issues associated with this vehicle will be presented in this paper, along with a comparison of the performance capabilities of this technology vs. conventional vehicle technology.

INTRODUCTION

In the last year the U.S., Japan, and European nations have committed hundreds of millions of dollars to developing computers that can "think" more like humans, moving and acting independently according to what their electronic senses tell them. For now, these mobile thinking manned transport vehicles will have to serve the planetary mission designers on wheels or tracks, and depend on human operators for major decisions. However, DARPA is currently funding work at Ohio State University on a six-legged robot which is aimed at achieving mobility closer to that of humans and animals than to conventional vehicles. This will allow manned vehicles to venture into cluttered environments, steep slopes, and areas accessible to animals or humans but not to wheeled vehicles.

In recognition of the above circumstances, this paper is devoted to a summary of the design comparisons of legged versus traditional mobility systems for manned transport on Mars.

APPROACH

A number of Rover vehicle point design configurations have been proposed over the years which appeared to have the potential for providing Mars surface operations of high science yield. However, the analytical tools did not exist for comparing these designs. Thus, it was impossible to select an optimal vehicle configuration for the mission options of interest. To eliminate this difficulty, an attempt has been made to generate some preliminary rover vehicle requirements, for comparison with a compilation of the capabilities of existing rover vehicle point designs. This information was then used to eliminate all but the most promising rover vehicle design concepts. For the remaining vehicle candidates, a comparison was made of their predicted performance capabilities. Each of these issues will be addressed in more detail below.

VEHICLE PERFORMANCE REQUIREMENTS AS DEFINED BY THE JOHNSON SPACE CENTER

Table 1 outlines the mobility requirements for a manned Mars rover vehicle capable of performing a site traversal on the Mars surface. The following traverses were selected as the basis for the definition of these requirements: a traverse for a Mars operational scenario which is equivalent to an idealized Lunar Appollo 15 scenario, the traverses planned for the Candor Chasma region of Mars, and the Viking Lander 1 and 2 geologic sites.

A survey was conducted to identify the performance characteristics of all existing rover vehicle point designs documented in the current literature. These vehicle performance characteristics were compared against the Mars rover vehicle requirements, as presented in Table 2 (Refs. 1-14). Based upon this comparison, only three vehicles appeared as candidates for mars surface operations: (1) a six-wheel rover (ex. Lunar Rover Vehicle (LRV), (2) an ELMS (Lockheed Loopwheel Vehicle), and (3) a walker.

CONVENTIONAL VEHICLE PERFORMANCE COMPARISON SUMMARY

A performance comparison of walker technology versus alternative concepts will be deferred until the following section. Empirical data on component performance characteristics is required as input into analytical models describing the performance of the wheel and loopwheel vehicles. Thus, comparisons of vehicle performance could only be found for the point design concepts identified above. A discussion of the perfor-

TABLE 1

MOBILITY CHARACTERISTICS

CRITERIA	REQUIREMENT
1. Maximum slope capability (Affects: wheels, drive, wheelbase, tread)	45 deg, soft soil
2. Ground clearance (Affects: suspension, wheels, wheelbase, tread)	(A) Straddle a 35 deg-wedge formed by two intersecting crater walls (B) Undercarriage clearance 16 in. (approx) (Within central compartment area)
3. Maneuverability (Affects: wheels, suspension, steering, tread, wheelbase)	(A) Turning radius 10-15 ft (approximately) (B) Front and rear steering (C) Reverse drive
4. Stability (Affects: wheel suspension, tread, wheelbase)	Approximately 40-50 deg for traversing crater walls of soft soil and providing for some wheel sinkage
5. Obstacle capability (Affects: wheel, suspension, wheelbase, tread)	3 ft (approx)
6. Crevasse capability	2-3 ft (approx) (Not critical)
7. Roving route capability (Drag, torque, power)	
(A) General slopes	5 deg (approx) continuous over a considerable route length
	(B) Local slopes 20% of route assumed to be 30-deg crater walls

TABLE 2
COMPARISON OF ROVER PERFORMANCE

Rover	Ref.	Type	Number of Wheels	Max Slope Capability deg	Ground Clearance m $(x10^{-2})$	Turning Radius m $(x10^{-2})$	Stability		Obstacle Capability m $(x10^{-2})$	Crevasse Capability m $(x10^{-2})$	Mass kg	Range m $(x10^{3})$	Velocity m/hr	Remarks
							Pitch deg	Roll deg						
LRC A	1	Wheel	4	7.5	12.7	90			5	18	20-35	.050		
LRC B	1	Wheel	4	7.5	12.7	90			5	18	35-60	.020		
LRC C	1	Wheel	4	7.5	12.7	90			5	18	60-90	1.0		
RPI	2	Wheel	4	40.0	73.7	456		25	14	76				90% of Wheel Diameter
McD	3	Wheel	4-2	24.0	43.0	290			50					
GM (JPL)	4	wheel	6	20°	24.0	120	45	45	53	60				
Lunokhod	5	Wheel	8											
MM (LRV)	6	Wheel	4	25	12.0		45	45	10 (μ=0.6)	24 (μ=0.6)	66.8	0.05-0.1	56	
JPL - Lockheed	7	Loop-Wheel	4	32.0 (on grass)	125.0				56		290			Scuff Steering
Lockheed	8	Loop-Wheel	3	36.5		1.4 Lv			85% of ELMS-24	90% of ELMS-25			0.5-2	
Mobil Lander	9	Loop-Wheel	2-1	36.0*	28				29-39 (μ=0.6)		675			
MBB				20.0	25				8.1 (μ=0.6)		180			
Dual LRV	10	Wheel	6	35.0*			57	45	100	100	449	1000		
MM74	11	Wheel	4	5.0*	21	Scuff	40	60	5.7	31	127	10-50	80	
Grumman	12				30						20			
	12				30						56			
	12				40						100			
Mars Ball	13	Wheels	2	10-20 (Max)	185									
LRV	14	Wheels	4	<30*	35 (crater ledge)	0 or 457	40-45	40-45	8.10"	27"	200	1500	$1-1.5x10^3$	
Mission Requirements				45	40.6	305-457	45	45	3'	2-3'	400	100	576	

LV = length of vehicle

*analytical only

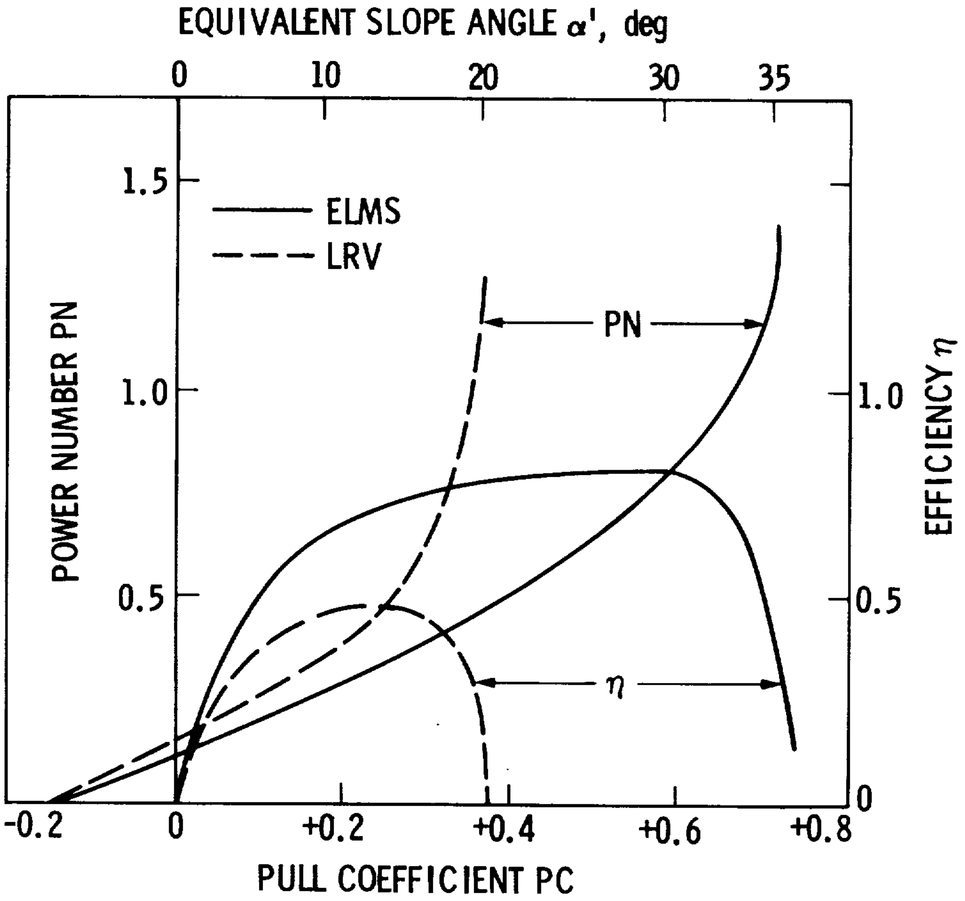
mance capabilities for these two vehicles is provided in Refs. 15-16, and a comparative summary will be outlined below. This comparison is not satisfactory from a mission/system engineering perspective, since it is necessary to examine the entire range of performance and packaging capabilities of these vehicles. Consequently, a comprehensive examination will still be required to assess which vehicle design can best satisfy the manned Mars operational scenairos and mission launch mass contraints.

Figure 1 shows a comparison of the performance characteristics of a large-scale, single 3 x 3 loop wheel (ie. 3 wheels with all 3 wheels driven) Elastic Loop Mobility System (ELMS) concept and a 6 x 6 wheeled Lunar Rover Vehicle (LRV) concept in loose, air dry soil. The Pull Coefficient (PC) and the Power Number (PN) can be considered to represent respectively the specific energy output by the system and the specific energy input to the system, both normalized with respect to the applied normal load and distance traversed by the rover unit. This plot should be indicative of the soft-soil slope angle that can be negotiated by the rovers at a given energy input. Higher slip values developed on slopes at the same thrust and torque level tend to indicate a relative increase in the specific energy consumption of the rover compared to its performance on level ground. This relative performance degradation increases with increasing PC values until a 100-percent-slip failure condition is reached at which the system is immobilized.

In addition to the vehicle's power efficiency, the following performance characteristics must be included in the assessment of an optimal vehicle design for the manned Mars mission: obstacle negotiation, ride quality, and maneuvering capabilities. We note that the 3 x 3 loop wheeled vehicle has been shown to have an obstacle climbing capability which is equivalent to the 6 x 6 wheeled vehicle. For climbing large obstacles (ex., 3-foot obstacles), both the six wheeled vehicle and the 3 x 3 loop wheeled vehicle will display a substantial angular displacement of its rigid frame, as shown in Figure 2. Both vehicle designs are maneuverable enough to enable them to navigate either over or around the boulder fields associated with the Viking Lander 1 and 2 geologic sites (Ref. 17). It is believed that vehicle traversals associated with alternate sites may be less abundant in rocks, but still subject to opera-

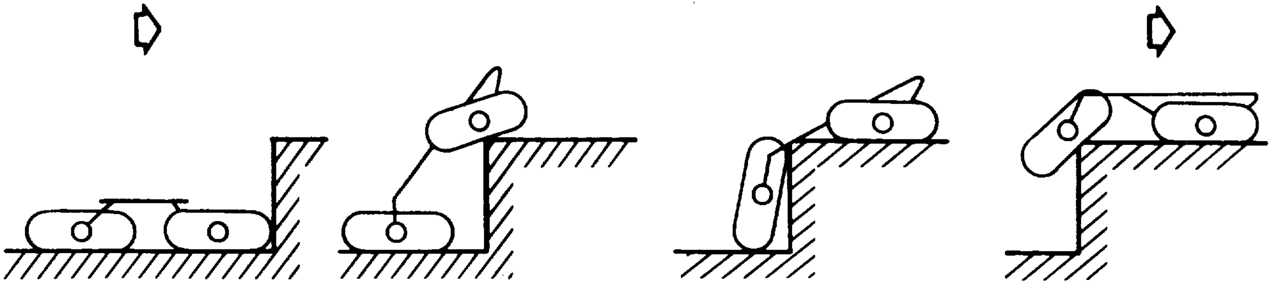
COMPARISON OF PERFORMANCE CHARACTERISTICS OF LARGE-SCALE, SINGLE ELMS UNIT AND LRV WHEEL IN LOOSE, AIR DRY SOIL

Figure 1



OBSTACLE NEGOTIATION BY 3 x 3 ELMS VEHICLE MODEL AND 6 x 6 "ELASTIC-FRAME" WHEELED VEHICLE

Figure 2



tional restrictions due to the presence of the sandy, sloping soil encountered along the traverse.

Clearly, the above two vehicles cannot satisfy all of the requirements outlined in Table 2. Thus, these requirements may have to be relaxed. It should be noted, however, that the power required for obstacle negotiation may represent a constraint on vehicle selection. For climbing over obstacles, for moving around very tight spaces, and for platform stability during drilling operations, the walker technology (discussed below) offers a potential advantage over conventional vehicle designs.

UNCONVENTIONAL LEGGED TECHNOLOGY FOR A ROVER VEHICLE

In the above discussion, no assessments have been made of the wheeled and loop wheeled vehicle technology performance capability in comparison with walker technology. To this end, Odetics Corp. was asked to generate the design of a walker vehicle which could be compactly stowed within a $1m^3$ volume and which could satisfy the Mobility characteristics outlined in Table 1. This vehicle has a variable stance and gait, and omnidirectional movement capability (Ref. 18).

Figure 3 shows the vehicle in its fully deployed configuration, traversing a 1 m wide trench. In this configuration, the vehicle design is inherently stable, having a large base with a low center of gravity. In Figure 4, the vehicle is shown traversing a 1 m boulder. Comparison of Figure 3 with Figure 4 shows that the main body frame of the vehicle has now been elevated to facilitate large boulder traversal while maintatining platform stability. The stresses experienced by the payload are thereby minimized with this design.

UNCONVENTIONAL ROVER LEGGED TECHNOLOGY VERSUS ALTERNATIVE CONVENTIONAL ROVER TECHNOLOGY COMPARISONS

A preliminary performance evaluation has been made of wheel, loop wheel, track, and walker vehicle technologies. For this comparison, the specific resistance of these vehicles was plotted against each other as a function of speed, as shown in Figure 5. The specific resistance, e (Ref. 19), is defined as: $e = P / (WV)$ where P is the mechanical power input to the vehicle--that is, the output power of the prime mover; W is vehicle weight; and V is vehicle velocity. Specific resistance can also be thought of as the inverse of the lift-to-drag ratio, where "drag" is

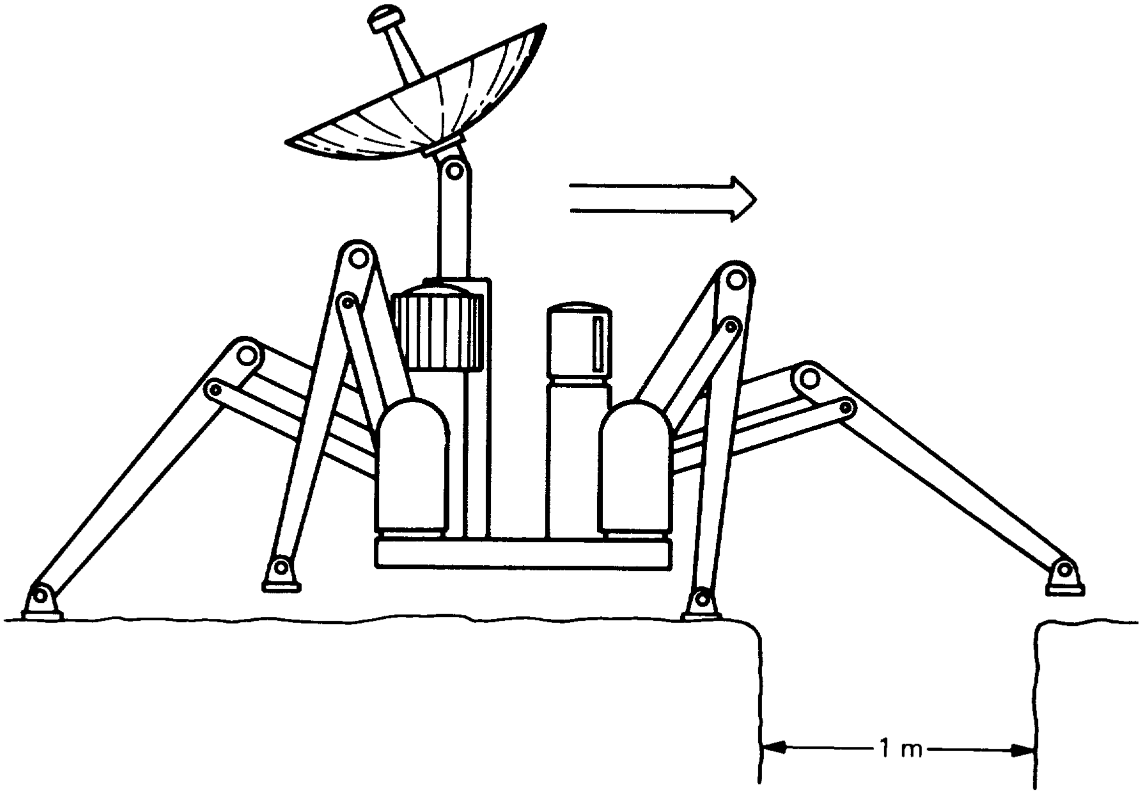


Figure 3. Mars "Rover" Traversing 1 meter Wide Trench
(Four legs shown)

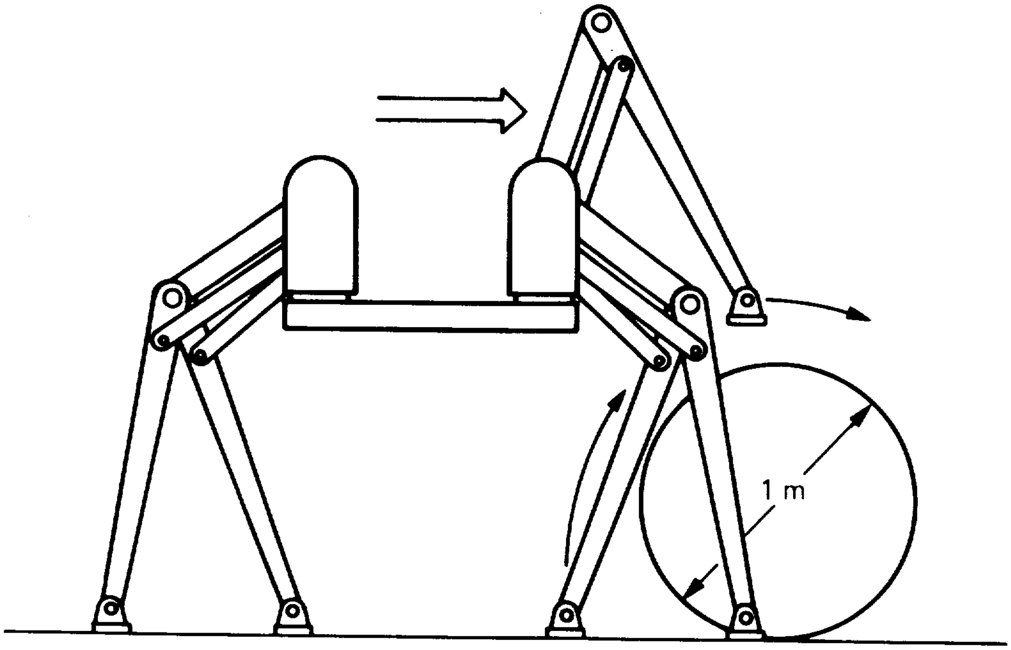
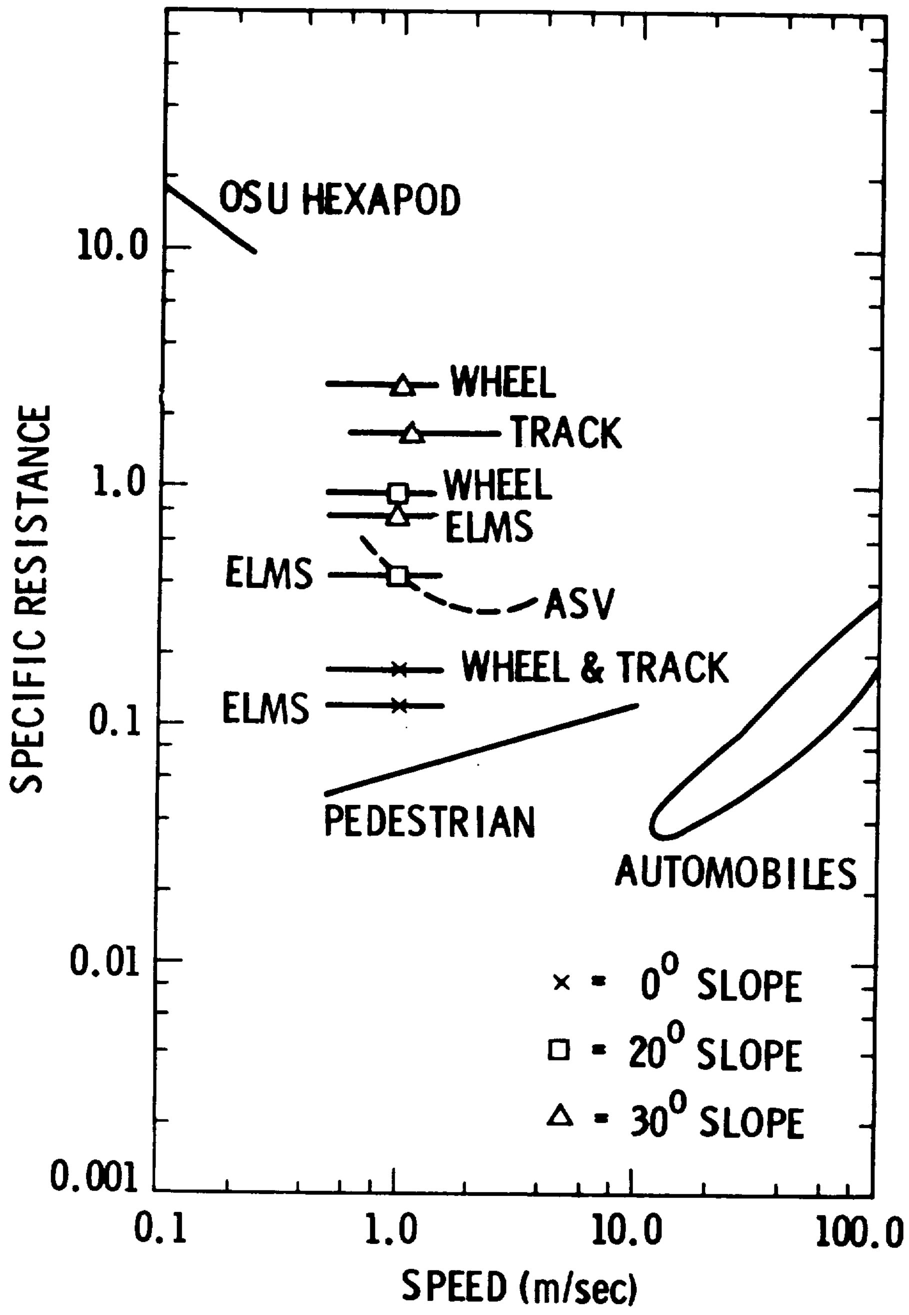


Figure 4. Mars "Rover" Raising One Leg Over An Obstacle
(Four legs shown)



SPECIFIC RESISTANCE $\left\{\epsilon = \dfrac{\text{POWER}}{\text{WEIGHT} * \text{VELOCITY}}\right\}$ AS A FUNCTION OF SPEED [NOTE: SPECIFIC RESISTANCE IS THE INVERSE OF THE LEFT-TO-DRAG RATIO, WHERE "DRAG" IS AN EFFECTIVE DRAG INCLUDING ALL ENERGY-DISSIPATION MECHANISMS]

(FIG. 5)

an effective drag including all energy-dissipation mechanisms. From this plot, it may be seen that recent advances in legged locomotion (i.e. the Adaptive Suspension Vehicle ASV) currently make this technology competitive with wheel, track, and loop wheeled systems operating on prepared surfaces. It should be noted that the ASV speed has been optimized for over 2 m/sec and the leg has been designed to support loads far greater than those required for currently envisioned manned or unmanned Sorties on Mars. Thus, it is anticipated that the power consumption of the vehicle should improve with reoptimization of the vehicle's leg design for the lower speeds and reduced loads.

The walker's design is flexible enough to provide for the integration of claws, picks, or alternative grappling devices with removable treaded forrt designs, in order to prevent foot slippage. Furthermore, the vehicle's design offers limited foot contact with the soil, as compared to wheels which are continually compressing the soil surface and pushing sand out of the way as they go. Thus, this vehicle should be able to succesfully negotiate 45 degree slopes in air dry soil simulant (Ref. 18). Contrary to the walker described above, the relative performance of wheeled vehicles and loop wheeled vehicles degrades rapidly for increasing slope angles. If the energy performance of the walker can be improved to a state roughly equivalent to that of 6 x 6 wheel or 3 x 3 loop wheel vehicles, it is anticipated that this vehicle will out-perform alternative concepts on the steep slopes and rugged terrain conditions which are anticipated to be encountered at the geology sites of current mission interest.

Before any final vehicle selection can be made, a model of the terrain-vehicle system for off-road locomotion must be developed. This type of analysis is critical to the optimal selection of a vehicle concept, and will ultimately provide a considerable cost savings in the final phase of the vehicle's engineering design and development.

DARPA UNCONVENTIONAL LAND VEHICLE PROGRAM

Currently, the Defense Advanced Research Projects Agency (DARPA) has an unconventional land vehicle program which is focused on the development of a walking machine. However, most of the program's effort is directed toward the solution of the complex issues associated with the walking machine's control, in order to provide a field test of a large scale version of this machine in FY '86. A well-focused research and development program for the transfer of this technology to space applications must be directed toward improving the vehicle's power efficiency, stability, and control.

ROVER VEHICLE DESIGN ASSESSMENT SUMMARY

A preliminary examination has been made of existing rover vehicle concepts in comparison with a proposed set of Mars rover operational requirements. The 6 x 6 wheeled vehicle, 3 x 3 loop wheeled vehicle, and walker vehicle technologies were analytically compared for the following point design concepts: Lunar Rover Vehicle, Elastic Loop Mobility System, OSU Hexapod, and Adaptive Suspension Vehicle. Based upon this comparison, the 3 x 3 loopwheel vehicle showed equivalent stowage and step climbing capability, as well as improved slope climbing performance and efficiency charcteristics over a 6 x 6 wheel vehicle. However, neither vehicle can satisfy the 45 deg Mars obstacle negotiation requirements. Furthermore, both vehicles suffer in the area of platform stability during traversal of rugged terrain and exhibit some difficulty in negotiating around obstacles. On the other hand, the hexapod vehicle offers excellent platform stability and it can currently satisfy all postulated Mars rover operational requirements (i.e., step climbing, obstacle traversal and negotiation, and slope climbing). Walking vehicles show an energy cost problem in comparison with the more conventional rover technologies. This issue must be addressed if this technology is to ever be employed for Mars rover applications.

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