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Automated Vehicle for Enhanced Work Crew Safety

Edward N. MacLeod, Principal Investigator
Marianne Chiarella, Program Manager
MacLeod Technologies, Inc.

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Program Manager: *Don M. Harriott*
Project Manager: *Shashikant C. Shah*
Production Editor: *Marsha Barrett*
Program Area Secretary: *Carina Hreib*

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Strategic Highway Research Program
National Academy of Sciences
2101 Constitution Avenue N.W.
Washington, DC 20418

(202) 334-3774

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EXECUTIVE SUMMARY

The automated vehicle conversion system presented in this report provides a low-cost method of reducing worker exposure to hazardous conditions. Automation of a traffic control vehicle not only eliminates the risk to the life of the driver but also eliminates the labor expense of a driver. Safety is additionally enhanced to work crews and motorists by allowing the system to be used in situations where the added expense of a driver is not practical. This is particularly true for local highway departments with limited budgets. Future benefits include automated collision-prevention and completely autonomous intelligent vehicle tracking, navigation and control for IVHS.

In this Phase I, MTI has demonstrated the automated follow vehicle capability on both reduced-scale and full-scale vehicles. The resulting automated system is easily adaptable to existing highway maintenance vehicles. The approach taken in Phase I has significant potential for successful commercialization in Phase II and beyond.

1.0 INTRODUCTION

During routine roadway maintenance it is desirable to have a traffic control vehicle follow a work crew or maintenance vehicle. Typically this vehicle would display a flashing arrow or sign to warn oncoming motorists of the work being performed ahead. The driver of this vehicle is in a particularly hazardous position from oncoming traffic, especially at night, in restricted visibility situations, in tunnels or on bridges. MTI has demonstrated automation of a vehicle with the goal of replacing the driver of the traffic control vehicle.

A typical automated follow vehicle application is illustrated in Figure 1. A worker in the tow vehicle is laying down cones to block off a work area. The automated vehicle is following behind maintaining fixed distance and relative angle to the tow vehicle. The lead vehicle is termed the tow vehicle because it invisibly tows the follow vehicle. The navigation components depicted in Figure 1, the scanning laser and laser beam detectors, are part of MTI's proprietary vehicle guidance system called CONAC. CONAC (for Computerized Opto-electronic Navigation and Control) is described in detail in Sections 1.1 - 1.5.

The automated vehicle conversion system includes computerized tracking/navigation control, add-on vehicle steering and pedal control modules, obstacle detection and safety systems. Converted vehicles may be quickly switched between conventional manual driving, manual radio control or automated follow under computer control. The system incorporates rapid feedback from fixed sensors positioned on the front fender of the follow vehicle. Precise follow vehicle distance and angle offset relative to the tow vehicle are determined many times per second.

The navigation and control computer is the size of a briefcase and resides in the automated follow vehicle. It receives navigation data and outputs control commands to the automated follow car servo control motors many times per second. The add-on steering and pedal control motors replace the human driver in the automated vehicle. Steering and pedal servo motors are adaptable to any vehicle. A typical automatic transmission vehicle may be converted into a fully automated vehicle in less than one hour. Once a vehicle is converted, this vehicle may be switched from automatic control to driver control or back in less than one minute.

Safety systems include ignition cut-off circuitry, a brake actuator safety device, secure radio transmission for the remote operator link and obstacle detection.

The photograph provided in Figure 2 was taken during final Phase I qualification testing at Hanscom Airport in Bedford, MA. This scene depicts the full-scale automated follow vehicle in operation. The follow vehicle is a Dodge Caravan. The tow vehicle is a Chelmsford, MA, DPW truck.

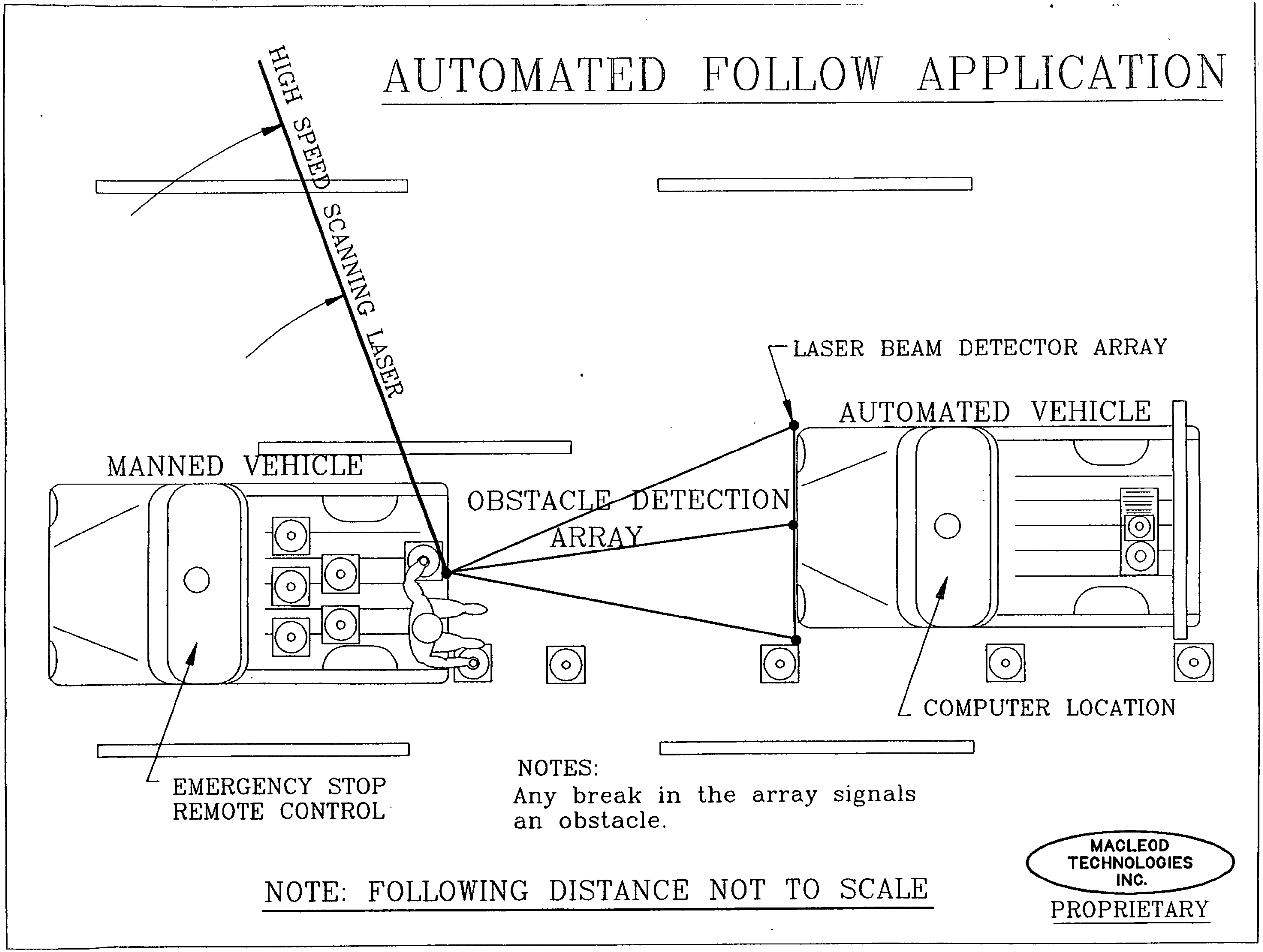
AUTOMATED FOLLOW APPLICATION
HIGH SPEED SCANNING LASER
LASER BEAM DETECTOR ARRAY
AUTOMATED VEHICLE
MANNED VEHICLE
OBSTACLE DETECTION ARRAY
COMPUTER LOCATION
EMERGENCY STOP
REMOTE CONTROL
NOTES:
Any break in the array signals an obstacle.
NOTE: FOLLOWING DISTANCE NOT TO SCALE
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FIGURE 1.

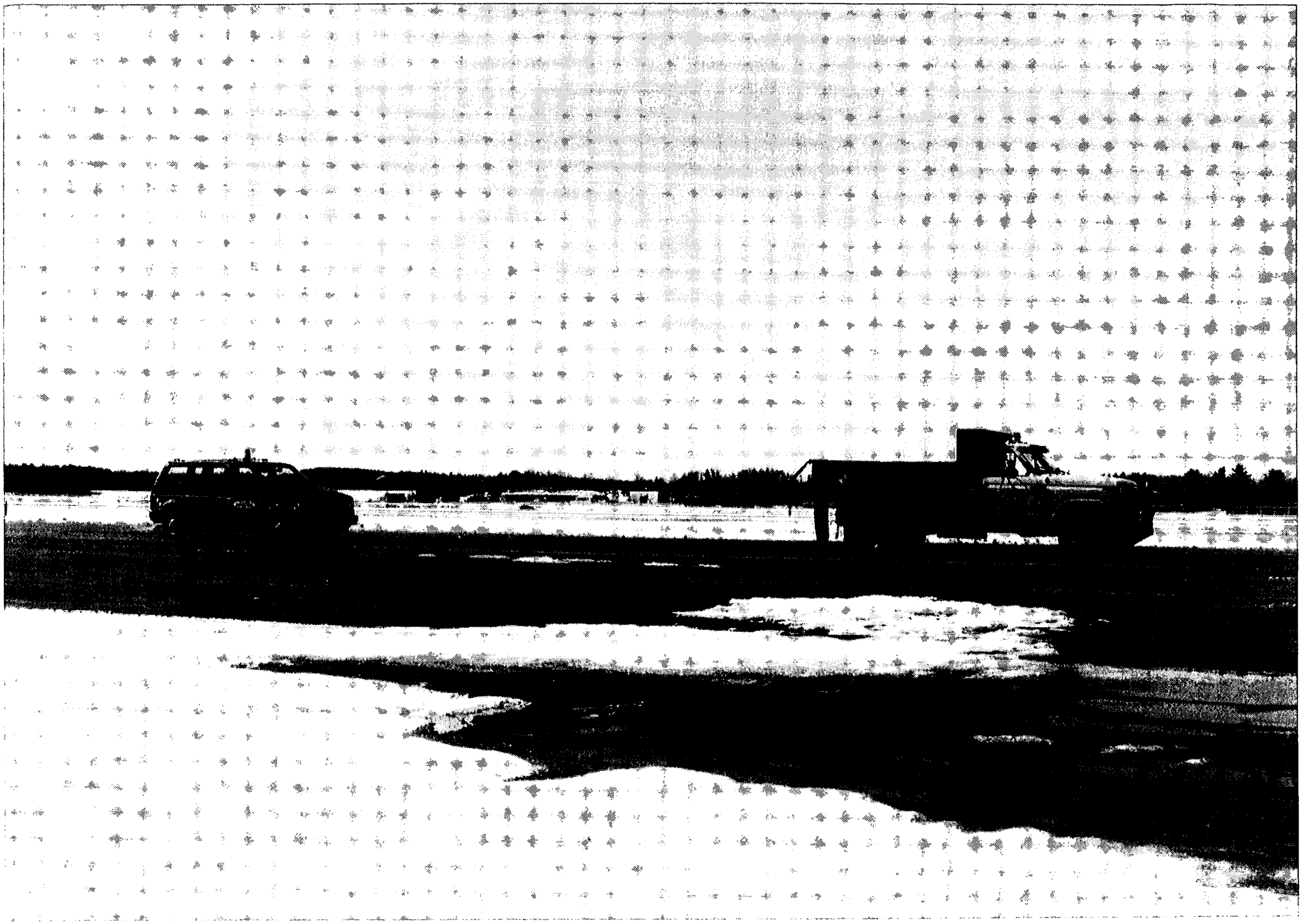


FIGURE 2. AUTOMATED FOLLOW VEHICLE IN OPERATION

1.1 CONAC - AN OVERVIEW

CONAC is an acronym for Computerized Opto-electronic Navigation and Control.

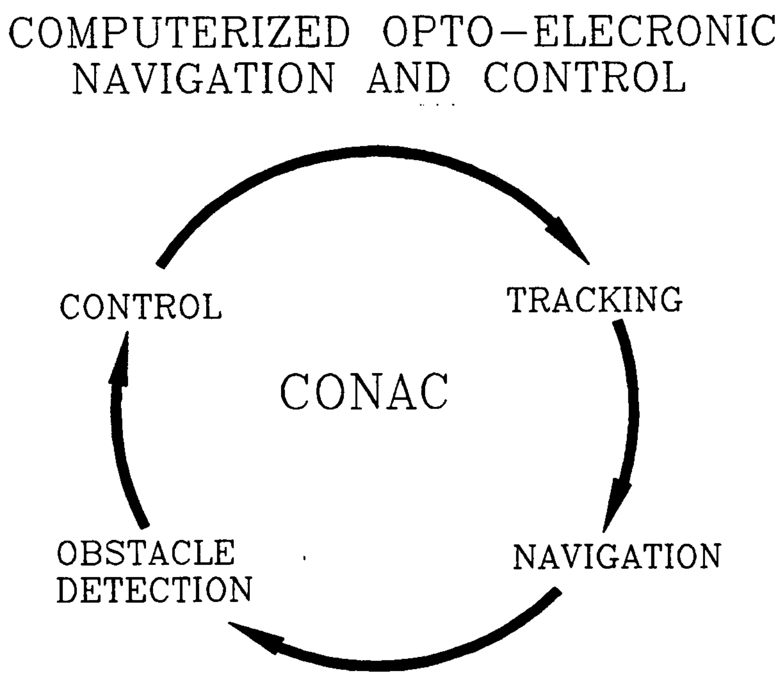


FIGURE 3.

As depicted above, this new computer-based, highly intelligent mobile robot technology effectively merges obstacle detection, precision high-speed tracking, intelligent navigation, and computer control.

MTI is the first company to demonstrate this closed loop capability with sufficient speed and accuracy to meet the needs of automating conventional commercial vehicles.

CONAC is the only technology specifically designed for mobile robot tracking, navigation and control. Like Loran and GPS, CONAC uses fixed reference beacons to establish a conventional coordinate system. In this application CONAC navigation devices have been termed Mobile Opto-electronic Beacons (MOBs) and Opto-electronic Position Sensors (OPS). These two devices are the key components in the CONAC system. The chief advantages of this system, over other systems, is accuracy and speed in a conventional two-dimensional Cartesian coordinate system. CONAC reduces mobile robot tracking data to its absolute essence. A series of only four electronic pulses are able to communicate distance and relative angle to the control computer with extraordinary speed and precision.

1.2 MOBILE OPTO-ELECTRONIC BEACON (MOB)

As shown in Figure 4, the MOB emits a structured laser beam creating a fan shaped projection. Also housed in the MOB is an electronically speed controlled motor. This precision motor spins the fan shaped of laser light around a vertical axis at any selected rate between 1,000-10,000 RPM, scanning the environment many times per second. A 3000 RPM beacon was used in this application.

1.3 OPTO-ELECTRONIC POSITION SENSORS (OPS)

As shown in Figure 5, an opto-electronic sensor is able to precisely sense the passing of the scanning laser beam projected by an MOB. The sensor produces an electrical pulse that is measured to one microsecond with precision digital clocks. Because the OPS electronics are extraordinarily sensitive, minimal laser power is required. Built-in signal amplifiers and filters produce an absolute, sharp digital pulse as the scanning laser passes. Experiments at MTI show response delays of our proprietary sensor is in the nanosecond range. There is no need for the computer to interpret ambiguous signals as in other electronic navigation approaches.

1.4 ANGLE DETERMINATION USING TIME

The Time-to-Angle conversion illustrated in Figure 6 provides the precise relative angle between the MOB and the selected OPS. The reference pulse represents the pulse generated by the first OPS in a series of three. In Figure 6, the time between the Reference Pulse and the OPS Pulse is T1.

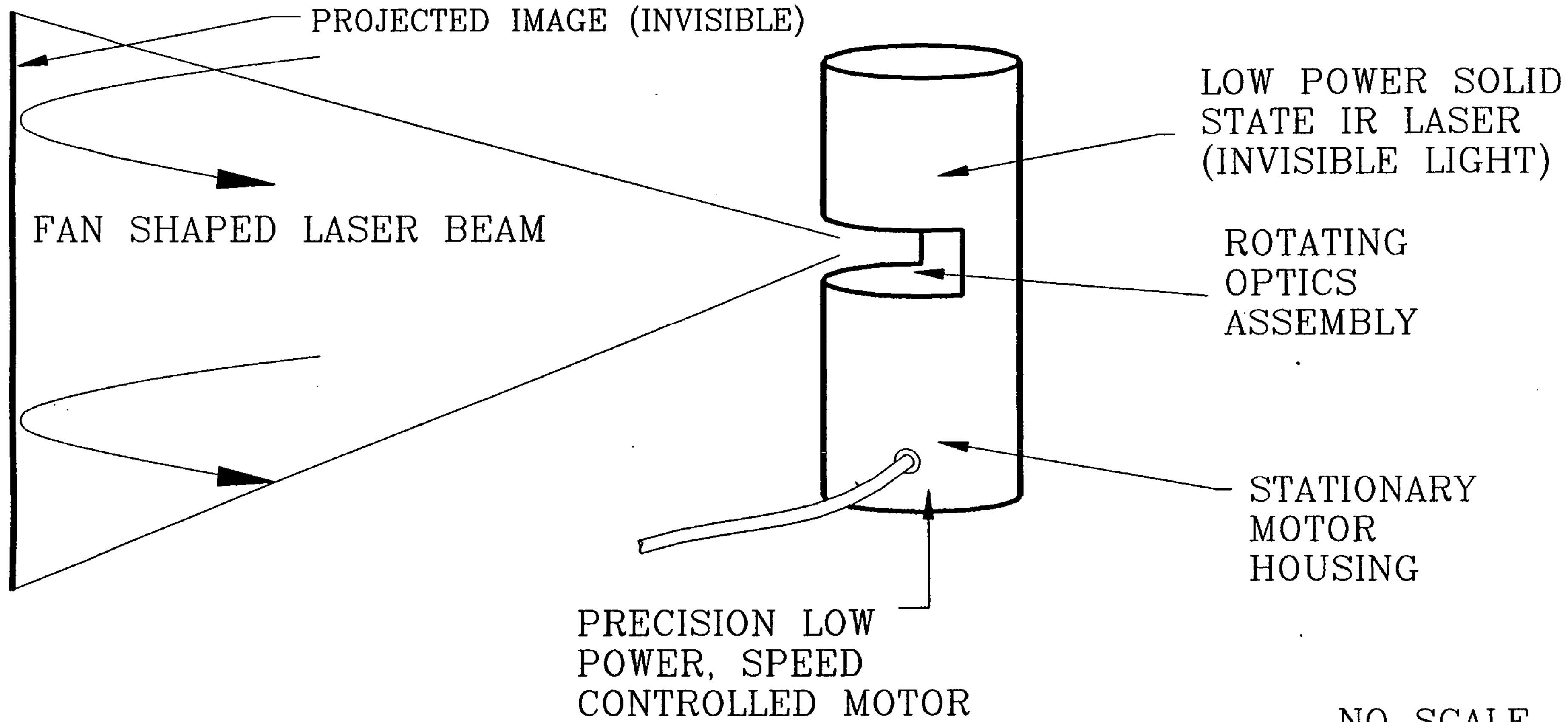
The time for one complete revolution of the MOB is called ROTIME. The relative angle is then simply a ratio of times. The angle from the reference pulse to the OPS is defined by the following equation:

$$\text{ANGLE} = 360 \text{ (degrees)} \times \text{T1/ROTIME}.$$

This angle represents the relative angle or bearing to the OPS from the MOB.

Using computer-compatible electronic clocks, it is possible to measure with great precision the relative time lapse between the Reference Pulse and the OPS Pulse. The Reference Pulse triggers the start of electronic timers on the CONAC computer. Each subsequent OPS pulse stops its dedicated electronic timer. Note that the first OPS triggered is also the last OPS triggered. Each timer is accurate to better than one millionth of a second.

MOBILE OPTO-ELECTRONIC BEACON (MOB) BASICS



NO SCALE

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FIGURE 4.

OPTO-ELECTRONIC POSITION SENSOR (OPS) BASIC FUNCTION

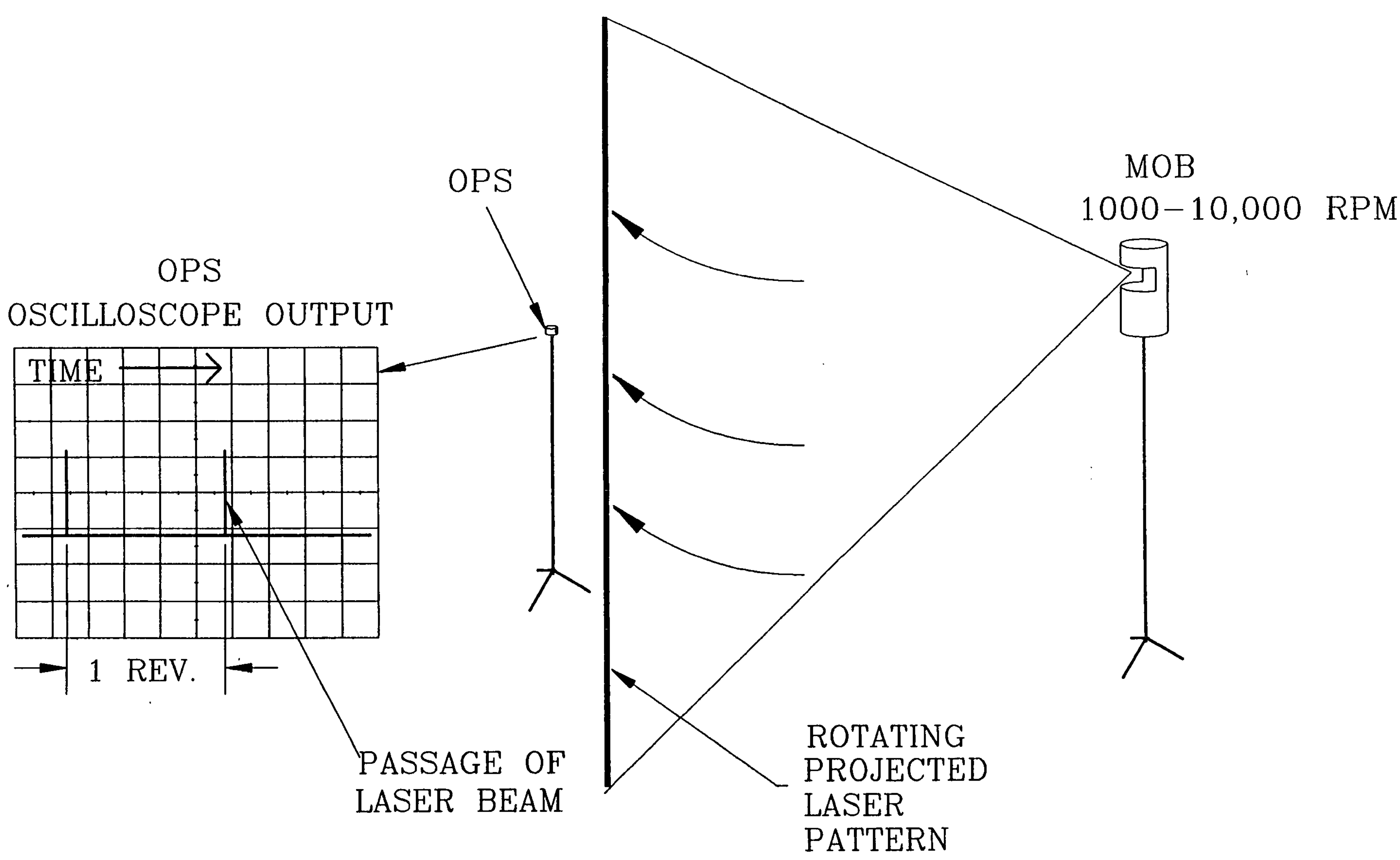

FIGURE 5.

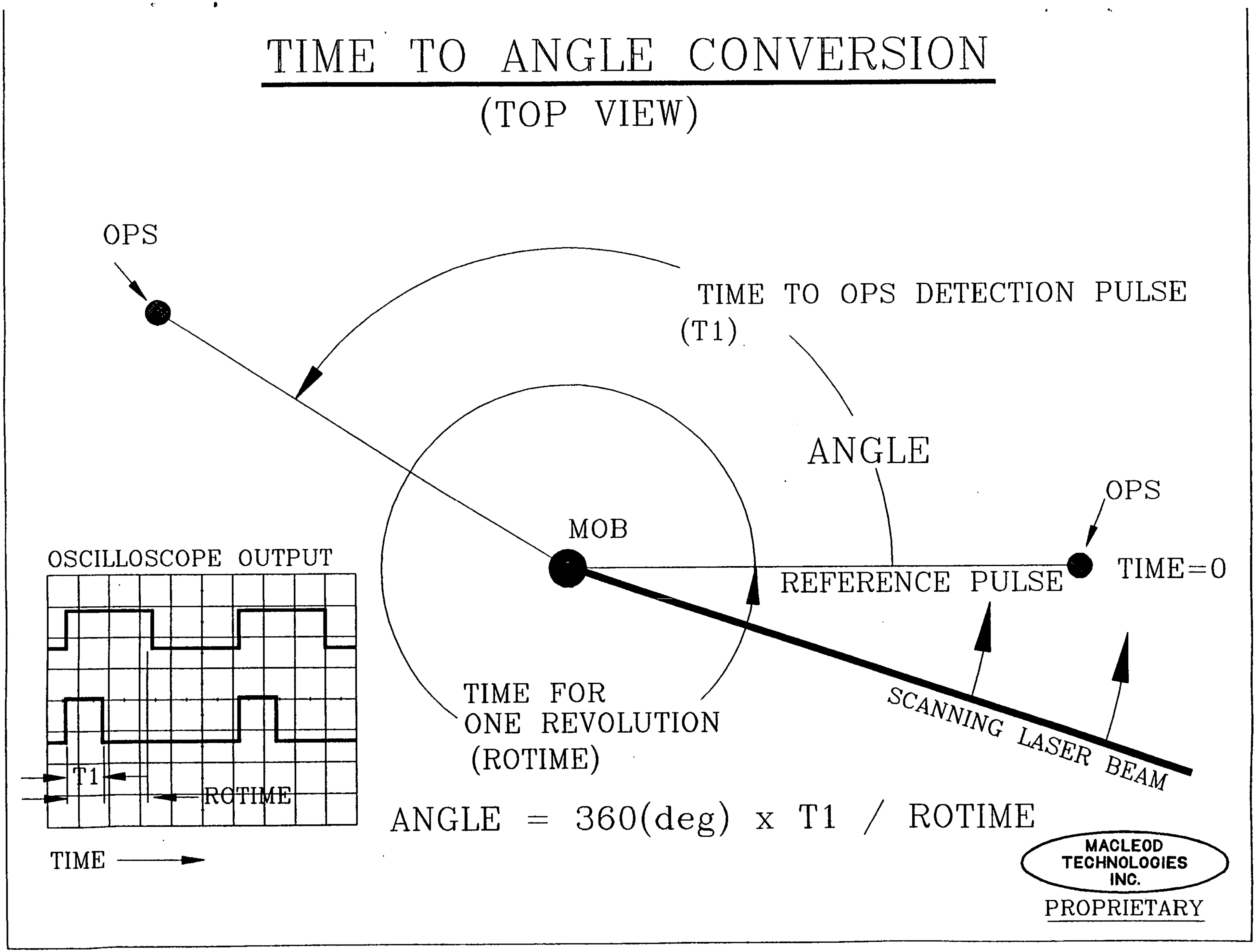
TIME TO ANGLE CONVERSION
(TOP VIEW)
OPS
TIME TO OPS DETECTION PULSE
(T1)
ANGLE
OPS
MOB
TIME=0
REFERENCE PULSE
OSCILLOSCOPE OUTPUT
T1
ROTIME
TIME
TIME FOR
ONE REVOLUTION
(ROTIME)
SCANNING LASER BEAM
ANGLE = 360(deg) x T1 / ROTIME
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FIGURE 6.

1.5 DISTANCE AND RELATIVE BEARING DETERMINATION USING ANGLES

The CONAC computer analyzes the timing signals produced by the OPS to determine mobile robot distance and relative bearing to the MOB.

Two angles are required to calculate the distance and relative bearing measurements. These angles are referred to as Angles A, B in Figure 7. Given the precise spacing of the OPS and the two measured angles, precise distance and relative bearing to the MOB are calculated by the CONAC computer.

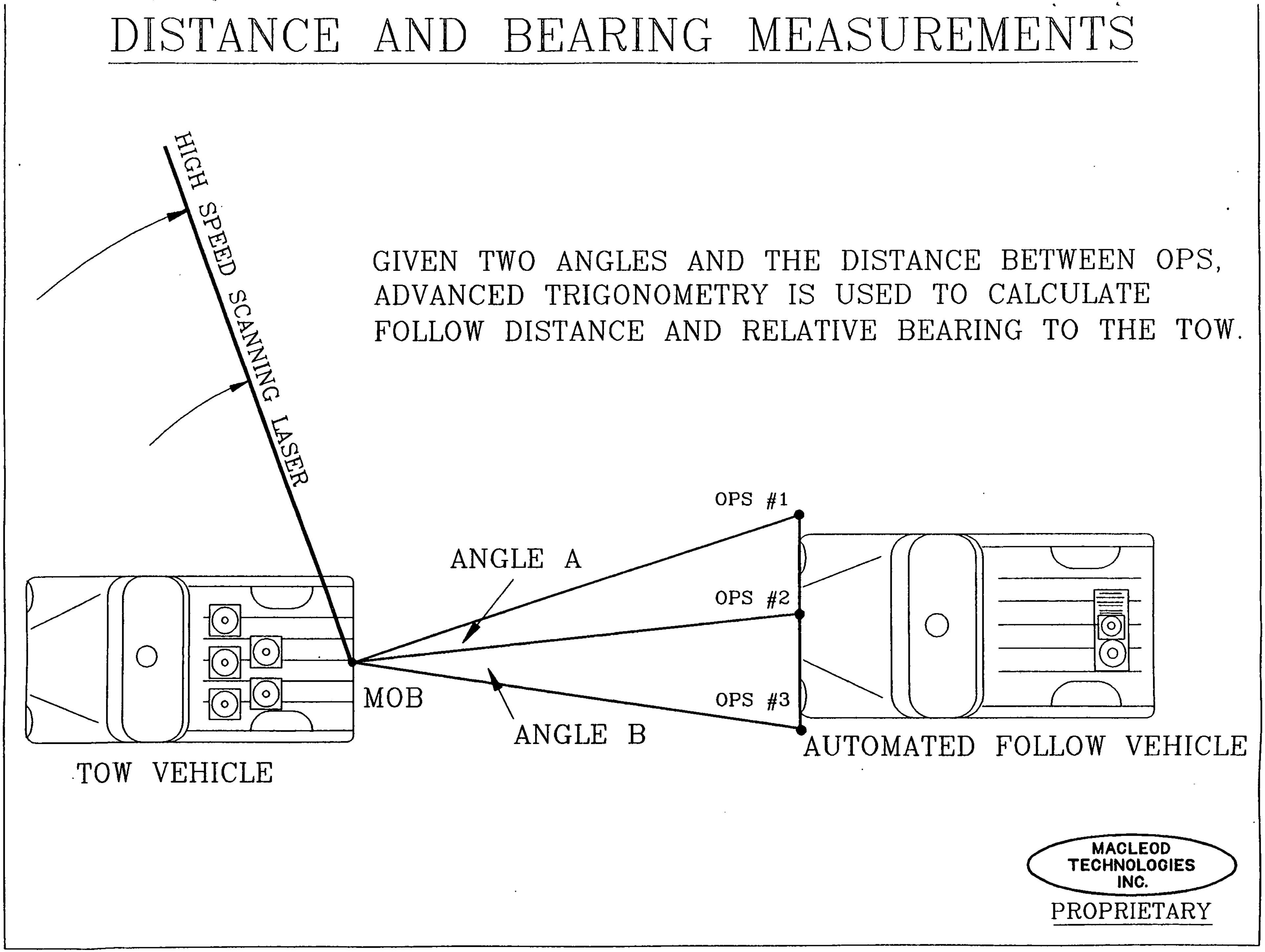
DISTANCE AND BEARING MEASUREMENTS
GIVEN TWO ANGLES AND THE DISTANCE BETWEEN OPS, ADVANCED TRIGONOMETRY IS USED TO CALCULATE FOLLOW DISTANCE AND RELATIVE BEARING TO THE TOW.
HIGH SPEED SCANNING LASER
OPS #1
OPS #2
OPS #3
ANGLE A
ANGLE B
MOB
TOW VEHICLE
AUTOMATED FOLLOW VEHICLE
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FIGURE 7.

2.0 PHASE I TECHNICAL OBJECTIVES

This section outlines the key technical objectives of Phase I. The objectives listed in this section are reprinted from MTI's proposal "Automated Vehicle For Enhanced Work Crew Safety", dated November 14, 1991. In Phase I, MacLeod Technologies, Inc. developed hardware and software to demonstrate these objectives.

* Follow vehicle will automatically match tow vehicle speed up to 5 MPH.

* Angular accuracy will be such that the follow vehicle will track behind the tow vehicle within +/- 1' (+/-30.48 cm) perpendicular to the tow vehicles path.

* Distance accuracy between the tow vehicle and the follow vehicle will be maintained within +/- 5 percent of follow distance.

* The relative angle between the controlling vehicle and the automated vehicle will be +/- 45 degrees from center and adjustable.

* Convert a typical automatic transmission vehicle into a fully automated vehicle in less than 2 hours.

* Once a vehicle is converted, this vehicle may be switched from automatic control to driver control or back in less than 2 minutes.

* In automatic follow mode, the follow distance will be manually adjustable from 8' (2.44 m) to greater than 120' (36.57 m) bumper to bumper distance. Changes may be made from the tow vehicle cab.

* System will be operable in rain, snow, night, day and fog. Phase I demonstration of this will be weather permitting.

* System will have manual remote override for human control of three point turns, tight "U" turns and parking maneuvers.

* The automated vehicle will stop and sound its horn if a pedestrian or animal wanders between the vehicles. (Activation of the horn was not used.)

* Only wireless operation between the tow vehicle and the follow vehicle will exist.

* The automated vehicle will activate a highly visible rooftop beacon or strobe during periods of automated motion.

* The automated vehicle will stop quickly and in a controlled manner in the event the tow vehicle stops suddenly.

2.1 SCHEDULE

All program tasks were designed to meet the technical objectives stated in Section 2.0. Figure 8 provides the completed milestone chart for Phase I. All tasks were completed on or near their scheduled dates.

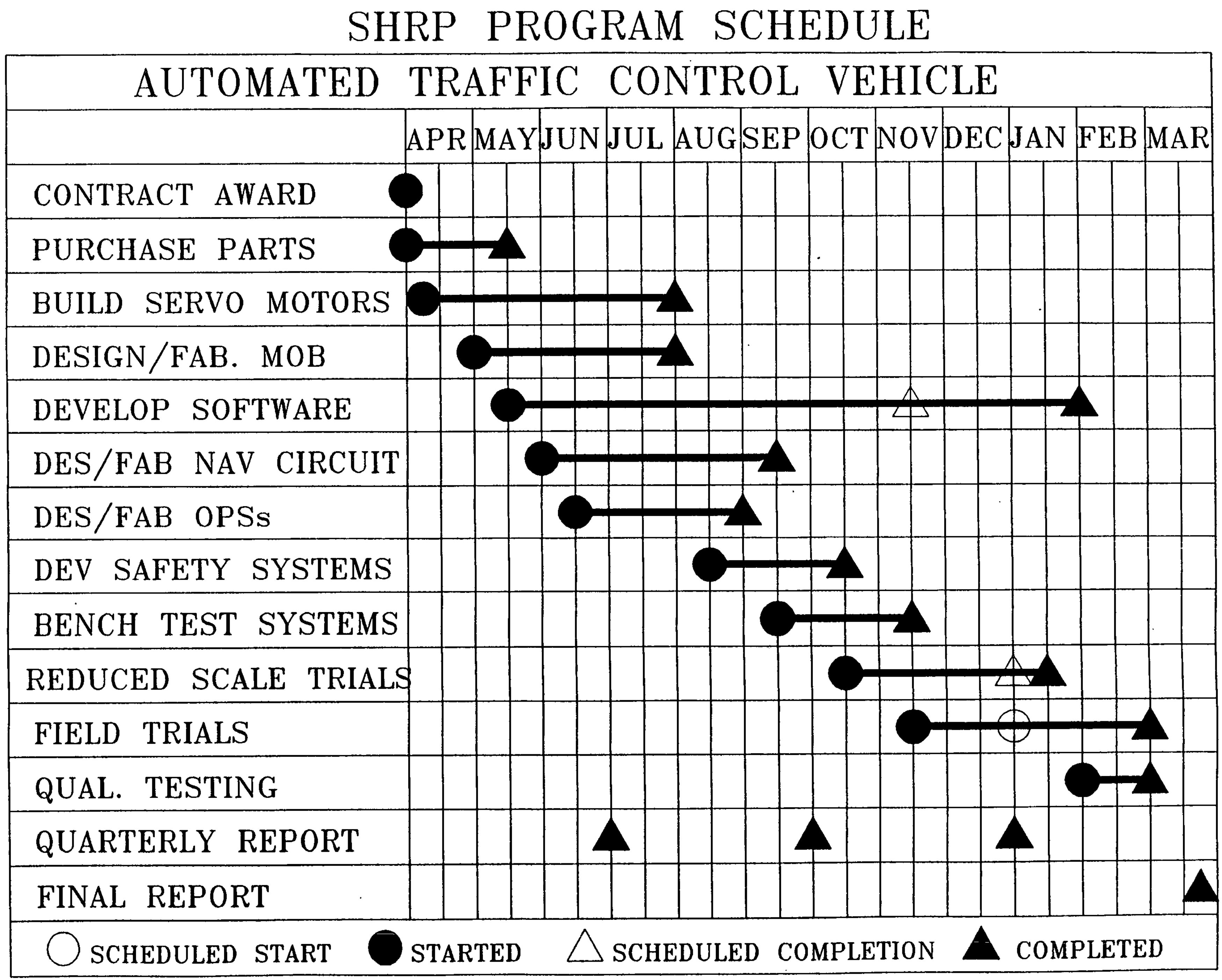
SHRP PROGRAM SCHEDULE
AUTOMATED TRAFFIC CONTROL VEHICLE
APR MAY JUN JUL AUG SEP OCT NOV DEC JAN FEB MAR
CONTRACT AWARD
PURCHASE PARTS
BUILD SERVO MOTORS
DESIGN/FAB. MOB
DEVELOP SOFTWARE
DES/FAB NAV CIRCUIT
DES/FAB OPSs
DEV SAFETY SYSTEMS
BENCH TEST SYSTEMS
REDUCED SCALE TRIALS
FIELD TRIALS
QUAL. TESTING
QUARTERLY REPORT
FINAL REPORT
SCHEDULED START
STARTED
SCHEDULED COMPLETION
COMPLETED

FIGURE 8.

3.0 PHASE I TASK RESULTS

This section reports individual milestone results for Phase I. The tasks correspond with those presented in the milestone chart in Figure 8. Detailed qualification test results are presented in Section 4. Unless otherwise specified, components were designed and fabricated by MacLeod Technologies, Incorporated.

3.1 CONTRACT AWARD

Formal start date was set at April 1, 1992. Work began immediately upon notification.

3.2 PURCHASE PARTS

All long-lead items were purchased early in the program. Significant purchases were a portable 386 computer with math coprocessor and half-card expansion capability, a digital data acquisition board, and specialized electronic and opto-electronic components. No program delays were incurred due to long-lead items.

3.3 BUILD SERVO MOTORS

MTI off-the-shelf steering and pedal servo motor designs were applied to meet the needs of this project. Figure 9 is a photograph of the servo motors installed in the full-scale test vehicle, a 1986 Dodge Caravan.

Figure 10 provides a close-up view of the floor-mounted servos. Note the brake link contains a fail-safe brake actuator.

First time conversion from a typical automatic transmission vehicle to a fully automated vehicle was performed in less than 20 minutes with a skilled installer and one support technician. Once a vehicle is modified, it can be converted from automatic control to driver control in less than 2 minutes by the driver.

Field testing using manual joystick control of the servos demonstrated outstanding all-around servo performance. Early field testing was performed in a typical, rural setting with moderate traffic using the manual joystick. A driver was on standby at all times to take over control if necessary.

Later field testing using computer control of the servos demonstrated successful automated results as can be seen by the qualification test results in Section 4.

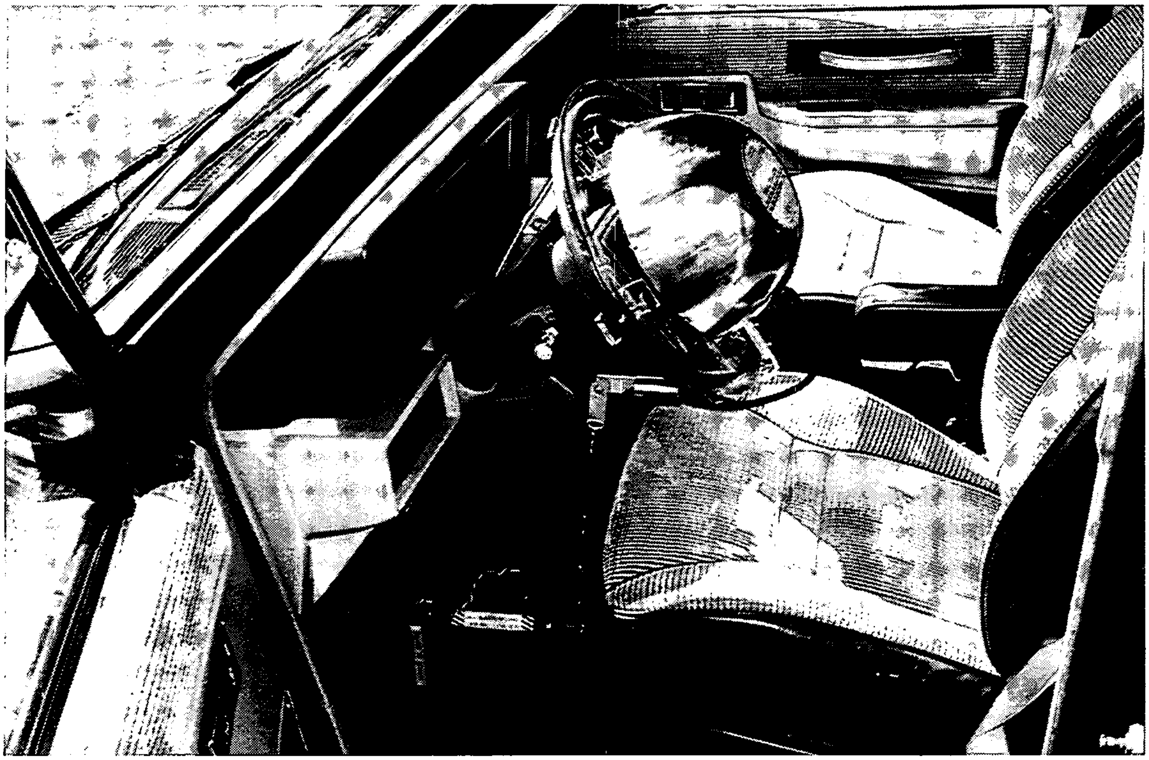

FIGURE 9. STEERING AND FLOOR PEDAL SERVO MOTORS.

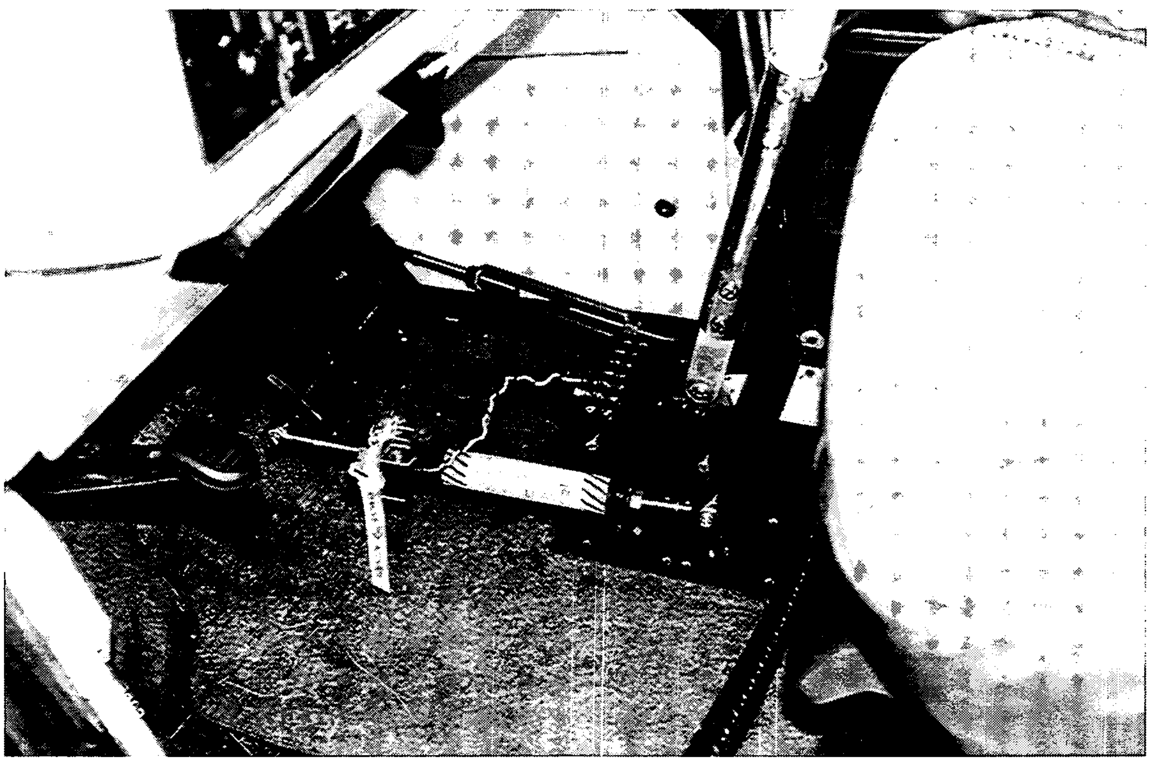

FIGURE 10. SAFETY BRAKE ACTUATOR DEVICE ON FLOOR MOUNTED SERVOS.

3.4 DESIGN/FABRICATE MOBILE OPTO-ELECTRONIC BEACON (MOB)

An optimal MOBILE OPTO-ELECTRONIC BEACON (MOB) was designed and fabricated to meet the stated goals of this project.

The MOB is the system component that resides on the tow vehicle and is the "tow" point on which the follow vehicle maintains relative position (i.e., distance and relative angle). The MOB is attached to the rear of the tow vehicle via a simple bumper mount. Figure 11 shows the final qualification MOB unit mounted on the truck used in qualification testing.

The MOB is powered by 12 volts DC which can be supplied by the tow vehicle battery. The MOB projects a rotating beam of

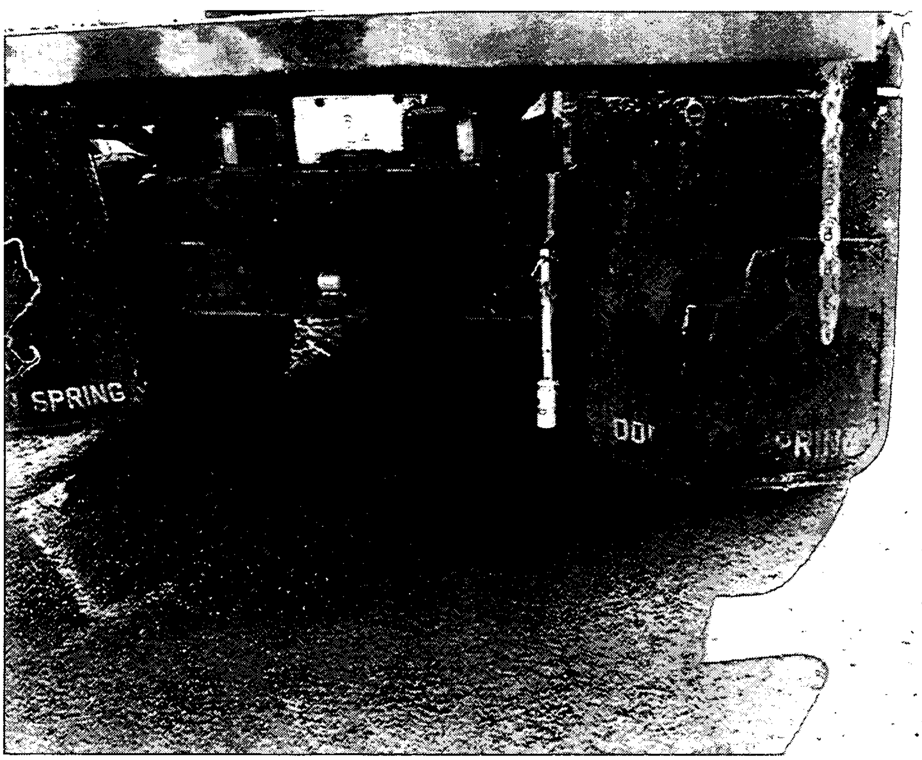

FIGURE 11. FINAL QUALIFICATION MOB UNIT ON TOW VEHICLE.

structured infrared laser light (at an invisible wavelength). Mirror speed is adjustable and in the range of 500-8000 RPM. To achieve 25 telemetry updates per second, the qualification MOB unit was designed with a 3000 RPM mirror speed. A disk drive style speed control circuit was used. The high rotational speed of the mirror assembly sheds wetness via centrifugal force, which is highly desirable for outdoor application. The projected beam is detected by three Opto-electronic Position Sensors (OPS) that are tuned to the same laser frequency.

3.5 DEVELOP SOFTWARE

Automated vehicle control software was designed and implemented in Phase I for both the indoor software debug vehicle and the outdoor full-scale follow vehicle. Follow vehicle algorithms were first developed using computer simulation, then tested on the indoor reduced-scale vehicle and finally incorporated into full-scale system trials.

Figure 12 illustrates a screen from the Phase I automated follow vehicle computer simulation.

It can be seen that the follow vehicle accurately tracks the tow vehicle at constant distance and relative bearing offsets. Control algorithms developed using this simulation were incorporated into the final system.

Reduced scale vehicle illustrated in Figure 13 was used to test follow vehicle control algorithms during software development. The major reason for using a reduced-scale vehicle over a full-scale vehicle during software development is for safety and indoor convenience.

The control flow diagram of the complete automated follow vehicle software system is given in Figure 14. The software contains modules to acquire follow vehicle navigation data, compute follow vehicle position updates from that data, calculate control values for the servo motor assemblies that drive the follow vehicle, monitor the remote operator control box and check for obstacles.

In Follow Mode, control algorithms adjust steering, throttle and brake servos in a smooth and human-like fashion. Very smooth throttle and brake control was achieved by incorporating a scheme into the speed control algorithm to jump over the range of hysteresis in the floor pedals. Steering was performed according to a follow vehicle turn radius model. The vehicle turn radius limits the lateral motion of the follow vehicle. Figure 15 illustrates the follow vehicle turn radius computation. This model has been proven to provide smooth control over steering. The follow vehicle does not steer directly towards the tow point, but follows the calculated turn radius towards the tow point. A turn radius is calculated for every follow vehicle position update (25 times per second max).

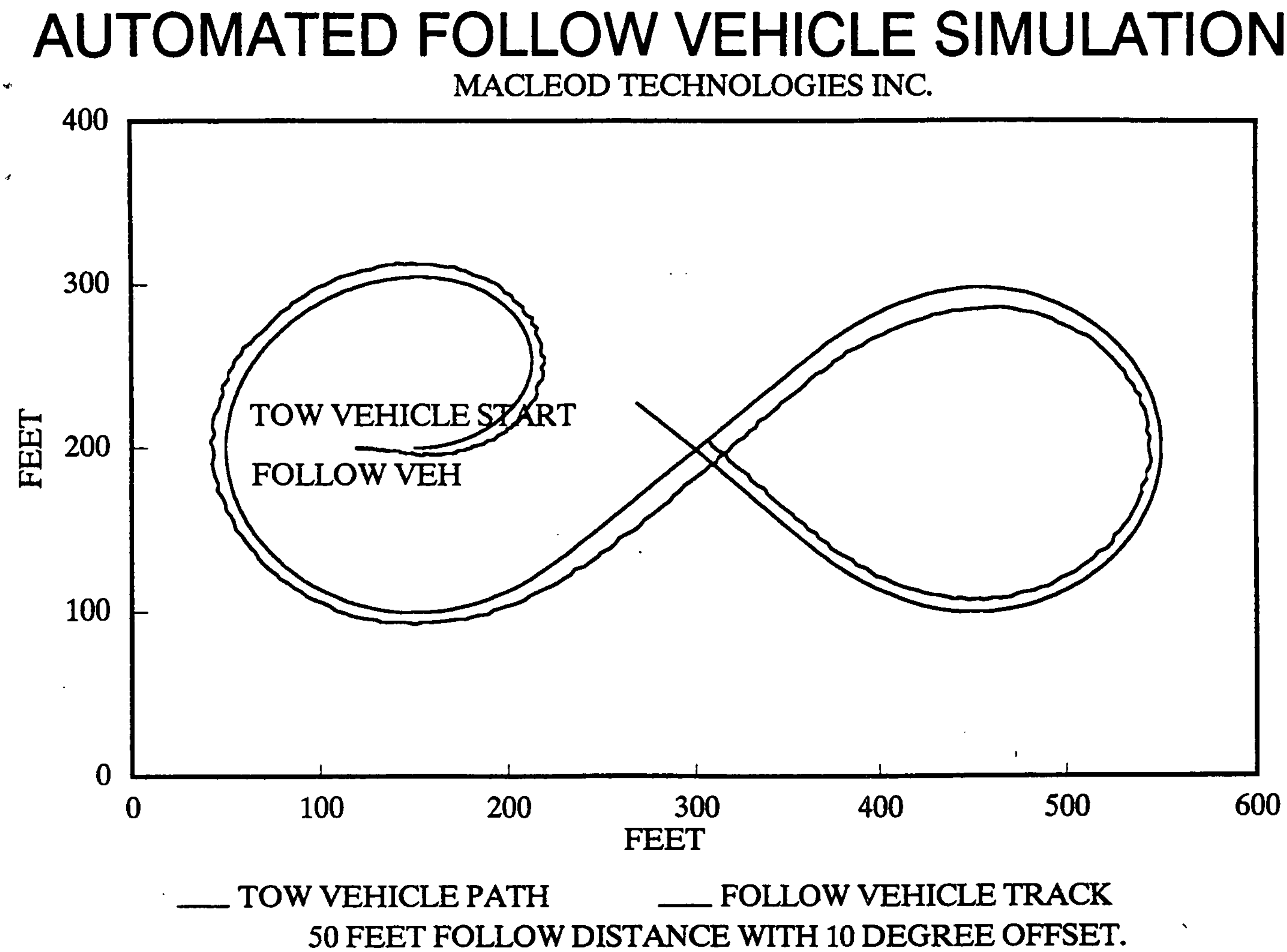

FIGURE 12. AUTOMATED VEHICLE SIMULATOR

This figure represents a screen from the Phase I automated vehicle simulator. Follow control algorithms were developed and tested using the simulator before proceeding to reduced-scale and full-scale implementation. The space between the tow vehicle and follow vehicle in this figure represents the 10 degree follow offset. The simulator made it possible to quickly test the effects of changing many control parameters.

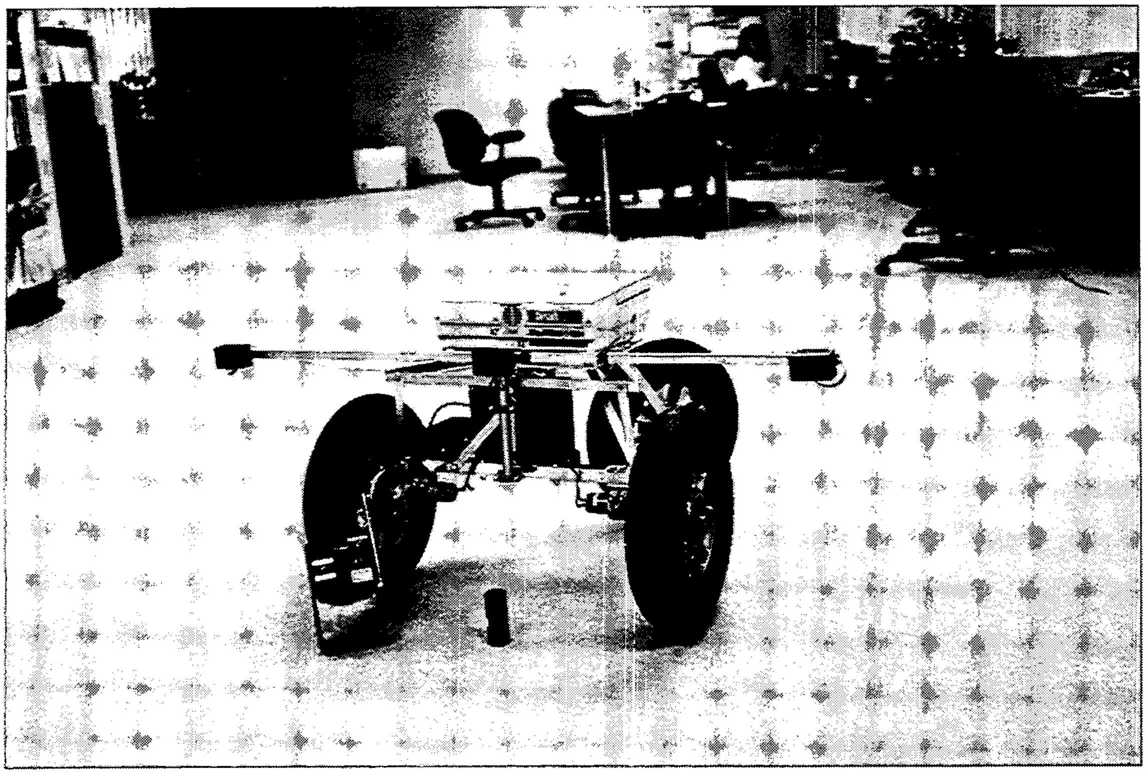

FIGURE 13 REDUCED-SCALE FOLLOW VEHICLE

3.6 DESIGN/FABRICATE NAVIGATION CIRCUIT

Computer interface circuits for navigation data acquisition were designed to meet the goals of this project. A single board approach for follow car navigation and control was accomplished. This board attaches to the portable 386 computer located in the follow car.

Timing circuits were designed and fabricated that convert incoming OPS signals into clock signals for accurate and reliable navigation. Digital to analog control circuits to command steering, throttle and brake servos have also been fabricated and tested.

Much testing was performed on the Navigation Circuit in both indoor and outdoor environments. Indoors, the Navigation Circuit performed at 100% (25 uninterrupted position updates per second).

Outdoors and integrated into the full-scale vehicle, modifications were made to the Navigation Circuitry to isolate the board from system electromagnetic interference. All susceptible cabling was shielded and opto-isolators were incorporated in the Navigation Circuitry to completely isolate the onboard computer from the rest of the system. All external wiring uses common and reliable modular style connectors.

FOLLOW VEHICLE SOFTWARE CONTROL FLOW

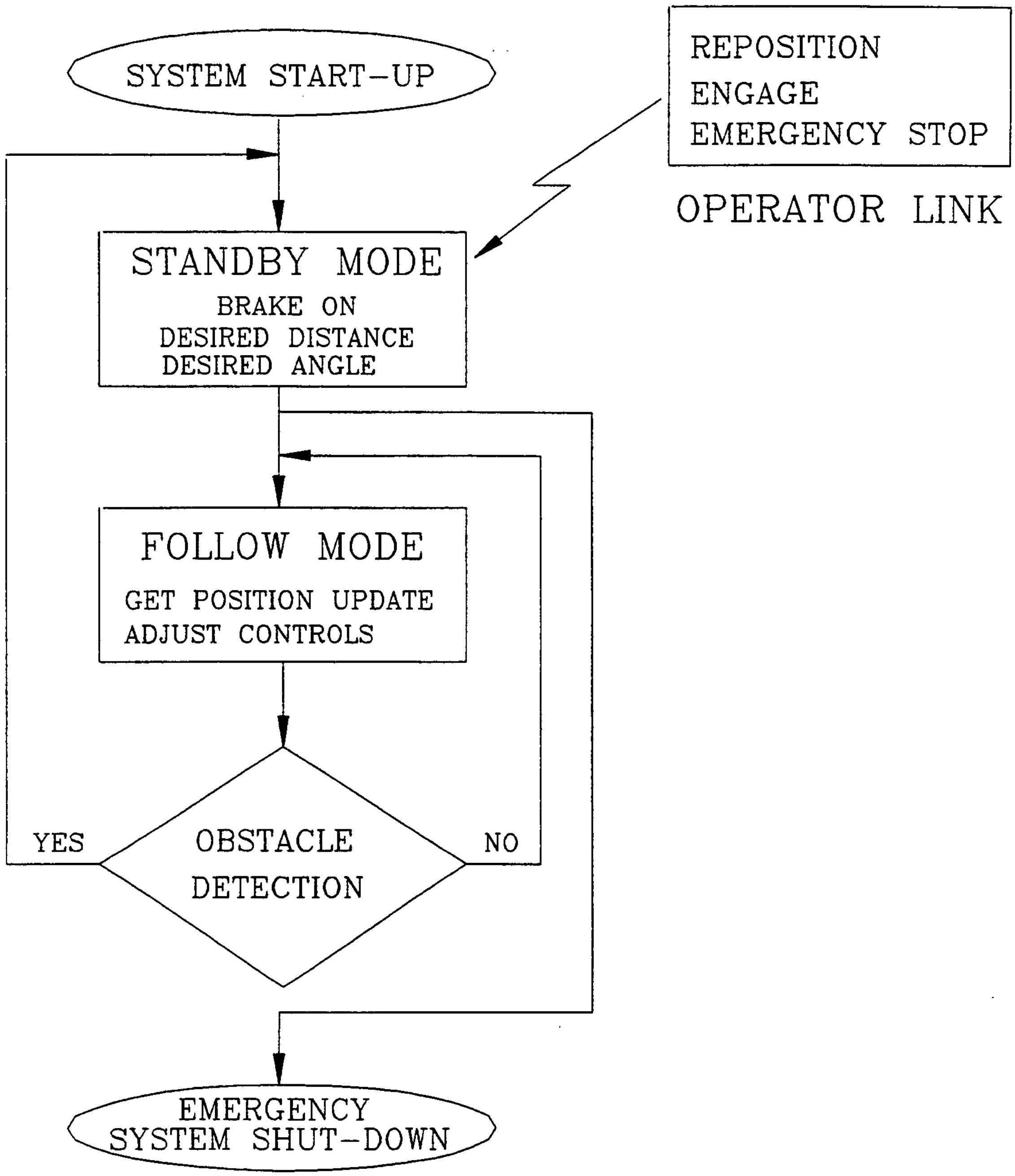

FIGURE 14

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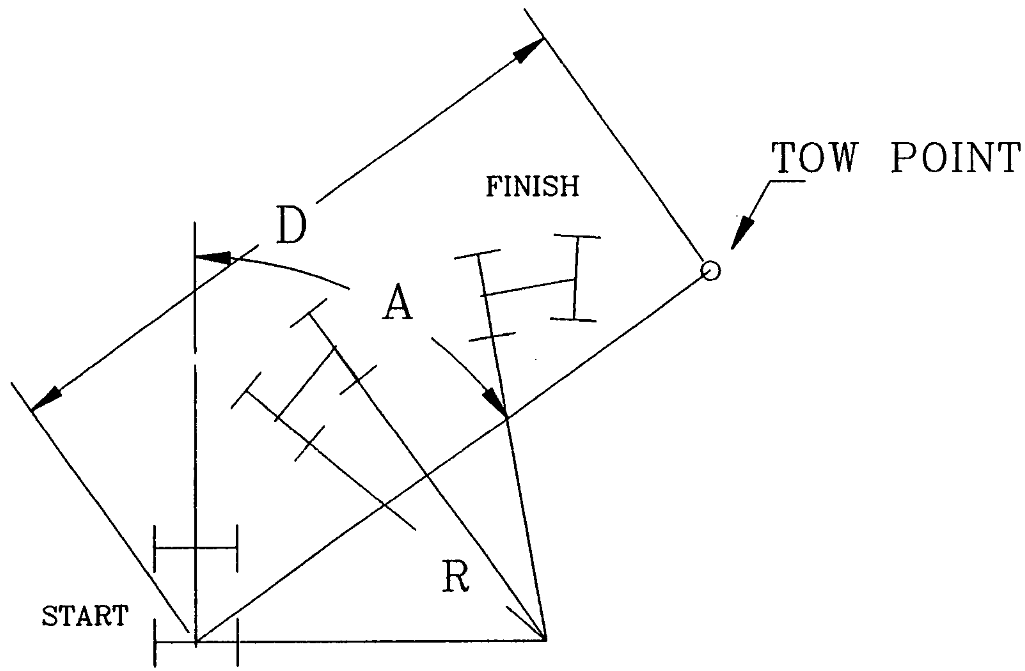
FOLLOW VEHICLE TURN RADIUS (R)

$$R=D/(2*COS(90-A))$$



THE FOLLOW VEHICLE STEERS ALONG A CALCULATED TURN RADIUS TOWARDS THE TOW POINT. THIS APPROACH ALLOWS COORDINATED TURNS BETWEEN THE TOW AND FOLLOW VEHICLES.

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FIGURE 15.

3.7 DESIGN/FAB OPTO-ELECTRONIC POSITION SENSORS (OPS)

Opto-electronic Position Sensors (OPS) were designed and fabricated to meet the range, weather and mounting requirements of this application. Field of view for opto-electronics is 110 degrees laterally allowing the specified +/- 45 degree vehicle to vehicle operation. Solar rejection and sensitivity is excellent even in direct sunlight. The OPS are shown mounted on the full-scale vehicle in Figure 16.

Fast switching infrared sensitive diodes were used to provide maximum sensitivity to the laser wavelength of the MOB while providing maximum rejection of other wavelengths. Three OPS components are mounted on the front bumper of the automated traffic control vehicle. The OPS transmit electronic pulses to the navigation timing circuitry in the on-board laptop control computer, signaling detection of the MOB energy. Precise follow car position and bearing data relative to the tow vehicle are achieved by advanced trigonometric calculations on the precise timing waveforms triggered by the OPS pulses as outlined in Section 1.

3.8 DEVELOP SAFETY AND HUMAN INTERFACE SYSTEMS

All proposed safety systems were completed with completion of the software obstacle detection algorithms and fail-safe brake actuator/ignition cutoff circuitry. Obstacle Detection was accomplished using the optical beam contact between the MOB and OPS. This method of obstacle detection has been termed the "electric eye". An obstacle detection array is created by the navigation components between the tow and follow vehicles as was shown in Figure 2. This electric eye obstacle detection approach was demonstrated on the software debug vehicle and response to obstacles was seen to be near instantaneous. Response in full-scale qualification testing was also seen to be near instantaneous.

The hand-held remote control box shown in Figure 17 was fabricated to allow the driver of the tow vehicle to perform an emergency shut-down of the automated vehicle. In addition to the emergency shut-down, the remote box allows the driver to reprogram the tow distance and relative angle to tow of the automated vehicle. The Emergency shut-down button is the big red button on the control box. When pressed it triggers the safety brake to release and cuts off the vehicle ignition.

The remote hand-held control box is the only operator interface to the follow vehicle. To reposition the follow vehicle, the driver simply throws the REPOSITION-ENGAGE toggle switch to REPOSITION. The hand-held device transmits a code to the computer to stop the towed car and standby for new follow coordinates. The driver then repositions his tow vehicle to the new tow configuration (distance and relative angle) and then

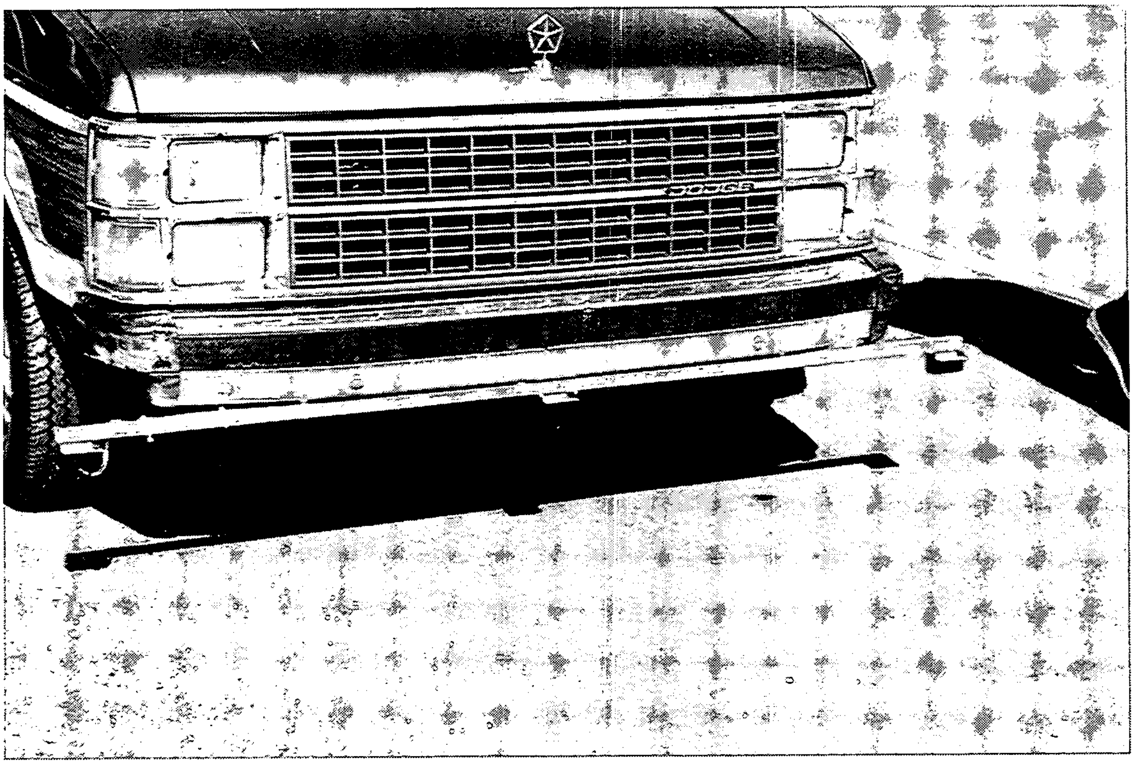

FIGURE 16. OPS MOUNTED ON FULL-SCALE FOLLOW VEHICLE.

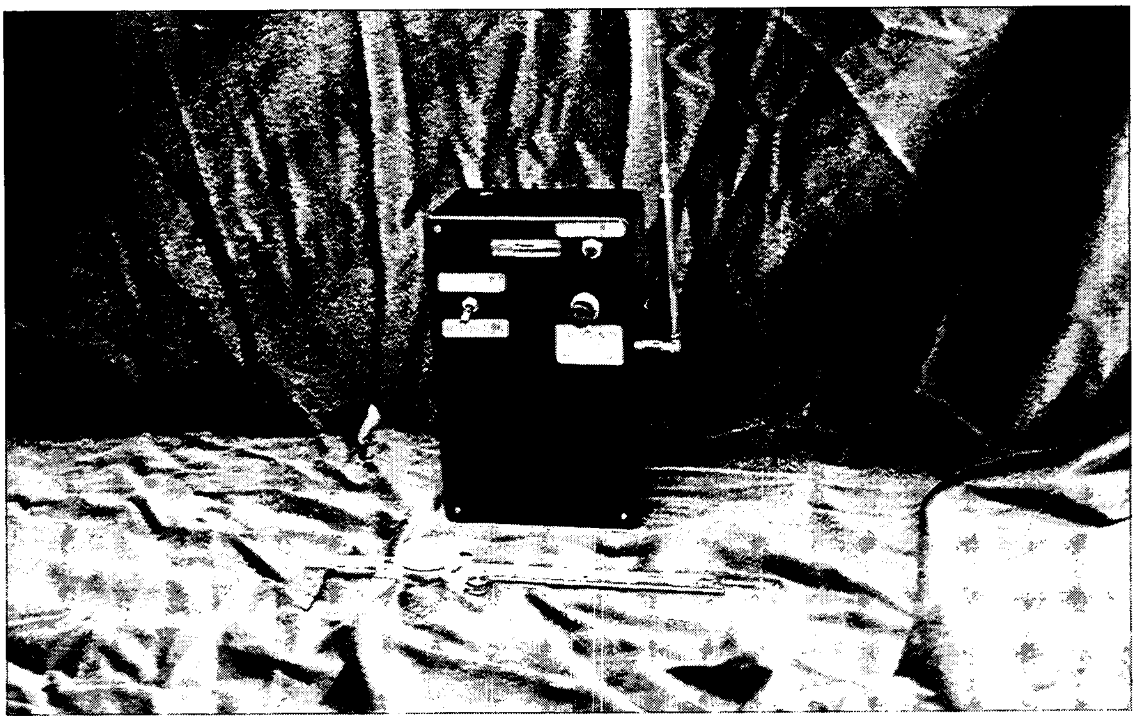

FIGURE 17. REMOTE OPERATOR CONTROL BOX FOR MANUAL CONTROL.

switches the toggle switch to ENGAGE. The computer in the towed vehicle immediately computes the bearing and distance to the tow vehicle and uses this new distance and offset data to shadow the tow vehicle. The small red button in the upper right corner of the box is to check the unit's battery. The unit is wireless and rechargeable.

3.9 BENCH TEST SYSTEMS

Hardware system bench testing was performed throughout the entire project to refine system prototype designs and to provide tested hardware subsystems to aid in software debugging.

3.10 REDUCED-SCALE TRIALS

Reduced-scale trials were performed in Phase I to test computer models and algorithms in a controlled environment. It was desirable to test and debug software on a reduced-scale vehicle for obvious safety and convenience reasons. The reduced-scale test vehicle shown in Figure 13 was built to meet the needs of the reduced-scale trials in this effort. The vehicle carries the laptop computer and performs the function of the towed vehicle but at a reduced scale. The maximum speed of the vehicle is equivalent to a brisk walk. This vehicle allows up to 4 hours of continuous operation from a single recharge.

3.11 FIELD TRIALS

Vehicle servo motors and navigation systems were tested outdoors on the full-scale test vehicle. Initially, manual joystick control was used with human driver input. The servo motor components tested most satisfactorily during joystick operated control. Field testing was performed on a rural street setting with a driver on standby at all times. No human override was necessary.

Computer control over the vehicle servo motors was later tested on the full-scale vehicle. Control algorithm parameters for steering, brake and throttle were adjusted for optimal performance. For safety reasons, all prototype testing was conducted with a standby driver in the automated vehicle. No human override was necessary during field trials.

4.0 PHASE I QUALIFICATION TESTING

Qualification testing was performed during reduced-scale testing and full-scale testing to demonstrate Phase I goals and objectives. Phase I qualification testing emphasizes full-scale automated follow vehicle system performance.

4.1 QUALIFICATION TEST SET-UP

Full-scale qualification testing took place on a taxi-way at Hanscom Airport in Bedford, MA (see Figure 18). The tow and follow vehicles are shown in Figure 19. The tow vehicle is fitted with the MOB on its rear bumper as shown in Figure 11. A 12V battery was used to power the MOB. The follow vehicle is fitted with three OPS on its front bumper as shown in Figure 16.

The follow vehicle is also fitted with MTI-designed servo motors for steering, throttle and brake control. All follow components including the onboard computer are powered by the follow vehicle battery. A human driver was present during qualification testing. However, human override was never required.

The follow speed was limited to 5 MPH during the full-scale qualification tests. This satisfies the Phase I goal that follow vehicle speed will automatically match tow vehicle speed up to 5 MPH. Because MTI's CONAC system provides telemetry on follow vehicle position updates at such a fast rate (typically 20 updates per second), much higher follow speeds can be achieved. In fact, higher speeds are desirable. The 5 MPH limitation on follow speed required frequent brake throttle manipulation. At higher speeds only throttle corrections would be required, which would enhance the smoothness of speed control.

The calibration targets on the side of the follow and tow vehicles were used for photo analysis of the test. The targets are spaced 12′ (3.66 m) apart on the follow vehicle. The targets are visible in Figure 2.

4.1.1 QUALIFICATION SYSTEM START-UP PROCEDURE

The System Start-Up procedure is as follows:

STEP 1) start the follow vehicle engine,
STEP 2) turn on the onboard computer (the follow vehicle is now in Standby Mode),
STEP 3) switch to REPOSITION on the remote control box (this sets the follow distance and relative follow angle from the tow vehicle),
STEP 4) switch to ENGAGE on the remote box (the follow vehicle is now in Follow Mode). If any obstacles are detected while the follow vehicle is in Follow Mode, then the follow vehicle returns to Standby Mode.

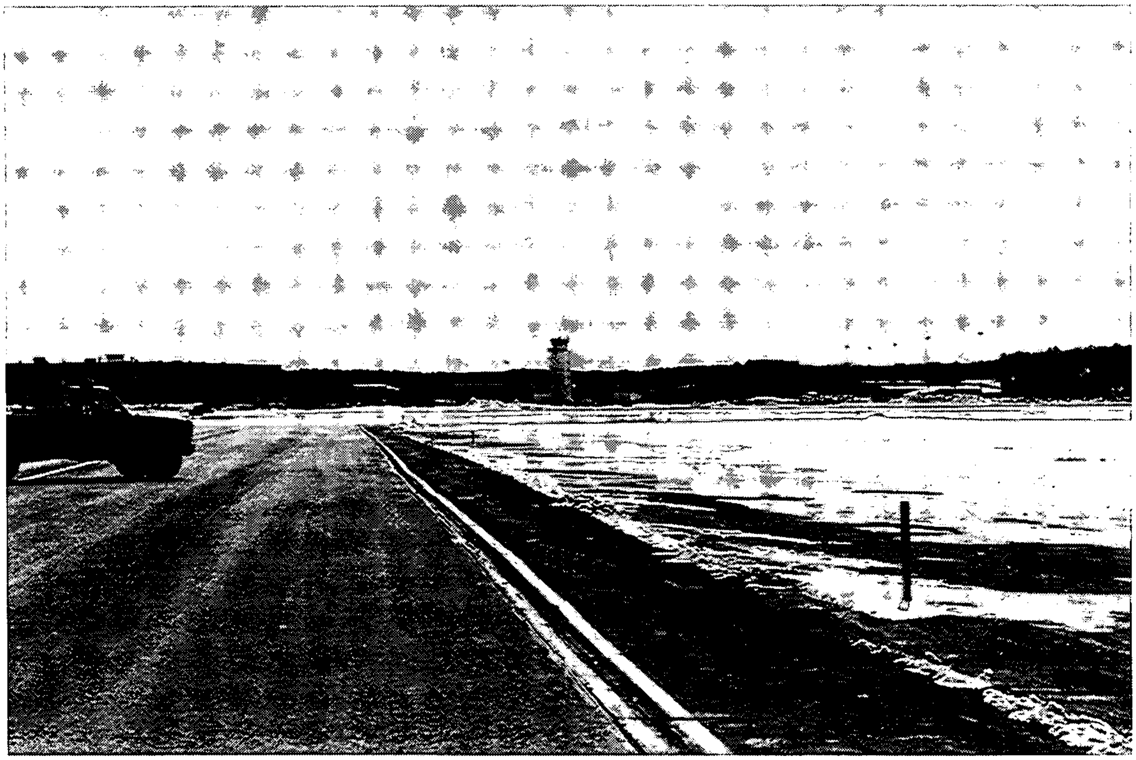

FIGURE 18. FINAL PHASE I QUALIFICATION TEST SITE HANSCOM AIRPORT, BEDFORD, MA. MARCH 1993.

FIGURE 19. FULL-SCALE TOW AND FOLLOW VEHICLES.

4.1.2 QUALIFICATION SYSTEM OPERATION

In Standby Mode the follow vehicle brakes are fully engaged and the throttle is completely off. The steering control is not affected by switching between Standby and Follow modes of operation. The operator remotely executes the REPOSITION-ENGAGE sequence from his hand-held remote control box.

In Follow Mode, follow vehicle position updates are received 25 times per second using a MOB operating at 3000 RPM. These position updates are incorporated into a feedback control loop to calculate the brake, throttle and steering commands to drive the follow vehicle. Extensive computer modeling to test the numerous different control approaches was performed in Phase I.

The approach chosen for full-scale qualification testing incorporates the relative velocity and acceleration of the follow vehicle with respect to the tow vehicle for speed control. Steering control incorporates the turn radius method illustrated in Figure 15.

The qualification test results presented in this section emphasize results collected during an outdoor qualification test at Hanscom Airport in Bedford, MA.

4.2 VEHICLE TRACKING TEST RESULTS

The performance of the system navigation components, the MOB and OPS, is presented in terms of vehicle tracking accuracy in Figure 20. The vehicle tracking accuracy is a good indication of CONAC performance since high quality incoming data from the sensor subsystem is required for accurate vehicle tracking. Documented operation up to 120′ (36.57 m) in all weather and lighting conditions was achieved. The low standard deviations in Figure 20 in both Distance To Tow and Angle To Tow measurements reflect reliable vehicle tracking operation even at very long ranges.

4.3 FOLLOW CONTROL TEST RESULTS

The Phase I goal stated that distance accuracy between the tow vehicle and the follow vehicle will be maintained within +/- 5% of follow distance. Reduced-scale testing has been demonstrated to perform well within this limit with a maximum follow distance of 100′ (30.48 m).

Figure 21 shows telemetry data of the follow vehicle′s distance to the tow point (i.e., the MOB on the tow vehicle) for a typical qualification test run. The data was collected over a 1 minute span of the test. The variability in the follow distance is seen to be +/- 5.4% of the follow distance. The approximate speed of this test run was 5 MPH. All follow control tests exhibited smooth coordinated control of throttle and brake.

VEHICLE TRACKING PERFORMANCE

	MEAN	STANDARD DEVIATION	KEEP RATIO	DISTANCE (FT.)
ANGLE TO TOW (DEG.)	1.84	1.43	0.889	60
DISTANCE TO TOW (FT.)	60	0.098		
ANGLE TO TOW (DEG.)	19.7	0.065	0.336	100
DISTANCE TO TOW (FT.)	96.866	0.134		
ANGLE TO TOW (DEG.)	27.5	0.09	0.298	120
DISTANCE TO TOW (FT.)	109.23	0.108		

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FIGURE 20.

Figure 20 summarizes Vehicle Tracking Performance over an increasing range in follow distance. Follow distances range from 60' to 120'. The Keep Ratio reflects the number of position updates used by CONAC to control the follow vehicle. At a 60' follow distance, for example, approximately 9 out of 10 position updates are used. The measures of performance are Distance To Tow and Angle To Tow. Distance To Tow is the distance along a straight line between the MOB and the middle OPS. Angle to Tow is the angular offset of the follow vehicle in relation to a centerline from front to rear of the tow vehicle. The MOB laser power used was 5 milliwatts and MOB rotation speed was 3000 RPM.

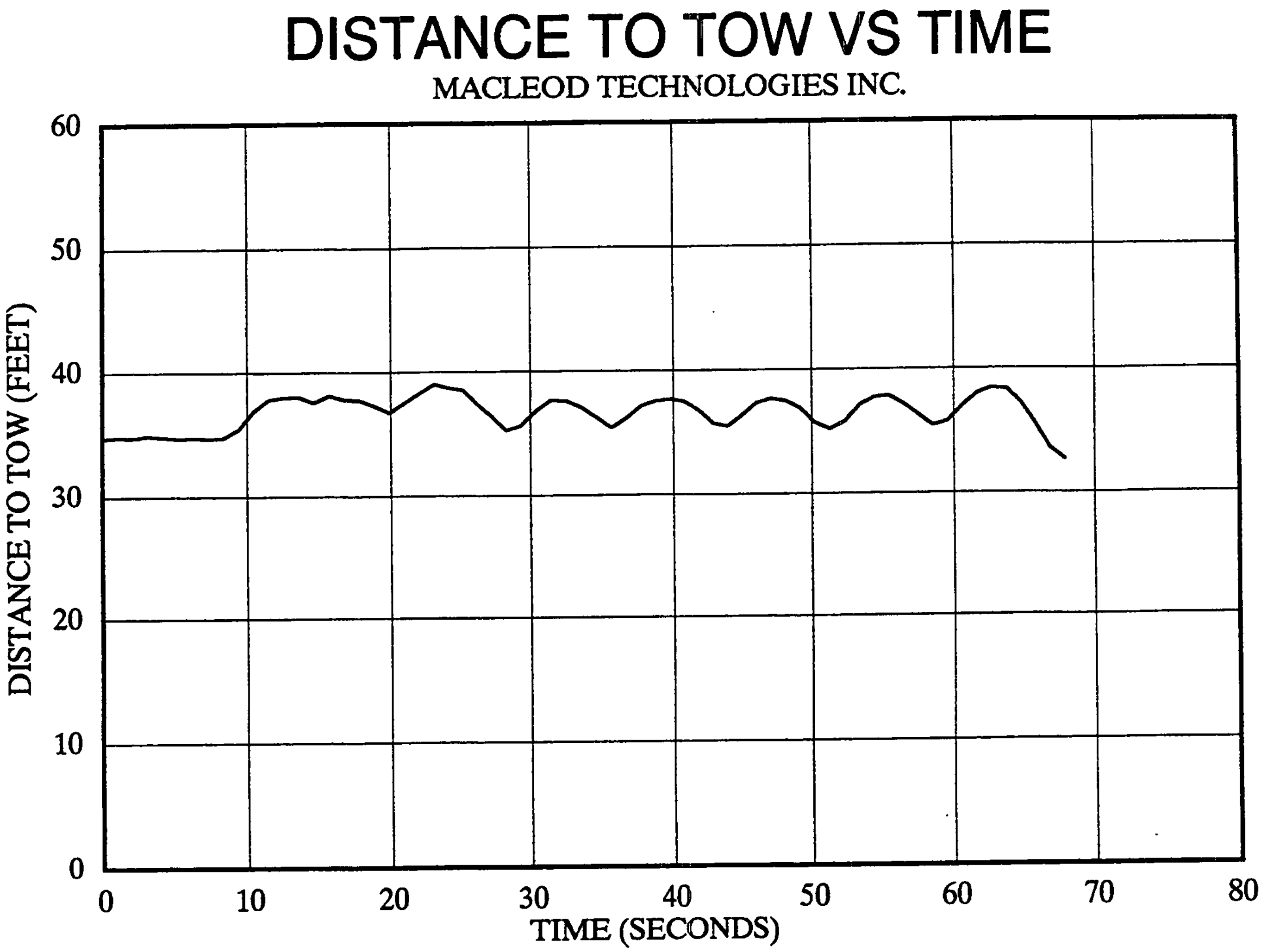

FIGURE 21. FOLLOW DISTANCE TEST RUN

The data presented in this graph was collected during Phase I Qualification Testing at Hanscom Airport, Bedford, MA. The data were acquired using a .5 second sample rate during a typical follow run. The follow speed was approximately 5 MPH. The navigation circuitry and software generated 25 relative position updates per second. All 25 updates every second were used in controlling the follow vehicle. Follow distance accuracies better than +/- 5.4% of the follow distance were achieved.

4.4 ANGULAR ACCURACY TEST RESULTS

The angular accuracy test quantifies the automated steering performance of the follow vehicle. The measurement convention is as follows:

straight ahead towards tow point: steering = 0,
turn left towards tow point : steering < 0,
turn right towards tow point : steering > 0.

The graph in Figure 22 shows telemetry data collected for a single test run. The data collected is sampled at a rate of 1 in 25 actual follow vehicle position updates. The maximum lateral motion achievable by the follow vehicle is limited by its maximum turn radius, which is incorporated into the steering control algorithm.

The Phase I goals stated that angular accuracy will be such that the follow vehicle will track behind the tow vehicle within +/-1' (+/-30.48 cm) perpendicular to the tow vehicles path.

Both reduced-scale and full-scale testing showed angular accuracy within inches of preset relative angle settings.
Angular accuracy of the follow vehicle in relation to the tow vehicle is expressed in terms of "ANGLE TO TOW" in Figure 22. The minus sign in ANGLE TO TOW means that the follow vehicle is offset to the right of the tow vehicle facing the rear of the tow vehicle.

The measurements may be expressed in distance perpendicular to the tow vehicle by the following equation:

$$X = 50' * \mathrm{SIN}(\text{ANGLE TO TOW}),$$

where X is the perpendicular distance to the tow point and 50' (15.24 m) is the follow distance. According to the data collected in the full-scale test, the follow vehicle maintained +/-1.2' (+/-36.57 cm) relative perpendicular alignment with the tow vehicle at a 50' (15.24 m) follow distance. The Standard Deviation of the Angle To Tow was used to calculate this relative perpendicular alignment.

The relative angle between the lead controlling vehicle and the automated vehicle achieved the goal of +/-45 degrees from center and adjustable.

4.5 OBSTACLE DETECTION TEST RESULTS

The automated vehicle stops in a controlled manner if a pedestrian or animal wanders between the vehicles. If any of the navigation components (OPS or MOB) are blocked for at least 40 milliseconds (1/25th of a second) then the obstacle-detection functions are activated. The automated follow vehicle is

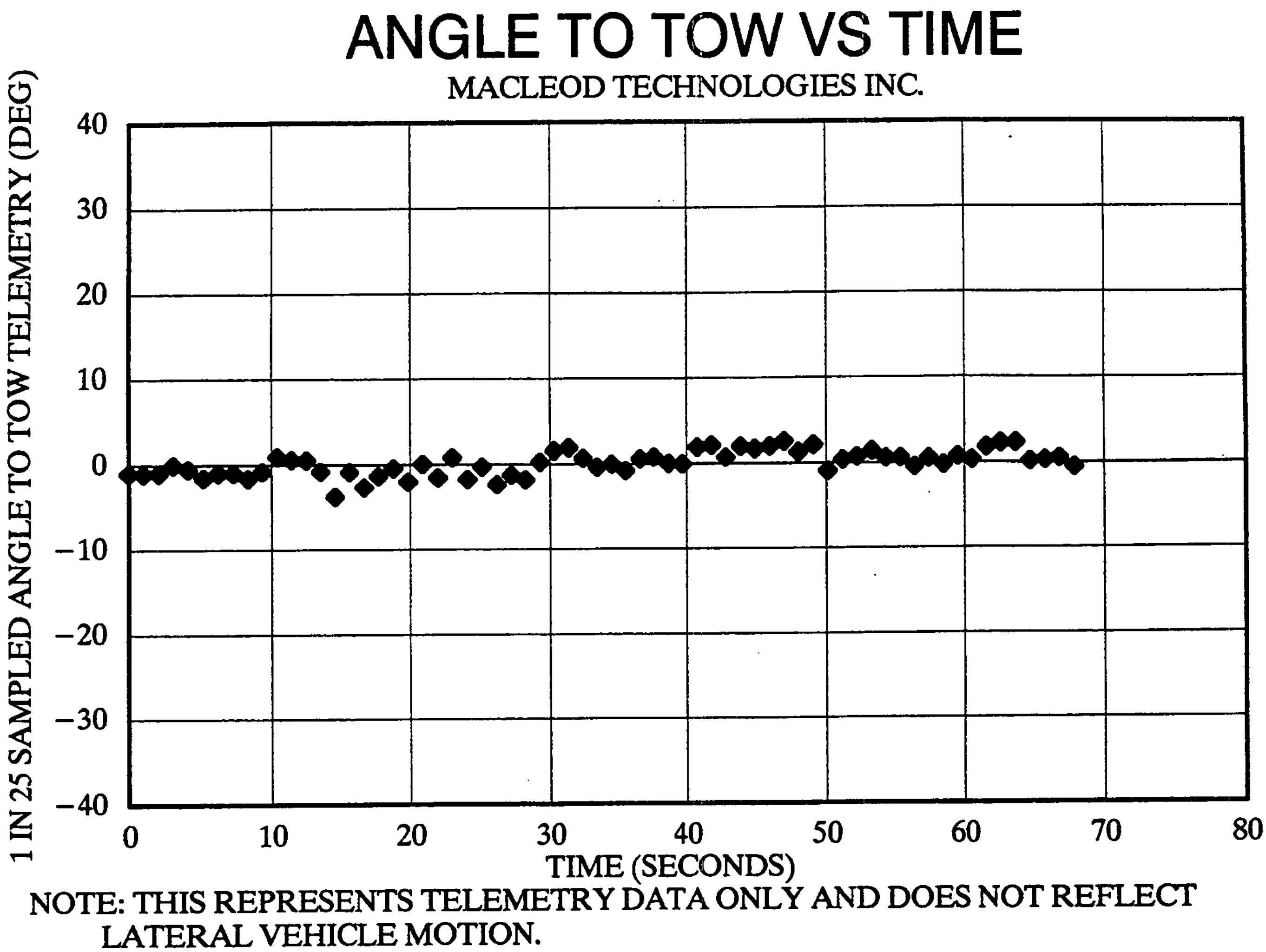

FIGURE 22. RELATIVE ANGLE TEST RUN

The graph in Figure 22 depicts the control data used by the follow vehicle to maintain a fixed angular offset from the town vehicle. The data does not reflect the instantaneous lateral motion of the follow vehicle. The data shows that the follow vehicle maintained a follow offset of zero degrees which means that the follow vehicle followed directly behind the town vehicle.

immediately stopped and enters Standby Mode, where it awaits the Reposition signal from the remote control operator box. The obstacle detection functions worked reliably in both indoors and outdoors testing.

4.6 QUALIFICATION TEST SUMMARY

In summary, qualification testing was extremely successful. From a passenger's viewpoint in the automated follow vehicle, the ride was smooth and on-track. The data acquired by MTI's navigation system were accurate and reliable. The steering, throttle and brake control algorithms exhibited human-like driving over the automated follow vehicle.

5.0 PHASE I CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The automated follow vehicle concept demonstrated has been proven to be accurate, reliable and safe. The navigation system acquired very accurate Distance To Tow and Angle To Tow measurements in both indoor and outdoor conditions. All safety systems operated as expected. Overall, the Phase I automated follow vehicle system exhibited outstanding performance, meeting and in most cases exceeding Phase I goals.

5.2 RECOMMENDATIONS FOR FUTURE DEVELOPMENT

Cursory recommendations are provided in this section for further development of the automated follow vehicle concept. The recommendations presented here reflect lessons learned from Phase I. A more comprehensive treatment on future development would be given in a formal Phase II proposal.

5.3 CONTROL SOFTWARE ENHANCEMENTS

Control algorithm parameters should be optimized to maximize control system performance. Responsivity of the control system must be fast enough to maintain smooth control over the follow vehicle. The algorithm parameters that control speed of the follow vehicle were discussed in Section 3.5. An automated calibration routine for maintenance workers to use should be included. This calibration procedure may be executed once at the beginning of a work session or it may be necessary to adjust the parameters as the vehicle warms up or weather conditions change.

5.4 VEHICLE SERVO MOTORS ENHANCEMENTS

A manual override switch is desirable to disengage steering servo motor control to allow normal manual operation of the steering wheel. This would facilitate repositioning of the follow vehicle by a human driver. The vehicle processor would enter Standby Mode when this occurs and await repositioning by the remote operator control box. A single lever would alternate between manual and automated modes of operation. This is much more operator-friendly than removing the steering motor assembly every time the follow vehicle is repositioned.

In Phase I, the anti-rotation steering servo arm was placed from the steering wheel to the brake box on the driver side floor as seen in Figure 9. This rod should be moved to connect to the dashboard behind the steering wheel. This would facilitate a human driver getting in and out of the automated vehicle.

5.5 ALL-WEATHER TESTING

Satisfactory CONAC performance was observed in many outdoor conditions. Hard data, however, was not obtained in this effort with weather as the only variable. Further testing is recommended. System tuning and testing was performed in bright sunlight, clouds, heavy rain, 2 inch/hour (5.08 cm/hour) snow, sleet, and night-time conditions. Neither the system hardware nor the system electronics suffered any damages due to the varying weather conditions. No conditions rendered the CONAC system inoperable. Bright sunlight was observed to cause slight degradation in system range of operation. MTI is currently developing improvements to the CONAC sensors to increase their robustness in bright sunlight. Unfortunately these enhancements were not available at the time of testing. Development and execution of a Test Plan to quantify the individual effects of varying weather conditions on system performance is recommended.

Further development in weather-proofing navigation OPS and MOBs should include incorporating a tiny thermostatically controlled heater in each component. The heater should activate below 34 degrees Fahrenheit. This heater would melt snow and ice collected on the OPS or MOB and control humidity in the devices.

6.0 COMMERCIAL APPLICATIONS

As a result of Phase I, commercial potential of the automated follow vehicle application were explored. Authorities at the Central Tunnel Artery Project in Boston, MA expressed high interest in the automated follow vehicle as a potential solution to many tunnel-related applications. Specific applications were 1. to enhance work crew safety in the tunnel, 2. to automate the water tank truck that follows the tunnel washer to refill the washer, and 3. to provide automated follow vehicles to protect the water tank follow truck. Due to the restricted space in the tunnels, a follow vehicle would protect work crews as is its intended purpose. Due to the late night hours during which tunnel washing takes place, the human drivers are at risk of being hit by drunk and/or drowsy drivers.

6.1 COLLISION-PREVENTION SPIN-OFF

The technology proven in this effort is an excellent match for collision prevention for manned vehicles. The technology significantly exceeds the capabilities of existing collision prevention techniques presently being researched. The precise vehicle to vehicle position awareness makes it possible for an onboard computer to predict impending collisions with other vehicles. If a bearing to a vehicle is constant and closure rate is computed to be excessive, the computer could actuate the brakes. In a head on collision, both vehicles would be overridden. To avoid system confusion in heavy traffic, computer controlled OPS sensitivity would reduce data to only the nearest vehicles. Obviously, research is necessary to test decision algorithms and hardware.

It is possible for this equipment to be added to any vehicle on a relatively low cost aftermarket basis. For the approach to work, all vehicles must be equipped. The end result however would be the elimination of head on collisions, rear end collisions and intersection collisions. Even collisions from sleeping or drunk drivers could be prevented.

7.0 ABBREVIATIONS

CONAC	Computerized Opto-electronic Navigation and Control
DPW	Department of Public Works
MOB	Mobile Opto-electronic Beacon
MTI	MacLeod Technologies Incorporated
OPS	Opto-electronic Position Sensor
RPM	Rotations Per Minute