Improved mobility in a multi degree of freedom unmanned ground vehicle[1]

Michael R. Blackburn[2,a], Richard Bailey[b], and Brent Lytle[b]
[a]SSC San Diego, 53560 Hull Street, San Diego, CA 92152
[b]ACEi, 25133 Avenue Tibbits, Unit A, Valencia, CA 91355

ABSTRACT

Mandelbrot, through his analysis of Fractals (Mandelbrot, 1977), has shown that the complexity of the physical geometry of nature is similar at all scales. This implies that a robot of fixed dimensions will always be too big to get through some passageways, and too small to get over some other obstacles. However, as others have demonstrated, increasing the number of the vehicle's motion degrees of freedom (dof) may permit it to change its conformation and dimensions, affording to it a greater range of environmental dimensionality through which it may move. This paper contains a description of our multi dof unmanned ground vehicle (UGV), including the variety of basic behaviors of which it is capable. Our UGV is a six-dof, sensor-rich small mobile robot composed of three segments – a central core and two tracked pods. The rotations of the pod tracks are the primary mobility mode (2-dof) of the vehicle. The pods are attached to the core at opposite ends, each by a single "L" axle that rotates through 180 degrees (2-dof), serving to improve balance and leverage. The pods can rotate 360 degrees about their end of the axle (2-dof) providing increased mobility over obstacles. The UGV in compact form is 17.6" long, 16.2" wide, and 4.6" tall, but can extend to 49" long to climb over obstacles or cross chasms, or rise to 16" high to straddle low obstacles. In its extended mode its maximum width is 9.5" permitting it to squeeze through an opening of that size. The UGV can independently draw in its two outer pods to grasp and longitudinally traverse horizontal pipes or logs or travel within a narrow culvert.

Keywords: UGV, Mobility, Obstacle Negotiation, Variable Conformation

1. INTRODUCTION

Combat operators do not like to carry a lot of weight into the field. For this reason, we have tried to make their supporting equipment, including unmanned ground vehicles (UGV), small and light. But the combat operators who have had experience with our versions of UGVs report that mobility is a serious limiting factor in their usefulness. Because of their small wheel radius, the small UGVs rarely can scale obstacles of heights greater than 7 inches[3], regularly stall on underbrush, and frequently fail to penetrate dense growths of trees. These challenges to vehicle mobility are minimized to the degree that operators can carry the UGVs to their operational sites, and then teleoperate the vehicles through the line of fire or into other high risk regions.

A common approach to improving mobility in manned vehicles has been to increase the size of the vehicle. The larger wheels and greater ground clearance of a big vehicle avoid possible high centering on fallen logs, road ridges, and rocks, and permit the fording of small streams. Greater vehicle weight permits crushing small bushes, ground rubble, and other fences both natural and man-made, but larger vehicles must be left behind when barriers, otherwise porous, refuse to be bulldozed over[4]. Large vehicles, however, do have the advantage that they can carry the operators and their baggage. It

---

[1] This work was supported by the Office of the Secretary of Defense Joint Robotics Program Coordinator
[2] mike@spawar.navy.mil, phone (619) 553-1904; fax (619) 553-6188
[3] The iRobot PackBot is an exception to this specific limitation by virtue of its flippers that effectively increase the forward wheel radius to about 11 inches.
[4] In May of 1995, a stolen tank from a California National Guard armory was eventually stymied after high centering on a concrete highway divider of not more than four-feet in height. Great size and weight appear to offer diminishing returns with respect to improved mobility.

would seem that we must choose between small size, light weight and limited mobility, and large size, great weight, and great mobility. But, we unfortunately do not get all that we pay for when we buy into larger vehicles.

Benoit Mandelbrot through his analysis of Fractals[5] explained one simple condition of nature in which the structural complexity was self-similar over all dimensions. The implications for unmanned ground vehicles of this universal natural condition are that vehicles of fixed dimensions will always be too small to get over some obstacles, and always too big to get through other obstacles. This poses a difficult to solve dilemma when the unmanned vehicle is too small to get itself into the theater of operation, or when it must be left behind because it is too large to proceed. In neither case can the robot perform its mission. There appears to be no one size of vehicle that is ideal.

Mandelbrot's law has always applied to man and beast as well. In response, nature provided one mechanism to improve our chances of getting around in its dimensional complexity. That mechanism was multiple degrees of motion freedom. Our multiple degrees of motion freedom permit us to change our own dimensions with respect to the prevailing dimensionality of the environment. With this mechanism we can straddle, reach, climb, crawl, squeeze, and roll. But, occasionally we still find ourselves imprisoned when our limits are exceeded by the barriers.

As a consequence of our physical limitations we have attempted also to reduce the physical complexity of our environments. We have done this by leveling, grading, paving, and constructing ramps, steps, pathways and portals. The urban environment is configured to conform to our most common dimensions and mobility. But our dimensions and mobility were configured by evolution to optimize our survival chances in our original natural environments, long before the advent of cities.

With respect to the question of improving mobility in an unmanned vehicle, we need to consider the natural environment in which it may have to operate, as well as the environments that we have modified to accommodate human dimensions and capabilities. Our robots, in order to get around with us, to go where we can go with our degree of facility, may need to have both our gross dimensions and our dimensional flexibility.

One of the early requirements for the robots developed under DARPA's Tactical Mobile Robots Program was the ability to climb stairs. This too has been one of the principal demonstrations of the mobility of the Honda ASIMO[6] humanoid robot. But climbing stairs hardly encompasses the mobility capabilities of a human. Rather, when at work, or when under true tactical conditions, humans are required to perform much greater feats than ascending or descending a staircase. The mobility envelope within which we might expect our soldiers to perform will surely include some of the following:

- Traversals on a planar surface at rates less than four minutes per statute mile.
- Balanced traversals for one hundred feet across a horizontal four-inch beam.
- Vertical jumps over a seven-foot bar.
- Vertical climbs of a thirty-foot rope
- Vertical climbs of a fifty-foot ladder or wall with foot and hand holds.
- Horizontal jumps over a twenty-eight-foot span.
- Crawls beneath or slips between a ten-inch space.
- Swims in sea-state-one for one mile.

Of course, few humans can perform to any of the above extremes[7]. Perhaps the best way to get a good impression of the limits of the human mobility envelope is to watch the series of events at world-class track & field or gymnastics competitions. As an alternative, and one with unequivocal military significance, is to examine the mobility required by a basic recruit training confidence or obstacle course. We provide two images of the obstacle course at the Marine Corps Recruit Depot in San Diego in Figures 1 and 2. These courses stress the strength and agility of young recruits without the

---

[5] B. Mandelbrot (1977) Fractals: Form, Chance, and Dimension, W. H. Freeman & Co.
[6] http://world.honda.com/ASIMO/
[7] One might argue that a more practical standard for a robotic assistant should be the modal performance standards of the human population. But some developers may question the wisdom of applying such mediocre and languorous standards to a robotic species with fewer constraints and greater evolutionary promise.

benefit of levers or cushions. The course requirements are established not only to test the physical fitness of the recruits, but also to assess the readiness of the recruits to meet actual operational conditions. If we intend for our robots to accompany the operators in the field, perhaps the robots too should meet those same strength and agility standards.

Figure 1

Figure 2

Needless to say, there is currently no UGV or robot that can run this course, although there are several that could run around it while avoiding the obstacles entirely.

The U.S. robotics community has tended to define a limited set of task-specific capabilities and built dedicated robots accordingly. Thus we have the concepts for a snake robot, a throwable robot, a man-packable robot, and a robot mule (to list of few of the UGVs developed or proposed). This is not without precedent as nature has also elaborated a great variety of sizes and mobility modes for species dedicated to rather specific ecological niches. Yet, for each natural agent, regardless of size, the employment of multiple degrees of motion freedom is the rule, and is evidence of its broad applicability over scale. The present discussion is also an example of this approach. We have attempted above to define a set of capabilities – those contributing to the mobility of man. We do this for the simple reason that we foresee a demand for robots working independently along side of us. Our broad ecological niche will be their niche. Our mobility challenges will be their challenges.

2. APPROACH

We did not choose to initially build a humanoid robot, primarily because we did not have the resources. However, we have not attempted to make the case herein that a robot must look like us in order to work alongside of us[8]. An effective robot collaborator might have six legs, each terminating in a dexterous gripper. For rapid transit, the six legged robot might assume any number of possible gaits, from tumbling like an active spoked wheel, to hexapod running like a cockroach, to bipedal running with four hands free to carry and manipulate objects. Such a robot has been proposed and early prototypes developed by Dinesh Pai[9], now at Rutgers University. Surely, though, more important than appearance will be utility, and important for utility will be mobility, dexterity, initiative, competence, and trustworthiness – pretty much what one would ask of any employee or compatriot.

Instead of attempting a humanoid robot, we focused on the requirements of the Army's Future Combat Systems soldier UGV and produced a tracked vehicle, weighing under 30 pounds, with multiple degrees of freedom to demonstrate any advantages those degrees of freedom might offer for mobility. We also wanted to assess the physical implementation and control issues that might arise with that increased complexity. We will focus the remainder of this paper on a

[8] In Japan, however, humanoid robots are designed to appear human like, and to exhibit human like behaviors. The rationale for this is that the civilian customers are more likely to accept robots working among them if the robots are familiar in appearance.

[9] D.K. Pai, R.K. Barman, S.K. Ralph, Platonic beasts: Spherically symmetric multilimbed robots. *Autonomous Robots*, 2(4) 191-201, 1995.

description of our vehicle, so far called the Novel Unmanned Ground Vehicle (NUGV), on its capabilities, and on some of its quirks.

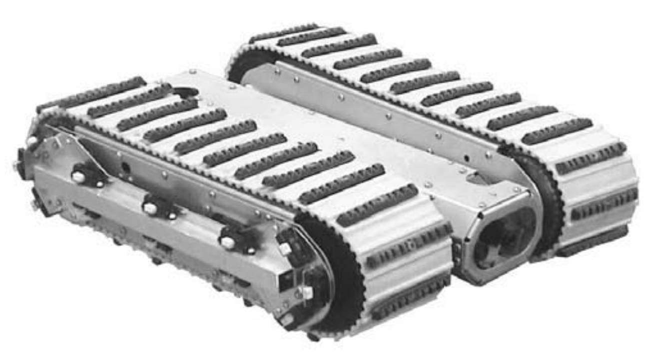

Figure 3

The NUGV, pictured in Figure 3, is a six degree of freedom small mobile platform that gains its mobility from the activation of its two tracked pods, each with two degrees of motion freedom in addition to the motion of the tracks. Each tracked pod is connected to one or the other end of a tubular central core by way of an "L" shaped axle. The core end of the axle provides for 180 degrees of pod camber, while the pod end of the axle provides for 360 degrees of pod tilt. The two tracked pods plus a single central core complete the morphology of the vehicle. The NUGV is symmetrical on all three axes so that it can operate with equal facility in either forward or reverse directions from either orientation of the vehicle with respect to gravity. Power, motors, sensors, computers, and radios are distributed fairly equally among the three sections of the NUGV. As a consequence, weight is also fairly equally distributed. The three sections communicate via low power Maxstream 9XCite[10] radios. This, along with independent power in the sections, permits us to eliminate physical wires or slip ring connections between the rotating sections. The NUGV, in compact form, is 17.6" long, 16.2" wide, and 4.6" tall. The pods, when rotated 180 degrees on the tilt axes, can extend the reach of the NUGV to 49 inches. When the pods, in that extended position, the maximum width of the vehicle at any point along its longitudinal axis is reduced to 9.5 inches. If we then co-rotate the pods 90 degrees on the camber axes, the two pods will lie in line and the minimum width of 8.5 inches is achieved. The width of the pod tracks is 4 inches, which provides a semi-stable stance on level surfaces in most configurations.

The vehicle is powered by eighteen 3.7 volt Li-ion batteries, six per section, which provide a decent power density to weight ratio. Normal duration of operation per charge is a little over one hour. Recharging time is about six hours. Normally the batteries are recharged in situ.

The motors are commercial Black&Decker power tool drive motors with integrated gear reductions. For the tilt and camber drives, this is further reduced by planetary gears to a final input/output ratio of 50/1, which provides sufficient torque for any tilt or camber motor to lift the entire vehicle.

On-board processing is performed by three Rabbit 2000 microprocessors[11], one in each section of the vehicle. We program in C, using the Rabbit development environment, and download the code to the flash memory of each processor for execution - a fairly easy process, but one which still involves much trial and error.

Control of the NUGV can be accomplished currently by either teleoperation or local (embedded) reactive algorithms. Planned work will permit cooperation of teleoperation and reactive behaviors, and local adaptive behaviors based on intrinsic value measures. Feedback for local control is made possible by a variety of sensors including rate gyroscopes, accelerometers, speed encoders, voltage and amperage meters, magnetometers, plate contact switches, and IR proximity sensors. (One can only have too many sensors when one has run out of A-D converters.) The vehicle also hosts four color video cameras and stereo microphones, though yet does not use either of these types of distance sensors for local control.

---

[10] http://www.maxstream.net/products/xcite/module/9xcite.php

[11] http://www.rabbitsemiconductor.com/

Teleoperation is difficult with six degrees of motion freedom. Operators (including the developers) suffer from inadequate situation awareness created only from the video camera returns, and inadequate response times. The most practical control strategy with vehicles of this type might be for the operator to specify a target location, and a target task to be performed, and then release the vehicle to manage its mobility tasking and target tasking on its own, and intervene by negation only when the execution seems to be going awry[12]. A complete set of on-board sensor based reactive behaviors, coordinated by adaptive processes coupled to remote events detected through on-board distance sensors will be required to achieve the necessary degree of independence of the vehicle from teleoperation. This is our objective.

3. RESULTS

Some of the various stable conformations of the NUGV are shown in the following figures[13]. These conformations are all expected according to the control laws that define the vehicle's reactive processes. The multiple degrees of freedom permit adjustments in the center of gravity to maintain balance, and establish appropriate contacts for leverage and traction.


Figure 4

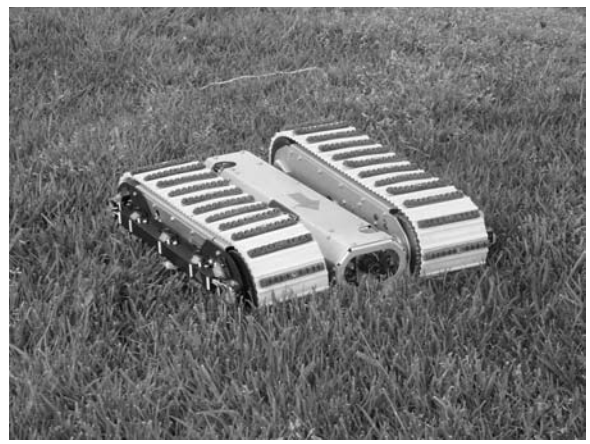
Figure 5

The low stature of the NUGV permits it to pass under many barriers as seen in Figure 4. The low stature, however, gives it a rodent's view of the world which is rather unfamiliar to human operators. Vision at an altitude of 2 inches does provide a good perspective on the cut of the grass (Figure 5) but is not too useful for path planning. The low vehicle stature also increases the likelihood of communication losses. These inconveniences place greater importance on viable local controls of mobility and navigation.

The NUGV assumes new conformations when traversing steep slopes or upon encountering obstacles, but reactively returns to the conformation of Figures 4 and 5 after a period of uninterrupted running on a level surface, where it is most stable and can move most quickly.

Climbing curbs and the first step of a staircase would be impossible for a vehicle with only 2-inch radius wheels and no other appendages, but the NUGV is able to thrust forward an entire tracked pod to grip the step rise, while pushing forward with the rear tracked pod. This maneuver, with its changing conformations, is seen in Figures 6, 7, and 8.

[12] A companion paper at this Conference describes the approach to a control architecture that would permit the vehicle to execute independently of the operator most of its mobility tasks. See M.R. Blackburn and R. Bailey, Foundations for learning and adaptation in a multi degree of freedom unmanned ground vehicle.

[13] The reader's indulgence is requested with these figures as they are all staged. The NUGV in reactive mode does not stay still long enough to photograph these maneuvers safely

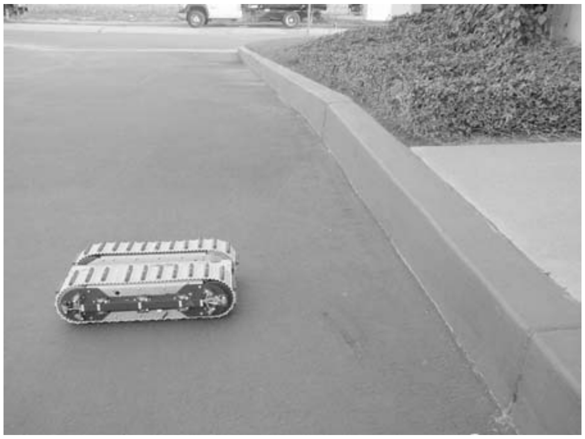
Figure 6

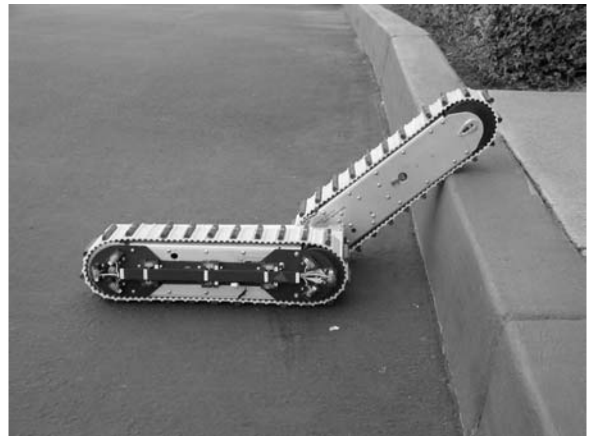
Figure 7

Each pod opens on the tilt axis relative to the center as one of its leading IR whisker sensors detects the step rise. Pod rotation ceases when the step edge is encountered by one of the side IR whiskers. Both pod tracks remain in continuous rotation through this maneuver. As the vehicle is pulled up and upon the step, the trailing pod's end IR whiskers can detect either the step rise or the ground plane, causing that pod to rotate outward from the center. The three rules embedded in the pods that govern the tilt motor and consequent pod rotation are:

- If there is activation of the end IR whiskers, rotate the pod away from gravity (detected by the pods' accelerometers).
- If there is activation of a side IR whisker sensor in the direction of rotation, suspend rotation.
- If the activations of the IR whisker sensors differ along one side, adjust the pod rotation to zero that difference.

Stair cases can be taken in one or two different modes. If the step depth is greater than the length of the vehicle, the NUGV can address each additional step as if it was the first step, folding up again into it compact running conformation until the lead IR whisker sensors again encounter the next step rise. However, if the forward pod encounters the rise or the step edge before the center pod is again horizontal on the step, the NUGV will remain in an extended position, as shown in Figure 9, covering two or more steps and glide up the staircase in the extended configuration.


Figure 8


Figure 9

The conformation is continuously subject to change as the NUGV at present has no concept of a staircase, but takes each step as an obstacle in its own right and then follows the three rules above to optimize its contact with that step surface. Such adaptations to step conditions are shown in Figures 10 and 11. The opening and closing of the pods tend to present the longitudinal surfaces of the pods to the obstacle where traction can be achieved. The direction of rotation depends upon the pods current orientation with respect to gravity and from which end of the pod the contact is initially made and sustained. Pod rotations cease when the pod end IR whiskers are brought out of range of the surface on which it was rolling. At this time however, the pod side IR whisker sensors that detect a step surface or step edge attempt to maximize track contact with the surface by triggering tilt motions in the appropriate directions to equalize the IR signals along the length of the pod side that is in contact with the step.

Figure 10

Figure 11

Narrow gaps down to a minimum width of nine inches can be passed through by the NUGV after assuming an inline position as shown in Figure 12.

Figure 12

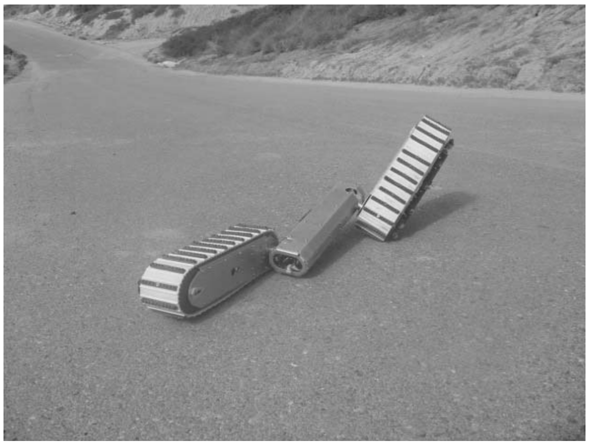

Figure 13

Turning while in line is rather difficult, however. So far we have had to return the vehicle to the extended position, from which the tilt of one or both pods can be used to reduce the lateral friction in the turn. Camber can also cooperate to change the angle of attack of the pods upon the ground, achieving some degree of diagonal thrust. This flexibility is demonstrated in Figure 13.

In Figure 14, the NUGV is seen riding atop a horizontally oriented telephone pole. The camber dof permit the vehicle to maintain good tread contact with the pole and in conjunction with the tilt axes, to adjust the attack of the tracks on the pole to maintain orientation and balance, similar to the method shown for executing turns in Figure 13. The method of mounting a telephone pole is a bit of a challenge for the human operator, particularly with the orientation of the pole pictured in Figure 15, but can be accomplished with the right combination of track thrust, camber, and tilt between the two pods. Once on the pole, the pods could be closed against the side of the center, but at considerable risk to balance, and this would not be done reactively on a pole with a slope greater than about 20 degrees.

Figure 14

Figure 15

For getting up out of the grass, the NUGV can assume the configuration of Figure 16. By continually rotating the pods in phase a type of walking behavior can be accomplished. In this behavior, balance is critical as the NUGV is unstable on two legs.

Figure 16

Figure 17

The balance errors are best handled with camber corrections, however, as the tilt angles of the two pods need to remain approximately 180 degrees out of phase. A stable static posture, due solely to adjustments of the pods' camber dof that shift the vehicle's center of gravity away from the direction of roll, is evident in Figure 16. The reader can test this method for himself by standing with one foot approximately 24 inches in front of the other and noticing the shifts of his center of gravity necessary to achieve balance.

Adjustments in the center of gravity can be accomplished cooperatively by the employment of both tilt and camber dof. Camber is more useful for correcting errors in roll when the pods are extended, but when the pods are parallel to the core, tilt also opposes rolls of the core. When the conditions are favorable, the NUGV reactively returns to its closed configuration of Figure 17.

4. LESSONS LEARNED

Increasing the degrees of mobility freedom increases the range of obstacles through which or over which the robot can traverse, but this approach is limited. Limits include compression and folding factors, material strength and leverage factors, and control factors. With our geared electric drives, each new dof adds unwelcome weight and bulk to the platform. Sony has demonstrated impressive results with its 27 plus degree of freedom QRIO entertainment robot, though it is designed only to operate in improved environments. The QRIO, an elaboration of the earlier SDR-4X, is a humanoid robot with the associated distinct asymmetries in morphology[14]. These asymmetries impose burdens on the mobility degrees of freedom that are not present in a vehicle such as the NUGV. While balance is critical for vehicle protection in both cases, a vehicle whose most stable position is its preferred running position does not have to devote resources to restoring that position should balance fail. Vehicle designs that permit safe tumbling, such as the University of Michigan's RHex[15], offer significant operational advantages.

It is difficult for a human operator to simultaneously and remotely control more than two degrees of freedom. Thus, robots that require more than two degrees of freedom for improved mobility and/or end-state task execution will require local control processes to perform the coordination of those multiple degrees of freedom. The human operator will turn out to be the weak link in the control process otherwise.

We were fortunate that our final vehicle weight was equally distributed. But this may only make sense when power and leverage are also equally distributed. Distributed weight should facilitate the management of the vehicle's center of gravity that is necessary for balance and leverage.

We have found it prudent to download as much of the control functions as feasible to the lowest levels of the processing stations. This reduces bandwidth requirements of the system bus, and shortens the control loops that are closed by local sensors, improving reliability and speed. It also distributes the processing load more equally among the available resources.

All of our controllers have needed two types of information: the first on system state, and the second on how the state is changing. The state input characterizes the relationship of the parts to one another and to the environment. The change input characterizes how our system's conformation is evolving. A state variable might be how much current is applied to a particular motor, while a related change variable would be the direction and velocity of the driven element. As always, the use of change information is a convenient way to ignore DC offsets in the sensors.

We are assigning the highest priorities of control to the lowest levels of control. The biological model for this design decision is the hot stove analogy. Local reactive behaviors should invariably protect the integrity of the agent, and should be over-ridden only after the consequences of doing so are well registered at the higher control levels. We have applied this design principle in the negative obstacle avoidance behavior of the NUGV, and in the feedback control of leverage. For negative obstacle avoidance, a pod will detect a ledge when its IR whiskers at 2, 4, 8 or 10 o'clock (depending upon orientation and travel direction) detect a sudden decrease in activity. This triggers a reversal of its track drive command from the center's controller unless the central controller inhibits that reversal after processing the pod's

---

[14] http://www.sony.net/SonyInfo/QRIO/top_nf.html
[15] http://www.rhex.net/

data indicative of the imminent ledge crossing. Descending stairs requires such an inhibition of the negative obstacle response. The center controller receives information from both tracked pods, and tests the depth of the chasm by opening the pods when both pods encounter a negative obstacle. If the opening pod encounters the next step, the NUGV progress down to the step, otherwise it climbs back up. For walking or in the process of certain obstacle negotiation, the center controller must inhibit the pod's tendency to stop its rotation when an object is encountered, and its attempt to maximize its contact with the object.

We initially made the mistake of saturating the lower controllers with control commands from higher. If the lowest levels have the highest priorities, they should have a significantly greater proportion of the output space in which to vote. At each level of the control, a summation of influences from the different sensors linked to reactive behaviors that determine the final output at that level, but when those commands are sent to a lower level, a new competition should occur with the higher level output contributing as a peer at best. In this way the higher levels of control may tune the lower, but negation of the actions of the lower controllers should occur only when critical objectives are perceivable only at the higher levels.

The limits of our present approach are due to the inability of the NUGV to sense beyond its immediate environment. In essence, it can feel but it cannot see. We expect, however, that the adaptive rules for "seeing" navigable places in the environment will be much facilitated by the first ability to sense physical contact.

5. FUTURE PLANS

There are several things that we intend to do to improve the NUGV as a research and development tool. And these improvements should be demonstrated before we attempt to market it as an applied tool. The limitations of this vehicle are common to others of its size. The on-board energy reserve is insufficient for long-term tasking. The ability to perceive the greater topology of the environment necessary for path planning is inadequate. Its protections from the elements - dirt, water, heat, and collisions are inadequate. And its power train is inefficient and noisy.

To employ vehicles of this size, perhaps we need to think more about how small animals achieve their objectives. That is, perhaps we should think more like a small animal.

- By running so close to the ground, a chemical sensor could make up for the NUGV's inability to "see" objects at a distance.

- The low profile of the vehicle stresses radio communications, so we may have to develop a deployable (and recoverable) antenna.

- The utility of GPS for such a low ground dweller is similarly suspect, and thus should not be the primary source of navigation information for vehicles of this type.

- We must also design the vehicle's control processes around its energy requirements. We need to develop and incorporate into the basic functions of the vehicle energy recovery, storage, and transduction methods.

- Improvements to the power supply could go two ways. First, we need direct access to the batteries so that they can be quickly replaced with newly recharged batteries. Second we need a method whereby the robot can recharge its batteries on its own. Solar regeneration might be possible if we could afford to permit the robot to bask in the Southern California sun during the day, and perform our tasking at night.

- The power train could be improved through the use of brushless motors and a continuously variable speed/torque transmission that would permit the most efficient use of the motors.

- Weight reduction is critical to improved performance and improved durability. We need to redesign for material strength, flexibility, and levity.

- We need to modify the track tread design to accommodate the full range of positions and forces that the pods will produce. We are considering a sinusoidal series of overlapping fan-shaped nodules running around the track in place of the present sequence of orthogonal bars. This new design should smooth the ride during rotations over the ends of the pods, and provide improved traction on step edges and when the vehicle is progressing across a slope.

- The NUGV needs a payload bay from which different payloads can be extended. The need for payload stowage stems from the desirability of maintaining the symmetry and invertability of the platform. Within this payload bay, the most useful new payload, besides an energy recovery device, might be a flexible manipulator arm. The arm should serve multiple purposes, including grasping, vehicle cleaning, and assisting in mobility.

- Video and audio must be digitized and made available to the on-board processors. The use of fish-eye lenses, mounted on the outboard sides of the pods, coupled to high density CCD video sensors could significantly improve situation awareness both for the vehicle and for an operator/observer. With this video data, image stabilization and manipulation could be performed electronically.

6. CONCLUDING COMMENTS

With the NUGV we are yet a long way from providing a robot than can keep up with and work alongside humans. We have shown that additional degrees of motion freedom have definite advantages for mobility, and mobility will be a key determinant for the utility of robots in the human arena. A second requirement will be dexterity. We expect that the implementation processes for these two requirements will be essentially the same. Dexterity should be achieved by the addition of motion degrees of freedom. When those degrees of freedom are not required for mobility, they may be employed for manipulation.

Should we move forward and build a robot that can stand on its own two feet. Perhaps, but we should only attempt to do so when reasonably assured that it would not injure itself by falling over. To be so assured, we might provide the robot with the capabilities to roll, sit, crawl, and climb, before we expect it to walk. Falling then would not be as much as a catastrophe as it would be a controlled regression to the ground. For the readers who have watched children develop from infancy, this should not be a novel idea. As always, the use of compliance in joints and in other structural materials would help to prevent damage.

With regard to the dimensions of a robot, small and light is desirable if the operator has to carry it around or insert it into tight places. Large is useful if the operator needs strength, durability, and payload in the robot, including energy reserves. Human size is useful if one wants to dance with the robot. If it could dance, however, it should be able to carry itself, and thus would not have to be small and light. But a human sized robot could take up a human sized amount of space in any common transporter, such as a helicopter or HMMWV. If the robot goes along, somebody else may have to be left behind, which could be good or bad, depending upon the nature of the mission.