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Development of an Enhanced Mobility Testbed

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Abstract

This paper describes a novel vehicle platform under construction at DRES which is designed to exhibit greatly enhanced mobility by employing hybrid running gear. The paper discusses the Articulated Navigation Testbed (ANT) and the considerations which determined its configuration and capabilities. First, as strictly an unmanned vehicle, it must employ teleoperation or some level of autonomous control. Second, it is to possess superior off-road mobility when compared to more conventional vehicles. Increased mobility reduces the computational workload needed to operate in a highly unstructured off-road environment. Third, it must be adaptable and have a flexible mission architecture. By maximizing modularity of the vehicle systems, the design team believes the resultant vehicle will provide a generically mobile chassis upon which DRES researchers can take robotics out of the lab and into the field.

Introduction

In the battlefield of the future, it is very likely that many roles will be filled by unmanned vehicles. The goal of the Defence Technologies Division (DTD) at Defence Research Establishment Suffield (DRES) is to conduct research into creating, controlling, operating, and applying unmanned vehicles in simulated or real military scenarios. The Vehicle Concepts Group within DTD is primarily concerned with research into superior vehicular platforms that facilitate unmanned operation. This paper discusses the design of such a vehicle, which is now being built at DRES. It is important to note that this document is only intended to disclose the design, and not to discuss applications of the vehicle in either manned or unmanned missions.

A review of the literature revealed that many research institutions around the world are developing conformal platforms [2,3,4,5]. These are vehicles which possess special geometry of one kind or another that allows them to conform to highly unstructured terrain. The two most popular formats seen are the doubly-articulated six-wheel-drive rover projects and the hexapod or six-legged walking machine. Both have advantages and disadvantages, evident in the performance of research prototypes.

In an effort to combine the advantages of rolling and walking, DRES personnel conceived the Articulated Navigation Testbed (ANT), a multi-unit, articulated, proof-of-concept (POC) demonstrator. Its locomotion is provided by hybrid running gear comprised of wheels attached to legs. The goal is to produce a "generically" mobile vehicle chassis that facilitates unmanned control and possesses an architecture adaptable to any assigned mission.

Mobility Considerations

Definition of Mobility

Vehicle mobility over land is determined by several factors, many of which specifically relate to vehicle configuration and capabilities. It is very easy to single out one outstanding aspect of the performance of a vehicle and call it a highly mobile vehicle, but it is also very misleading to do so. Researchers from the NATO countries have arrived at a standard for quantifying overall land vehicle mobility in terms of Speed Made Good (SMG), the highest effective speed operating in a prescribed terrain unit of assumed isotropic properties.

Speed Made Good may be calculated using a FORTRAN computer simulation program called the NATO Reference Mobility Model (NRMM) [1]. The NRMM main module predicts the theoretical

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limit of speed caused by each of a list of factors, then selects the lowest of this set of speeds as the effective SMG in each terrain unit. If one or more of the limits is zero, then the terrain unit in question is flagged as NO-GO and the vehicle is said to have no trafficability in that unit. In other words, terrain with those properties is impassable for the selected vehicle.

The factors in the NRMM which limit vehicle speed are therefore either controlling factors [C] or NO-GO factors [N], depending on whether the terrain unit is or is not trafficable, respectively. These factors are listed in Table I, along with brief explanations of the vehicle, terrain or scenario parameter which sets each. The table also contains the vehicle modification(s) most likely to improve each limit.

To create a truly mobile land vehicle the greatest possible balance of performance in all areas must be sought. Only then can mobility be considered "generic".

For example, a vehicle capable of climbing a dry 70% grade might be called mobile by the casual observer, but gradability is only one mobilty factor. If the same vehicle loses traction on flat ground in 5 cm of mud it is not a "mobile" vehicle. Collective measures of mobility include, but are not limited to: agility, stability, maneuverability, gradability, trafficability, ride quality, and linear feature crossing capability.

It is possible to identify a few unconventional vehicle technologies which would allow a vehicle to modify some of its characteristics, identified in Table I, in order to enhance its mobility. That is the basis for the highly conformal nature of the ANT. For example, the table indicates that off-road mobility may be enhanced by raising the ground clearance. It also indicates that lowering the center of gravity may aid on-road mobility. The ANT can raise or lower both on demand, unlike most vehicles.

Table I: NRMM Speed Made Good Limiting Factors

Factor Description	Type	Vehicle Characteristic
Excessive sinkage/belly drag	N	Increase ground clearance
Excessive obstacle density	N	Tighten turning, increase clearance
Excessive vegetation density	N	Tighten turning radius, articulate body
Obstacle override hang-up condition	N	Increase ground clearance
Inadequate forward obstacle clearance	N	Increase footing approach angle
Inadequate traction for grade	N	Increase footing contact or number
Inadequate visibility to progress	N	
Ride quality limited (human occupant)	C	Improve suspension dynamics
Tire speed limited	C	Select more suitable tire for mission
Soil/slope/vegetation drag (motion resistance)	C	Increase ground clearance or power
Limited visibility	C	
Maneuvering around obstacles	C	Tighten turning, increase clearance
Maneuvering around vegetaion	C	Tighten turning radius, articulate body
Obstacle impact speed limit	C	Improve suspension dynamics
Obstacle override force (human occupant)	C	Improve suspension dynamics
Driver prudence in vegetation	C	
Skidding due to curvature	C	Increase footing and/or decrease roll
Tipping due to curvature	C	Lower center of gravity

Present Technologies

Present vehicular locomotion systems are not good at all aspects of mobility, and vehicle design always involves compromise in the selection of running gear, defined here as the vehicle subsystem which interfaces to the terrain. All vehicles using conventional running gear suffer in one or more mobility factors. For example, wheeled vehicles are typically more agile and maneuverable than tracked vehicles, but possess higher ground pressures and are therefore less trafficable. Tracked vehicles have lower ground pressure and superior traction and are therefore more trafficable, but are not agile or efficient due to (usually) larger overall mass and much larger internal motion resistance.

Both wheels and tracks have been proven successful for negotiating roadways and moderately unstructured off-road terrains. Neither has exhibited strength in highly unstructured terrain. Very rugged, "mobility-hostile" environments are the targeted application of walking vehicles which are being investigated by several institutions around the world. Some research prototypes employ "pogo-stick" locomotion on anywhere from one to four legs [2,3,4], but others contend that walking locomotion can only be achieved efficiently and stably with six or more legs [5]. Movable legs provide a vehicle chassis with highly variable footing positions, thus allowing it to conform to extremely rugged terrain which would completely block the passage of either wheels or tracks of comparable dimensions.

The Adaptive Suspension Vehicle project in the United States is the most technologically advanced hexapod in the opinion of the authors, and is cabable of effective and stable locomotion by stepping in turn with two intersecting tripod sets (fore and aft legs on one side in conjunction with center leg opposite) [5]. The ASV can negotiate random terrain with discrete elevation changes up to a meter in height as long as sufficient flat spots are available to place three footholds on each step. Unfortunately, due to the complexity of coordinating multipedal stepping motion, vehicles like the ASV are very slow in less hostile terrains, and are easily surpassed by wheeled and tracked vehicles.

The Articulated Navigation Testbed

The ANT will possess superior off-road mobility compared to conventional vehicles. The concept vehicle is comprised of multiple body modules, and is steered by articulation. Each module contains a rigid structure to which member systems of the module are attached, two legs connected to the structure by rotatable hip joints, and wheels attached to the lower ends of each of the legs. Each wheel is mounted to the output shaft of a powered wheel motor.

The vehicle moves by either turning the wheels, rotating the legs to which the wheels are attached, or a combination of both. The typical configuration is a three module platform, although it may be extended to four, five or longer depending on specific mission requirements. It can also be minimally configured with two modules as it is shown in Figure 1, though in this mode, its walking capabilities are diminished.

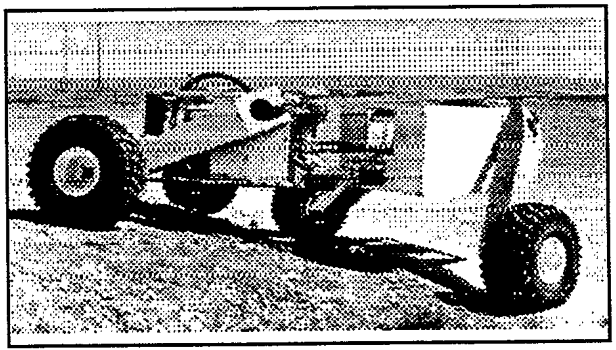

Figure 1: Minimally configured ANT

The minimal configuration would be used in situations where only wheeled operation was required by a mission. However, if a three module platform were used, only two modules (4 wheels) or less are required for locomotion. The third module may then have one or both wheels and/or legs removed, and the wheel motors and/or hip actuators may be used to mount and manipulate auxiliary implements. This modularity was a prime consideration in the vehicle design, so that the third module and any successive modules contain only their required actuators and serve as a skeleton to which mission-specific hardware can be attached.

The articulation joint between modules may have one or two degrees of freedom. Yaw capability is always present, and is moderated by a rotary actuator. The joint may be free in the roll axis, fixed in the roll axis, or controlled in the roll axis through the inclusion of a rotary spring, damper, and/or, actuator. Pitch freedom or compliance is not required, as one principal motivation for using legs is the ability to follow longitudinally variable elevations with a relatively flat body geometry.

The vehicle employs multi-body articulation, so each chassis module follows the arc travelled by the preceding module, and may exactly follow the track of the preceding module if leg geometry is selected appropriately. Thus in terrain with high obstacle density, and particularly in vegetation, the articulated steering provides successive obstacle avoidance for all trailing modules.

Modular Architecture Considerations

Powertrain Modularity

In order to accommodate the many degrees of freedom of the vehicle, power delivery is accomplished by an electrical, hydraulic or combined electro-hydraulic distribution system, depending upon the selection of actuators required for the vehicle mission. In keeping with the design goal of modularity, and in order to provide a slight rearward balance to the vehicle, the rear module shown in Figure 2, is reserved for power generation equipment. It contains an internal combustion engine used solely to drive one or more hydraulic pumps and/or electric alternators, depending once more on the type of actuators used.

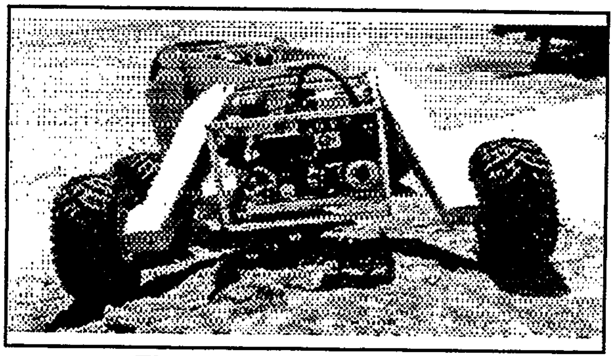

Figure 2: *ANT Rear Module*

Power is distributed through a central manifold in each chassis module, and bussed between modules in paired cables and/or fluid hoses. The second module contains its own manifold and actuators, and also houses the batteries, primary fuel cell for the engine, and the central computer system which coordinates the vehicle motions.

One principal advantage with electric or hydraulic wheel drive systems is a simplified powertrain control function. Mechanical transmissions use clutches and gear sets which add weight and are quite inflexible. Speed is controlled by varying engine throttle. Electric or hydraulic wheel drives provide gearing, both forward and reverse, speed control, and braking through fluid flow or current in a flexible cable or hose, respectively. Vehicle speed and direction are integrated into a single control function, which is likely non-linear or piecewise linear at best, but may be linearized by software.

Control System Modularity

The many degrees of freedom in this vehicle make it capable of very complex motion; and some degree of computer control is essential. It would take a sizable team of human operators to coordinate all the actuators visually. Complementing the modular chassis design, a downward delegation of control responsibility is designed into this vehicle. Each leg/wheel combination is managed by a microcontroller using feedback from transducers on the hip actuator and wheel motor. All microcontrollers are connected in a network mastered by a central processor. In the event a leg is replaced with an auxiliary implement as mentioned earlier, the microcontroller associated with that leg is also replaced with a microcontroller programmed to operate the added implement.

The principal advantage to this distributed control approach is that it largely simplifies the central processor task load. Periodically, the central processor downloads new set points for the actuators, and the closed loop control algorithms executing in the microcontrollers run continually based on the current set point. The accuracy of control is enhanced by this approach because the distributed controllers can run at update frequencies of several hundred samples per second due to the small computational requirements they have. Large scale chassis geometry changes require a relatively slow dynamic response, and are not even required during travel on smooth terrain. This means the central processor does not have to run a continuous control algortihm. The slaved controllers take care of all the real time feedback control loops.

A secondary advantage to the distributed control approach is enhanced self-recovery. In a military scenario, it is quite possible that one or more legs may be lost or crippled. While such an occurrance will certainly affect the overall mobility of the vehicle, the central processor will not be directly affected by the lack of response from the damaged appendage(s). The vehicle will retain some degree of "limp-home" capability as long as the engine continues to operate.

The central processor in the ANT is not necessarily a computer system. It may in fact be a human operator employing joysticks or potentiometers to establish controller setpoints. It may also be a very complex computer system capable of navigating the vehicle autonomously over rugged terrain. It is important to reiterate that the vehicle design team set a goal of achieving generic mobility, not specific to the future applications of this platform in either manned or unmanned missions.

Proof-of-Concept Platform

Simulation

DRES employs DADS (Dynamic Analysis and Design System) for modelling vehicles and vehicle subsystems [6]. It is a comprehensive 3D rigid body simulation package complete with mechanical, hydraulic, and control element libraries, an X-windows interface, and a utility program which extracts model elements from Pro/Engineer, a parametric CAD/solid modeller also in use at DRES.

Kinematic model

A kinematic model was constructed of a three-unit ANT, to be used as a Proof-of-Concept (POC) design aid. It contained three identical chassis bodies and six leg/wheel bodies with the relative motions of joints being prescribed by drivers. Kinematic models do not include dynamic response characteristics, mechanical flexure or control constraints of course, but rather make the assumption the hip angles and wheel speeds are achieved instantaneously.

Dynamic model

The current simulation model of the ANT is dynamic, including force and torque response data for the actuators and motors, tire flexure, and full computation of the equations of motion based on mass and inertia properties of the bodies. This model is used to determine the capabilities of the vehicle when constrained by those parameters.

The dynamic model will be validated by the Proof-of-Concept vehicle, and when the simulated performance becomes a suitably accurate representation of the vehicle performance, the model may be used for two follow-on tasks: optimization of the vehicle design for any future revisions, and the simulation of ANT vehicles in operational scenarios.

Construction

Status

The Proof-of-Concept vehicle is nearly complete mechanically, with all powertrain components and actuators in place. Considerable effort was expended in placing feedback sensors for all actuators and motors in protected locations, while ensuring each modular subsystem remained together.

Hardware and software development has advanced using off-chassis electronics where possible, as the networked microcontrollers are not yet installed. Development of the microcontroller network software is on the critical path to the eventual fielding of the ANT vehicle.

When the networked distributed controllers are mounted and operational, the present system integration phase will be complete. It is expected that shakedown trials will begin early in 1994. During the summer, a validation study of the dynamic model will be conducted.

Plans

The POC ANT platform will be retained by DRES and serve as a technology demonstrator. One possible application in the near term would see the ANT in service as a tow vehicle for a mine detector platform known as the Vehicle Mounted Ordnance Detector (VMOD). Normally pulled behind a truck, the VMOD platform could become a front-mounted mission module of the ANT, enhancing the vehicle safety, because detection would occur before the vehicle passed over the mine, and the vehicle could avoid the mine by lifting the appropriate wheel.

The dynamic model and lessons learned from the POC vehicle may be used to create one or more application variants to suit Canadian Forces or Canadian industry. Areas of application may include, but are not limited to: mine detection and/or clearing, reconnaisance, surveillance and target acquistition functions. The vehicle could also be applied for remote observation of dangerous areas in mining, or for selective logging operations in remote areas in forestry.

Application to higher research areas include the possibility of using connectionist control architectures to investigate self-modifying behavior based on sensing of the local environment. Can the ANT be made to detect and avoid obstacles, with little or no human interaction? Can it be made to identify friend or foe and take appropriate action? These are some of the questions the authors intended this technology demonstrator to answer. Integration of the ANT with other DRES research activities in robotics is planned to follow the model validation phase.

Summary

The principal objective in creating the Articulated Navigation Testbed is to demonstrate a platform with "generic" mobility. It is to combine the efficient mobility that conventional platforms have on roadways and mild cross-country terrains with the enhanced mobility that conformal platforms have in very rugged cross-country terrains. The inherent modularity in the vehicle presents many possibilities for application.

The Articulated Navigation Testbed has been simulated and is under construction at a Proof-of-Concept stage. If Canadian Forces or Canadian industrial concerns have identifiable requirements for a similar vehicle, DRES will be in a position to assist. Further technology base development will be aimed at supporting the continuing research thrusts of DTD unmanned vehicle research.

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