MOBILITY ANALYSIS OF SMALL, LIGHTWEIGHT ROBOTIC VEHICLES

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Abstract

Currently, the Army is developing a smaller, leaner fighting force as part of the Future Combat Systems initiative. Therefore, there is an emphasis on small, lightweight vehicle systems (less than 2000 lbs), including small robotic systems. When the Army is presented with a new vehicle concept, the NATO Reference Mobility Model (NRMM) is utilized to determine the 'go / no go' capability. Another fundamental method for predicting large vehicles' behavior on varied terrain is to use Bekker's equations for vehicle soil interaction. These equations form a phenomenological model that describes a vehicle's performance using inputs defining the vehicle's weight, wheel or tracked design, and the necessary soil parameters.

Although Bekker derived semi-empirical formulations and the NRMM used entirely empirical relations for the terrain interaction of large, heavyweight vehicles, it is unclear whether these formulations scale to smaller, lightweight systems. There is additional model uncertainty when looking at other forms of exotic mobility that do not utilize a traditional wheel or track configuration. This study presents a state-of-the-art analysis on the metrics that define small vehicle mobility and possible approaches to addressing exotic robot mobility classification.

Introduction

Vehicles have been a part of our lives since the dawn of the wheel. The importance of vehicles grew as personal travel became convenient with the release of the Model T and has continued to expand. Robotic vehicles are now joining the transportation field as unmanned explorers of the moon and ocean floor. Robots have extended themselves into almost every aspect of life from hospital orderlies[1] to planetary rovers, to the lawn-mowing robot, Robomower. Industry has shown the usefulness of using robots to aid in tasks that are mundane, difficult, and/or dangerous for a human operator. The military has been involved in research to utilize the technology to assist its fighting forces in the face of new dangers such as chemical and biological warfare. Robots keep soldiers out of harms way by taking on the more difficult tasks that used to be delegated to only the bravest of soldiers- such as scouting or mine clearing.

With military investment in robotics, several spin-off corporations have developed to bring the technology of robots into the public domain. One of these corporations, iRobot, is pursuing both markets of public consumers and military with its Roomba (Figure 1)- a robot that presents the company's first step in intelligent robotic household appliances, and the Packbot (Figure 2)- a robot that is currently being used in the caves of Afghanistan to seek out hazards and inform soldiers.

Figure 1: Roomba, intelligent vacuum from iRobot

Figure 2: Packbot, man portable tracked ground vehicle

Robots are visible in all different aspects of society, from intelligent home appliances to stealthy spies searching caves for potential dangers. Robots have also played an important role in search and rescue operations. In the aftermath of the World Trade Center bombing, many rescue-bots were used to search for victims trapped under the rubble.

DARPA is funding two programs[2], TMR (tactical mobile robots) and HMTM (high-mobility tactical microrobots) to create the next generation of military robots. The TMR's goal is to create robots to act in the dangerous situations faced by soldiers and rescue workers. From this program, a marsupial robot called Raptor was created. It releases microbots that go out to collect information. Another robot created from this initiative was Spike, a throwable robot (Figure 2).

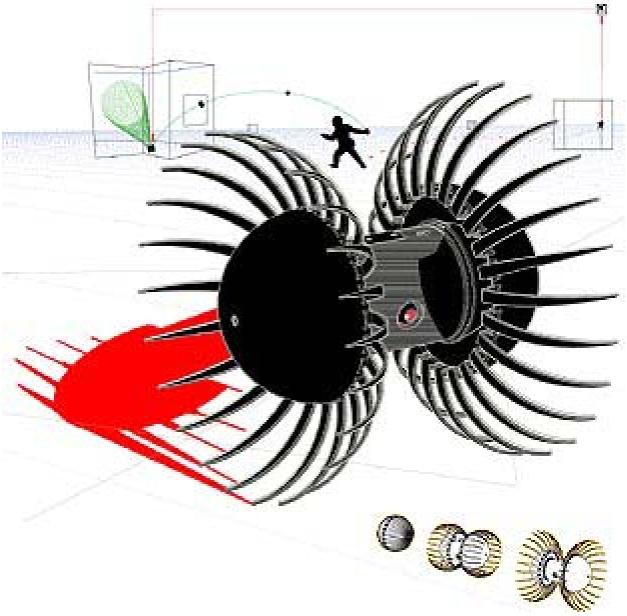

Figure 3: Sketch of Throwable Microrobot in Development[2]

Five important issues (Blitch's Five Imperatives[2]) have been raised in respect to the new military technologies: "A TMR must be able to get back on its feet when it has fallen. It must be able to recover from communication loss. It must know where it is. It must be tamperproof. And it must be able to maneuver around complex obstacles." This list deals with the basic hardware and intelligent controls issues involved in this type of robotics. This study will focus on gauging the mobility of a small, lightweight vehicle in off-road scenarios and the associated metrics of the vehicle-terrain interaction, path-planning, and vehicle metrics.

Most people have an intuitive sense of what mobility is, but can it be quantified? The NRMM users guide[3] defines intrinsic mobility for a particular situation as "the maximum feasible speed-made-good by a vehicle between two points in a given terrain" with speed-made-good defined as "the straight-line distance between the points divided by total travel time, irrespective of path." The implications of this definition are complicated. First, there is the speed (a vehicle performance metric used as a baseline for comparison), then there are two points- the path- that the vehicle needs to traverse, and finally a given terrain. Inherent in terrain are the various obstacles and soils that can impede a vehicle's progress across a landscape. The definition captures the essence of the mobility problem- performance metrics, path planning, and terrain-vehicle interaction. These are the core of the issues discussed here.

Background

There are three main methods for modeling off-road vehicle mobility. They range from a macroscopic to microscopic view of the vehicle soil interaction. The macroscopic or global view of mobility is embodied in a series of empirical relations that comprise the NATO Reference Mobility Model (NRMM). This model gives an overall evaluation of a vehicle traversing through a series of different soil conditions, road types, and obstacles. It is a tool to generalize the capability of a vehicle moving over a particular terrain. An intermediate view of the vehicle soil interaction is a hybrid method that is semi-empirical called Bekker's Methodology. Bekker uses a linear, one degree-of-freedom (1-DOF) model to predict soil behavior such as sinkage and soil thrust when acted upon by a vehicle. Bekker's model is phenomenological and is mostly used by design engineers to better understand the interaction of the running gear configuration – i.e. tracked or wheeled- with the terrain. With this model, different parameters of either wheeled or tracked vehicles can be analyzed to find the best match for the particular terrain. The most detailed physics-based model looks at the microscopic interaction of the terrain and vehicle. This type of model is a finite element analysis (FEA) model. A three-dimensional, high spatial and temporal resolution FEA model is complex, but it provides a detailed representation of the tire-soil interaction (Figure 4).

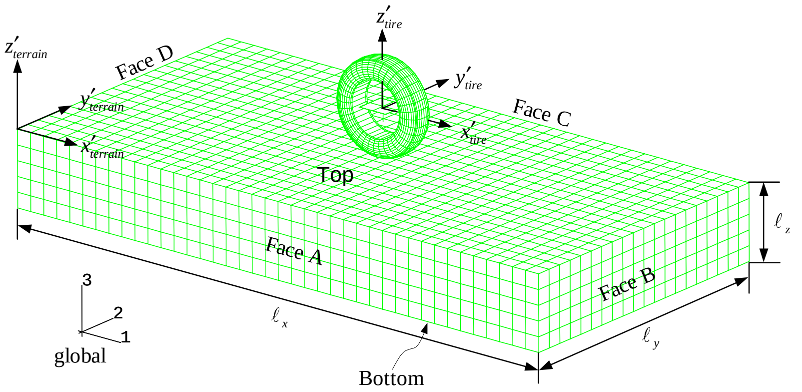

Figure 4:Finite Element Soil Model in Relation to the Tire[4]

NATO Reference Mobility Model (NRMM)

The Waterways Experiment Station (WES) developed the NRRM, which is a FORTRAN computer simulation program commonly utilized by vehicle developers, users, and acquisitioners to simulate a particular vehicle traversing a specified terrain. The program user inputs various parameters such as the vehicle characteristics, weather conditions, season, driver influences, type of terrain, various obstacles, as well as others. The outputs from the program are the speed-made-good, power efficiency, and go/no go verdict for the input scenario. The NRMM software consists of two parts: the Road Module and the Areal Module. The Road Module is the on-road capability of a vehicle whereas the Areal Module is the off-road capability of the vehicle. In addition, NRMM has several add-on packages that are preprocessors to the actual NRMM code and extend the capability of the NRMM software such as the Obstacle-crossing Module and the Vehicle Dynamics module (VEH DYN).

The Obstacle-crossing Module is used to simulate the vehicle traversing trapezoidal shaped mounds or ditches as specified by the user. The vehicle can either be wheeled or tracked and contain two portions- the main vehicle and a trailer with limitations on the suspension assemblies and tire inputs. There are two main types of input files: the vehicle specification file and a terrain file. The vehicle specifications give the appropriate geometries and characteristics. The terrain file gives the number and type of obstacles. The output of the program gives the inclination, position, interferences, and traction requirements of the simplified two-dimensional vehicle.

The VEH DYN module simulates the dynamic characteristics of the vehicle over a specified terrain and gives accelerations and motions at the driver's station. It calculates the maximum speed a human driver could tolerate for the particular terrain conditions and vehicle specifications.

The Areal Terrain Unit Module looks at the limitations to the maximum achievable speed on a specified terrain based on the following factors:

1. Traction available to overcome the combined resistances of soil, slope, obstacles, and vegetation.
2. Driver discomfort in negotiating rough terrain (ride comfort) and his tolerance to vegetation and obstacle impacts.
3. Driver reluctance to proceed faster than the speed at which the vehicle could decelerate to a stop within the, possibly limited, visibility distance prevailing in the areal unit (braking-visibility limit).
4. Maneuvering to avoid trees and/or obstacles.
5. Acceleration and deceleration between obstacles if they are to be overridden.
6. Damage to tires.

Table 1: Areal Terrain Unit Module Speed Limiting Factors[3]

Two of the speed limiting factors to note are the driver-related factors. An inherent assumption in the NRMM is that these are manned vehicles. Most of the vehicles are teleoperated, autonomous (unmanned). Without a human operator, the vehicle is able to operate beyond typical human comfort levels, as long as the vehicle's systems remain intact (including potential payload). This assumption is a serious impediment to using the NRMM to understand an unmanned vehicle's behavior over a specified terrain.

Other inputs of interest into this portion of the code involve the scenario. The scenario inputs may include the season, weather conditions, sensitivity of driver tolerances, and tire pressure variation. The first two inputs affect the soil characteristics computed in the module. The second two inputs are vehicle-terrain interaction parameters.

The second portion of the core code is the Road Module which calculates the maximum average speed on various types of roads ranging from highways to trails. In general, the Road Module is the on-road capability of a vehicle whereas the Areal Module is the off-road capability of the vehicle.

The aforementioned sections describe the main components of the NRMM code. A large underlying portion of the code that has not been discussed is the empirical soil relations that provide the terrain characteristics of the vehicle. The soil parameter, called the 'cone index', used in the NRMM is determined empirically with the use of a tool called the cone penetrometer. The cone penetrometer (Figure 5) is a 30º apex angle circular cone a with a ½ sq. in. base area, mounted on a 36 in. long, 3/8 in. diameter graduated shaft[9]. The cone index is the resisting force divided by the base area of the cone. The cone index is typically measured at a depth of 72 inches.

One of the main outputs of the NRMM is the 'go/no go' characteristic of the vehicle inserted into a possible scenario. Sinkage is considered a "soil failure" and the issue in a "no go" situation is that the vehicle cannot develop the necessary traction to overcome how far the vehicle has sunk into the soil. "Go" situations are divided in terms of various weighting functions in regards to path efficiency, power requirements, etc. Simply because a vehicle can make it through a specified soil and terrain does not mean that it can do so efficiently. The efficiency of the vehicle through the terrain is measured by the power levels required to accomplish the mission as well as through the speed-made-good metric.

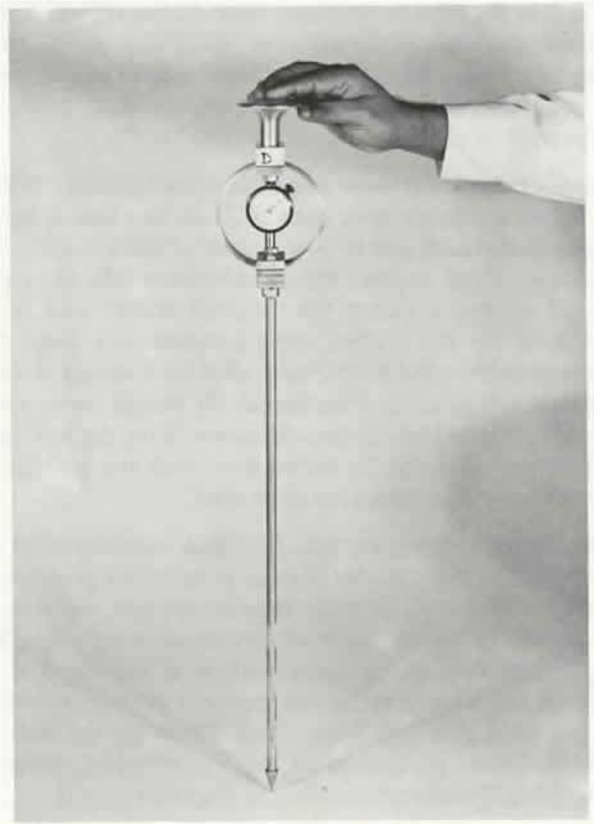

Figure 5: Cone Penetrometer[9]

Bekker's Method

Bekker's Derived Terramechanics Model (BDTM) is widely used as a tool by vehicle designers to make decisions about the capabilities of the running gear configuration and its general design. The main assumption of the BDTM is that the soil is isotropic and homogeneous. The model does not apply to a layered soil configuration such as soft soil over hard pan. The overall relations concluded frm the BDTM in regards to soil characteristics are 1) for a perfectly cohesive soil, soil thrust is a function of the contact patch only and 2) for a perfectly cohesionless soil, the soil thrust is a function of vehicle weight only.

Bekker utilized a tool called a bevameter to measure his soil parameters. A picture of a wheeled bevameter is shown in Figure 6.

Figure 6: Wheeled Bevameter[5]

The bevameter makes two measurements: one for the pressure/sinkage relationship of soil and the other for the shear stress/shear displacement relationship. The measurements regarding the pressure and the sinkage of the soil are performed at a constant rate of loading with plates that vary in diameter. The tests are conducted below where the bearing capacity of the soil fails. Before that point, the soil sinkage characteristics are governed by stress-strain relationships in the elastic-plastic range and below that point, the soil is in plastic equilibrium and the sinkage aspects are driven by the changes in the failure zone geometry. The strength of the soil, based on its bearing capacity, are determined from the pressure-sinkage curves produced by the bevameter. The second portion of the bevameter measures the strength properties of soil and slip/shear parameters by rotating a ring with a constant angular velocity in the soil and measuring the required torque to maintain the angular velocity[9]. With the bevameter measurements, Bekker derived relationships for the aforementioned soil characteristics. A brief description of the seven measurements involved and their interpretation is provided below.

The seven parameters Bekker determined were necessary to model the terrain-vehicle dynamics with arbitrary loads and footprint geometry are c, φ, k_c, k_φ, n, K_1, and K_2. Maximum traction generated is determined by c, Coulomb parameter, and φ, Mohr circle parameter. The next set of parameters, k_c and k_φ are developed from empirical studies based on cohesive and frictionless soil deformation from Equation 4 with n as the exponent of soil deformation. K_1 and K_2 are related to the damping of the system and the natural frequency in regards to the bulk soil model of a spring-mass-damper system.

It is important to note the differences between the Bekker method and the NRMM method of determining soil parameters. The Bekker method uses a bevameter and a series of seven parameters, whereas the NRMM method uses a cone penetrometer and one parameter measured. An empirical relationship relating Bekker's parameters to the cone penetrometer has been developed by WES:

$$CI = 1.625(\frac{k_c}{n+1}((z+1.5)^{n+1} - z^{n+1} + 0.517k_\phi(\frac{(z+1.5)^{n+2}}{(n+1)(n+2)} + \frac{z^{n+2}}{n+2} - \frac{(z+1.5)z^{n+1}}{n+1})) \qquad \textbf{Equation 1}$$

where CI is defined as the cone index. Figure 7 represents a graphical view of how the soil cone index relates to the resistance to motion of a vehicle. The 'ruts' are related to the amount of contact area for a soil. The total motion resistance is for the particular soil index. The chart also relates the characteristic NRMM 'no go' metric showing that there is a point at which the vehicle cannot move in the particular soil type. The specific vehicle looked at is an M113A1 with a gross vehicle weight of 11.6 tons. The pass characteristic accounts for the number of vehicles that are proceeding over the same portion of the terrain and the plot shows how the vehicle cone index changes respectively. As more vehicles traverse the same path, the soil is compacted increasing the vehicle cone index and increasing the motion resistance.

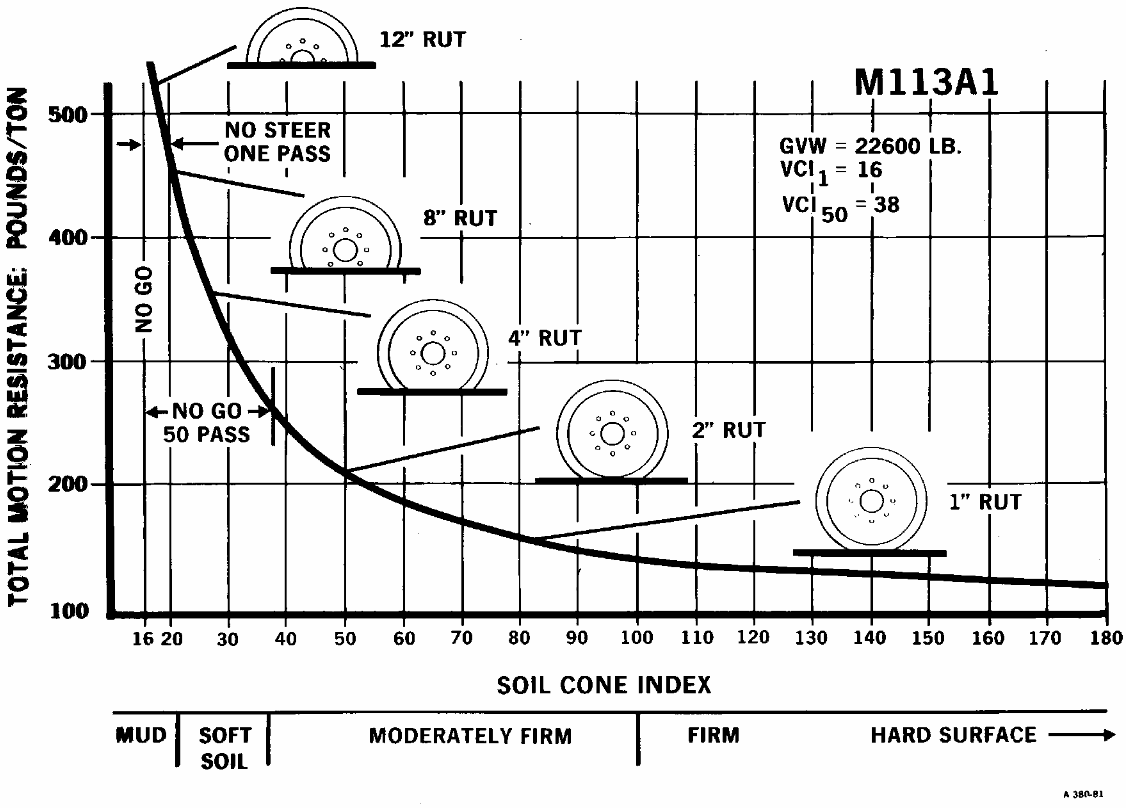

Figure 7: Soil Cone Index vs. Total Motion Resistance[5]

Another set of equations useful for correlating the Bevameter values to the WES cone index are the WES mobility indices. The equations provided output a relative evaluation of mobility in terms of different factors. Comparing two similar wheeled or tracked vehicles, the mobility index offers a comparison of the potential mobility based on the various factors described below. The mobility index for wheeled vehicles is given in Equation 2 and tracked vehicles' mobility index is given in Equation 3. The common elements of each equation are: *CPF* is the contact pressure factor, *WF* is the weight factor, *GF* is the grouser factor, *CF* is the clearance factor, *EF* is the engine factor, and *TF* is the transmission factor. For the wheeled vehicle, *WLF* is the wheel load factor and *TiF* is the tire factor. For tracked, *BF* is the bogie factor and *TrF* is the track factor.

$$MI_{wheeled} = (\frac{CPF \times WF}{TiF \times GF} + WLF - CF) \times EF \times TF$$ **Equation 2**

$$MI_{tracked} = (\frac{CPF \times WF}{TrF \times GF} + BF - CF) \times EF \times TF$$ **Equation 3**

The pressure/sinkage relationship is given by the following equation:

$$p = k \cdot z^n = (\frac{k_c}{b} + k_\phi) z^n$$ **Equation 4**

P is the contact pressure, *k* is the modulus of soil deformation, and *b* is the smallest contact patch dimension. *Z* is the sinkage depth and the last three variables (k_c, k_φ, n) are determined experimentally from the soil tests. One assumption of this equation is that the soil is uniform from the surface to the sinkage depth and that the pressure beneath the plate used in testing is equivalent to the pressure beneath a small portion of the running gear[9].

The second important relationship that Bekker developed involves the relationship between shear stress and displacement. This relationship was developed by examining the correlation between the soil shear strength and vehicle slip. Bekker observed that when the vehicle started, the maximum shearing force at the contact point was not generated immediately but rather was reached after a short amount of time during which the soil was compacted to a certain degree. Based on the different soils involved in the experiments, Bekker made correlations between series of curves corresponding to the soil shear stress generated from soil slip tests to a one degree of freedom aperiodic motion with a dominant damping term. Equation

5 demonstrates this type of motion with *b* representing a damping coefficient greater than unity and *ω* as the natural frequency of the system.

$$x(t) = A_1 e^{(-b+\sqrt{b^2-1})\omega t} + A_2 e^{(-b-\sqrt{b^2-1})\omega t}$$ **Equation 5**

Equation 5 implies that the soil can be modeled in simple terms as one degree of freedom spring-mass-damper system typical to dynamics. Based on the observations, *t* correlates to slip *j* and the *x(t)* relates to the shear stress developed, *τ*. The final relationship presented by Bekker to describe slip and shear stress is given in Equation 6.

$$\tau = A_1 e^{(-K_2+\sqrt{K_2{}^2-1})K_1 j} + A_2 e^{(-K_2-\sqrt{K_2{}^2-1})K_1 j}$$ **Equation 6**

K_2 is the same as the damping coefficient represented as *b* in Equation 5 and K_1 is the ratio of the product of the natural frequency of the system and time elapsed to the slip (*ωt/j*).

BDTM is valid for large vehicles within a certain region because soil deformation can be linearized around a specific set of loadings. The estimates generated by this method allow a vehicle designer to better understand the various parameters that affect the configuration of the running gear.

Finite Element Analysis

Finite Element Analysis differs from the previously described models by using a microscopic look at the tire-soil interaction. This method is a highly complicated, three dimensional model that looks at physical and material properties of the tire and soil. The tire and soil are discretized into finite elements, connected at various nodes. The elements have various shapes, mesh sizes, configuration, and number that are set by the user. The careful choice of these parameters is necessary to ensure a timely and convergent solution. A difficulty with this method is defining the soil properties. Soil is acted upon by the elements to create a stratified soil with physical relationships that vary spatially and temporally and are not well-defined[6]. To simplify the model, the soil is commonly assumed to be homogeneous, but this is a source of error in the models.

Wheels vs. Tracks

The major categories of heavy vehicle locomotion methods involve wheels, tracks, or a combination of the two. To decide which method is best, it is important to look at the terrain of the specified mission. There are some generalizations to be made regarding the use of wheeled or tracked vehicles. Wheeled vehicles have more maneuverability (in conjunction with the steering methodology) and are more adaptable to the terrain (depending on the suspension implemented) than tracked vehicles[7]. The tracked vehicle is able to go over a larger range of obstacles when compared with a similar sized wheeled vehicle.

Another issue to consider in the area of obstacle negotiation is how the vehicle conforms to the obstacle. Although the tracked vehicle is able to traverse a wider range of obstacles for a similar sized platform, the wheeled vehicle has a more adaptable suspension that can shape itself to the terrain, making the vehicle more attractive in terms of stealth and dynamic loading. Payload and sensor packages could potentially be sensitive to the ride quality. One major downside of wheeled vehicles is they are not as agile in traversing obstacles as compared to tracked vehicles.

Wheels are able to achieve higher speeds and are typically lighter. If the vehicles will be towed to the base of deployment, it is important to consider that wheels can reach up to 60 mph while tracks can only go up to 30 mph. Tracked vehicles have higher internal resistance so they are less efficient. Generally in military applications, large vehicles up to 20 tons are wheeled and 35 to 65 ton vehicles are tracked. In between 20 and 35 ton vehicles, either are used.[8]

Small, lightweight vehicle systems have a scaling issue with terrain in comparison to larger vehicles. Many obstacles in a large vehicle's landscape pose little or no problems whereas, some of the same obstacles pose a huge obstacle from the small, lightweight vehicle perspective (Figure 8).

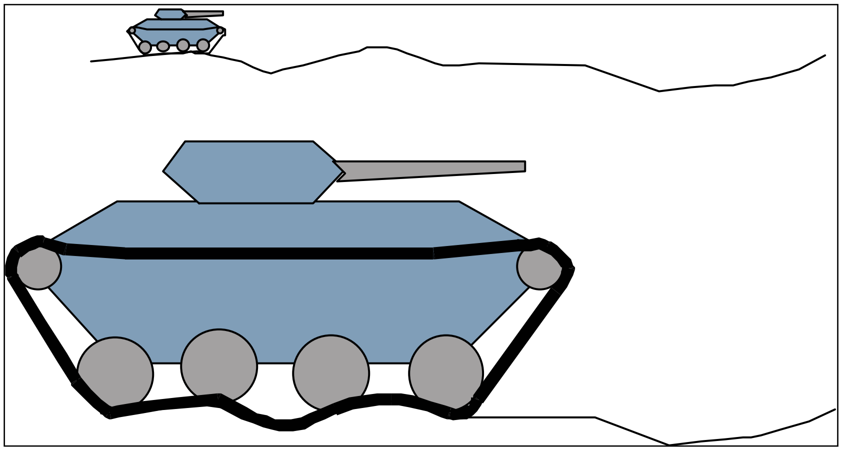

Figure 8: Small Lightweight Vehicle Crossing a Given Terrain vs. Large Heavy Vehicle

An approach to formulating the off-road mobility problem is suggested by Karafiath and Nowatzki[9]. They stated that the shear strength of soil is the governing issue of mobility problems. Their methodology for solving the off-road vehicle mobility question involves the following assumptions:

a) The load on the running gear is constant.
b) The terrain is even.
c) There is no interaction between vehicle power train and the driving force (torque, thrust) applied to the running gear.
d) The travel velocity is constant and sufficiently low so that a "steady" or "quasi static" state may be assumed to exist in the soil.

Table 2: Assumptions for off-road mobility[9]

From these assumptions the authors[9] conclude that the terrain-vehicle interaction are affected only by the geometry of the running gear, the shear stresses at the running gear interface, and the balancing of the loads on the running gear with the interface stresses. Although two of the assumptions are grossly inaccurate (b and d) from a small vehicle perspective, it is useful to look at the methodology behind the authors attempt to formulate a solution. It is important in small vehicle applications that the terrain is addressed as if it were extremely unstructured and dynamically changing in response to the vehicle so, consequently, the assumptions about the vehicle and its running gear can most likely be scaled down to a smaller size but the terrain's evenness and steadiness does not.

It is unclear whether the NRMM will scale to systems of this size because of the underlying soil parameters used for calculations are determined through empirical tests and only large, manned ground vehicles with wheeled or tracked running configurations were considered. Experimental tests have been conducted showing the NRMM's vehicle cone index (VCI) to the actual measured VCI for vehicles ranging from 1000 lbs to 3000 lbs[7]. The VCI is a measurement that incorporates the degree of flotation and traction achievable for a vehicle on a specified soil. It will be discussed further in the metrics section. Two figures are provided from the General Dynamics study[7] looking at the comparison between the actual and calculated VCI for wheeled (Figure 9) and tracked (Figure 10) vehicles. Two tires ("normal" and terra tires) and three tire pressures (low, medium and high) are analyzed on the wheeled vehicles for the VCI.

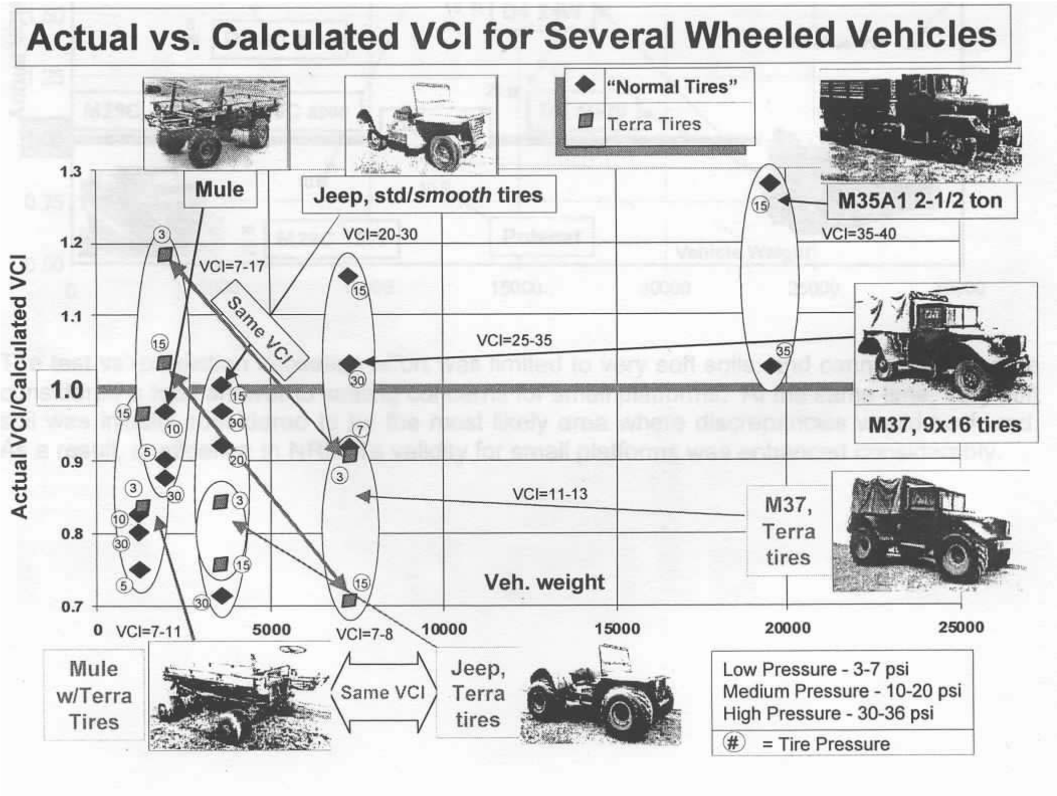

Figure 9: Actual vs. Calculated VCI for Several Wheeled Vehicles from General Dynamics[7]

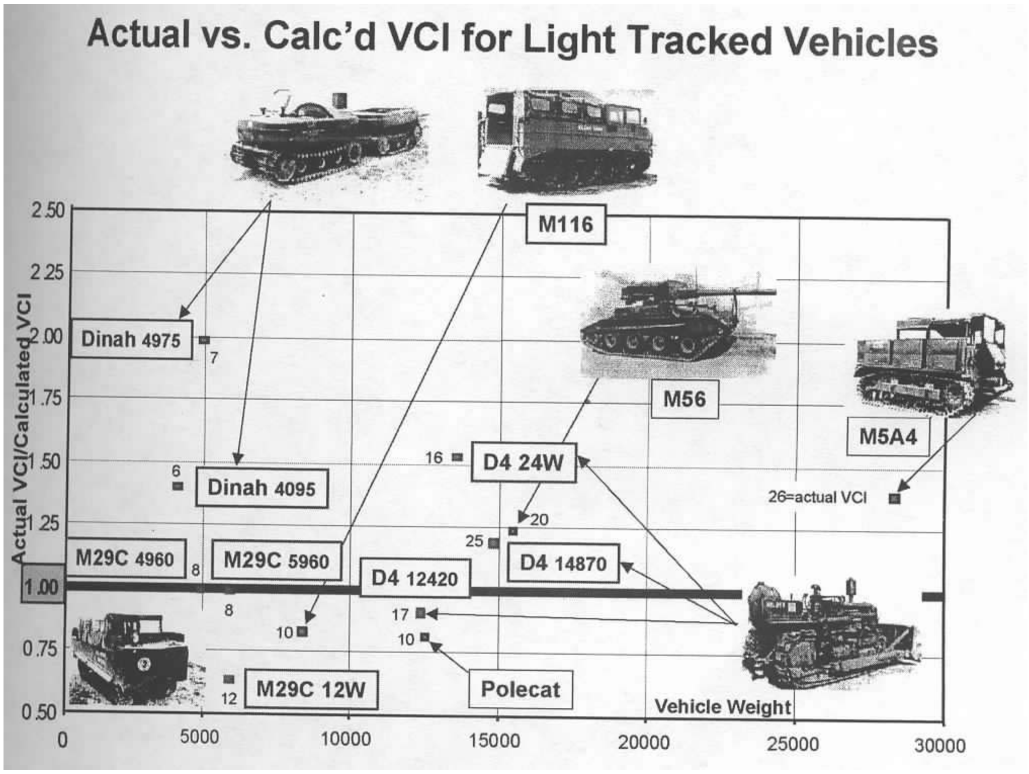

Figure 10: Actual vs. Calculated VCI for Light Tracked Vehicles from General Dynamics[7]

Since the BDTM is linear and 1-DOF, scaling of these equations are in some instances more appropriate for smaller vehicles since the system has been largely linearized around the assumption that the soil characteristics are perfectly uniform. The smaller, lightweight vehicles do not have to address the issue of soil's non-linearity because they are influencing the soil much less than the larger, heavier vehicles. The shear forces and sinkage forces are based on the vehicle's weight (sandy, cohesionless soil) or on the running gear's contact area (clay-like, cohesive soil) in the extremes and the robotic vehicles are lightweight and small. On the other hand, a simplified model of the vehicle and its dynamics is not going to work for a little vehicle in most instances because the forces experienced are going to be much greater due to the increase in obstacle size.

FEA can scale down to the small, lightweight vehicle arena but it is a computationally complex model with many parameters.

An interesting question arises in terms of how does one verify any of the aforementioned models? Previously, a vehicle would be outfitted with sensors and taken to the particular terrain to run experimental tests regarding the soil and obstacles. Robots have the potential, and are almost guaranteed, to have to traverse a variety of terrains ranging from on-road to off-road. Given that robots are a smaller, lighter class of vehicles, a specialized test track and obstacle course has been developed at the SouthWest Research Institute[2] for testing. These tests will be vocal in determining mobility metrics as it gives a baseline comparison for many different types of vehicles.

Analysis

If the Army were presented with two contracts for potential vehicles and they wanted to compare them to find the best vehicle for the job, what would be the best way to accomplish this? When looking at a traditional vehicle concept- larger and tracked or wheeled- the Army would utilize the NRMM software and input the necessary parameters. The program would then output the necessary go / no go characteristics of the vehicle interacting with the specified terrain, as discussed in the background section. The NRMM used heavy vehicles to create the necessary terrain data and is consequently generally used to determine the characteristics of heavier vehicles with limited configurations (tracks and wheels only). Some work has been done to test the validity of the NRMM for vehicles in the range of 1000 lbs to 3000 lbs but mostly for wheeled vehicles. Is there a way for the Army to have a 'mobility toolbox' that would enable them to make the same educated decisions, like those enabled by the NRMM, for even lighter vehicles with varied types of locomotion methodologies? Since there are no such toolboxes available to date, a good starting point to developing an extension of the NRMM for small robotic vehicles would be to look at the various metrics that manufacturers are using to give consumers an idea of the capabilities of a robot. Several people[10,11,12] have analyzed the distribution and size characteristics of various natural terrain obstacles such as gaps[12], rivers[10], ditches[10] and trees[11]. Examples of the distributions are provided in the metrics section. Based on these statistical distributions, the Training and Doctrine Command (TRADOC) has defined metrics that a military vehicle operating in a particular scenario needs to either meet or surpass.

If one looks at mobility as the all-encompassing definition of the capability of a vehicle to get from point A to point B, then there are various metrics that can be used to define it. For different missions and terrains, different metrics will be stressed. For instance, if the mission was to gather information in a swampy marshland the useful metrics to describe the necessary vehicle requirements would be different than the useful metrics for a munitions payload in a desert environment.

The current metrics used to describe the mobility of wheeled and tracked vehicles are fairly well defined. The question to be answered is if from these metrics a vehicle's performance can be predicted reasonably well for a given terrain (within 20 to 30% accuracy). The following section lists the metrics that manufacturers[13] are using to describe their robots' characteristics, TRADOC's suggestions, as well as industry experts[7]. From this compilation of metrics commonly used, main categories emerge in which to classify the various metrics. Terrain-vehicle interaction is one of the main metrics of mobility and incorporates obstacle negotiation. This heading describes the ability of the vehicle to overcome specified obstacles. Part of the control aspect involved in robotics for this metric would include the self-recognition of obstacles and the intelligent decisions regarding the robots capability to overcome the obstacle, get out of the situation if it cannot, or avoid the obstacle altogether if the robot cannot overcome it. The traditional vehicle specs of performance measures for the robot are another category of metrics. These give the operators a good handle of what the vehicle is capable in terms of on-road characterizations. Using the data collected regarding the various terrains that a robotic vehicle would encounter provides minimum requirements that are necessary for a vehicle to be considered for a contract or conversely, if utilizing a pool of robots, a robot can be chosen for a particular mission by matching the robot criteria to the mission specifications.

Many of the current research trends in mobility are focusing on the dynamics of the vehicle-soil interaction[14]. For small vehicles, the dynamic forces of the vehicle interacting with various terrain obstacles and soil parameters, especially at high speeds, pose structural problems. The ability to operate the vehicle at its maximum safe speed while making intelligent decisions based on the terrain to be negotiated is a key goal of small vehicle mobility. The main issues to this problem resulting in mission failure are immobilization (either the vehicle gets stuck in the terrain or has a component failure) or loss of power.

Metrics

The metrics are divided into two categories: vehicle-terrain interaction and vehicle metrics. Vehicle-terrain interaction relates to the vehicle's ability to avoid or address an obstacle or other potential interaction with the terrain. Vehicle metrics relate how well a vehicle can traverse a terrain. The following sections describe current metrics in use to describe wheeled and tracked vehicle mobility characteristics. Both categories of metrics relate to issues of path-planning. Many of the metrics are given a "typical" or "desired" value. These values were provided through research done by General Dynamics[7] and other military groups. Statistical distributions of the various obstacles have been determined through various government contracts[10,11,12] to provide designers with metrics for designing vehicles in terms of obstacles, soil, and overall mission objectives.

Vehicle-Terrain Interaction

Tree and Stump Knockover: In forested areas, trees and stumps are a common problem. From the General Dynamics mobility study[7], the group determined that a robot vehicle should be able to overcome a 2-3" diameter tree or stump through analysis of various NRMM vehicle cone index tests and WES reports. The metric also applies in urban situations to the vehicle climbing over pipes.

Tree and Stump Avoidance: There will be some cases in which the robot will not be able to knock over a tree or stump, and even if it could, would not do so in the interest of stealth. WES has done studies that show an average distribution of trees in various mission specific regions of the world. It is important to know the density of trees to design a robot that should be able to go around the trees that present a large difficulty. The study found that the vehicle should be able to maneuver around trees randomly spaced at 9-12 feet apart. Figure 11 shows an example of the tree spacing distribution used to determine the specifications for the metric.

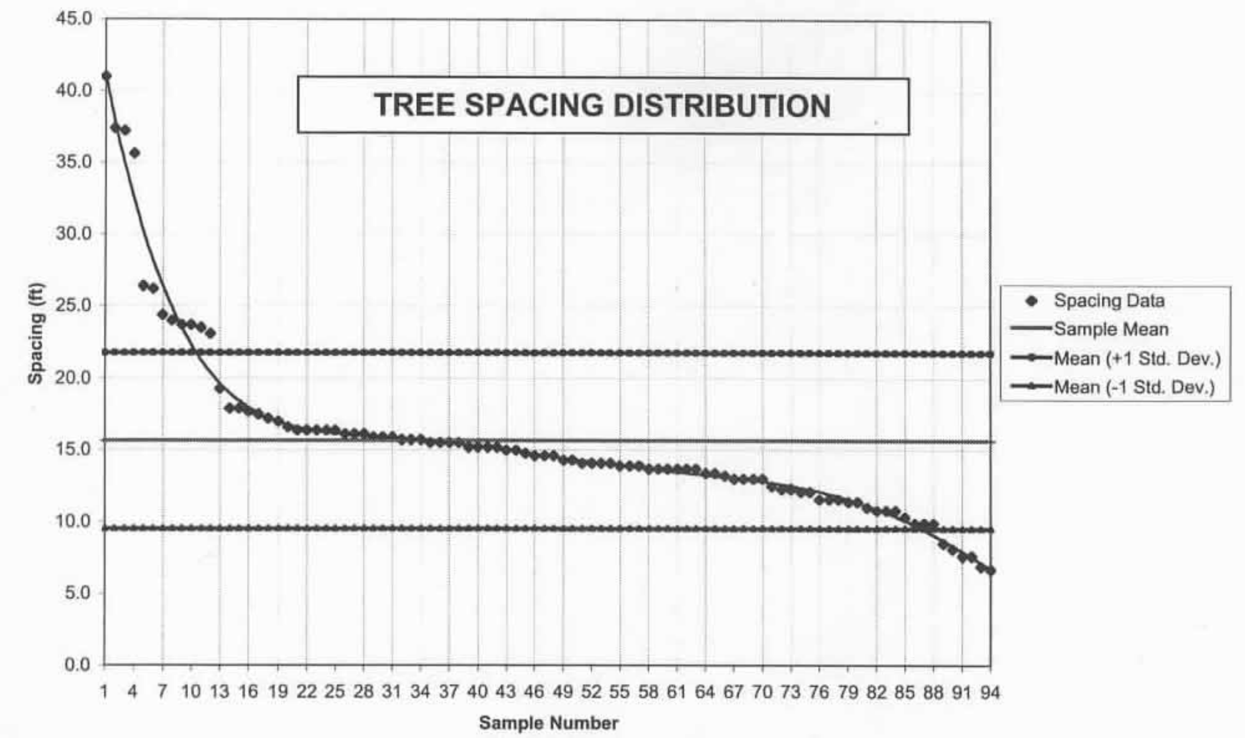

Figure 11: Tree Spacing Distribution[7,11]

Gap Crossing: This metric was determined from a WACROSS[15] study looking at various natural features that would necessitate a 'gap crossing'. These natural features include ditches, streams, rivers, drainage features, and other such 'gaps'. For a vehicle to cross 50% to 70% of the gaps for a particular mission, the study found that a gap crossing of 1-2 meters was necessary. Figure 12 shows gap widths in Germany. Various areas of potential military involvement were analyzed. The shaded area relates to the 1000 lb to 3000 lb vehicles studied[7].

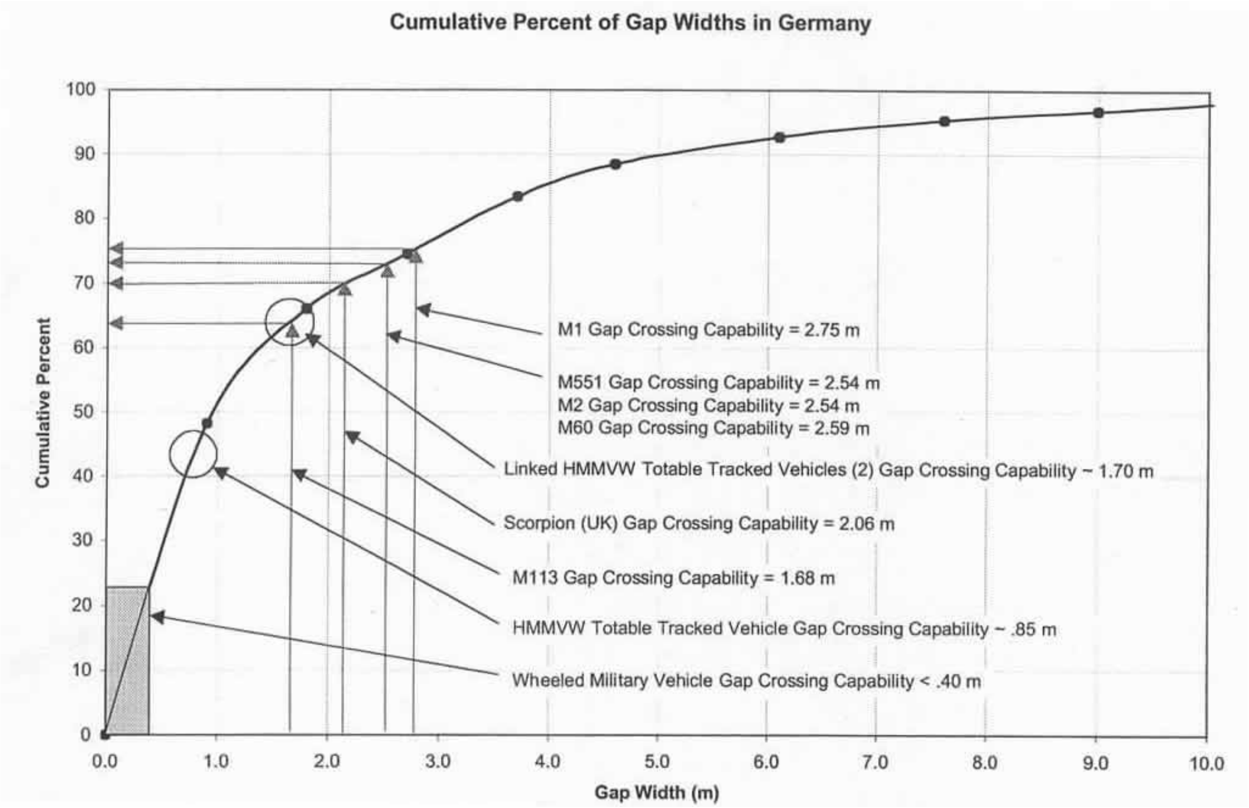

Figure 12: Cumulative Percent of Gap Widths in Germany[7,11,12]

Fording: It has been proposed that, as a practical measure, a vehicle should be able to wade through water 4-5 feet deep through similar studies prior[10]. The vehicle must be waterproof and able to maneuver through water. The study proposed that the vehicle sink to the bottom and negotiate its way by maintaining traction with the bottom since currents could shift the path of the vehicle. Utilizing a swimming or propeller method is another possible action.

Vertical Step Crossing: Climbing discrete steps is possible in wooded areas where trails have been built. Utilizing this trail might be easier than attempting to scale the slope. Certain rock formations also have a step-like characteristic that would utilize this metric. The vertical step crossing is most pertinent in urban situations where stairs are a widely used method to get to different levels of buildings. A typical vertical height the vehicle should be able to address is 10”-20” for natural obstacles or 7” risers for stairs.

Tunnels and Sewer Openings: Although tunnels and sewers are not normally considered part of an off-road mobility scenario, there are many situations in which an off-road robot might still encounter them. For instance, there are drainage pipes that are located in forests to direct runoff. Also, even when considering an off-road robot, there are times when the robot will need to go through an urban area or the end goal will be the urban area. It is possible to use two separate robots and utilize a marsupial system of sorts but if possible, the robot should have sufficient capability to do on-road, urban-type demands. A standard opening typically found for tunnels and sewers is 24" -36"[16].

Lift and Lower: Although not in use for typical vehicles currently, in a robotic situation, it could be necessary for the robot to be able to scale either up or down a very steep slope. Utilizing onboard tools such as a winch and a grappling hook is one way to address this. The standard sized ledge is not fully quantized but could also be determined through similar studies mentioned before.

Slope: The vehicle needs to be able to negotiate a slope such as a hill, angled rock, etc. angled between 45° and 60°. This is the average slope in many situations of climbing out of a ditch or river bed where the vehicle was fording. Figure 13 shows a range of slope distributions for three regions where potential mission scenarios could occur.

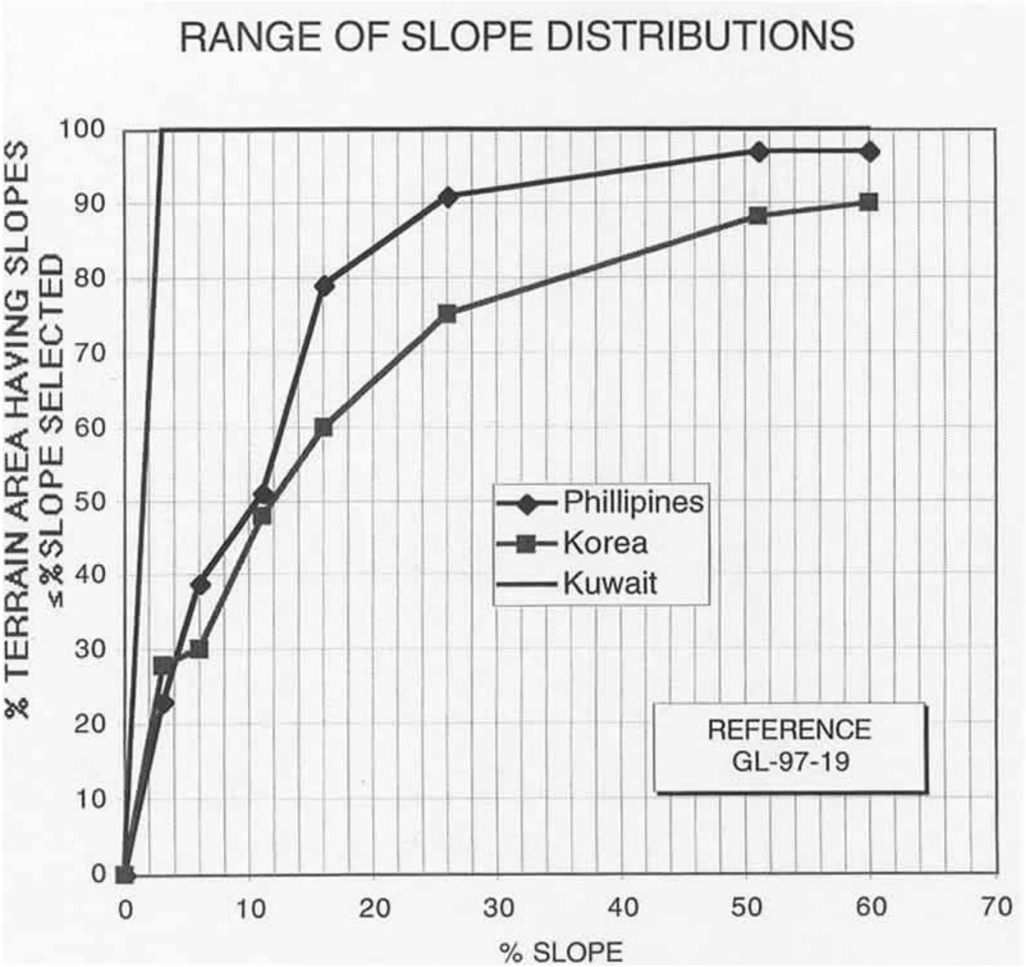

Figure 13: Range of Slope Distributions[10]

Ground Clearance: How far the bottom of the vehicle is from the ground is another important metric in off-road locomotion. The vehicle should be able to clear relatively minor obstacles by just driving over them. A variable height mechanism would allow the robot to slide underneath a fence or clear small plants and stones.

Vehicle Cone Index (VCI): VCI is used to determine the degree of flotation and traction achievable for a particular running gear configuration in a specified soil. A similar measurement relating to the soil only called the rated cone index is a measure of the soil's actual strength and needs to be higher than the VCI for the vehicle to have any sort of traction.

Drawbar Pull: Drawbar pull is the total thrust minus the total resistances of the vehicle. This is a simplified measure of the vehicle's ability to move. If the value is less than or equal to zero then the vehicle will be not be able to move. There are a couple of different versions of this metric given in the BDTM relating to pure soil only, the addition of grousers or tracks to the soil, and finally to the total tractive force a distance from the front of the contact area.

Vehicle Metrics

Power to weight ratio: It is proposed[7] that this metric can be indicative of the performance of the vehicle in terms of acceleration, speed on grade, speed in soft soils, on-road speed, and vegetation override capability. Power can overcome many different obstacles that, due to a vehicle's inherent lack of mobility, would be immobilizing. It is typically rated as horsepower per ton and based on analysis[7], 20 to 35 hp/ton appears to be a good range for 1000 lb to 3000 lb vehicles.

Turning radius: Turning radius addresses the maneuverability of the vehicle. It is desirable for the vehicle to have a tight turning radius or possibly even zero turning radius to increase the options to escape from a potentially immobilizing situation. In terms of traversing through a densely wooded area, this metric describes if the vehicle is able to negotiate between and around trees. Different types of steering mechanisms implemented are omni-directional, skid, or track steer.

Endurance: Endurance is the ability to maintain vehicle operations over distance and time. There are many different variables that are involved and would best be represented through an experimental relationship for various payload levels and terrain characterizations. A measurement provided suggested the vehicle be able to operate with a 6 lb payload for 6 hours minimum or ideally 24 hours without recharging. The distance portion of endurance can be classified as range in terms of the mileage traveled.

Maximum payload: Payload is a key metric in terms of the robot being able to transport some critical piece of equipment, supplies, or sensors into battle. Without payload, the capacity of the robot would be severely limited in its ability to perform its inherent functions. Normalizing the payload by the weight enables a better comparison between various weight classes. Payload applies to path-planning and terrain-vehicle interaction. Both metrics are used in the sense that the vehicle needs to be conscious of the sensitivity of the payload to the vehicle-terrain interaction and choose a different path.

Maximum speed: The maximum speed will depend on the type of terrain and the obstacles encountered as well as the size of the vehicle. Since speed differs greatly based on the vehicle weight and size and engine power, a normalized metric is useful for comparison. In many cases, speed is given in terms of body lengths per second.

Maximum Acceleration/Deceleration: These characteristics are important in terms of terrain-vehicle interaction because the vehicle needs to be able to respond quickly to the surroundings to either avoid an obstacle or negotiate it. The acceleration/deceleration is related to reaction time of the robot. The metric is based on vehicle power and braking and can also be normalized in terms of the length of the vehicle.

Shock Resistance: Part of the requirements of the robots will be on the method of approach. One way to insert a robot into a mission scenario is through an air-drop or even throwing it into enemy territory. The robot should be able to withstand (i.e. still function normally with all components intact) a significant amount of shock from such a fall.

Invertibility: Invertibility is the ability of the vehicle to operate if it is flipped over. In rough off-road terrain, the ability for the vehicle to operate "upside down", enables another flexible design element. It is difficult to design a vehicle that operates like this when sensors and payloads are involved because many times those objects are orientation specific for operation or stability. Another possibility is having a mechanism for the vehicle to right itself if it gets overturned.

Table 3 presents a summary of the metrics analyzed.

Vehicle-Terrain Interaction	**Vehicle Metrics**
Tree and Stump Knockover	Power to Weight Ratio
Tree and Stump Avoidance	Turning Radius
Gap Crossing	Endurance
Fording	Maximum Payload
Tunnel and Sewer Openings	Maximum Speed
Lift and Lower	Maximum Acceleration/Deceleration
Slope	Shock Resistance
Ground Clearance	Invertibility
Vehicle Cone Index	
Drawbar Pull	

Table 3: Metrics Table

Modern Locomotion Methods

The metrics discussed in the previous section have all been developed with the more traditional tracked and wheeled vehicles in mind. Much of the current research today is looking into more exotic locomotion methods for a variety of tasks and terrains. The various methods can be classified based on their gaits. Many of the robots are biologically inspired. It seems that because of the exotic methods used for locomotion and what will be designed in the future, many of the methods will not be defined well by the metrics for wheeled and tracked vehicles. Each of the various groups will be analyzed to see how the metrics described in the previous section apply and if there are new metrics that can easily be foreseen. The analysis is to be used as a starting point to understanding how adequately the metrics for wheeled and tracked vehicles describe a particular locomotion method on a specific terrain.

Walking Robots

Walking robots are perhaps the most widely recognized novelty in robots since the track and wheeled vehicles. A walking robot is modeled after a human and attempts to emulate the various movements that humans are capable of performing. As quoted by Digney and Penzes[17], "One key to the soldier's success is that he is based upon a human body, a platform with unparalleled flexibility and generic functionality well suited to the environment. The body can be controlled in ways that are limited only by the innovations of the human mind. On the other hand, robotic platforms provide their control systems with a limited number of options through which to solve mobility and task challenges." There are several issues involving control and mobility with these robots. They are limited by technology but are starting to becoming more sophisticated. The most advanced walker to date is Honda's Asimo (Figure 15). The walker is able to right itself if knocked over and recognize visual cues.

Figure 14: Sony's Aibo Robotic Dog

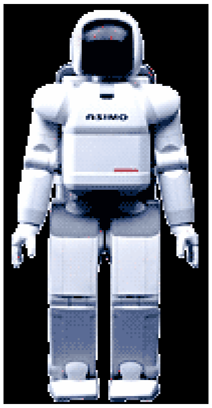

Figure 15: Honda's Asimo, walking robot

Sony has created a small robot canine called Aibo (Figure 14) that utilizes a walking locomotion. There is a small bi-pedal walking robot that accompanies Aibo known as SDR. As with many other robots, there is more than just one gait pattern programmed. Aibo is also able to crawl. Another example of a walker is the legged wheelbarrow from UC Berkeley[18]. As discussed in the article, "According to a U.S. Army Report, only 50% of the Earth's land surface is accessible to wheeled or tracked vehicles[19], whereas humans and other animals can access almost all of it using legged locomotion." This explains part of the intense research efforts in this area. Bekker[20] has also done numerous studies on the power requirements for various types of locomotion and concluded that "A wheel driven in a soft terrain may not be as economical as walking or running: it requires more power per unit of weight." (see Figure 17)

Figure 16: Walking Wheelbarrow from UC Berkeley[18]

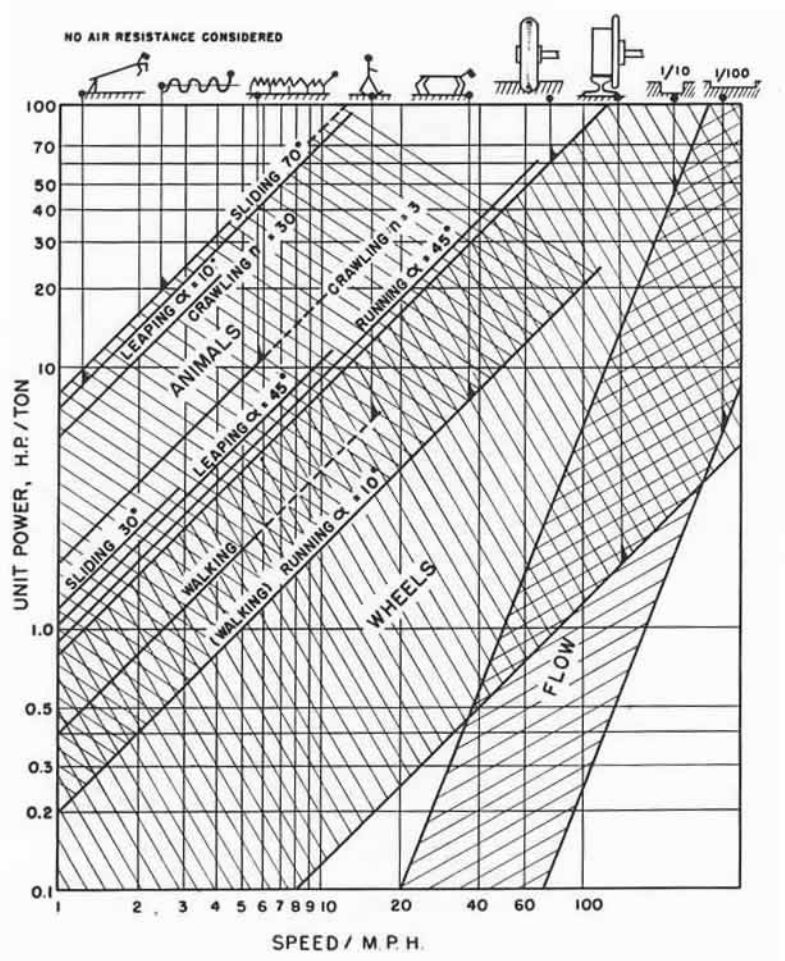

Fig. 12

Figure 17: Speed of various animals and wheels and their unit power required to achieve that speed[20]

Metrics

Metrics for the walking robot are still heavily dependent on the previous metrics discussed. For the current technology, obstacle avoidance, endurance, and payload are going to be important metrics. Immobilization is a key issue for the walker robots as well. The two most debilitating circumstances for a walking robot and robots in general, include immobilization and energy depletion. Due to the complicated nature of walking robots, many times they are not completely autonomous. Some other considerations might be the center of gravity height or the resistance to getting knocked over. Many bipedal robots are susceptible to falling with a slight external impetus- this force might be an important metric in terms of designing the location of the center of gravity and any adaptive control (like adaptive suspension) that could change this in a situation where there are many external forces.

Advantages

Walkers have the advantages as mentioned by Digney and Penzes[17] for a wide range of movements from walking to crawling to climbing. There are few biological species (much less robots) that can combine all of these methods of movement into one package. Humans have amazing capabilities that, if robots could emulate, would be of great benefit to the robotic world in terms of mobility. In general, the advantages of walking machines can be classified as follows: better fuel economy, higher speed, greater mobility, better ride quality, less environmental damage, and greater range of possible terrain[18]. One of the main reasons for the above qualifications is the fact that a wheel vehicle can sink into the terrain and needs to generate traction to get out of the self-created depression whereas the legged vehicle can simply step out of the depression it made, utilizing much less energy (Figure 18).

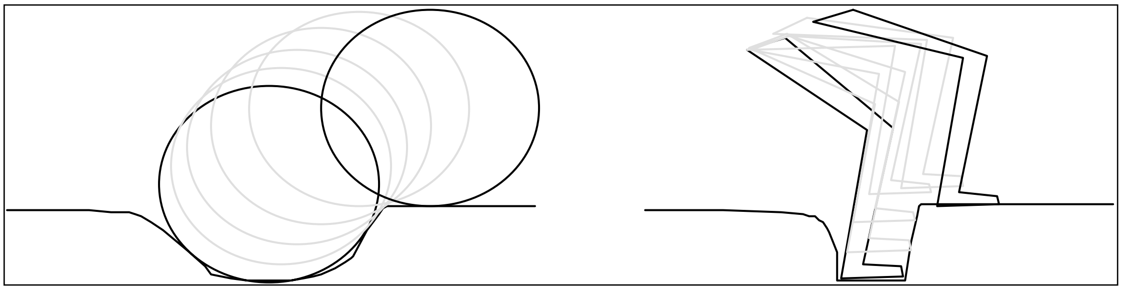

Figure 18: Wheeled vehicle and legged vehicle climbing out of a localized depression

Disadvantages

Major disadvantages of walking robots are the complexity of the joints, actuators, controls, and sensors involved. With increased complexity comes increased cost and increased development time. The technology is available for wheeled robots now but as time progresses, sensors, actuators, and power supplies will advance enabling more robust and inexpensive walkers. The major issues will still be control. The more actuated degrees of freedom a vehicle has the more difficult the control issues involved. Balance is also an issue for walking robots. Passive bipedal walkers seem to best mimic natural walking motion, whereas most others in this category wobble from side to side to ensure that the center of gravity is over the foot.

Hopping Robots

Hopping robots typically utilize a spring-like actuator to store energy and release it as kinetic energy. The three main issues with these robots are steering, jumping, and self-righting capabilities[21]. Motion discontinuity is another aspect of this gait. It is important to ensure that the robot is designed durably enough to handle the impact of the hop. Figure 20 shows a first attempt at a hopping robot from the University of Verona and CalTech[21]. Major issues involved the inefficiency of the hop- 80% of the energy was dissipated in various mechanisms- non-robust steering, and self-righting difficulties. Another group of scientists from Carnegie Mellon University[22] used the biological inspiration of a cricket for their hopping robot design. They also utilized a wheel to simplify the design. A very unique design component of the cricket robot (shown in Figure 19) is the implementation of McKibben artificial muscles. The majority of the issues involved in the creation of this robot, besides control, was the need for many custom manufactured pieces for the small robot. The design pictured also was unable to generate enough compressed air to actuate the legs autonomously so the design is tethered. Future research involves a self-contained hopper as well as one that is purely legged. The combination of legs and wheels allows the hopper to walk and position itself for the next jump.

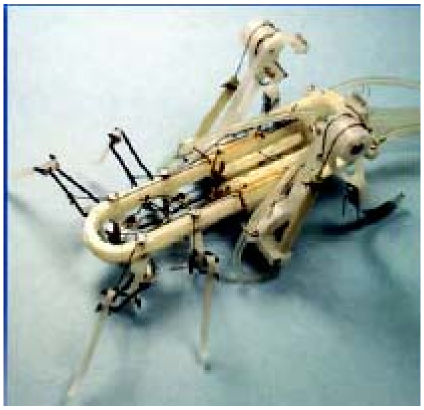

Figure 19: Case Western Reserve University Cricket-Based Robot

Figure 20: 1st Generation of Hopping Robot from Fiorini and Burdick[21]

Metrics

A new metric to consider would be hopping range and maximum height. A substitute could be a spring coefficient that could describe this based on an equivalent spring loaded object that would reach the maximum height as given when released straight up or the maximum distance when released at a 45° angle. Two spring coefficients might be necessary if the robot is able to utilize a secondary technology during flight to extend its range (i.e. something like retractable wings).

Advantages

Hopping robots do not have to deal with obstacle negotiation in the same terms as a wheeled and tracked vehicle. The hopping robot has other concerns such as bumping into low tree branches and large slope climbing but maneuvering over or around tree stumps, gaps, and stairs is a minor issue if relevant at all. Another advantage of the hopping robot is its ability to reach higher areas more rapidly than other locomotion methods. Hopping gives this robot speed and agility in crossing large distances and bypassing a lot of obstacles that otherwise present an impediment to wheeled or tracked vehicles.

Disadvantages

Hopping vehicles are typically smaller due to the difficulty in launching heavier masses. As the mass of the vehicle increases, the mass of the components necessary to launch the vehicle also increase. With a small vehicle, the payload fraction is a lower ratio for the aforementioned reasons. Similar to the walking robots, the sensors and actuators are complicated. The power requirements are also increased. If the robot is hopping only, it leaves the reconnaissance and stealth capabilities lacking as there is not a discreet way to get around. Another difficulty is path-planning for the hopping robot in that it is a series of 'hops' and the robot does not remain in full contact with the ground for the entire path length. Defining the path and having a wheeled vehicle follow it is not as difficult as having a jumping robot that can be affected by wind speed and the angle that it lands on the ground.

Rolling Robots

Rolling robots are usually spherical or disc-shaped. This enables low energy movement of the robot. A weighted pendulum can create the motion or simply a motor applying a torque to wheels. An example of a rolling robot is the SuBot (Figure 21).

Figure 21: SAIC's SuBot

Rolling robots have low friction and locomote by moving their center of gravity within a fixed sphere or circular disc. Combining this gait method with another, such as hopping, substantially improves the overall mobility of the robot. Rolling robots are limited in the same sense as wheeled robots when it comes to obstacle negotiation.

Metrics

Rolling robots include wheeled robots so the metrics are the same as the ones mentioned prior. Another metric that might be included would have to do with the mobility of the center of gravity or how quickly the rolling robot can change direction to adjust its path mid-roll.

Advantages

Since so much research has been done in the field of wheels, rolling robots have some of their advantage. Also, some rolling robots have implemented a large wheel/sphere design that aids in overcoming obstacles.

Disadvantages

The rolling robot shares similar disadvantages with the wheeled robots but is also limited in a payload sense. The rolling robot is usually encapsulated inside a sphere or wheel and requires a dynamic generation of momentum to shift its center of gravity for movement. The payload would need to be inside the robot which has limitations based on the other technology involved. There are some rolling robots that are wheels only and the invertibility of the payload becomes an issue. Spherical rolling robots might also have a vertical step or slope traversal impediment if not enough momentum is gained prior to the obstacle negotiation.

Running Robots

Running robots are an extension of walking robots although usually there is some period of time when the locomoter is airborne. The robot does not need to be airborne to be classified as a running robot though. One example of such is the RHex[23] (Figure 22). RHex utilizes a gait that is more similar to "grounded running"[23] that incorporates a clock-like tripod gait. The gait is based on the idea of a spring loaded inverted pendulum (SLIP). The RHex is another example of biomimetic robotics that has analyzed the movement of cockroaches as the basis for its design. As discussed prior, there are many difficulties with walking robots including the issue of balance. RHex is stable with the clock-like tripod gait and its six legs of support. Bipeds encounter more difficulties with balance in airborne running gaits so dynamic balance is a debilitating issue.

Figure 22: RHex walks through gravel[24]

Metrics

Similar metrics to the walking robots apply with the addition of certain running adaptations, such as airborne time and resistance to immobility.

Advantages

Running is considered one of the more efficient means of travel by Bekker[20]. Like humans, robots have the potential to be quick and agile. It is the combination of this gait with others that makes a robot robust, quick, and adaptable with the right technology. Running simply increases the advantages of walking robots by enabling quick movement from one location to another, which is useful in terms of a battle scene or when time is an important metric for a mission scenario. In terms of survivability, running makes it more difficult for the enemy to lock onto a target.

Disadvantages

Current actuator technology cannot operate at the high speeds and high torque necessary for most running operations[23]. Due to the complicated aspect of a running robot and the portion of the gait in which the robot would be airborne, the stress and fatigue on the components also raises a material issue. The running robot has similar disadvantages to the walking robots in terms of complexity in controls, actuators, and sensors. Balance is also a big issue with the interaction of an external force such as an obstacle interaction and the robots recovery time and capability. The walking and running robots have the complexity of the motion to work through, as well as creating intelligent behaviors for the robot whereas the wheeled and tracked vehicles do not need well-defined motion control algorithms, so more of the research can focus on the intelligent behaviors in response to terrain negotiation stimuli.

Sliding Robots

Sliding robots are characterized by snake-like gaits. Snake robots have many different gaits but can mostly be classified as sliding. Although Bekker[20] has stated that crawling and sliding modes of animal locomotion are the least efficient in terms of power requirements and energy lost, snake robots have found their niche in the robotic world. Their biomimetic model, the snake, has unique mobility in its ability to get through narrow cracks and crevices. Due to the lack of a rigid skeleton, snakes are able to slither around obstacles and wrap themselves around trees to climb them. For snake bots to evolve to the locomotive capabilities of their biological counterpart, sensor and actuator technologies are still in need of updates. The majority of snakebots in use today are being touted for their search and rescue efforts because of their serpentine ability to squeeze in among the rubble to search for victims[25]. In terms of military, urban situations for the snakebot or dense jungles for the future possibilities of a fully flexible and automated robot would make good use of this locomotion method. Snake robots also are in the running for space exploration (Figure 23).

Figure 23:A Third-Generation Model of a Snake-bot Being Developed for Mars Exploration[26]

The start of the snakebot locomotive effort began with Mark Yim of Xerox Palo Alto Research Center. Its name was polybot and it was able to change shape to fit the task assigned to it. Snake robots are potentially capable of several different modes ranging from ring mode, to inching mode, to twisting mode, to bridge mode and to wheeled-locomotion mode (Figure 24).

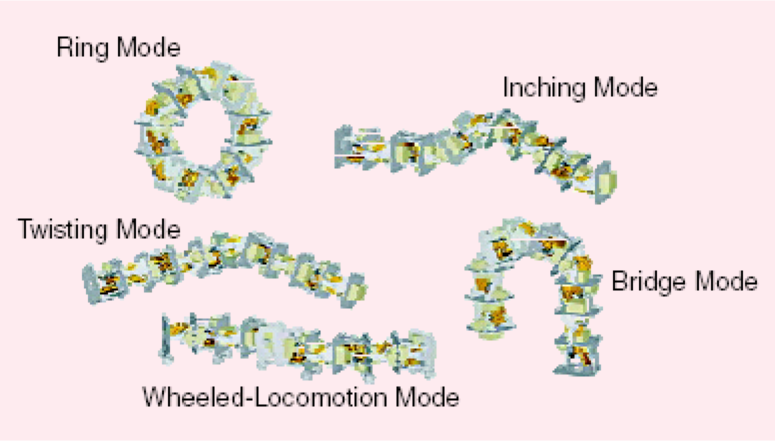

Figure 24: Locomotion Methods of a Snake Robot[25]

Metrics

Metrics for a snake robot could include a similar metric to those of the hopping robots in terms of a spring constant. There are some snakes that potentially have a “strike zone”- this is an area that the robot could either deliver an attack to (as onboard weapon) or how far it can leap by curling its body up. A snake robot is also unique in the sense that it can utilize its body to locomote through loose soil. A metric regarding the robots ability to ‘swim’ through the soil could also be helpful. The max torque and angular speed are also important metrics and define how quickly the snake robot can change positions or articulate itself.

Advantages

Snakebots most advantageous design points are the fact that they can change their shape easily as they are simply a line of actuated joints. They can ferret through building debris or through the dense tangle of vines and roots that are a snaring point for wheeled vehicles because of their ability to slip through cracks and crevasses easily. Because of their simplified design, many of the proposed snakebots are fairly inexpensive and could be used as a commercial product as well[26].

Disadvantages

Whether or not snakebots will become as lithe and quick as their biological counterparts, will be left to technology advances. Their size is also typically small, thereby limiting the payload. Unless the robot was built on a larger scale and the payload placed inside (albeit still limited by geometry constraints), as the snake gets bigger, it will become more cumbersome with the necessary joint actuators and power required to drive the robot. The power requirements also limit the size of the robot in that the robot needs to actuate each individual segment to perform most tasks.

Further Research

Much of the research being conducted in the area of small vehicles is being done in the sensor and perception area, as well as the intelligent controls arena. Even though there is a focus in current research efforts in these areas, the question of mobility will become more prominent as the technology allows the terrain to be well-known and defined through sensor perception. The autonomous aspect of these robots will become increasingly more popular and widely used. Along with the autonomous capability comes the communication of the data that the robot was able to retrieve. Underneath all of these considerations is the main consideration of how does one incorporate the mission scenarios into the design of the robot to enable enhanced mobility characteristics. If the robot is not well-equipped for a particular environment or terrain then the whole mission can fail. A second avenue being actively pursued in the field of mobile robotics is the use of cooperative robotics. In this work, the robots are linked together to form a chain that enables increased mobility for vehicle-terrain obstacles such as gap crossing, slope negotiation, and others.

Conclusions

In analyzing the various locomotion methods and metrics, it would be useful to determine a set of generic metrics that apply to all of the robots, regardless of the locomotion method employed. Looking at the original definition of speed-made-good, this overall metric needs to embody the three critical issues to small vehicle mobility. Is it possible for there to be one metric for performance evaluation, path-planning, and terrain-vehicle interaction? Or even one for each? It seems that this would be severely limiting and possibly over-simplifying the issue at hand. Comparison of the various locomotion methods can be viewed with a set of general metrics that apply universally. As an example, the power necessary to provide an adequate range over a specified off-road terrain would be a better way to make comparisons. The work being done at research institutes like SWRI will also provide valuable empirical insight into the question of small vehicle mobility.

There are still many modes of locomotion and gaits that were analyzed here and this is by no means an exhaustive study, but to see what shape robotics is taking is interesting and gives insight into what the field holds in store for the rest of the century. Advances in sensors and actuators will enable the development of more complex and lifelike machines. Controls will always be a needed area for the robot to operate smoothly with timely responses to outside stimuli. Inside of the field of controls enters in the whole new realm of intelligent robotics, where a robot can learn from its surroundings. For an autonomous robot, an intelligent control system is important in attempting to figure out how to get mobilized if it gets stuck because when a robot is sent out into the field, there is no one to go and right it, refuel it, or reset the system. The robot is on its own. Designing a robot to survive and complete its mission is what the Army has been doing since its inception with its soldiers. The robot will never replace the soldier, but it can be an aid that extends all of the soldiers senses. The robot will possibly never be as mobile as its human counterpart or any of its biomimetic inspirations but they are useful and knowing how to define their mobility is important. In the infamous words of one soldier, “And now you know- and knowing’s half the battle!”

References

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[1] Reuters, “Hospitals Take Robots for a Spin”, http://www.wired.com/news/medtech/ , March 6, 2003.

[2] Behar, Michael. “The New Mobile Infantry.” WIRED magazine, Issue 10.05, May 2002.

[3] Ahlvin, R.B. and P.W. Haley. *NATO Reference Mobility Model Edition II Users Guide.*

[4] Pan, Weidong and Dario Solis. “High Fidelity Tire-Soil Interaction Modeling and Simulation for VPG Applications.” 14th International Conference of the ISTVS proceedings, Vicksburg, MS, October 2002.

[5] U.S. Army presentation on Bekker and Mobility, Dr. Gorsich. February 2003.

[6] Le, Anh Tuan. “Modelling and Control of Tracked Vehicles.” Thesis, Department of Mechanical and Mechatronic Engineering, The University of Sydney. January 1999.

[7] General Dynamics Land Systems. “High Mobility Robotic Platform Study: Final Report.” Prepared for US Army TARDEC, Warren, MI. August 1999.

[8] Unterseher, Lutz. “Wheels or Tracks? On the ‘Lightness’ of Military Expeditions.” Project on Defense Alternatives, Briefing Memo #16. December 2001.

[9] Karafiath, L.L. and E.A. Nowatzki. *Soil Mechanics For Off-Road Vehicle Engineering*. Trans Tech Publications, 1978.

[10] Nutall, C.J. “An Assessment of the Inland Water Crossing Performance of Selected Tactical Support Vehicles (WACROSS).” GL-79-1. January 1979.

[11] Blackmon, C.A. and J.K. Stoll. “An Analytical Model for Predicting Cross-Country Vehicle Performance.” Appendix B; Volume 1: Lateral Obstacles. T.R. 3-783. December 1968.

[12] Robinson, J.H. et al. “Gap Crossing Analysis Within Theaters of Operation.” GL-93-24. August 1993.

[13] Activmedia Robots website, http://www.mobilerobots.com/. 2003.

[14] Iagnemma, Karl and Steven Dubowsky. “Terrain estimation for high-speed rough-terrain autonomous vehicle navigation.” Unmanned Ground Vehicle Technology IV, SPIE Conference Proceedings, April 2002.

[15] C.J. Nuttall, Jr. “An Assessment of The Inland Water Crossing Performance of Selected Tactical Support Vehicles (WACROSS).” GL-79-1 January 1979.

[16] Thornsberry, Marc. “Standard Drawing Details for Public Improvements.” City of Springfield, MI. May 2002.

[17] Digney, Bruce L. and Steve Penzes. “Robotic Concepts for Urban Operations.” Unmanned Ground Vehicle Technology IV, SPIE Conference Proceedings, April 2002.

[18] Neuhaus, Peter and H. Kazerooni. “Industrial-Strength Human-Assisted Walking Robots.” IEEE Robotics & Automation Magazine, December 2001.

[19] “Logistical Vehicle Off-Road Mobility.” U.S. Army Transportation Combat Developments Agency, Fort Eustis, VA. Project TCCO 62-5, 1967.

[20] Bekker, M.G. *Off-the-Road Locomotion*. University of Michigan Press, 1960.

[21] Fiorini, Paolo and Joel Burdick. “The Development of Hopping Capabilities for Small Robots.” Autonomous Robots, Vol. 14, pp. 239-254, 2003.

[22] Birch, Matthew, et al. “Cricket-Based Robots.” IEEE Robotics & Automation Magazine, December 2002.

[23] Altendorfer, et al. “RHex: A Biologically Inspired Hexapod Runner.” Autonomous Robots, Vol. 11, pp. 207-213, 2001.

[24] *RHex: The Compliant Hexapod Robot*, http://www.rhex.net/, 2003.

[25] Erkmen, Ismet, et al. “Snake Robots to the Rescue!” IEEE Robotics & Automation Magazine, September 2002.

[26] Bonsor, Kevin. “How Snakebots Will Work.” http://electronics.howstuffworks.com/snakebot.htm. April 2001