Using modeling and simulation to evaluate stability and traction performance of a track laying robotic vehicle

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ABSTRACT

DOD has been involved in the research, development and acquisition of unmanned ground vehicle systems to support the troops in the field while minimizing the risks associated with supplying these troops. Engineers and scientists at TARDEC are using computer based modeling and simulation (M&S) to investigate how modifications to unmanned ground vehicles impact their mobility and stability, and to predict performance levels attainable for these types of vehicle systems. The objective of this paper will be to describe the computer-based modeling, simulation, and limited field testing effort that has been undertaken to investigate the dynamic performance of an unmanned tracked vehicle system while conducting a full matrix of tests designed to evaluate system shock, vibration, dynamic stability and off road mobility characteristics. In this paper we will describe the multi-body modeling methodology used as well as the characteristic data incorporated to define the models and their subsystems. The analysis undertaken is

Figure 1 – Track Laying Robotic Vehicle Snapshot

applying M&S to baseline the dynamic performance of the vehicle, and comparing these results with performance levels recorded for several manned vehicle systems. We will identify the virtual test matrix over which we executed the models. Finally we will describe our efforts to visualize our findings through the use of computer generated animations of the vehicle system negotiating various virtual automotive tests making up the test matrix.
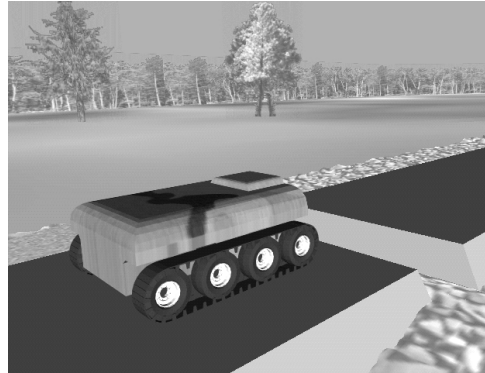
KEYWORD LIST

Modeling and Simulation, multi-body dynamics, track soil interaction, robotic, tractive effort, vehicle stability.

INTRODUCTION

Wheeled and tracked vehicle systems must be capable of operating on the Virtual Proving Ground (VPG) and in synthetic environments for testing, training, design and trouble shooting evaluations. Drawing on simulation, limited field testing and vehicle characterization, TARDEC engineers are attempting to reproduce ground vehicle behavior that is both autonomous and more realistic. The primary purpose of this effort was the development of a high-resolution computer based dynamic model of a tracked robotic vehicle for use as a virtual prototyping tool, and to provide a capability to predict automotive performance characteristics for smaller tracked vehicles with and without band track.

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14. ABSTRACT
The objective of this paper will be to describe the computer-based modeling, simulation, and limited field testing effort that has been undertaken to investigate the dynamic performance of an unmanned tracked vehicle system while conducting a full matrix of tests designed to evaluate system shock, vibration, dynamic stability and off road mobility characteristics. In this paper we will describe the multi-body modeling methodology used as well as the characteristic data incorporated to define the models and their subsystems. The analysis undertaken is applying M&S to baseline the dynamic performance of the vehicle, and comparing these results with performance levels recorded for several manned vehicle systems. We will identify the virtual test matrix over which we executed the models. Finally we will describe our efforts to visualize our findings through the use of computer generated animations of the vehicle system negotiating various virtual automotive tests making up the test matrix.

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Fully three dimensional vehicle models of a Tracked Robotic Vehicle were created using the Dynamic Analysis and Design System (DADS), which is a commercially available multi-body modeling methodology currently incorporated into Virtual.Lab Motion from LMS Inc. The model was used to evaluate the potential performance gains through the addition of a rubberized "band" track on a wheeled high mobility vehicle virtual prototype, on up, down and side sloped off road terrains, evaluating ride quality while traversing rough cross country terrains, and identifying performance improvements during vertical step and gap crossing. High definition computer-generated animation capabilities were developed and utilized to assist in the overall vehicle performance evaluation. These capabilities were instrumental in providing visual queues to the engineer developing the model as well as providing graphical representations and animation where gains were found.

TARDEC is the US Army's Tank, Automotive Research, Development and, Engineering Center and is responsible for providing engineering support to Army and Program Executive Officers, Program Managers, and program decision makers. TARDEC also is responsible for researching innovative technologies that can improve the capabilities of DOD ground vehicles. One form this support takes is providing ground vehicle engineering expertise during Army vehicle system acquisitions. TARDEC engineers and scientists identify automotive performance capabilities necessary to meet system operational requirements, and these automotive performance requirements are part of the document that the prospective contractors design against. During the Army's acquisition process TARDEC engineers and scientists are tasked with the evaluation of the contractors' proposed designs against the automotive performance requirements and determine the degree of risk for the designs not meeting any of the requirements. To do this the Army has embraced Modeling and Simulation and has successfully applied it to assist with these tasks by developing tools to allow the Army to predict performance levels prior to selection of

1. Vehicle Hull (Hull)	
2. Left Idler (LI)	11. Right road arm #1 (RA1)
3. Left road arm #2 (LA2)	12. Left road wheel #1 (LW1)
4. Left road arm #3 (LA3)	13. Left road wheel #2 (LW2)
5. Left road arm #4 (LA3)	14. Left road wheel #3 (LW3)
6. Right Idler (RI)	15. Left road wheel #4 (LW4)
7. Right road arm #2 (RA2)	16. Right road wheel #1 (RW1)
8. Right road arm #3 (RA3)	17. Right road wheel #2 (RW2)
9. Right road arm #4 (RA4)	18. Right road wheel #3 (RW3)
10. Left road arm #1 (LA1)	19. Right road wheel #4 (RW4)

Figure 2 - Track Vehicle Model Block Diagram

the winning offeror. One such Army developed M&S tool is the NATO Reference Mobility Model (NRMM) which predicts ground vehicle mobility capability based on characteristic vehicle design data (dimensions, spring rates, tire rates, dampers, etc). One drawback of the NRMM is in that it is only two dimensional (pitch-plane models). Also, the NRMM is based on decades of Army field testing, on a litany of ground vehicle systems, and the empirical database upon which it is based contains track vehicles much heavier than many of the robotic track laying vehicles being considered to assist with Homeland Security or for components of future Army operational requirements. These databases also do not contain much information relating to the recently developed Band Tracks whose performance characteristics allow greater speeds and lighter vehicles. These are only some of the reasons for undertaking the work described in this paper, to develop a lightweight track vehicle analysis tool, and to incorporate a rubberized band track analysis capability.
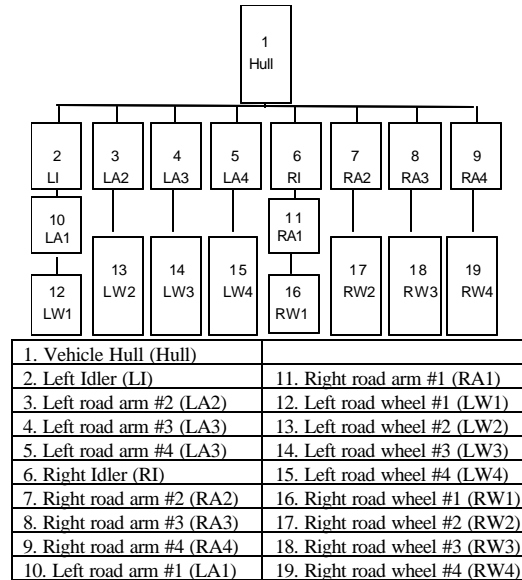
The track vehicle model has been, and is being applied to allow Army design engineers to make informed design decisions as to the capabilities of a smaller track laying vehicle, both robotic and otherwise. The track vehicle model provides vehicle development engineers with a better understanding of a vehicle's performance characteristics and makes the investigation of design changes that could lead to better performance much easier. The simulations provide the design engineer with the opportunity to analyze vehicle modifications, identifying performance improvements while

carrying out numerous mission scenarios. By using virtual prototyping, the Army is able to quantify performance characteristics for various vehicle designs in a fraction of the cost and time it would take to build and test prototypes or technology demonstrator vehicles.

TRACK VEHICLE MODEL

Fig. 1 shows a computer generated graphical representation of the band-tracked robotic vehicle with 8 powered wheels and a total weight of 3,000 lbs. Figure 2 identifies the vehicle components making up the model and contains the track vehicle spanning tree which provides connectivity information used to assemble the model. A single rigid body represented the vehicle hull (hull). The vehicle we are describing in this paper has a band track wrapping around four independently suspended wheels/tires, and the rear suspension of each track has an additional longitudinal translation degree of freedom, as well as a spring and damper to allow for maintaining track tension. Eight additional bodies are connected to the hull by vertical, single degree of freedom translational joints. Eight rigid bodies (LA1, LA2, LA3, LA4, RA1, RA2, RA3 and RA4) represent the eight road arms. The eight road wheels are represented by rigid bodies (LW1, LW2, LW3, LW4, RW1, RW2 RW3, and RW4) and are attached to their respective road arms by transverse, single degree of freedom revolute joints.

In addition to the bodies and joints making up the basic system kinematics, the vehicle model also contains a number of special subsystem models necessary to make it emulate the tracked vehicle dynamics. A rolling wheel model was included to model the road wheels with 20 inch radial ply tires. Spring-Damper models were incorporated into each of the road arm joints to provide springing and damping, and a track-ground module was developed to compute and apply the tractive efforts generated at the track/ground interface. The track-ground module applied these forces to the road wheel centers to propel, brake and steer the robotic vehicle while traversing various terrains while performing several virtual proving ground automotive mobility and vehicle dynamics tests.

The tracked vehicle is steered by a simplified second order controller model which minimizes the angle between the vehicle centerline and the tangent to a specified trajectory, and which minimizes the lateral displacement of a vehicle midpoint relative to the trajectory. Steering commands on the vehicle are supplied by driving the vehicle road wheels in equal but opposite directions. The second order algorithm provides position and velocity feedback for a more stable control. The error signal is converted to a torque which is divided between left and right tracks and applied to rotational springs on the road wheel hubs which apply these torques through their respective wheels to the ground. The gain in this controller model was made inversely proportional to vehicle speed to reduce steering sensitivity at higher speeds for better steering stability.

The vehicle speed is controlled by a speed control algorithm. A desired constant or variable speed control signal is input to the model and used as a reference. The speed of the vehicle is determined by projecting its velocity vector along the chassis fore-aft centerline. This result is compared to the desired speed and a corrective torque is generated. One eighth of this torque is applied to each road wheel to propel, or brake the corresponding wheel, which effectively controls the vehicle motion.

TRACTION

Applying this model as an engineering tool capable of identifying and characterizing automotive performance required accurate representation of the track/soil interface characteristics for the vehicle while traversing varying soil conditions. To accomplish this we took advantage of the works done by Bekker [1] and Wong [2], which identify pressure sinkage and shear strength relationships.

For this work we considered the track as consisting of individual shear plates, and during run time we computed sinkage and shear stress based on the soil type and the normal pressure exerted by each individual shear plate, resolved and summed these shear forces. These shear forces oppose the driven wheels' drive torques and provide force at the centers of the wheels to propel the vehicle. Similarly the ground normal forces are passed through the tires and wheels to the wheel centers to support the vehicle.
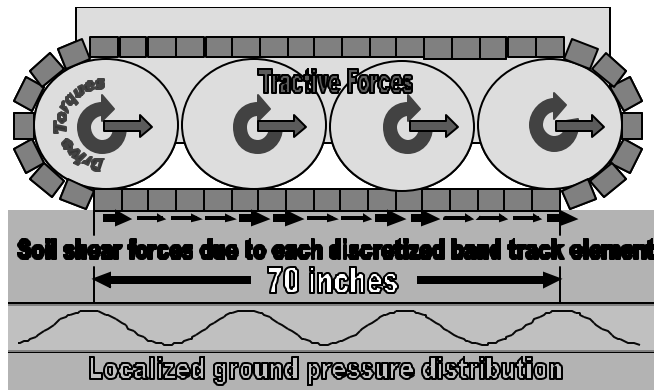

Figure 3. Robotic Vehicle Track Soil Force Diagram

To compute the soil shear strength we used the criterion due to Mohr-Coulomb which postulates that the material at a point will fail if the shear stress at that point in the medium satisfies the following condition [2]:

$$t = c + s \tan f \qquad\qquad \text{Equation 1}$$

Where t is the shear strength of the material, c is the apparent cohesion of the material, s is the normal stress on the sheared surface, and f is the angle of internal shearing resistance of the material. [2] Therefore we think of soil as a combination of two constituents, a cohesive component and a frictional component, and the shear strength of the soil as that given by Equation 1. Multiplying the shear stress by the shear plate area ? in contact with the ground we find the maximum shear force for each shear plate (for the given soil) is:

$$? t = ? (c + p \tan f) \qquad \text{or} \qquad F_{shear =} ?c + N \tan f \qquad \text{Equation 2}$$

Where N is the normal force exerted on the shear plate by the ground. Note that for the case of a purely frictional soil (e.g. dry sand whose cohesion c => 0, and f ˜ 35°) the maximum tractive effort that the soil is capable of supporting is W tan 35° or 0.7 times the weight of the vehicle [1]. Conversely for a purely cohesive soil (e.g. saturated clay f => 0) the soil's ability to generate tractive effort is only dependant on the surface area of the track coming into contact with the ground and not dependent on the vehicle weight [2]. Therefore the physics behind a tracked vehicle maintaining mobility in soft soil breaks down as follows: the soil shear strength must be great enough to withstand the total force required to propel the vehicle over a given terrain divided by the number of track shoes on the powered vehicle in contact with the ground at any one time. This gives us the threshold shear strength per track shoe which the soil must exhibit in order for the vehicle to negotiate the terrain in question. Vehicle designers reduce the required soil shear strength per track shoe by increasing the track shoe area (cohesive soils), thus spreading the load over more track shoes, and lowering the aggregate soil shear strength required. However, there is a trade-off to this approach, because as we increase the number of track shoes, we are reducing the distance between the shoe penetration planes into the ground which tends to further reduce the soil shear strength. If the soil is not strong enough to withstand these forces, then the vehicle cannot negotiate the section of terrain in question.

For many terrains the soil shear strength increases with soil penetration depth. If the terrain in question exhibits this characteristic, then its possible to design a track shoe or shoe insert which will dig deeply enough into the soil to reach that soil whose shear strength is great enough to propel the vehicle. Unfortunately, due to the multitude of possible soil conditions, this fix will only meet with success on those terrains which meet this limited criteria and it is therefore not possible to analytically quantify the performance capability gained from this type of track configuration. But it makes sense that designing the shoe or grouser as wide and as long as possible, without causing interference between the track and hull, will maximize pulling power over the greatest number of terrains.

The magnitude of the normal force applied by the ground against the track is another factor playing a large role in tracked vehicle pulling power. The pulling power is directly proportional to the normal force and, therefore, a heavier vehicle will have greater pulling power.

Another factor contributing to tracked vehicle pulling power is the uniformity of the track to ground pressure from the front of the vehicle to the rear. Evenly distributing this load over the vehicle length will maximize the pulling power, but, as always, the vehicle system will successfully negotiate a terrain only if the soil shear strength of the terrain is great enough to support the pulling shear imparted by the track shoes of the pulling vehicle (see discussion above). The two items that contribute the most to track to ground uniformity are the pulling vehicle's cg and terrain non-uniformity. The challenge of modeling the tractive effort of the vehicle track then becomes identifying the normal force exerted on each track shoe due to ground contact. These ground to track normal forces are greater directly beneath the wheel centers and are reduced from these peak forces as a function of the track tension, and the amount of ground sinkage beneath the wheels. The angle the track makes in front of and behind the wheel

The model's terrain files, which normally provide elevation and slope for any point on the course, were modified to include soil type and condition (c and f) for any point in the database.

During run time the tractive efforts were computed based on the soil condition and the normal force beneath each track shoe. These normal forces depend on the soil penetration, the track tension, and the angle the track makes between the road wheels. From figure 4 we can see that if the track angle between road wheels is zero, then the track tension has no vertical component to contribute to the track shoe normal forces for those shoes not directly beneath the road wheels. To identify the track angle required the track-ground module to query the terrain database to identify the elevation and gradient beneath each track shoe, compute the angle, and the ground penetration. From these solving for the normal forces followed as:

$$N = T \sin (?) + w \qquad\qquad \text{Equation 3}$$

Where T is the track tension, ? is the track angle with respect to the straight line between the bottoms of consecutive road wheels, and W is the track shoe weight. This normal force when combined with Equation 2, and the track shoe area, the soil cohesion and the soil internal friction angle allowed computing the soil shear force available for that shoe. Summing all the shear force for the tracks contacting the ground gave a net shear force available to propel the vehicle. Resolving the drive torque being called for by the driver controller to a force (dividing by the rolling radius of the driven wheel) and applying the smaller of the two forces (available shear force for the entire track, or the force called for by the control torque) gave us a good representation of how the physical system would function.

We considered incorporating the shear stress – shear displacement relationship for shear curves of a simple exponential form: $t = t_{max} (1-e^{-j/k})$ where t_{max} is given by Mohr's Condition, j is the shear displacement, and k is referred to as the shear deformation modulus which can be represented by the line tangent to the shear curve at the origin and the horizontal line representing the maximum shear stress t_{max} [2], but for our initial work we considered tmax to be sufficient for computing the tractive effort available to the vehicle. We plan to implement this as part of our deformable terrain work.
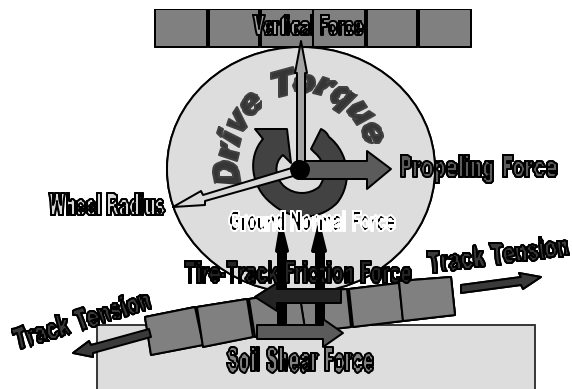

**Figure 4. Track Tension Contribution to Shoe Normal Force**

SIMULATION TEST SCENARIOS

The track vehicle is expected to operate safely on- and off-road under various terrain conditions including smooth pavement, highways, rugged cross country, side slopes and soft-soil environments. Occasionally on-road operations such as cornering at excessive speeds or evasive maneuvers may require steering commands which generate high lateral accelerations. The most prevalent problem with off-road operation is encountering large obstacles such as rocks, mounds, sand dunes or holes which may induce large roll angles. Lateral-turning, on-road evasive maneuvers, discrete obstacle, and cross-country courses were chosen to facilitate these evaluations. In addition, all simulations were assumed to take place on dry, non deforming surfaces, and with the exception of the cross country simulations, on flat, level surfaces. The following simulations were developed:

Allied Vehicle Test Publication 03-160W (NATO Double Lane Change) – We programmed a double lane change maneuver in the controller and selected the maneuver's gate dimensions based on the AVTP 03-160W. We have been using the AVTP double lane change for several years, and it was required in the performance specification of the Marine Corps Medium Tactical Vehicle Replacement that the Army procured (at 45 mph), and has been in the performance requirement for practically every ground vehicle system acquisition since. The maneuver consists of a transition from the right lane to the left lane and back again. Cones are placed on the test track identifying the course dimensions, and the longitudinal distance the driver has to complete each lane change transition, L_{eff}, is 24 meters + the overall length of the vehicle (see Figure 5.).

Figure 5. NATO Double Lane Change Course Dimensions
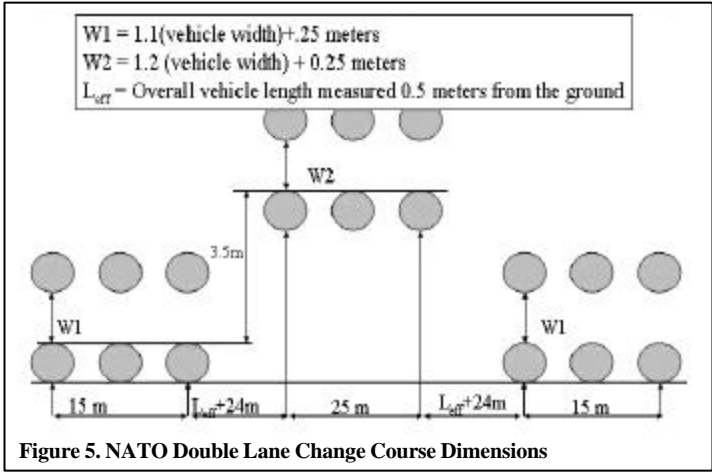
Bump and Vertical Step Courses - A bump course was set up to investigate repeatable, worst case transient conditions that the system might experience that could produce instabilities and degrade ride-quality at various speeds until uncontrollable conditions became apparent. For the computer implementation, the vehicle system was initialized in a steady state, straight-ahead operation on a flat level road, and then it accelerated to speed and rode over the positive discrete obstacle. The discrete obstacle course uses single ramped bumps (positive bumps) as shown in Figure 6, and the models are aligned so that only the left or right side of the vehicle hits the bump at constant speed during each simulation. The system then returns to a steady state, straight-ahead operation on a flat level road. Several size bumps using this geometry were fabricated and exist at the Aberdeen and Yuma Proving Ground Army test facilities, the Army Corps of Engineers Research Development and Engineering Center (Vicksburg, MS), and at TARDEC. Additionally we increased the ramp slope and bump to model vertical steps.

Figure 6. Positive Bump
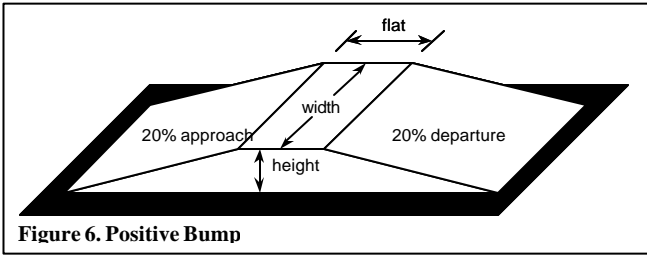
Pothole-Gap Course - A pothole course was set up to investigate a worst case condition that each system might experience that could produce instabilities and degrade ride-quality at various speeds until unsafe conditions became apparent. For the computer implementation, each vehicle system is initialized in a steady state, straight-ahead operation on a flat level road. This set of simulations emulates a vehicle system performing a negative discrete obstacle maneuver such that the system will experience a terrain that decreases 6 to 12 inches in altitude in a short distance with an approximate 100% slope during approach and departure. The discrete obstacle course uses single potholes (negative bumps) as shown in Figure 7 and the models are driven over one pothole at a time at constant speed. The test is aligned so only one side of the vehicle system encounters the pothole. This was done to provide asymmetric input in order to investigate performance during relatively large roll angles. Once through the pothole the system returns to a steady state, straight-ahead operation on a flat level road. Additionally, we increased the pothole width, ramp slopes, and depth to model gap crossing.

Figure 7. Pothole Dimensions
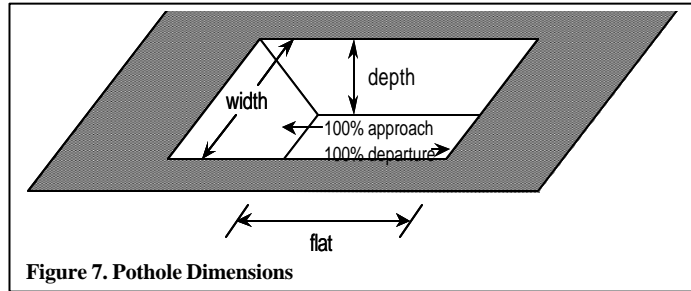
Cross Country Courses - The vehicle models were set up to negotiate cross-country courses at various constant speeds based on a look-ahead speed controller that attempts to maintain maximum speeds as road conditions warrant. Figure 8 lists the measured left and right track elevation profiles as functions of distance traveled along the course of the cross country courses that were used in this analysis.

Course	Section	Test Facility
Belgian Block	2000 ft. section	Aberdeen Test Center (ATC)
Churchville Mild	2000 ft. section	Aberdeen Test Center (ATC)
Churchville Rough	2000 ft. section	Aberdeen Test Center (ATC)
Munson Gravel	2000 ft. section	Aberdeen Test Center (ATC)
Perryman 1	500 ft. section	Aberdeen Test Center (ATC)
YPG 1.09 RMS #2	500 ft. section	Yuma Proving Ground (YPG)
YPG 1.34 RMS #3	500 ft. section	Yuma Proving Ground (YPG)
YPG 1.79 RMS #4	500 ft. section	Yuma Proving Ground (YPG)
YPG 3.42 RMS #5	500 ft. section	Yuma Proving Ground (YPG)

Figure 8. Cross Country Courses

VISUALIZING RESULTS

DADS provides the capability for reporting any of the vehicle states from any of the simulations, but because we did not explicitly model each track shoe element with rigid bodies, joints, and contact elements in DADS, we needed to include track shoe position and orientation reporting in the track-ground module. During run time as the track-ground module is processing the shear force developed by each track shoe, it also computes each track shoe's orientation and
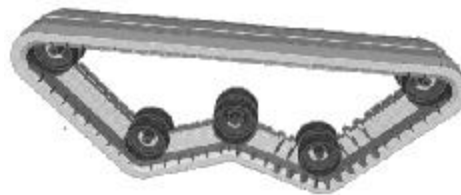

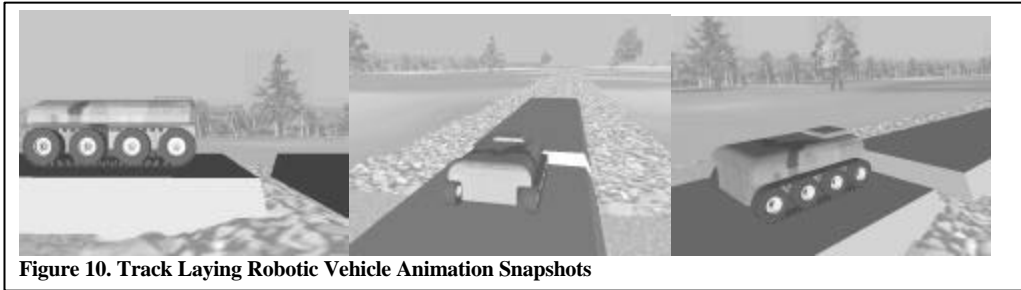**Figure 9. Combat Vehicle Band Track Snapshot**

Figure 10. Track Laying Robotic Vehicle Animation Snapshots

position. This information in saved for later animation post processing. During this post processing we use the data to develop Virtual Reality Modeling Language VRML files of simulations and they can be shown interactively on web browsers with a VRML plug-in installed. Figure 9 is a snapshot taken from our model of a combat vehicle band track, and Figure 10 shows snapshots generated of the track laying robotic vehicle.

CONCLUSIONS

With the advent of rubberized band tracks and track over tires becoming ever more prominent, we undertook developing a method to simulate the action the track has on vehicle mobility, traction and stability. In this paper we identified the underlying physics in track-ground module, stepped through our process of assembling the model and described the assumptions we made in resolving soil shear forces up to the drive wheels when we pass the forces developed by the track-ground module to the core DADS model. Work will continue on the model's development, making it easier to assemble, standardizing the data inputs, and validating the predictions providing the Government with another tool for evaluating automotive performance of vehicle systems prior to build or buy.

ACKNOWLEDGEMENTS

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