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## MONTHLY REPORTING CHECKLIST

Submitted by: University of Michigan \_\_\_\_\_

Report Month: September 2002

TTP No.: ALO-7-C1-61 (UMichigan) \_\_\_\_\_

### **EARNED VALUE ANALYSIS DATA.** Check *one* box in Line A and *one* box in Line B.

A. How is your project's schedule doing compared to your TTP baseline?

1. As planned.

B. How is your project's total cost doing compared to your TTP baseline?

2. As planned

### **PTS NARRATIVE INPUT CHECKLIST.** Check that you have prepared the following narrative inputs:

1. **SIGNIFICANT ISSUES/PROBLEMS/CONCERNS:**  
Note if there are any problems; otherwise, state "None." Report only problems considered "showstoppers" or fatal flaws (i.e., a lack of funding will cause the project to be shut down).

2. **CORRECTIVE ACTION:**  
If a significant issue/problem/concern in Section 1 above is described, this section is required; otherwise state "None needed."

3. **SUMMARY ASSESSMENT:**  
This should be a BRIEF paragraph summarizing the overall status of the project. This section is a synopsis of the entire report.

During this past month, work has continued in robust navigation, sensing, and radiation imaging. The novel OmniPede vehicle is progressing well, with a new innovation utilizing treads. Work using the Sick laser range scanner for map-building resulted in searching for sources of artifacts from outdoor images. Work to upgrade an earlier generation gamma camera is proceeding rapidly with all 16 elements functional, and new efforts are exploring more efficient imaging techniques. Work in the area of optical sensing is completed with the defense of our doctoral student.

4. **COST VARIANCE:**  
**If you checked number 4 or 6 in the Earned Value Analysis section, you must provide an explanation here. Explain funding issues such as variances, carryover, commitments, incorrect FIS data. Avoid using only the words "Within budget." Some narrative is preferred.**

Within budget.

5. **SCHEDULE VARIANCE:**  
**If you checked number 3 or 5 in the Earned Value Analysis section, you must provide an explanation here. Note if the project is on schedule, ahead of schedule, or behind schedule. If behind, explain what is being done to bring the project back on schedule.**

On schedule.

6. **TECHNICAL STATUS:**  
This is likely to be the longest section of the narrative and describes the technical accomplishments during the reporting period. Provide enough detail to inform, yet avoid extensive details

that can confuse the reader.

## 6.1 Obstacle avoidance

### 6.1.1 Elevation Map-building with the Sick laser rangefinder (LRF)

This month we focused on a persistent problem with the Sick laser rangefinder. For some time now we observed in our outdoor experiments the creation of false readings that we call “artifacts.” These artifacts appear in almost all of our outdoor experiments but not in indoor ones. Common to these artifacts is that they always appear in the center of range finder-created terrain maps. In order to solve this puzzling problem we investigated several possible causes:

1. **Indoor versus outdoor:** We examined our large volume of indoor map building data, collected both on the Gorilla vehicle and on the linear motion table. We found no artifacts in the indoor data. This suggests that artifacts were caused by outdoor factors.
2. **Ambient lighting:** We carried out some map building experiments at nighttime and found that artifacts still occurred. This means sunshine (or ambient lighting) is not the cause of artifacts. We did note, though, that artifacts occurred only in certain outdoor areas, but not in others.
3. **Vehicle motion:** To test whether vehicle motion was causing the artifacts, we ran the map-building program while the Gorilla was stationary. In these experiments, the map-building program still assumed that the vehicle was moving forward at a constant speed, although it was, in fact, motionless. We found that there were substantial artifacts when the Gorilla stood motionless in some locations but not in others. We also ran this experiment in daytime and at nighttime. Since artifacts still existed in some areas of testing even though the vehicle was standing still, we concluded that vehicle motion is not the cause of artifacts.
4. **Electromagnetic interference:** We ran many experiments in different locations around our building. We didn’t find noticeable artifacts in the front of the building. However, we observed substantial artifacts in a few locations. From these experiments and from the geometric relationship between these “hot spots” we conclude that the observed artifacts most likely are the result of electromagnetic interference from underground power cables.

We are still trying to further solidify our conclusion by additional experiments, and will eventually send this information to Sick, the German manufacturer of our laser rangefinder.

## 6.2 Position Estimation

### 6.2.1 Odometry experiments

As explained in last month’s report, the off-the-shelf Pioneer AT has two motors on each side, but the two motors are linked by a timing belt. This linkage makes the two motors act exactly like one, but with twice the torque (and twice the weight) of a single motor for each side. Earlier we theorized that additional odometry information could be gained from uncoupling the two motors/wheels on each side so that each of the four motors would drive one of the four wheels. We had also equipped with encoders two of the motors that didn’t have encoders mounted on them in the off-the-shelf configuration, for a total of four encoders. Furthermore, we employed four individual control loops, one for each of the motors.

This month we performed extensive experiments to determine the odometric accuracy of each of the above described two configurations:

Configuration (A) – motors coupled (off-the-shelf configuration) and

Configuration (B) – motors uncoupled (i.e., 4 independent motors, encoders, and control loops). We performed the experiments on loose sand in our new 15'x15' indoor sandbox. Our findings were as follows: In configuration (B) we observed that on the somewhat uneven sand many times only three wheels of the suspensionless Pioneer would contact the ground. The fourth wheel was spinning freely in the air. As a result, the other wheel on the side of the free-spinning wheel would not have enough torque to move the robot and the robot would effectively get “stuck.” When the same situation occurred while running the cross-coupled controller (CCC – explained in earlier monthly reports) power to the stuck wheel would be gradually increased and the robot would eventually free itself from the “stuck” condition. Nonetheless, the resulting motion was not very smooth and odometry errors were introduced by the freely spinning wheel.

In configuration (A) the robot moved significantly more smoothly than in configuration (B). We accredit this to the fact that when one wheel is “in the air” twice the torque (i.e., from both motors on that side) is available to the remaining wheel, so in effect the robot doesn't get stuck to begin with if one wheel is “in the air.”

With regard to odometric accuracy we found that in configuration (A) a winding test path of 11 m length would average an error of 10 cm. In configuration (B) the average error was about 35 cm if we didn't apply any of our earlier developed expert rules for odometry. However, when we applied those rules (as explained in earlier monthly reports) we were successful in reducing odometry errors for the test path to an average of 10 cm, just like in configuration (A).

We conclude from these results that configuration (A) is the most desirable one because odometry errors are small and motion is smooth. For vehicles in which configuration (B) is inherently used, such as is the case in certain multi-degree-of-freedom vehicles, then similar accuracy as in configuration (A) can be obtained by using our expert rules, but motion may not be as smooth as in configuration (A).

### **6.2.2 Crossbow IMU testing – 3-D experiments**

After a lengthy search we found that the high noise levels of our Crossbow Inertial Measurement Unit (IMU) were due to an incorrect assembly by the manufacturer and we returned the unit for repair. The manufacturer adjusted the unit so it would then perform to specifications and we received the improved unit back.

We performed necessary changes in our control software to be able to use the three gyroscopes and three accelerometers built into the Crossbow IMU and we have now begun experimentation with the unit in a rugged terrain environment. We also adapted our FLEXnav sensor fusion software to work with all the components in the Crossbow IMU. These changes include the use of different scale factors and compensation functions as well as ensuring the correct interpretation of the data packets coming from the unit.

For next month we expect to be able to run key experiments comparing the Crossbow's built-in Kalman Filter-based sensor fusion approach with our novel FLEXnav sensor fusion approach.

### **6.3 Novel mobility concepts**

This month saw a significant increase in interesting activity in our work on novel mobility concepts, and specifically our work with the OmniPede. We recall that our original vision for the OmniPede was that of an elongated, articulated body with many feet/hands densely distributed all over the periphery and all performing a “shoveling motion.” We expected that this body would be propelled forward no matter where it contacted the ground because of the shoveling motion of the feet/hands, some of which would always be in contact with the ground.

We found that in practice our physical implementation of this concept provided much fewer feet/hands than what we had foreseen in our original vision. In an abstraction of this discrepancy we defined an artificial dimensionless unit that we tentatively call propulsion ratio,  $P_r$ .  $P_r$  is measured as the surface area of propulsion,  $A_p$ , divided by the inert surface area of the body,  $A_i$ .  $A_p$  is the combined area of all footprints in contact with the ground, and  $A_i$  is the surface area of the vehicle body that may be *potentially* in contact with the ground. On flat and hard terrain  $P_r$  is theoretically infinite, because, since the feet protrude out of the body everywhere, no inert area of the periphery could potentially be in contact with the ground, that is,  $A_i = 0$ . However, on soft terrain the feet sink into the ground and on rugged terrain obstacles protrude out of ground, resulting in potential contact between the ground and portions of the inert body periphery. In this case and for the OmniPede the propulsion ratio  $P_r$  is undesirably low.

Another problem with the OmniPede design is the fact that opposite feet on neighboring segments may be moving toward each other during portions of their trajectory. On flat, hard terrain this is not a problem. But when the feet sink into soft terrain such as gravel, then this opposing motion tends to “grip” (i.e., try to compress) the gravel between the opposing feet. Since gravel can’t be compressed, forces in the gears that drive the feet toward each other increase dramatically and may cause breakage.

A third problem is that converting rotary power, such as that from a motor, into walking motion is generally inefficient and produces only poor speed/power ratios.

After reviewing and analyzing these shortcomings we developed a break-through innovation that seems to promise a solution to all three of the above problems at once. This new solution, tentatively called “OmniTread” is discussed next.

### **6.3.1 New OmniTread design**

After reviewing in great detail the technical problems with our current working OmniPede prototype, we conceived of what appears to be a substantial improvement on our existing design. This new design replaces the feet by continuous tracks that move their cleats alongside the periphery of each segment in longitudinal direction. Each segment has a cuboid shape and thus a front, a back, and four sides. Two tracks run longitudinally along each side, for a total of eight tracks per segment.

We built a single-segment proof-of-concept prototype using rapid-prototyping Fischertechnik components. The prototype suggests that the new segment design is feasible and that it will indeed solve at once all three of the problems mentioned above for the OmniPede.

Like our OmniPede design, the torque for all eight tracks of a segment will be provided through a single drive shaft spine that runs through the center of all segments and is powered by a single motor. Also, we will retain the pneumatic actuation of the 2-DOF joints connecting the segments.

Implementation of the OmniTread design will require a new design for the tracked segments. This, and the fabrication of at least three segments will realistically take 8-12 months. Our new M.Sc. student Malik Hansen will focus his efforts on the OmniTread design.

In parallel we will continue to study improvements for the existing OmniPede design, at least until we can test the OmniTread design and confirm that it does indeed present a major improvement over the OmniPede’s legged motion design.

### **6.3.2 Current OmniPede design**

We are continuing to work with our current OmniPede in parallel with our design of the new OmniTread system. Specifically we analyzed mechanical failures that result when feet get locked (for example, when moving on gravel, as explained above).

Another fault we observed is that gears belonging to the 5-bar mechanism that generates the foot trajectory can skip when a leg is blocked. Furthermore we found that skips in the gear will change the

phase between gears and actually change the foot's trajectory. Repeated gear skipping can bring the 5-bar mechanism into a singular configuration that will stall the mechanism altogether. It is possible to eliminate this limitation from the 5-bar mechanism by re-machining the slider element of the 5-bar mechanism. It is also possible to avoid skipping of the gears by more accurately fitting those gears. We are still evaluating these possible fixes.

Yet another fix that is easy to implement is to provide the legs with some compliance so that if too much torque was applied to them they would bend instead of applying too much force on the gears. We made a simple prototype of such a compliant design. In this design the foot can pivot around its mounting point at the distal end of the leg when it hits an obstruction – an elastic silicone hose that covers the pivot point restores the foot to its normal position once the obstruction is cleared.

Another area of improvement is the redesign of the shape of the feet. Giving each foot a larger footprint (think “snowshoe” rather than “walking boot”) would significantly reduce the problem of feet sinking into gravel or sand and the problems associated with that.

### **6.3.3 Active pneumatic suspension vehicle**

Yet another research thrust that has been lingering at our lab – mostly at the brainstorming level – for almost a year now is that of an active pneumatic suspension for mobile robots. The rationale for this effort is the insight that on very rugged terrain extremely effective suspension systems are required to minimize loss of traction. While this is not a new insight, it is, nonetheless, more relevant for mobile robots than for conventional off-road vehicles, because mobile robots rely on traction for odometry.

In order to gather some more information on the problem and possible solutions we prepared a basic one-degree-of-freedom model containing a double acting pneumatic actuator, along with the associated valves and an electronic inclinometer. The inclinometer is mounted on an aluminum base, and the pneumatic actuator is mounted normal to the base. The inclinometer provides limited pose feedback corresponding to the base's inclination. We then devised a control system that aims to preserve the horizontal position of the base by controlling the pneumatic actuator. The preliminary experiments made with two digital valves per cylinder were promising. However, this approach requires continuous airflow and introduces additional vibration of the entire mechanism. Advantages of the current valve configuration are the simplicity of the control algorithm, the fast response time, and the reduction of static friction through vibration. Another approach under consideration is to adapt the pneumatic actuator control algorithms that we are currently using in the OmniPede for proportional control of the pneumatic joint actuators.

## **6.4 Infrastructure**

### **6.4.1 Computer-to-computer communication**

One persistent problem in mobile robots is that as systems grow in complexity, it is often necessary to work with more than one onboard computer. Obviously these computers need to communicate and do so at certain speeds, depending on the processes assigned to each computer. While there are many ways to accomplish communication between computers, there are also limitations when working with mobile robots.

For practical reasons it is desirable to work with laptop computers as the main mobile robot controller. This is because in a research environment the use of self-contained computers (i.e., with display, keyboard, hard drive, etc.) is preferable over embedded computers. Yet, laptop computers are limited in their expansion capability and many of the available ports are already used for interfacing with sensors and controllers.

Another problem is that our onboard computers run code under the Linux operating system. Linux drivers don't necessarily exist for all communication channels and those that do have to be converted so they will work under the so-called Real-Time (RT) Linux.

We conducted a detailed review of possible communication channels, including Ethernet, USB, serial, parallel, and PCMCIA-to-parallel. We are now in the process of defining the communication needs of different processes and we are trying to match those with the different communication channels.

## 6.5 Radiation sensing and imaging

During the past month, effort has been made in finalizing the analytical method used to quantify the detector performance. Namely, calculating the resolution-variance trade off based on different detector geometry. A comprehensive Monte Carlo simulation has been made to verify the result from this theoretical approach. The results from this study will be summarized in the paper for the coming IEEE NSS-MIC Conference in early November 2002.

The readout system for the 5" PSPMT would be ready soon. We are also exploring the possibility of getting a (or more if necessary) larger sized position sensitive detectors from the Department of Radiology, Division of Nuclear Medicine. The new USB/Ethernet based readout systems has been designed and tested in Ohio State University and will be ready soon.

We also had a few discussion sessions with Prof Jeff Fessler (a known expert in radiation imaging) in improving the theoretical performance estimation methods currently used. Several possible approaches will be studied in our future research.

### 7. MAJOR ACCOMPLISHMENTS:

Note MAJOR accomplishments during the reporting period; "None" is a valid, *occasional* entry.

We hosted a site visit by DOE's Dr. Gayle Dye and Mr. Roger Scott on September 4<sup>th</sup> with demos and presentations for the site visit.

We submitted two Abstracts to the SPIE's 17th Annual International Aerosense Symposium in Orlando, FL, in April 2003.

We hired and initiated a team of three undergraduate students that will help us conduct experiments. They will relieve our more experienced researchers from performing some of the very time-consuming and tedious experiments.

Our patent application for the "Apparatus for Obstacle Traversal" (i.e., the OmniPede) was approved by the U.S. Patent Office. We expect the patent to issue in December this year. We are evaluating the possibilities of extending this patent to our new OmniTread design.

Mr. Greg Sharp successfully defended his doctoral dissertation in vision for navigation.

**MILESTONES.** *Check that you have updated the status of your milestones.*

### 1. MILESTONE STATUS UPDATES:

Make sure you have provided a brief, one- or two-sentence comment on each active milestone and completion/new forecast date as appropriate.

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