MONTHLY REPORTING CHECKLIST

Submitted by: *University of Michigan* Report Month: May 2001
At request of U. S. Department of Energy/Albuquerque Office
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).

None

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

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 — the first prototype is being refined to increase walking speed and additional segments being designed. A robust platform based on a commercial ATV has been received, and parts identified and ordered for transforming it to drive under self control. The vision work for navigation is continuing, with work on understanding previously acquired data. Three papers were presented at the prestigious International Conference on Robotics and Automation, ICRA 2001, held in South Korea.

☐ **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.

On 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.

Obstacle avoidance

Indoor Obstacle Negotiation with Laser Range Finder

In April 2001 we kicked off a major new thrust within our area of expertise of obstacle avoidance. Since this work was not previously described in our monthly reports, we will describe in this section a brief description of this work as proposed in Michigan's FY'02 Renewal Proposal.

The new thrust is named "indoor obstacle negotiation." With "obstacle negotiation" we mean navigation on predominantly solid, man-made grounds that may be cluttered with debris. The challenge with obstacle negotiation is that some of the debris should be avoided, while other debris can be traversed by the robot's wheels. Indoor obstacle negotiation differs from conventional indoor obstacle avoidance in that the latter models the world as strictly two-dimensional, so that any sensed protrusion above ground level is considered an obstacle that needs to be avoided. Indoor obstacle negotiation is also different from outdoor/off-road obstacle negotiation in that the latter requires the detection of negative obstacles (i.e., ditches), and extremely rugged terrain (bushes, tall grass, water-filled holes, mountainous ground, etc.). Many researchers believe that the outdoor/off road obstacle negotiation problem can not be solved with current or near-term technology and that high-resolution aerial maps are required in addition to the vehicle's on-board sensors. It should be clear, however, that our proposed indoor obstacle negotiation will work outdoors as well, just as long as the outdoor terrain is not too rugged.

Part of our proposed work for indoor obstacle negotiation is the identification of a suitable primary sensor. Candidate sensors are 2-D LADAR (i.e., a laser that scans in one plane, such as the widely used unit made by Sick) 3-D LADAR (i.e., a laser that scans and "nods", thus producing a range image of an area); Flash LADAR (i.e., a laser that has no moving parts but produces a range image of an area); Stereo Vision; FLIR (infrared imaging); and millimeter wave radar. The most likely sensor candidate for our proposed indoor obstacle negotiation work is the LADAR made by Sick.

In the time frame addressed in our renewal proposal we will procure this sensor and perform extensive calibration and performance tests. It has been a successful research approach of our lab in the past to fully characterize a sensor before attempting to use its output in higher-level navigation schemes. We will apply this same approach to the new indoor obstacle negotiation sensor, and we expect to develop a comprehensive performance model for it that can be used in simulations and in sensor fusion applications.
Milestones for FY'02: Review of commercially available LADARs completed and selected LADAR procured. Selected LADAR calibrated and characterized (i.e., detailed performance tests completed).

To kick off this project efficiently, we have hired a new post-doctoral researcher, Dr. Cang Ye, who had previously done work related to outdoor obstacle avoidance at the University of Hong Kong. Since Dr. Ye arrived here in early April we have made significant progress in the in approaching this new project, as summarized below.

Literature Review on Obstacle Avoidance Algorithm

We conducted an extensive survey on existing obstacle avoidance methods, including

- global path planning (e.g., geometry-based algorithms, potential field methods, and heuristic or approximation approaches) and
- local path planning (e.g., potential field methods, certainty grid method, reactive systems using fuzzy control, neural networks, machine learning algorithms, as well as the University of Michigan-developed Virtual Force Field, Vector Field Histogram method and the Histogramic In-Motion Mapping (HIMM) approach).

We then adopted the HIMM method for map building in a 3-dimensional environment as the one envisaged for the indoor obstacle negotiation problem. We also adapted a global path planning method known as the "A*" algorithm, to generate local path segments for the on-board low-level motion planner.

Literature Review and Identification of primary sensor

Our literature review revealed that, as we had suspected, promising new sensor modalities like Flash LADAR, stereo vision, FLIR; and millimeter wave radar are either too immature or too expensive for our purposes. We therefore focused our attention on a very thorough survey of the leading commercially available laser range scanners, which include the products of Sick Inc, Acuity Research, and Riegle. Our survey was based on abundant information acquired from the robotics literature on map-building using laser scanners, technical descriptions, and technical specifications from the manufacturers. Among many other technical specifications we specifically scrutinized and compared the scanning angle, sampling rate, range, measurement accuracy, and reflectivity characteristics of the various offerings. We have now completed this review and selected a product from Sick Inc. as the most suitable and cost-effective sensor. The particular model, the LMS200, costs under $5K, including all peripherals.

We ordered and received this scanner and have successfully interfaced it with our control computer. The preliminary scans taken in an indoor environment (including transparent objects, such as windows and objects with low reflectivity, such as matted black surfaces) indicate that this laser range scanner will be suitable for our map building purposes.

Obstacle Avoidance Testbed

After completing the calibration of the separated Polaroid sonar receiver last month, we added a further degree of automation to our system. Rather than reading the receiver output "manually" from a standard oscilloscope (which is time consuming), we installed a computer-based programmable oscilloscope (the ADC200-50 from Pico Technology Limited) with a maximum sampling rate of 50 MHz in our system. We are now writing software that will allow us to obtain automatic readings from that oscilloscope in our testbed system.

We also ran additional experiments with the Dimension Master Plus (DMP) unit (which, as may be recalled from last month's report, claims to produce a very narrow ultrasonic propagation pattern). Using our separated Polaroid sonar receiver for this test, the DMP was swept through pan & tilt angles of ±20° to produce a 3-D representation of the propagation pattern. Our test results indicate the existence of a primary lobe surrounded by six secondary lobes, equally spaced around the primary lobe. The primary lobe was approximately 10° wide. The Dimension Master uses a Polaroid 7000 Series transducer, which has a 40° propagation angle according to the manufacturer. It therefore seems that the 2-D sonar phase-array configuration used by the DMP is indeed effective at reducing the width of the primary lobe. However, we still intend to investigate the effects of the secondary lobes. This will be done once the new PC-based oscilloscope is fully integrated in our testbed.

We have also begun developing a numerical model for different sonar configurations based on acoustic theory. With this model we have constructed a 1-D sonar array model using two sonars with characteristics matching those of the DMP. The results agreed closely with the empirical test results with regards to the location and width of the primary and secondary lobes.

Binaural (coded) sonar techniques

We are currently adapting and debugging the software for the five new sonar systems that fully support the firing and triggering needs of our coded sonar technique. Work on this project was limited last month because of time spent on preparing for our ICRA 2001 presentation and the actual travel to that important conference.

Position Estimation

Low-cost positioning system

In continuation of our work during the past few months we have now completed the development of our low-cost position estimation system. The system consists of

1. one high-quality KVH fiber-optics gyroscope ($2K) that measures the rate of rotation around the on the Z-axes,
2. two low-cost Coriolis gyroscopes ($75 each) to sense rotation around the X- and Y-axis, and
3. two accelerometers used to measure tilt

We mounted items 2. and 3. inside a sealed metal box that reduces errors caused by radio frequency interference that affect the Coriolis gyroscopes. We also mounted this system on our Pioneer AT robot and performed some initial experiments. We will conduct more experiment during June. A fully functional 6-DOF positioning system based on these sensors will cost on the order of $2.5K.

Fuzzy logic multi-sensor data fusion

We are now continuing work under our major thrust toward the development of a new approach to multi-sensor data fusion using fuzzy logic and expert rules. The key idea in our approach is to fully exploit know physical characteristics of each sensor and its interaction with the environment. This knowledge is then incorporated into the algorithm by means of fuzzy rules.

While conventional approaches to sensor fusion are typically based on Kalman filters, we believe that Kalman filtering alone is not the optimal way for fusing data from different sensors. This is because Kalman filtering is a statistical method, which does not model all discrete physical events (such as a robot driving over a big bump). Our approach aims at specifically identifying discrete events as they occur and compensate for resulting sensor errors through judicious use of data from redundant sensor modalities. However, our method does not rule out the use of Kalman or other noise filtering techniques for the purpose of reducing errors due to Gaussian or other modelable noise.
We consider the development of an innovative multi-sensor positioning system using fuzzy logic and expert rules as our primary, long-term objective. We will continue extensive experimentation with both the low-cost positioning system described above and a low-to-medium-cost positioning system described below over the course of the months and years to come.

Search and selection of hardware components for the Gorilla positioning system

We have conducted and completed an extensive search on higher-quality Inertial Navigation Systems (INSs), Inertial Measurement Units (IMUs) and gyroscopes, for use onboard the new Gorilla mobile robot. We recall that the Gorilla, which is being designed to function on rugged indoor or outdoor terrain, will require a navigation system with six degrees of freedom (DOF).

We have found that most commercially available 3-DOF or 6-DOF systems are IMUs that require that the end-user take on the responsibility for sensor integration. Only a few of these IMUs incorporate three *high-quality* gyroscopes that are comparable to the KVH gyroscope that we have been using for several years, but these units cost on the order of $15K-$20K.

Bearing in mind that we have had good results working with the KVH-made fiber optics gyroscope, of which we have used several over the past few years, we decided to design our own low-to-medium-cost positioning system using one high-quality KVH gyro (~$2K) for the Z-axes and two medium-to-high-quality KVH gyros (~$1K each) for the X- and Y-axis. We have now ordered these three fiber optics gyroscopes. A fully functional 6-DOF positioning system based on these three gyros and other sensors will cost on the order of $5K.

Novel mobility concepts

OmniPede

After completing the construction of the first three segments of the OmniPede, we have now been focusing controlling the OmniPede's walking. For initial testing we machined linkages that rigidly connect the segments so that they would not rotate in relationship to each other. These linkages are necessary until actuators are installed to control the 2 DOF of each segment. We also machined a motor mount for a 24-volt motor that we are currently using to drive the mechanism. One of the first observations of the gait of the OmniPede was that it was very slow. To increase the walking speed of the OmniPede we employed two different methods. First we changed the worm gears so that there is a speed reduction from the motor to the legs of only 10:1 as opposed to the original 20:1 reduction. Secondly we ordered a more powerful motor capable of driving a total of six segments at twice the rpm. For the current stage of experimentation we will extend the OmniPede to a total of six segments.

We also corrected a problem with the OmniPede walking on smooth, man-made floors. This was done by attaching a non-slip material to the feet. With these additions the OmniPede walks very well on a variety of surfaces and also on inclines. The power consumed by the current 3-segment prototype of the OmniPede walking on a flat surface is around 3 watts.

Now that we have shown that this shoveling action of the legs can be used for walking we have moved on to controlling the positioning of the segments. This will allow us to "steer" the OmniPede and, more importantly, to traverse obstacles that a wheeled robot of comparable size would be unable to traverse. We revisited the question of how to actuate the joints between the segments. Specifically we looked at shape memory alloys, servomotors, and pneumatic and hydraulic linear actuators. We reconfirmed our previous choice of pneumatic cylinders because these allow us to control the stiffness of the body while also delivering high power in a compact package. We are now working on the design of the actuator mounts.

Infrastructure

Gorilla Mobile Platform

During last month we ordered most of the required components for the Gorilla. We also completed the design of several key mechanical and electrical sub systems, and have begun building some of them. Specifically

- We designed a mounting solution for the steering motor that allows the motor to be engaged with the steering mechanism when the vehicle is under computer control, and disengaged when a human driver steers the vehicle.
- We designed a mounting piece for the rear wheel encoders. It uses a timing belt that runs from the rotary part of the brake drum to a small pulley that is mounted on the shaft of the encoder. The brake drum had to be machined in order to hold the belt.
- We selected and ordered many electronic devices required for the Gorilla. Since the power supply available is 24Vdc, we selected a DC-DC converter that supplies 5 and 12 volts DC, and a DC/AC inverter that generates 120Vac. The computers will use the AC, while the encoders, gyroscopes, and other sensors will use the DC voltages. The laser measurement system, braking solenoid, and the drive and steering motor and controllers will use 24Vdc directly from the batteries.

Vision for Navigation and Mapping

We have run an experiment of multiview registration over nine partially overlapping views in the ATL basement data set. The views contain over 1 million data readings within a total volume of about 10x10x5 meters. Since few of the view pairs contain more than 50% overlap in viewing surface, we implemented a randomized maximum support algorithm for pairwise registration. This allowed us to successfully register view pairs that contain as few as 9% overlap between views.

The results of multiview registration are good but some errors are still visible. The maximum detectable error in registration is around 6 cm which is about 1% of the viewing volume, but is still 6 times greater than the sensor noise. We believe that since the errors are largely confined to one or two views, it may be possible to detect the poorly aligned views for additional processing.

A report containing the details of this work has been prepared and submitted to the IEEE conference on computer vision and pattern recognition (CVPR).

☐ 7. MAJOR ACCOMPLISHMENTS:

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

Our papers:

1. Shoval, S. and Borenstein, J., 2001, “Using Coded Signals to Benefit from Ultrasonic Sensor Crosstalk in Mobile Robot Obstacle Avoidance.”
2. Chung, H., Ojeda, L., and Borenstein, J., 2001, “Sensor fusion for Mobile Robot Dead-reckoning with a Precision-calibrated Fiber Optic Gyroscope.

were presented at the *2001 IEEE International Conference on Robotics and Automation*, Seoul, Korea, May 21-26, 2001, and are included in the proceedings.

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.