The Development of an Assessment Tool for the Mobility of Lightweight Autonomous Vehicles on Coastal Terrain

Marilyn E. Worley*, Ping Ren**, Corina Sandu*, Dennis Hong**
*Advanced Vehicle Dynamics Laboratory, **Robotics & Mechanisms Laboratory
Virginia Tech Blacksburg, VA 24060

ABSTRACT

This study focuses on developing an assessment tool for the performance prediction of lightweight autonomous vehicles with varying locomotion platforms on coastal terrain involves three segments. A table based on the House of Quality shows the relationships—high, low, or adverse—between mission profile requirements and general performance measures and geometries of vehicles under consideration for use. This table, when combined with known values for vehicle metrics, provides information for an index formula used to quantitatively compare the mobility of a user-chosen set of vehicles, regardless of their methods of locomotion. To study novel forms of locomotion, and to compare their mobility and performance with more traditional wheeled and tracked vehicles, several new autonomous vehicles—bipedal, self-excited dynamic tripedal, active spoke-wheel—are currently under development. While the terramechanics properties of wheeled and tracked vehicles, such as the contact patch pressure distribution, have been understood and models have been developed for heavy vehicles, the feasibility of extrapolating them to the analysis of light vehicles is still under analysis. wheeled all-terrain vehicle and a lightweight autonomous tracked vehicle have been tested for effects of sand gradation, vehicle speed, and vehicle payload on measures of pressure and sinkage in the contact patch, and preliminary analysis is presented on the sinkage of the wheeled all-terrain vehicle. These three segments—development of the comparison matrix and indexing function, modeling and development of novel forms of locomotion, and physical experimentation of lightweight tracked and wheeled vehicles on varying terrain types for terramechanic model validation—combine to give an overall picture of mobility that spans across different forms of locomotion.

Keywords: lightweight vehicles, robotic ground vehicles, mobility, off-road vehicle performance, coastal terrain

1. INTRODUCTION

Vehicle mobility is defined by the Department of Defense as the "overall capacity of a vehicle to move from place to place while retaining its ability to perform its primary mission" [1]. Traditionally, the term has been used to asses the capability of a manned ground vehicle, with predilection for large wheeled or tracked military vehicles. Several semi-empirical methods have been developed to analyze the mobility of such vehicles, for example the Cone Penetrometer Technique [2] and Bekker's methodology [3,4,5]. With the recent development of light military or space exploration ground vehicles, and vehicles that use new locomotion strategies including legs and spoke-wheels, the meaning of vehicle mobility must be viewed in a larger context, and the evaluation tools have to be expanded.

This study focuses on analyzing the mobility of autonomous ground vehicles that use different means of locomotion on coastal terrains. An overview of the research elements involved in this analysis is illustrated in Figure 1. This study will investigate the mobility of four categories of autonomous ground vehicles, as defined by the vehicle locomotion method: Vehicles are categorized as wheeled, tracked, legged, or spoke-wheeled. The challenges in evaluating the mobility of these vehicles stem from the characteristics of the soil and terrain profile, vehicle performance during obstacle negotiation maneuvers, operational environmental conditions, insufficient experimental data to evaluate performance metrics, and the availability of vehicles that use legs or spoke-wheels for modeling and testing. Existing methods to predict the mobility of heavy vehicles cannot be directly applied to light/robotic vehicles or vehicles that use alternative locomotion methods such as legs or spoke-wheels. Moreover, the task to compare the mobility of two vehicles from different categories is hampered by the lack of common applicable evaluation criteria.

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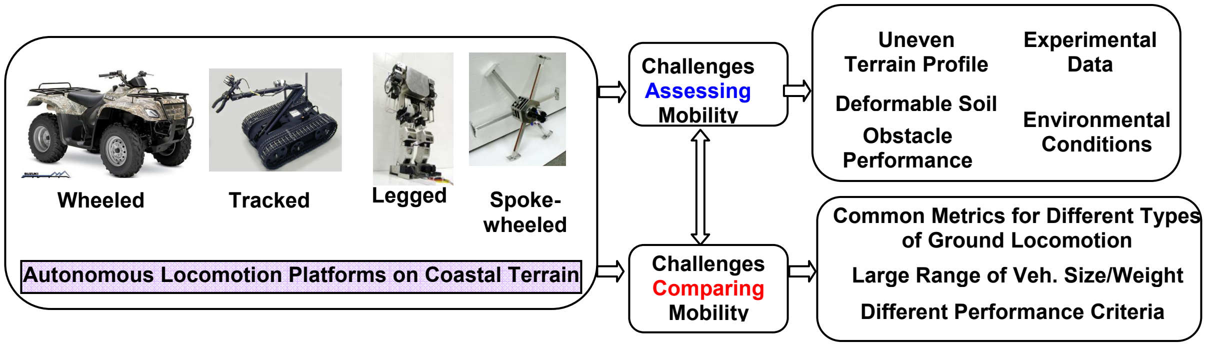

Figure 1. Research components for vehicle locomotion on coastal terrain

The objectives of the present work are to: (1) Identify a common set of metrics that will allow a quantitative comparison of the mobility of legged, wheeled, and tracked vehicles on coastal terrain. (2) Evaluate the use of alternative locomotion platforms that make discontinuous contact with the surface such as such as legged or spoke-wheeled vehicles. (3) Study the interaction of each vehicle with the coastal terrain and analyze basic parameters essential for the mobility of each category of vehicle.

2. REVIEW OF LITERATURE

The United States Marine Corps has set standards for the development of tactical unmanned ground vehicles (TUGVs) as outlined in [6]. These standards indicate the need for TUGV development specifically for off-road usage on the littoral (coastal) terrain, citing a base mission profile that includes 50% of traveled distance on cross-country (undeveloped) terrain. The standards specify that TUGVs should be developed to traverse at least 12 inches of level sand. Performance requirements are set using goal and threshold standards for development. Vehicle parameters such as speed, turning radius, slope-climbing capability, vertical obstacle negotiation, rollover recovery, and payload capacity are discussed. Mission requirements include impact considerations, daytime/nighttime operation, climate temperature, and sensing capabilities. Potential mission operations including rescue/recovery, tactical enforcement, reconnaissance, and their implications are presented. These provide the basis for many of the metrics used in autonomous vehicle comparison.

The comparison of autonomous vehicles using mobility measures has been attempted in [7]. The authors present preliminary performance comparisons of several theoretical wheeled and tracked vehicles creating the Bekker's Derived Terramechanics Model (BDTM) using parameters as outlined in [2,3,4,5,6]. While these efforts introduce parameters by which to compare lightweight autonomous vehicles, there is no formulaic measure of which of the vehicles is overall better suited for a given mission.

3. MOBILITY METRICS

The matrix of mobility metrics identifies pertinent measurable mobility performance criteria to form an assessment tool to compare vehicles of different locomotion platforms for their mission suitability. This tool presumes that all vehicles being ranked against each other meet the basic needs of the mission. This entails that, once mission needs and subsequent dependent vehicle performance parameters have been identified (via the matrix), all vehicles meet the minimum operating criteria. For instance, if there is a limited vehicle path, all vehicles have allowable dimensions for this path. Once viable mission candidates have been identified, they can be compared using the indexing function so as to rank the vehicles against each other in an intuitive and quick manner. Thus, this system can be used to quickly narrow down a wide pool of mission candidates for those vehicles best suited for a given mission. A further benefit of this system is that it is adaptable to user needs. Performance parameters and mission criteria can be added to expand the system for unforeseen specifications. Figure 2 shows a template for the mobility metrics matrix, which can be further expanded, as needed.

A = Adverse
L = Low Positive
H = High Positive

	Vehicle Parameters/ Performance Measures		Vehicle-Terrain Param.: Interaction					Vehicle Parameters: Geom.								Vehicle Parameters: Performance									Vehicle Parameters: Instrument Sensitivity				
	Terrain Characteristics and Mission Requirements	T/I	Tractive Effort/Soil Thrust (per veh.)	Compaction Resistance (per veh.)	Safe Weight	Sinkage	Slippage	Weight (Nominal)	Contact Area	Weight/Contact Area (High)	Ground Clearance*	Payload Support Area	Length (Longitudinal)	Width (Lateral)	Height	Vehicle Speed Range** (Low)	Vehicle Speed Range** (High)	Turning Radius (Minimum)	Slope Climbing Capability (Longitudinal)	Slope Traversing Capability (Lateral)	Energy Consumption	Payload Capacity (High)	Tow Capacity/Drawbar Pull	Jumping Ability	Vibration	Temperature	Light	Impact	Moisture
Interaction	Non-Disturbance Of Terrain			L	L	H	H			L	L																		
Interaction	Non-Impact of Terrain				L	H																							
Interaction	Rough/Uneven Terrain		H	L		L	L		H	L	L														H				
Interaction	Soft/Non-Cohesive Terrain		H	H	L	H	L																						
Interaction	Hard/Cohesive Terrain		H	H	L	H	L																						
Geom.	Water Hazards								L	L	H																		H
Geom.	Confined Travel Path Area								L				H	H	H			H	L	L				L					
Geom.	Obstacle Avoidance										H							H	L	L				H					
Performance	Distance of Travel															H	H				L								
Performance	Confrontation/Evasion																H											L	
Performance	Discontinuous Movement		H	L			H			H			L	L	L	L	L												
Performance	Rescue/Recovery											H										H	H						
Performance	Agility		L				A	A								H	H	H	H	H				H					
Performance	Time Limitations															H	H				A								
Performance	Daytime/Nighttime Mission																									H	H		

Figure 2. Mobility metrics matrix

3.1 The Relationship Between Mission Needs and Vehicle Parameters and Performance Measurements

The House of Quality (HOQ) structure [8] is used to tabulate the relationship between user-defined mission criteria and pertinent vehicle parameters and performance measurements. Mission criteria consist of desired vehicle-ground interactions, existing geometric terrain properties, and mission performance needs/purposes. For each category of mission criteria there is a vehicle metric category counterpart (interactions, geometries, and performances, respectively). Vehicle-terrain interactions refer to terramechanics measures of vehicle performance. Vehicle performance metrics refer to measures of vehicle power. A fourth vehicle metric category is comprised of instrumentation sensitivities to accommodate special mission needs specific to autonomous vehicles. As designed, the majority of identified relationships fall within like categories of metrics. Logically the geometry of the terrain imposes direct limitations on the geometry of the vehicle. The matrix reveals cross-category relationships that may otherwise be overlooked.

3.1.1 Interaction Measures

Mission requirements for vehicle-ground interaction are selected for sensitive mission details or important terrain composition properties. Improvised Explosive Device (IED) and mine management each involve careful consideration of the vehicle's disturbance of the threat device via non-impact of the terrain. Habitats involving sensitive balance of nature may require that vegetation or wildlife not be destroyed during the mission. Mission involving such habitats would require non-disturbance of the terrain Soft or less cohesive sand requires some different formulations than the hard or cohesive ground.

Vehicle parameters of interaction are those measurements of vehicle-ground interaction that establish the forces necessary for vehicle propulsion and the subsequent effects on the terrain, and are thus dependent on both the soil and the vehicle properties. Empirical relationships for these measures have been established in the work of M.G. Bekker [3,4,5] and J.Y. Wong [2] based on soil characteristics as outlined in Whitlow's *Basic Soil Mechanics* [8]. These formulas allow for the adverse or positive effect of locomotion type to be accounted for in the overall vehicle operation rating. Tracked vehicles can have advantageously lower ground pressures than wheeled vehicles, while wheeled vehicles can have lower values of slip and soil disturbance in the contact patch. Specific recommendations for the robot equivalent vehicle-ground interaction parameters are suggested later.

3.1.2 Geometries

Terrain geometries refer to measures of the soil and operation area to be traversed. Path limitations including size and obstacles limit the basic area of operation. Soil classifications identifying the granulation, cohesion, and friction properties of the terrain are used to identify desirable vehicle parameters for successful missions. Soft terrain requires lower ground pressure for vehicle performance. Vehicle geometries are basic physical measurements of the vehicle including weight, ground contact area size, overall vehicle size, and payload support area.

3.1.3 Performance

Mission performance criteria provide the basic functions that the unmanned ground vehicle (UGV) must fulfill or perform. Broad categories are given so that the user can define the importance or threat level associated with these functions. Vehicle performance metrics correspond to actions that the UGV may have to take to complete its mission. Some criterion have multiple levels, indicating that for certain missions low speed levels may be desired, for stability perhaps, and for other missions high speed ranges may be critical for mission performance.

3.2 Vehicle Ranking for Mission Suitability

Within the matrix each mission category is assigned (by the user) a level of importance to allow mission customization. Each connection between a mission need and a vehicle parameter identified using a high, lower, or negative impact marker. To avoid compounding the effect of a vehicle parameter, in cases where vehicle parameters overlap (tractive effort and vehicle weight, for instance) precedence is given to the parameter which encompasses the other (tractive effort, in this case.) Once these relationships are identified a simple indexing function is used to judge vehicles for mission suitability. Vehicles are rated against each other to create a relative score (for which there is purposefully no universal scale or range). From this relative score a large number of vehicles identified for mission deployment can be judged for relative predicted performance, dramatically reducing the candidate pool.

3.2.1 Impact Markers

General levels of weighting between mission parameters and vehicle parameters represent how strongly effects of the latter are felt on the former during mission performance, or the level of impact that the former has on the calculation of the latter. A high or strong positive marker (H) represents a beneficial, direct, or high dependency. This could indicate that the vehicle parameter is critical to the mission criteria, that the mission criteria creates a greater need for a better performance of the vehicle parameter, or that the mission criteria directly affects the need for or method of calculation of the vehicle parameter. A low positive marker (L) represents a beneficial relationship where the relationship is either indirect or not of great enough importance to warrant a stronger status. Correlation exists, but may be as an intermediate calculation. A negative or adverse marker (A) represents a situation where the vehicle parameter, no matter the level, will adversely affect the mission parameter. For soft soils there is a much higher level of sensitivity to or effect of compaction resistance than with harder terrains in terms of effect on mission performance. Agility has an adverse relationship with sinkage and slippage, but a strong positive correlation with turning radius and jumping ability. Energy consumption has an adverse relationship to mission time limitations. Markers provide for some tradeoff compensation between mission criteria. Each marker category is assigned a specific weighting for use in the indexing function.

3.2.2 Indexing Function

The various ratings in the mobility metrics matrix provide for a computational approach to comparing vehicles of different mobility platforms. Mission parameters are divided into T groups by their user-defined Threat/Importance (T/I) levels, $\ell_{T/I}$. Within the k^{th} T/I group, vehicles are rated for mission suitability first by the importance of each vehicle metric to the mission criteria, then by their comparative abilities to fulfill each vehicle metric category.

Table 1. Index Function Symbol Guide

	T/I Level	Vehicle Parameter	Vehicle
Value	$\ell_{T/I}$	p	None
Index	k	j	i
Range	T	M	V

In order to rate vehicles against each other, values of vehicle metrics must be normalized so as not to introduce unwanted effects of units and ranges imposed between unrelated parameters. As such, this indexing function rates vehicles against each other with an intuitive zero-to-ten relative rank. For the j^{th} vehicle metric (of those connected to the k^{th} group of mission criteria of equal $\ell_{T/I,k}$) the user selects an ideal or "best" vehicle candidate of the group. The "best" candidate can be chosen using military standards such as U.S. Marine Corps UGV Standards [6], or according to tested experience with the vehicle, but is always chosen for the maximum performance in that category, including cases where the metric has been identified in an adverse relationship to a mission criteria. Each i^{th} vehicle is scored for its performance level for the j^{th} metric—$p_{i,j}$—in comparison to the best level of performance of all V vehicles for that metric, or $p_{,best(V),j}$. This ranking factor is a pure measure of relative vehicle performance where the normalization dictates that the "best" vehicle for that metric receives a default score of 10. This rank is computed in Equation (1).

$$rank_{i,j(k)} = \frac{p_{i,j}}{p_{best(V),j(k)}/10}. \tag{1}$$

To give weight to the amount of connection of parameter p_j to a given mission T/I group two factors are used. The factors $n_{j,l}$, $n_{j,h}$, $n_{j,a}$ are equal to number of times a metric j is shown in the HOQ to be related to the k^{th} group of mission needs by a high, low, or adverse relationship, respectively. Each n-factor is combined with its respective weighting factor—w_h, w_l, *or* w_a—that provides a boost or penalty for each vehicle metric's level of relation to a given mission need. This combination factor of $wn_{i(k)}$ is a pure measure of the importance of the j^{th} metric to the mission parameter, as shown in Equation (2).

$$imp_{j(k)} = (w_l n_{j(k),l} + w_h n_{j(k),h} + w_a n_{j(k),a}). \tag{2}$$

The use of the level of Threat/Importance $\ell_{T/I,k}$ provides a pure measure of the importance of the mission parameter to the overall mission, and the final link between mission needs and vehicle performance. This mission T/I category weighting is used in combination with the impact marker weights to form a cumulative value by which to rank a vehicle directly against others in the population of vehicles under consideration. Rank of vehicle i is computed by Equation (3).

$$Q_j = \sum_{k=1}^{T} \ell_{T/I,k} \sum_{j=1}^{M} \left\{ (w_l n_{j(k),l} + w_h n_{j(k),h}) \left(\frac{p_{i,j}}{p_{best(V),j(k)}/10} \right) + w_a n_{j(k),a} \left(11 - \frac{p_{i,j}}{p_{best(V),j(k)}/10} \right) \right\}. \tag{3}$$

The adversarial effects are computed such that the vehicle with the best performance of a vehicle parameter is the least penalized of the group. For instance, if time limitations are identified in mission criteria, the vehicle with the best (or lowest) energy consumption rate will be penalized the least in comparison with competing vehicles with higher consumption rates. Each score Q_i will be a mission-specific rank of the i^{th} vehicle's mission suitability as compared to all V vehicles.

4. TECHNOLOGY DEVELOPMENT OF ROBOTS WITH WALKING LOCOMOTION

Considering the complicated environments of coastal terrain and the growing use of autonomous vehicles in dull, dirty, and dangerous applications [9], the development of novel robots with alternative locomotion strategies becomes necessary. Compared with lightweight tracked and wheeled autonomous vehicles, legged robots are more adaptable in the actuation of their locomotion platforms, and may therefore have the potential of greater agility in certain rough terrains and unstructured environments. Note that the legged locomotion discussed in this paper is equivalent locomotion with discontinuous contact with the ground. In the following sections, three types of robots with novel locomotion—a bipedal, a self-excited dynamic tripedal and an active spoke-wheel—are introduced. These locomotion platforms are unique in their complexity of dynamic interaction with the ground, which may include several phases such as the initial penetration into the soil, the power stroke in the soil and the withdrawal out of the soil [10]. When possible, theoretical work is presented to provide the basis for future robotic foot-ground interaction study to aid in developing equivalent vehicle-ground interaction parameters to use in the mobility metrics matrix. As suggested in [10], any proposed theory for mathematical models will require specific adaptation to small-scale applications such as walking robots, and further require physical testing and validation. Models and prototypes of these and other robots are under development at the Robotics and Mechanisms Laboratory in the Department of Mechanical Engineering of Virginia Tech. A summary of some basic specifications of current working prototypes is shown in Table 2.

Table 2. Basic Specifications of Selected Current RoMeLa Robot Prototypes

Robot	Foot Geometry	No. of Feet	Foot Dimensions L x W x T	Unloaded Weight	Max. Velocity	L x W x H	Approx. Turning Capacity (per step)
DARwin	Rectangular Plate	2	4.44in x 2.75in x 0.75in	4lbs	0.23m/s (0.50mph)	4”x9”x18”	45 degrees
STriDER	Cylindrical Spear	3	1-inch diam., 51.25inch long	10lbs	0.5m/s (1.10mph)	25” x25”x70 ”	45 degrees
IMPASS	Two center-hinged curved rectangular plates	6/wheel	4.5in x 1.75in x0.15in (plate thickness)	Body Incomplete	1m/s (2.25mph)	32.5 inches Eff. Wheel diameter	30 degrees

4.1 DARwIn (Dynamic Anthropomorphic Robot with Intelligence)

DARwIn, Dynamic Anthropomorphic Robot with Intelligence as shown in Figure 3, is a humanoid robot capable of bipedal walking and performing human-like motions. DARwIn is a 21 degree-of-freedom (DOF) system with each joint actuated by cordless DC motors. Implementing a computer vision system on the head and multiple force sensors on the foot, DARwIn can execute human-like gaits while navigating obstacles and traversing uneven terrain [11].

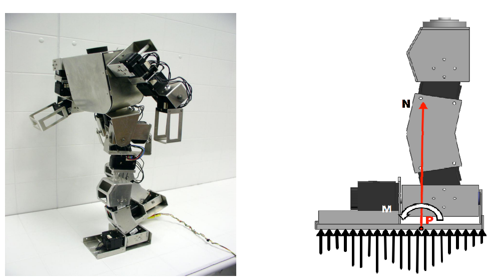

Figure 3. Current (Spring 2007) DARwIn prototype and foot with controlled force distribution.

The bipedal gait of DARwIn and the interaction between the robotic foot and the ground is dynamically controlled using a Zero Moment Point (ZMP) control. Ground interaction is similar to human walking. The rectangular foot is placed heal first, a rotation at an ankle joint presses the foot flat against the ground, and weight is transferred to this stance foot. Vertical force sensors on the stance foot feed measurements into a control algorithm to create a reactive robot stance, varying the vertical force distribution to keep the ZMP under the stance foot. An example of such a controlled force distribution is shown in Figure 3. Once the second foot is planted, the stance foot is lifted. Vertical force distribution is only considered in the profile shown in Figure 3, as forces lateral to the direction of robot path are not measured [11].

The dynamic loading process of robotic feet has been studied by Ingvast [12], addressing issues of horizontal deflection and contributing forces, as well as dynamic vertical force-deflection interaction that is specific to walking robots. To model the foot-ground interaction during loading and unloading (placement, weight shift, and lift of the foot), some models are proposed in differential forms to describe the relationships of soil deflection and changing force. It is assumed in [12] that the contact area does not change, the orientation of the pad of the foot does not change (no tipping or rotating about an ankle joint), and that ground interactions with the horizontal surface (such as from pileups of soil) are ignored. Based on Bekker's theory, a vertical deflection-force model and a horizontal deflection-force model for plastic soil are formulated, shown as Equations 4.1 and 4.2, as well as a one-dimensional horizontal deflection-force model for plastic elastic soils shown as Equation 4.3, which lay the foundation for further analysis of the vertical pressure-sinkage relationship, and the quantification of walking robot thrust as,

$$dF_z = \begin{cases} Az^{n-1} k_z dz, & z \geq z_{\max} \\ Ak_r dz, & z < z_{\max} \text{ and } F_z > 0 \end{cases} \tag{4.1}$$

$$dF_x = \frac{1}{K_p}\left(F_{\max}\, dx - F_x \left|d_x\right|\right) \tag{4.2}$$

$$dF_x = \begin{cases} \frac{1}{K_p}\left(F_{\max} - \left|F_x\right|\right) d_x, & F_x dx \geq 0 \\ k_e dx, & otherwise \end{cases} \tag{4.3}$$

In these equations z denotes vertical deflection and direction, x denotes horizontal direction, F represents a force vector in the given direction, A is the value of contact area, k_z and k_r are coefficients of ground stiffness in the vertical direction during load and during unloading/reloading, respectively, K_p is the modulus for lateral deformation for plastic soils, $F_{\max}$ is the maximum horizontal force based on vertical force and soil friction, and k_e as the elasticity constant for a plastic-elastic soil. Horizontal forces refer to those in the direction of robot travel. Motion in the y-direction (perpendicular to the travel path and to the normal force) is assumed to be zero. Models that do not make this assumption are also presented in [12].

Limitations on using the models include that the contact area of DARwIn is smaller than that assumed in the framework of Bekker's classical model, which assumes a rectangular contact area with a preferred width no less than 4 inches [3], and that DARwIn's ZMP control provides a special case where the vertical force distribution is dynamically controlled instead of passively utilized. More information on the fundamentals of compaction and propulsion of walking robots is presented in [10].

4.2 STriDER (Self-excited Tripedal Dynamic Experimental Robot)

STriDER, Self-excited Tripedal Dynamic Experimental Robot, as shown in Figure 4, is a novel three-legged walking machine that exploits the concept of actuated passive dynamic locomotion to walk with high energy efficiency and minimal control. Unlike other passive dynamic walking machines, this unique tripedal locomotion robot is inherently stable with its tripod stance and can change directions while walking [13].

Figure 4. Current (Spring 2007) STriDER prototype and foot.

To initiate a step, the legs are oriented to push the center of gravity outside of the stance legs. As the body of the robot falls forward, the swing leg naturally swings in between the two stance legs and catches the fall. Once all three legs are in contact with the ground, the robot regains its stability and the posture of the robot is then reset in preparation for the next step. The foot can be regarded as the end of the leg close to the ground. Each time a leg is placed, the foot will sink into the ground at its placement angle. During swing, stance feet will likely sink farther into the soft ground due to increased weight distribution. These stance feet will tilt as the body tilts, and thus any portion of the foot that is sunk into the ground will cut through soft soil. When a swing foot is initially lifted off the ground it will have tilted with the body, and will drag through soft soils until it is freed. As an example of adaptability, controls may be developed in the future to prevent some of this dragging effect.

Given that STriDER's feet are like spears, basic models for ground interaction may be based on theory behind the cone penetrometer's ground interaction as presented in [14]. This work presents formulations connecting the vertical force that must be exerted on the penetrometer's shaft in order to penetrate the soil to a given depth for plastic-elastic soils, and could be used to create an equivalent pressure-sinkage measurement for STriDER. Some technical reports concerning the effect that an upward flow of soil that results from ground penetration are also made,, and this shearing flow effect may assist in the formulation of an equivalent for compaction resistance. If it cannot be avoided using controls, the dragging motion will have to be studied more when prototypes are further developed for testing, but also has potential links to blade cutting as studied in the agricultural field [15].

4.3 IMPASS (Intelligent Mobility Platform with Active Spoke System)

IMPASS, Intelligent Mobility Platform with Active Spoke System, as shown in Figure 5, utilizes rimless wheels with individually actuated spokes to follow the contour of uneven surfaces and step over large obstacles. To move the wheel can rotate as a whole, much like a conventional wheel, and/or each spoke in the wheel can stretch in and out to push against the soil. As shown in Figure 5, foot consists of two rectangular plates hinged together at the center, with a curve of each blade up from the ground, formed at the end away from the hinge. During rolling, the foot can flex at its center hinge to react to the ground, and will dig into the ground starting at the curve of the blade, as necessary to create motion/thrust. When a spoke is actuated the applied pressure on the foot will "flex" the foot about its center hinge and/or sink the foot into soft soil.

Figure 5. Current (Spring 2007) IMPASS model, spoke-wheel prototype, and foot.

The shape of the feet of IMPASS lends itself to the bulldozer blade studied in the work of Bekker and Wong [5,2.] Models developed for the resultant force acting on the blade per unit width, caused by passive earth pressure and related to cutting depth, soil density, and soil friction, may provide a good measure for compaction thrust imposed upon IMPASS during the cutting of the foot into the soft soil. Pressure-sinkage relationships may be developed based upon the original work of Bekker, where rectangular plates were driven vertically into soft soil to impose a sinkage [3,4,5].

5. DESIGN OF EXPERIMENT

The vehicle-terrain interaction parameters used in the presented mobility metrics matrix relate to one or both of two basic off-road vehicle characteristics—ground pressure in the vehicle-ground contact patch and vehicle locomotion platform sinkage into the ground. Terrain composition and vehicle gross weight are considered in popular models for pressure vs. sinkage as static contributions, while vehicle speed is not often considered for its dynamic effect on these contact patch properties. Existing models were originally attained for heavyweight wheeled and tracked vehicles, and still require validation for their lightweight autonomous vehicle counterparts. To study the contact patch pressure and the sinkage of lightweight vehicles an experiment has been designed to test for effects of sand gradation, on-board payload, and vehicle speed.

Two vehicles were used in the primary experimentation: MATILDA, a light-weight autonomous tracked vehicle developed by MESA Robotics and modified by the JOUSTER laboratory at Virginia Tech, and a 2004 Suzuki Eiger four-wheel all-terrain vehicle (ATV). These vehicles were chosen for their predicted ability to operate on sand and for the fit of some performance characteristics into the 2000 U.S. Marine Corps TUGV Standards [6].

Table 3. Basic Parameters of Vehicles Used in Experiment

Vehicle	Unloaded Weight	Payload Capacity	Estimated Velocity Range	L x W x H	Tire Inflation Pressure	Estimated Turning Radius
MATILDA (tracked)	61lbs	125 lbs	0-2 mph	30" x 21" x 12"		Omnidirectional (can turn in place)
ATV (wheeled)	577lbs (unmanned)	200 lbs (on Rear Rack)	0-35mph	85.6" x 44.1"x 50.0"	4.5psi (front) 4.0psi (rear)	9ft.

For the experiment each vehicle has a unique speed range. For each vehicle three levels are chosen at equal steps. MATILDA's mechanical controls allow for a maximum speed of roughly 2 mph. Speed control was set in the computer control unit for levels of 50%, 75% and 100% throttle. The Eiger minimum speed is set at 2 mph, incremented at 2 mph to the maximum speed of 6 mph. (This maximum speed was set for driver safety).

The United States Marine Corps TUGV standards set a threshold payload capacity of 150lbs, and a goal payload capacity of 300 lbs. As such, whenever possible, these payloads are included in the experiment design. Each vehicle has three payload settings, one of which is unloaded. While MATILDA has a listed payload capacity of 125lbs, after some preliminary testing at MATILDA's three expected operating speeds, payload capacities were set at 0lb, 25lbs, and 50lbs to ensure movement at the 50% throttle level. The maximum ATV payload capacity (payload being weight in addition to driver weight) was chosen as 150lbs, to accommodate the rear rack on the ATV and meet the TUGV standards [6].

For this experiment five silica sands were chosen according to their sand gradations. Each sand is classified as fine, medium, or coarse according to the Unified Soil Classification System These five samples were chosen such that the bulk of the gradation (70% or more) fit between two standard U.S. sieves, so as to ensure the most uniform conditions. The coarsest sand (Best Sand 430) is close to classification as a gravel, having approximately 87% of the gradation by weight between 0.093in and 0.187in diameter (passing U.S. Standard Mesh 4 and retained within either U.S. Standard Mesh 6 or Mesh 8). One of the midgrade sands (Best Sand 1020) has 71% of the sand granules having diameters between 0.0334in and 0.066in. The finest sand (Best Sand 110) is close to classification as a clay, with 71% of the sand within a 0.029in-0.059in diameter range. All sands have a sphericity of 0.8 and roundness of 0.8 [17]. The sands used for testing are shown in Figure 6. Each square grid is 0.20-inches on each side.

Figure 6. Sand from experiments, coarsest to finest.

Each vehicle in this study represents a separate (independent) experiment. The general, the experiment guideline for each vehicle is a special case of the split plot design [18], with one blocking factor, one whole-plot factor applied as a balanced incomplete block design (BIBD), and two treatments for consideration, applied as split-plot factors using the randomized complete block design (RCBD), so that the overall design is characterized as SPD (BIBD,RCBD). The blocking factor is the day of experimentation, involving five levels or days. The whole-plot factor is the sand gradation, where each of the five gradations of sand was randomly assigned to a space of land, with four sand gradations tested per day. The split-plot factors were grouped such that the two effects of speed and payload were combined into nine settings, representing all low-high-medium combinations (such as maximum speed with minimum payload). For a given day and sand gradation, the nine treatment groupings were randomly ordered to assign treatments to the sand. Each day of experimentation consisted of 72 unique runs (36 for each vehicle) for a total of 360 experimental runs in five days. For this first set of experiments the sands were dry.

For each run two sets of data were collected. A pressure sensor embedded in the sand was used to record video of the contact patch pressure as the vehicle ran over the pressure pad. This video reveals characteristics such as shape and distribution of pressure, peak pressure and its location, and average pressure. After each run three measures of center-track sinkage were taken within an area over the embedded pressure sensor.

A second experiment was designed to look at the effects of compound vehicle loading on the contact patch pressure distribution and on the vehicle sinkage. The ATV was run without payload additional to driver weight at the intermediate speed of 4mph for 100 runs over four of the sands. At increments of ten runs at a time pressure data was taken during the run, and sinkage data after the run.

6. EXPERIMENTAL SETTING

The experiments to test the MATILDA robot and ATV on dry sand were held outdoors in winter 2006. The MATILDA robot and the ATV are shown in Figure 7. Approximately 4.5 tons of each of the five sand types were put into a hole dug into soft ground. Soft surroundings prevent interference that would exist with any hard supportive surface, such as concrete. Each hole was approximately 5 ft. wide, 7 ft. long (in the direction of vehicle travel) and 2.5 ft. deep. A Vertek DCP-1500 drop cone penetrometer unit with a soil moisture resistivity (SMR) probe confirmed that the sand remained dry. Compaction data was not collected due to the looseness of the sand. After each experimental run the soil was raked and smoothed to eliminate tracks and any compaction that may have occurred.

Figure 7. MATILDA robot and ATV used in the experiments.

A TekScan IScan pressure pad was used to record the pressure distribution in the contact patch. This pressure pad was embedded approximately six inches deep to record data for the ATV, and two inches deep to record data for MATILDA. The depth of embedding the sensor was used to offset any effect that the senor would have on contact patch properties. The depth of embedment was several times greater than the sinkage seen in the data.

Pressure for the ATV was measured for the rear right-side tire. The vehicle was set in two-wheel drive mode, with power to the rear wheels. The payload (above driver weight) was applied to the rear end of the vehicle. Speed was maintained by the driver using an onboard speedometer. Pressure for the MATILDA robot was observed for the rear of the left track where one major driving wheel exists. MATILDA was loaded on top in the center of the vehicle. Speed was maintained by computer-controlled power to the throttle motors.

Sinkage data was measured at three points within the tread of each vehicle. The data was taken above the pressure pad and in the center of the width of the tread. The sinkage was measured using an engineering scale measuring from the crown of the tread (the sand pushed to the side of the tire) down a specific point in the tread pattern that had identical counterparts within the area of the pressure pad.

7. PRELIMINARY DATA RESULTS AND ANALYSIS

The first round of experimentation on dry sand using the ATV has been completed. Preliminary analysis on the sinkage data is underway. Currently, the error terms indicate that further data collection at the dry level may be needed. As is, statistical analysis on the effects of each factor on the sinkage response shows that the most significant factors are the blocking factor of each day of the experiment, and the speed of the vehicle.

Certain preliminary speculations have been made based on interpretation of statistical plots. There may be some interaction between payload and speed at certain grades of sand, but this appearance of interaction may be due to the random error. The same may be true for speed and grade interaction at each level of payload. From the means plot of load and speed, it is indicated that the highest speed and heaviest payload result in the deepest tire sinkage. From the same plot, the sinkage responses to payloads of 0lbs and 75lbs behave almost the same at the three levels of speed, and are much more affected by the speed than when the payload is 150lbs. This same plot reveals that the sinkage response for a payload of 150lbs does not change much as the speed of the vehicle changes.

8. CONCLUSIONS AND FUTURE WORK

The development of the mobility metrics matrix and corresponding vehicle ranking function provide for the comparison of multiple vehicles of different locomotion platforms for mission suitability. The system is customizable for given missions including the importance or threat level of a given mission requirement, the addition of mission requirements and vehicle parameters, and the adjustment of impact markers, if desired. While vehicle-ground interaction parameters have been studied and modeled for heavyweight wheeled and tracked vehicles, their application to lightweight vehicles is currently being tested. Models and prototypes for novel robot locomotion platforms such as bipedal, tripedal, and spoke-wheel robots are in development. In the future, base missions can be developed to provide users with simple guidelines and starting points to characterizing their missions.

Concerning experimentation, continued work is needed to complete the dry dataset of MATILDA measurements. A more thorough analysis of the ATV dry data set is planned, specifically focusing on the measured contact patch pressures. Once the analysis of the dry datasets is complete, a second set of testing will be performed on the sands with a given level of added moisture content. Analysis of the dry versus wet datasets will provide insight to the effect of moisture on the contact patch properties of pressure distribution and vehicle sinkage. Beyond this, a study of the effect on measurements by the depth of embedding of the pressure sensor will be done.

Further development of the walking technologies must include a more detailed analysis of contact patch properties and the development and verification of terramechanics models. Further work will also include experimental testing of the legged and spoke-wheel vehicles, upon their complete development, under the same environmental conditions. Next the mobility matrix will be tested taking into account the working autonomous vehicles to provide validation of the proposed mobility evaluation system.

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