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SBIR 87-3

LOW COST MOBILE ROBOT

PREPARED BY

John M. Evans, Ph.D.
President

TRANSITIONS RESEARCH CORPORATION
15 Durant Avenue
Bethel, Connecticut 06801

October 7, 1987

FINAL REPORT

Approved for Public Release;
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PREPARED FOR

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY (DoD)
DEFENSE SMALL BUSINESS INNOVATION RESEARCH PROGRAM
DARPA ORDER NO. 5916
ISSUED BY U.S. ARMY MISSILE COMMAND UNDER
CONTRACT # DAAHDI-87-C-0448

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28. ABSTRACT (Continue on reverse if necessary and identify by block number) In the 1986 SBIR solicitation, DARPA identified a need for a low-cost mobile robot for laboratory research use. This report covers the work by Transitions Research Corporation in addressing this opportunity under a Phase I SBIR contract. TRC has developed technical requirements and selected a vehicle design, a control system, and a communications system to meet those requirements. Use of a common research vehicle base would reduce the time and cost to carry out experiments in navigation of mobile vehicles, would expedite sharing and comparing of research results, and would advance the understanding of the evolution of intelligence. (Keywords: test beds; vehicle control; motion control). ←				
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FINAL REPORT

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DARPA/SBIR PROGRAM PAN 57-87

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TRANSITIONS RESEARCH CORPORATION

15 Durant Avenue
Bethel, Conn. 06801

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1.0 Introduction

In the 1986 SBIR solicitation, DARPA identified a requirement for a low cost mobile robot for educational and laboratory research use. TRC was one of the contractors selected to address this opportunity.

Transitions Research Corporation (TRC) was founded in 1984 by Joseph F. Engelberger, the founder of Unimation, the first industrial robot company. TRC's charter is to pursue new applications of robots and automation, particularly robots for application in the service sector of the economy. John Evans, the founder of the automation program at the National Bureau of Standards, and founder of Nova Robotics, is the President of TRC. TRC's staff as of September 1987 is 20, with robot experience at GE, DEC, General Dynamics, General Foods, and Unimation.

TRC is developing mobile robots for floor cleaning, for fetch and carry tasks in hospitals and nursing homes, for pharmacy operations, and for transmission line inspection. TRC is also conducting a technology survey and market assessment for the development of a domestic robot.

TRC also provides consulting services and has supported major corporations and the Government on assessing automation and robotics for the NASA Space Station. TRC has provided briefings for the President of the United States and for Prime Minister Ghandi of India. TRC serves on the National Academy of Sciences and the Air Force Studies Board Committee on Robotics.

This SBIR project is one of three that TRC has recently been awarded. One of the remaining two covered a vision system for NASA docking and tracking in space. The other covered a servo controlled model of the human neck for realistic crash mannikin response for the Air Force.

2. Identification and Significance of the Problem

In the 1986 SBIR solicitation, DARPA identified the need for a test bed for mobile robot vehicle research. Many laboratories have been working on mobility for the last several years with no commonality in approach to allow comparison and sharing of results. As a result, many advanced robotics research projects have expended large amounts of time and money duplicating low level mechanical engineering efforts in the fabrication of barely adequate mobile bases, before even addressing the intended high level goals of funded projects.

A major goal of the TRC SBIR project has been to design and construct a low cost mobile robot which releases the robotics researcher from the wasteful duplication of effort involved in vehicle design.

Although the earliest mobile robot work goes back into the 1960's or early 1970's at SRI, Stanford, and Johns Hopkins, the most significant work has been carried out in the last several years. Computing power and low power CMOS components have reached the point where interesting experiments can be carried out with small, inexpensive, battery powered mobile bases. The entire personal robot field, which has now collapsed, was a series of such experiments, clearly showing how resources can be wasted in designing mobile bases. MIT, SRI, CMU, ORNL, the several DARPA autonomous vehicle projects, and many other groups are all attacking interesting problems in navigation with approaches that are both intriguing and promising, but without any common approach to vehicle design. In most universities, between one and two man years of graduate student effort is required to produce an operational vehicle.

DARPA has indicated that a mobile research base will advance the understanding of the evolution of intelligence. Brooks' work at MIT and the SRI work is directly targeted at this concept. A low cost research base would accelerate this work.

Several university and industry projects and the DARPA autonomous mobile vehicle projects have identified the control of multiple vehicles as an area of research interest for the future. Projects currently underway do not have the resources to build multiple vehicles to attack this problem. One exception is the DARPA AUV project in which two autonomous underwater vehicles will exhibit coordinated behavior in the first demonstrations in 1987. Fleets or squadrons of vehicles with intelligent coordinated behavior are of interest to the Army, Navy, Air Force, and to SDI. A low cost research base would allow multiple vehicle projects to be undertaken within reasonable budget constraints.

A low cost common vehicle for research in mobility would reduce the cost and increase the speed of research and would allow comparison and sharing of results, allowing researchers to focus on the real problems of interest in sensing and in navigation and machine intelligence rather than on unproductive low level hardware engineering and maintenance.

This project provides an analysis and a design of such a low cost research vehicle.

3.0 Requirements Definition

Objective 1 of our proposal was to define requirements for a low cost mobile robot.

TRC arranged a meeting with DARPA soon after the contract was signed to develop detailed requirements. DARPA indicated that they did not have specific requirements and that several contracts had been let on this topic. No specific guidance was provided.

TRC during the past two years has talked with researchers from MIT, CMU, Yale, Drexel, Martin Marrieta, FMC, JPL, Minnesota, Honeywell, GM, DuPont, IBM, USC, Tennessee, Arizona, SRI, UMass, UConn, Lehigh, Pennsylvania, NBS, New Hampshire, Michigan, ERIM, Boeing, Foster Miller, Westinghouse, Gould, and several other universities and companies. An attempt was made to define research objectives, to discuss alternative approaches to vehicle design, and to differentiate between basic requirements and optional requirements.

Recent literature, particularly the IEEE and SPIE Proceedings and reports from Carnegie Mellon University, were reviewed and analyzed in the same vein.

Finally, a "trial balloon" specification was put on paper and distributed to researchers in the field to assess the response. Subsequently, TRC's Labmate design, based on researchers' requirements, was actually fabricated and demonstrated at the AAAI show in Seattle in July, 1987.

Based on these investigations, conclusions have been reached and system requirements have emerged as follows:

1. There is no universal solution for mobility. Wheeled, indoor vehicles for laboratory application represent the largest near term market. Indoor mobility places size restrictions of 24-30" on outside dimensions parallel to the floor plane. Tile and carpet, obstacles to 1/4" in height, and 8% ramps must be navigated.

2. There is no universal agreement on wheel configuration or drive concepts. Two degrees of freedom seem adequate for most experiments. The simplest possible configuration is two wheel differential drive and this seems to reach the largest possible market.

Various, more complicated drive schemes might be offered over a period of time. Climbing stairs is of limited interest.

3. There is no agreement on payloads. In particular, arms and vision systems will tend to be unique to the objectives of the individual researcher. Therefore, a basic product should NOT include either arms or vision systems. Instead, a range of options might be offered over a period of time. A payload of at least 130 pounds (the weight of a PUMA 560 arm) and battery power to support substantial electronics and communications and to provide mobility for 6-12 hours between recharges is indicated.

4. There is no agreement on control hardware or software. Crowley's work on vehicle control was selected as a coherent design for an open architecture and was extended to explicitly allow point-to-point and continuous path control commands. No commonality was found on controls above the vehicle drive subsystem, which researchers are willing to treat as a black box.

5. There is agreement that the less expensive the better. DARPA identified a price between \$5,000 and \$50,000 in quantities of 100. TRC does not believe that there is a market for 100 research vehicles at the high end of this range. Between \$5,000 and \$10,000 is generally considered a reasonable price for a basic research vehicle. \$1000 is considered a reasonable price for an educational vehicle.

6. Some agreement on communications was found, at least for 9600 baud data communication. Communications requirements for vision data is not clear. The concept of providing support services to the researcher, particularly power support and communication support, has been proposed to TRC. This concept is developed below and will be expanded for a Phase II proposal.

A summary of requirements is given in Table 3-1.

Mobility: Wheeled; indoor; run on tile, carpet, ramps, run over wire, edges of carpets, elevator doors to 1/4". No requirement to climb stairs. Two degree of freedom mobility acceptable.

Size: Less than 30" wide to go through doorways and into offices. 6' height restrictions to get through door frame.

Weight: No restrictions.

Payload: 130 lbs or more. No definition of mechanical interface or distribution of payload.

Power: Battery, 12 or 24 Volt, at least 40 AH. Must run for at least 6 hours before recharging.

Control: Differential drive servoed steering with vehicle level control computer. Command set to include straight lines and turns with control of velocity and acceleration for point to point and continuous path motion.

Communication: 9600 baud data link.

Options: Arms, Computers, Cameras, Power Support, Communications Support, Proximity.

Cost: Less than \$10,000 for basic unit.

Table 3-1. Requirements Specification

4.0 Drive Concept Selection

Objective 2 of TRC's proposal was to Select a drive concept against the requirements identified under Objective 1. Many different approaches to mobility have been proposed and used. There is no approach that solves all problems, since different approaches have relative advantages and disadvantages in various applications.

As was stated above, TRC has chosen a two wheel differential drive concept as the simplest possible configuration for control and one that meets the needs of the largest number of researchers. Arguments for and against other concepts that were evaluated follow.

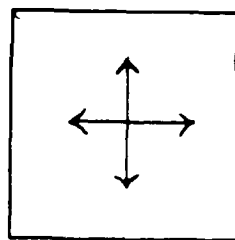
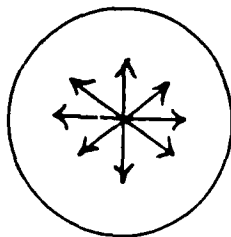
4.1 Vehicle Drive and Steering Configuration

Wheel and steering concepts have tremendous implications in terms of the complexity of the control system of the vehicle. This is evident after the fact to many researchers.

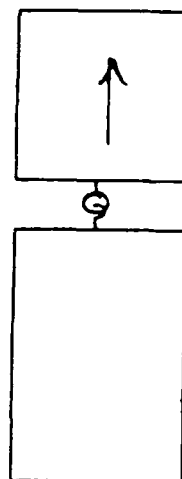
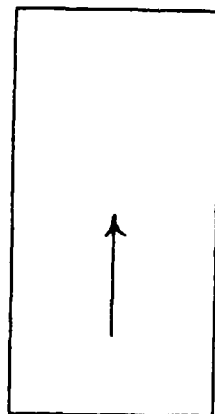
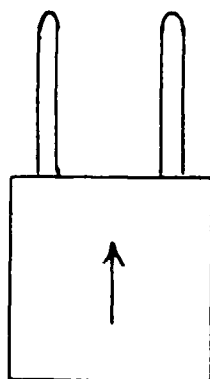
One of the best reviews of vehicle designs is from CMU [Muir and Neuman 86]. Unfortunately, the elegant kinematic control formalism that they develop is degenerate and not applicable to several common vehicle designs, but the overall kinematic analysis is elegant and useful. Several of the points that are made in that report will be repeated here.

The first consideration in evaluating a vehicle design is symmetry. If a robot is rotationally symmetric about a vertical axis, then a two degree of freedom drive system that provides translation and does not rotate the vehicle is optimum. If, as is usually the case, the robot is not rotationally symmetric because of directional sensors or arms or other tooling, then three degrees of freedom (two of translation and one of rotation) may be needed. Bilateral symmetry about a vertical plane aligned with the direction of motion is an optimum configuration in biological mobility and mechanics. Figure 4-1 diagrams rotationally and bilaterally symmetric vehicles. The arrows indicate directions of motion that maintain symmetry.

Figures 4-2 through 4-5 are configurations used in many research vehicles varying from two to six wheels and with two degrees of freedom. The two degrees of freedom are polar (r, θ) which come from differential steering, or translational (x, y) which come from "synchro" steering, or a mixed mode which derives from a separating the center of rotation from the steering mechanisms as in automobile or tricycle configurations.



Rotational Symmetry



Bilateral Symmetry

Figure 4-1. Rotationally and Bilaterally Symmetric Vehicles

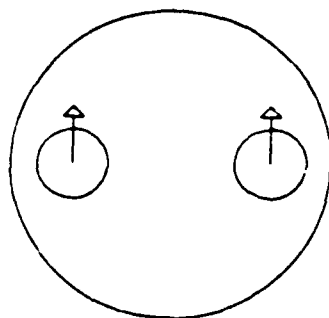
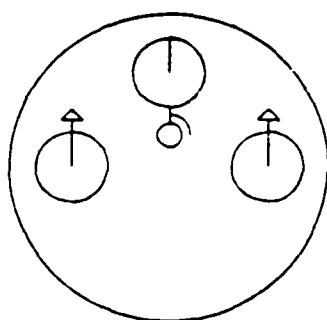
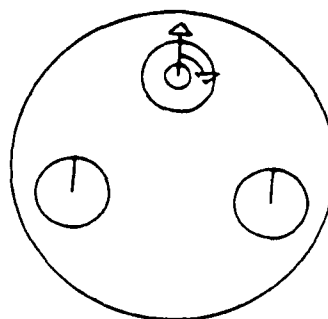


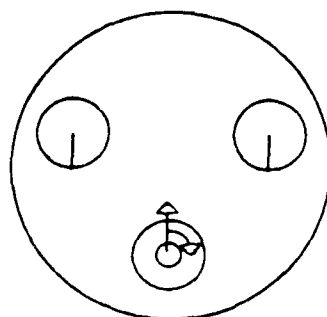
Figure 4-2. Two Degrees of Freedom, Two Wheels



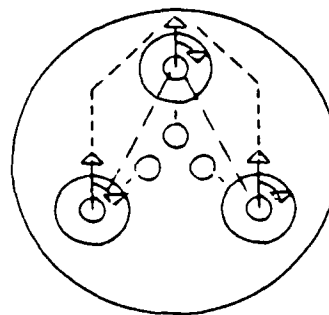
Differential Steering



Tricycle Steering

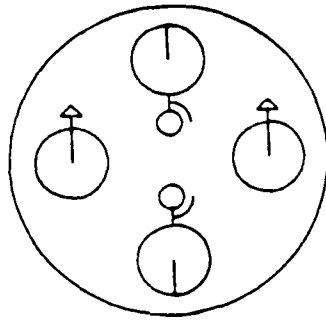


Tricycle

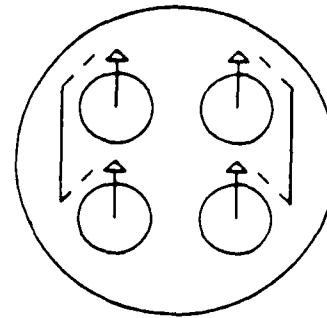


Synchro Drive

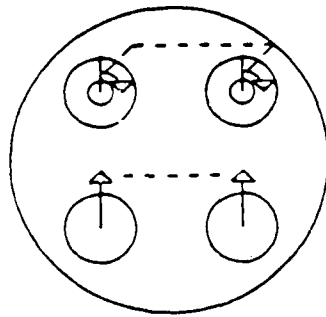
Figure 4-3. Two Degrees of Freedom, Three Wheels



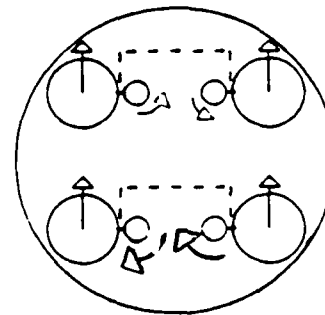
Differential Steering



Skid Steering

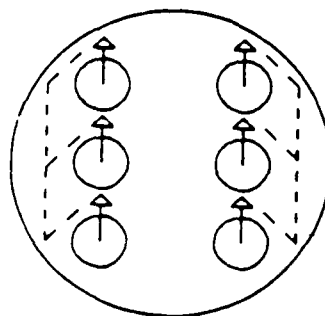


Automobile Steering



Forward and rear
wheel steering

Figure 4-4. Two Degrees of Freedom, Four Wheels



Skid Steering

Figure 4-5. Two Degrees of Freedom, Six Wheels

Differential steering uses a difference in rotation of the two drive wheels to rotate the vehicle about the mid point of the line between the drive wheels (the differential point). Driving the wheels together produces translation in the direction the vehicle is pointing. Control is accomplished by servoing the velocities of the drive wheels.

If the drive wheels are on the center axis of the vehicle, then both steering commands and motion are symmetrical from a control standpoint. This is the simplest drive concept from both a control standpoint and a mechanical design standpoint and hence is recommended to meet the desired objectives. At least one and preferably more than one passive wheel is needed to provide stability.

The two wheel system in Figure 4-2 is the TOPO from Androbot, Nolan Bushnell's former company, and the wheels are mounted with axles angled so the robot will not fall over on two points of contact. Another approach is two conventional wheels on a common axle with the center of mass below the axle. The robot in either case does "wobble" and hence does not provide a stable platform and these configurations are not recommended.

A four wheel (Figure 4-4) or six wheel (Figure 4-5) skid steering design is conceptually the same as two wheel differential steering but is not acceptable for an indoor vehicle from the standpoint of energy and potential damage in turning on carpet. Tracked concepts are rejected for the same reason.

"Synchro" drive or steering turns the wheels of the vehicles to all point in the same direction and then drives the wheels to produce translation. This can be accomplished with two motors linked to all wheels by belts or by shafts and gears. Denning, Cybermation, and Real World Interfaces have all adopted variations on this concept. The advantage of this concept is that the vehicle can translate in any direction with the body orientation fixed which minimizes energy for a symmetric body design. A turret or upper body can be rotated to point in the direction of motion, losing the energy advantage. Three wheels is most common (Figure 4-3), although four and six wheel designs have been described. It should be noted that this synchro drive is a two degree of freedom system, not three. Engineering problems with all of the implementations studied, mechanical complexity, and the problem of drift common to all of these systems leads to a rejection of this approach as a recommended design.

Tricycle or automobile (Figure 4-4) or wagon (bogie) steering produce a mixed translation and rotation. This arises from separation of the center of rotation, the differential point, from the steering wheels. Such arrangements are easy to control in the forward direction but not in the reverse. A variation is to steer both the front and rear wheels (Figure 4-4) symmetrically using an Ackerman linkage. This provides shorter turning radii, makes the center of the vehicle the center of rotation, and makes the control symmetrical.

Tricycle or automobile steering schemes are easy to control while moving in a forward direction if the sensing point is ahead of the differential point. In fact, they are unstable in reverse. A tricycle configuration is often chosen for an industrial automatic guided vehicle (AGV) and used in following a wire guide only going forward. A tricycle with the steering wheel in the rear (Figure 4-4) is used for fork lifts and pallet trucks with manual control. The lack of symmetry makes robot control more difficult and these approaches are not recommended.

Several approaches to three degrees of freedom are possible. One approach, which seems conceptually the easiest, is to have a third motor that rotates an upper body independently of the base. This should not be confused with an upper turret slaved to the steering motor in a synchro steering design. The upper turret must be completely independent of the wheel direction to provide a true third degree of freedom to allow, for example, rotation about an arbitrary external point while pointing a sensor or a tool at that point.

The second approach to three degrees of freedom is to independently point all wheels of the vehicle with separate steering motors to allow rotation about an arbitrary point as in Morevec's Pluto [Muir and Neuman 86 or Morevec 83]. This takes more motors and requires good position servos for steering and force servoed drives or single drive motor coupled to all wheels. Kuc at Yale has used force servoed drives with this configuration [Kuc 87]. Other approaches to three degree of freedom drives focus on wheels that can roll in any direction such as the Swedish and Stanford designs which were conceived for wheelchairs [Ilon 75; La 80]. The "Unimation robot" used La's design and the CMU Uranus used the Swedish wheel design. Mechanical complexity, cost, maintenance, and control problems lead to rejection of these designs.

Walking machines are not cost competitive with wheeled vehicles. Similarly, exotic active suspension systems are rejected because of cost and complexity.

The conclusion is therefore to adopt a two wheel differential drive scheme, a "turtle", as the simplest and lowest cost design approach consistent with the requirements of Table 3-1.

4.2 Mechanical Design of LABMATE Robot Research Vehicle

The mechanical design of TRC's LABMATE is shown in Figure 4-6. LABMATE has two powered wheels and four passive casters at the corners of the vehicle to provide stability.

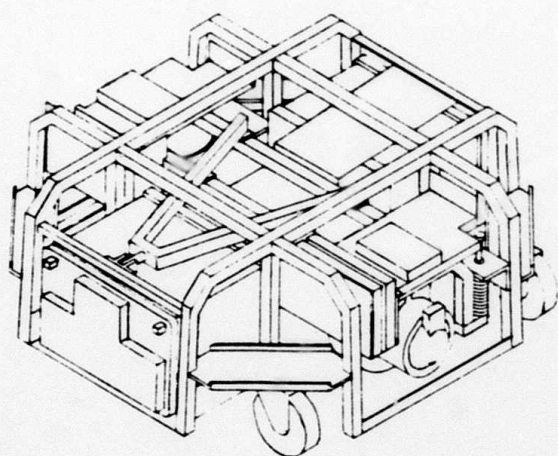
The drive wheels are mounted on an A-frame suspension linkage. One point of the linkage is a ball joint fixed to the vehicle frame. The other two points are affixed to the frame by springs. The force exerted by the springs is adjustable for different payloads. This suspension design provides positive traction of the drive wheels on non-planar surfaces and allows the LABMATE to be driven over cables, small obstacles, sills, and the edges of carpet without losing control or position registration. LABMATE has clearance and power to negotiate a 10% ramp.

The drive wheels have the motors and gear boxes mounted integrally in the wheel hub. The hard rubber tires have a measured coefficient of friction on linoleum tile of 0.65. 1000 line encoders are mounted on the motors.

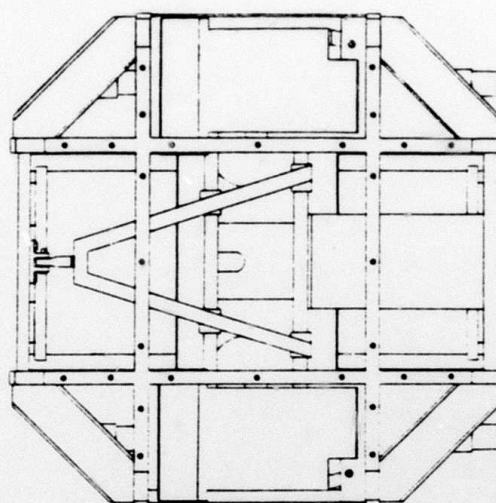
The frame of LABMATE is fabricated from welded tube steel with threaded inserts to provide attachment points for sensors and payload. Battery compartments are adequate for two 40 or 60 ampere hour sealed lead acid batteries.

The cover of LABMATE is a single piece of molded Kydex with four door panels for access to batteries and electronics. All interface points are brought to panels on the surface of the cover so the cover does not have to be removed for adding and integrating applications payloads.

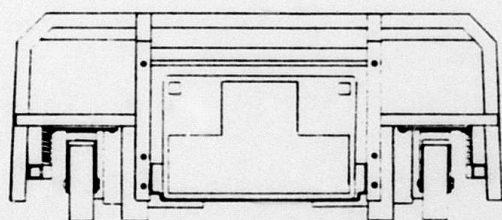
The mechanical design allows for packaging the electronics and the power amps in a sheet metal enclosure beside and above the drive motors. The specifications for LABMATE are given in Table 4-1.



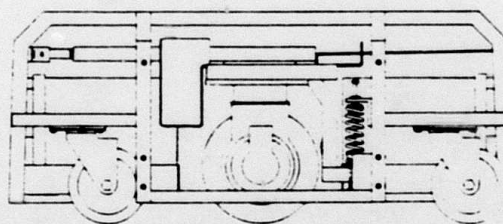
Isometric



Top



Front



Side

Figure 4-6. LABMATE Mechanical Design

SIZE:	11" x 27.5" x 29.5" (280 mm x 700 mm x 750 mm)
WEIGHT:	110 Lbs. (49 Kg.) (Less batteries)
LOAD:	200 Lbs. (90 Kg.)
SPEED:	0 - 40 in/sec (0-1000 mm/sec)
BATTERY POWER:	24 V (2 x 12V 40 AH or 60 AH batteries)
BODY:	High impact thermoformed plastic cover, over tube steel frame with multiple threaded inserts for mounting additional electronics or experimental equipment.
STEERING:	2 wheel differential steering on center axis with 4 passive casters and adjustable suspension.
FEEDBACK:	Encoders with .012 mm resolution per quad count.
DRIVE SYSTEM:	RS 232 interface, 9600 Baud 68HC11 based controls with 20 KHz PWM servos Open architecture to command: Velocity Straight Line Moves Turns, Zero to Infinite Radius Variable Steering for Sensor Based Control Programmable Acceleration Pause, Resume, and Emergency Stop Report Status
ACCESSORIES AND OPTIONS:	VME Card Cage 5V, +/- 12V Power Supplies Joystick Rate Gyro Proximity Sensors Warning Lights Battery Charger (Labmate sold without batteries) Batteries 12V 40 AH or 60 AH

Table 4-1. LABMATE Specifications

4.3 Drive Control Hardware

Objective 3 of our proposal was to define a control system for the mobile base that met the requirements specification developed under Objective 2. This task has consumed much of our engineering effort over the last year with the result of a very good general vehicle control system that solves a wide variety of application problems.

The basic concepts of the control are similar to the proposals of Crowley [Crowley 85a,b,c; Crowley 86; Crowley and Ramparany 87] and draw upon work by other researchers referenced by Crowley [e.g. Kanayama 85; Wallace et.al. 85].

The TRC vehicle control system uses the latest commercial components and is designed to provide an open architecture of maximum utility to the researcher.

The control electronics is shown in block diagram form in Figure 4-7. The vehicle control computer is a Motorola 68HC11 cpu which is a control computer designed for the automobile industry and executed in CMOS. This has proved to be a very good processor for subsystem development.

The servos are Hewlett Packard HCTL 1000 chips which provide digital servos with proportional, trapezoidal and integral velocity control modes. The HP chips have a programmable digital filter for closing a tachless servo loop and provide 20 KHz PWM output or linear output to the power stage.

The power stages are H bridges implemented with Motorola SenseFETs driven directly from the PWM outputs of the servo chips.

Safety and protection circuitry includes an active watchdog monitor circuit, fuses in the power circuits, and interlocks with bumpers.

LABMATE is designed to be controlled by a host computer. The vehicle control is a subsystem. A joystick for manual operation is an available option that is useful for moving LABMATE around the laboratory during development work. The host computer interface is a 9600 baud serial link.

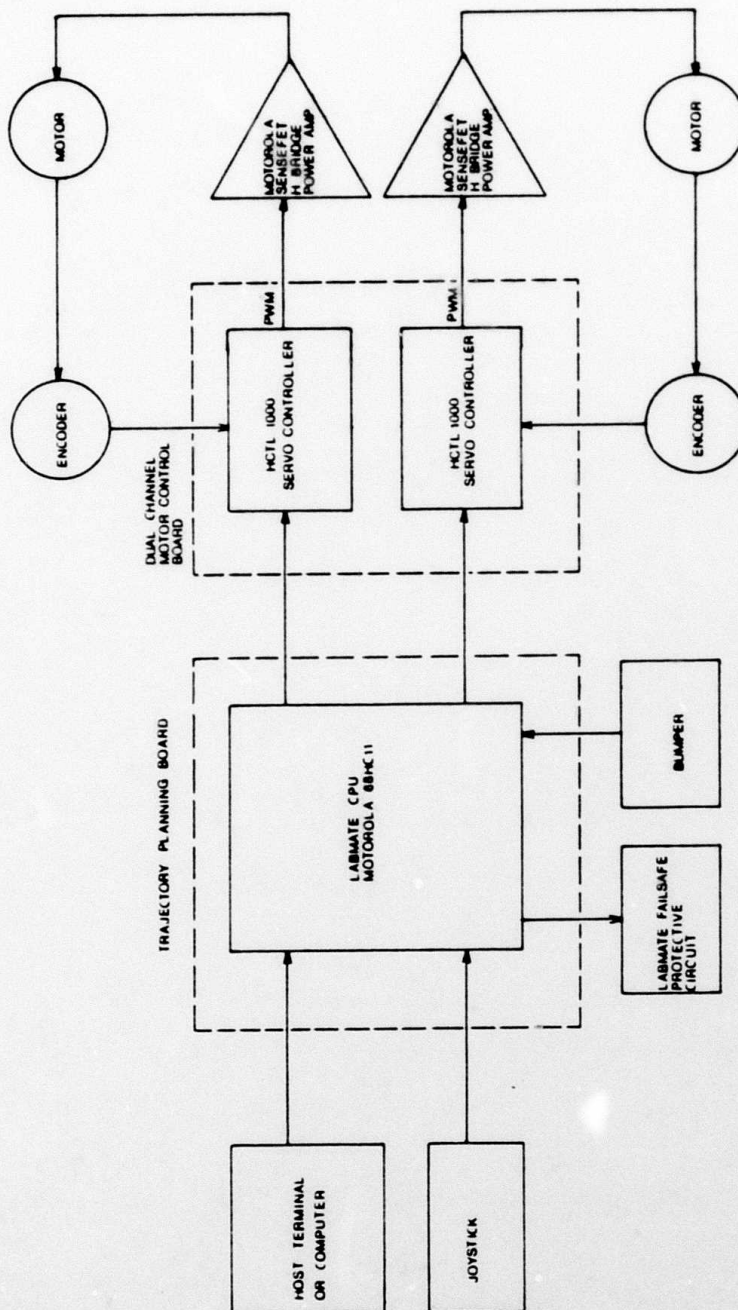


Figure 4-7. Vehicle Control System Hardware

5.0 Trajectory Control of Mobile Robots

Robotics researchers use test vehicles as controllable mobile platforms to conduct experiments in navigation, obstacle avoidance, sensing and other robot guidance techniques. The researcher is interested in controlling position, velocity, acceleration and direction of the vehicle from a "black box" point of view. Details of motor control, power and mechanical dynamics should be packaged within the vehicle control system, transparent to the researcher. Application interfacing should be in engineering units relevant to the researcher's experiments.

In the TRC LABMATE, drive controls are packaged as a black box from the researcher's point of view (refer to section 4.3). Figure 5-1 lists the commands available to the researcher to externally interface with the black box. These are divided into categories which include system initialization, point-to-point motion control, reporting, and continuous motion control.

00 = Initialize System	14 = Enable and Clear Encoder Heading
01 = Enable Joystick Mode	15 = Enable and Clear Gyro Heading
02 = Go (Continuous)	16 = Set Watchdog Timeout Value
03 = Turn (absolute)	21 = Read Position and Heading
04 = Turn (Incremental)	22 = Read Wheel Positions
05 = Go (point-to-point)	23 = Read Velocity
06 = Point-to-point Turn (absolute)	24 = Read Status
07 = Point-to-point Turn (Incremental)	31 = Emergency Stop
08 = Start a Continuous Turn	32 = Pause
11 = Set Velocity	33 = Resume
12 = Set Acceleration	
13 = Clear Position	

Figure 5-1. Labmate Control Command Set

The simplest control mode for robot vehicles is point-to-point straight line motion. The basic control strategy in this mode is to compute a goal point, turn in that direction, and go the required distance. This control mode is suitable for a wide spectrum of experiments. In many research settings, significant off-line computing time is necessary for image processing or sonar data processing to determine the next goal point; hence point-to-point strategy is sufficient.

For real time maneuvering, continuous path control is necessary. Straight line segments must be blended with curved arcs while maintaining velocity. Abrupt transitions of momentum or path curvature are neither physically realizable nor desirable. There are two different strategies for continuous path control. One is the execution of a planned path which smoothly blends distinct straight line and arc segments while maintaining velocity. The second strategy is servo control based on sensor feedback, such as sonar distance from a lateral wall. The control problem in the latter case is to program stable behavior which meets reasonable trajectory constraints; there is no path planning.

The following paragraphs develop the geometric and control theory of vehicle trajectory control, from the researcher's (external) point of view.

5.1 Point-to-Point Control

The Labmate robot base is driven by two fixed wheels using differential steering. The mechanical, geometric and control benefits of this widely used configuration are well known and described in section 4 of this report.

Point-to-point control consists of interleaved sequences of moves and turns, with a complete stop between elements. Straight lines and arcs of circles are natural move elements from the point of view of drive control commands.

5.1.1 Straight Line Segments

Point-to-point linear motion can be programmed by ramping up velocity at fixed acceleration "a" to a desired speed, then ramping down again. Distance travelled while accelerating is

$$D = a(t^2)/2$$

and velocity is $V = a*t$.

Units are millimeters and seconds for the Labmate.

Values of parameters can be derived by solving for any variable in terms of the others. That is, goal velocity or position may be given, or fixed acceleration may be specified, and velocity and distance derived. In practical terms, there is a limit to both velocity and acceleration, and reasonable trajectories will reach these limits. Thus a typical velocity profile consists of acceleration to maximum velocity, travel at that velocity, then a symmetric deceleration. Figure 5-2 illustrates the position and velocity profile. For obvious reasons, this is called a trapezoidal velocity profile and is commonly used in indexing control systems. The Hewlett-Packard servo chips have a trapezoidal mode that is used in executing these commands in the LABMATE drive controls.

If goal distance is specified, to be reached in the shortest time possible, control specification would be as follows.

$$V_{\max} = a \cdot t_1 = a \cdot t_3 \quad \Rightarrow \quad t_1 = t_3 = V_{\max}/a .$$

Hence,

$$D_1 = D_3 = a \cdot t_1^2 / 2$$

and

$$D_2 = D - (D_1 + D_3) .$$

Therefore,

$$t_2 = D_2 / V_{\max} .$$

In summary, the control sequence is :

- 1) Accelerate for $V_{\max}/a$ seconds
- 2) Cruise at maximum velocity for t_2 seconds
- 3) decelerate for $V_{\max}/a$ seconds.

The vehicle stops D units from its starting point. When a new goal point is computed (outside the vehicle control system), the robot may be turned θ degrees using a single command. Figure 5-3 illustrates a path composed of point-to-point straight line segments interleaved with pivot turns. Such turns are executed by driving one wheel forward and the other backward at the same velocity.

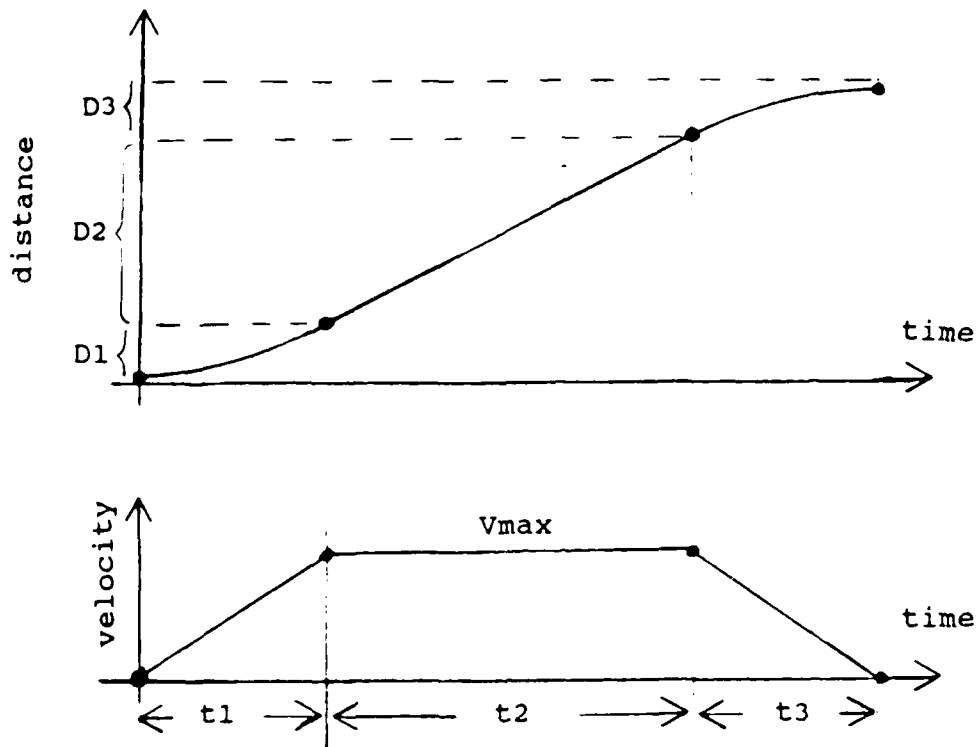


Figure 5-2. Velocity and Distance Profiles for Straight Line

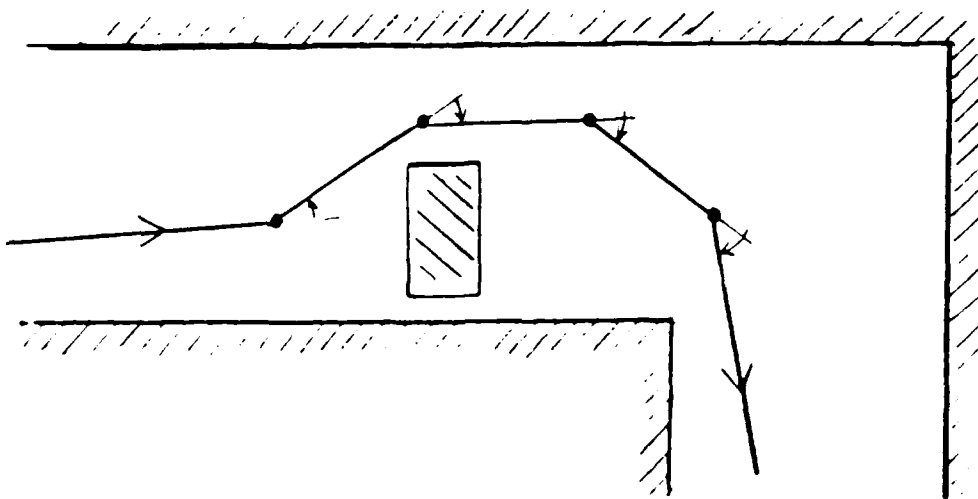


Figure 5-3. Point-to-point Control using Straight Line Segments

5.1.2 Circular Segments

Point-to-point control can also be augmented by adding circular arc segments to the repertoire, as illustrated in figure 5-6. Such segments are executed by driving the two wheels at different velocities. Figure 5-4 illustrates the geometry of circular arc motion. From proportionality of arcs A1, A, and A2, velocity of the center of the vehicle is

$$V = (V1 + V2)/2$$

and radius of curvature is

$$R = 2hV/(V2-V1)$$

where h is the half-width of the drive wheel base and radius of curvature is always measured from the midpoint of the two wheels, which is the geometric center of the vehicle. Note that radius of curvature is proportional to velocity and inversely proportional to the difference in velocities. Thus in ramping up from zero velocity, the right and left wheels must be accelerated at different rates. Using trapezoidal control mode, these accelerations are fixed, and proportional in the same ratio as V2 and V1 for the desired radius of curvature. That is,

$$V1 = a1*t$$

and

$$V2 = a2*t$$

where

$$a1 = a_{max} * V1/V2$$

i.e., choosing the maximum possible rate of acceleration for the outer wheel, consistent with the desired curvature.

In practical implementations, the velocity of the outer wheel of the vehicle may often reach the maximum velocity mechanically possible. Figure 5-5 illustrates the trapezoidal drive velocity profile for this case, applying the preceding equations for V1 and V2.

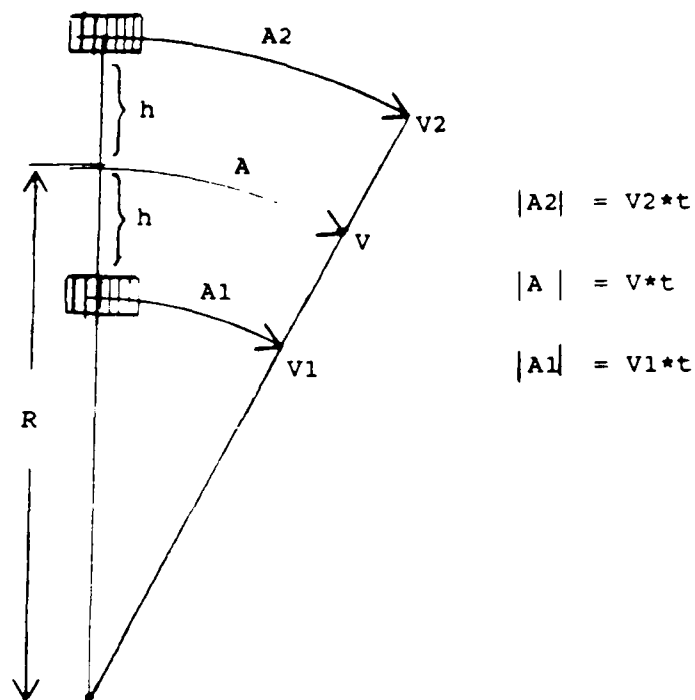


Figure 5-4. Circular Arc Vehicle Trajectory

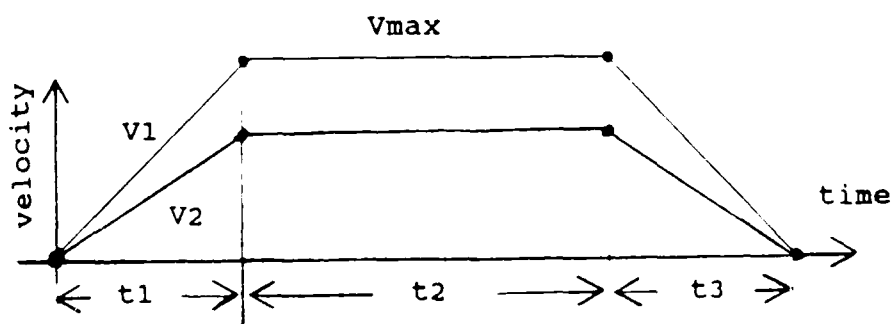


Figure 5-5. Velocity Profile for Circular Arc

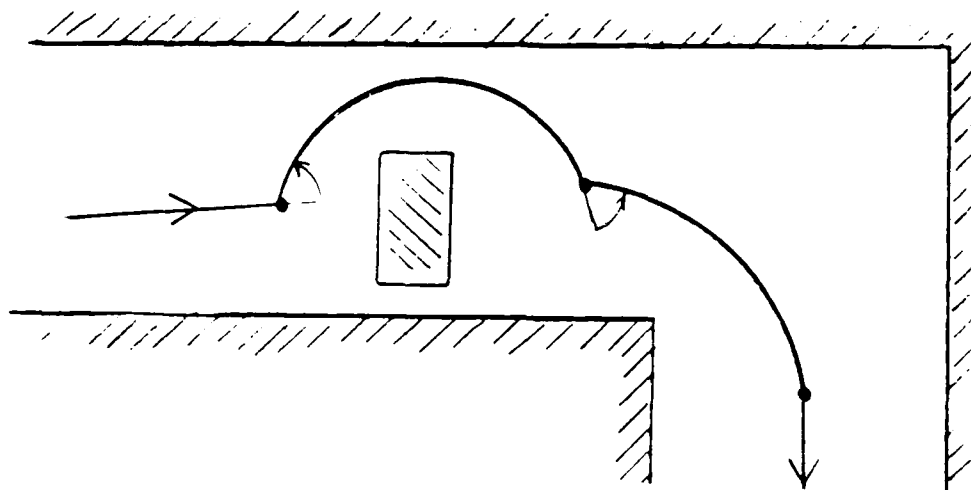


Figure 5-6. Point-to-point Control using Circular Arc Segments

Substitution of V_{max} into the equation for radius of curvature preceding yields expression of minimum radius of curvature possible for a given forward velocity V as

$$R_{min} = h / (V_{max}/V - 1) .$$

For example, if the vehicle is moving at half speed ($V = .5 * V_{max}$), then $R_{min} = h$ and the inner wheel stands still ($V_1 = 0$) while the outer moves at V_{max} . The converse problem is to express maximum forward velocity for a given radius of curvature as

$$V = V_{max} / (1 + h/R) .$$

For example, to achieve a radius of curvature equal to the width of the vehicle ($2h$), velocity must be slowed to $2/3$ of V_{max} . If the inner wheel is driven in reverse, radii less than R_{min} are achieved. In fact, $R = 0$ may be commanded, which results in one wheel driving forward and the other driving in reverse at the same velocity. When a turn is commanded that will result in velocity above the commanded or default value, the velocity command is overridden.

Net angle of turn may be controlled by rearranging the equations discussed above to solve for t or other parameters of choice, such as distance travelled. For example, for fixed radius of curvature R , angle turned is D/R , where D is distance travelled. D may be solved by integrating forward velocity

$$(V_1(t) + V_2(t))/2$$

with respect to time, t .

5.2 Continuous Motion Control

An ultimate goal of robot vehicle control is to transcend the jerky motion of point-to-point control by smoothly changing direction under continuous motion. This mode increases operational efficiency (lower energy consumption, quicker task completion) in applications, and is a requirement for robotic aircraft, which cannot stop in mid-air.

There are two strategies for continuous motion control. The first is to follow a planned trajectory, blending direction and speed across different segments. The second is to control vehicle motion using sensor feedback. Examples include visually tracking a moving target, or following a lateral wall at a controlled distance using sonar. Both motion control strategies are discussed in the following paragraphs.

In the planned trajectory strategy, power and inertia constrain path transitions. Energy and inertia constraints preclude instantaneous changes in either direction or velocity; these would require infinite impulses of acceleration. Thus position and velocity of individual wheel drives and vehicle must be continuous.

The blending of path segments with differing positions and slopes is a problem which arises in a number of engineering applications. In computer graphics and surface design, spline curves are used to match position and first and second derivatives with respect to spatial coordinates. In civil engineering, the "railroad curve",

$$y = bx^{**3}$$

is used to blend straight track into curved track, avoiding a discontinuity in angular momentum which would result from transition from a straight line to a tangent circle. Both types of blending are expressed in spatial coordinates. In mobile vehicles, it is more natural to address continuity in the domain of vehicle dynamics, with control expressed in terms of velocities of the differential drives, V_1 and V_2 .

Recall from the preceding discussion of circular arcs that the sum and difference of drive wheel velocities V_1 and V_2 are linearly related to forward velocity V and curvature $1/R$, respectively, of vehicle trajectory. Integration of velocity over time yields path length. Path length, s , and curvature, $c(s)$, are the so-called "natural" parameters for

the differential geometric expression of any curve. These can be integrated to yield the path of the robot as:

$$x = \int_0^s \cos \left(\int_0^s c(s) ds \right) ds$$

$$y = \int_0^s \sin \left(\int_0^s c(s) ds \right) ds$$

where c is curvature, $1/R$. Thus, history of drive wheel velocities yields vehicle trajectory. At first sight, the task of continuous motion control appears to be the derivation the natural equation of the curve from trajectory equations, and translation of the results into velocity command sequences. This would require computing and transmitting a rapid-fire stream of drive commands approximating the trajectory in short discrete segments. A more efficient approach is to choose, as building blocks, curvature transition profiles which correspond to simple drive commands of reasonably long duration. Computation and communication loads can thereby be reduced by at least an order of magnitude. The following paragraphs describe such a scheme, based on the efficiency of trapezoidal velocity control.

5.2.1 Clothoid Curves and Curvature Transition

Kanayama and Miyake (1985) wrote a landmark paper on curvature transition for robot control. Their analysis was based on trajectories whose curvature is proportional to curve length, that is,

$$c(s) = ks$$

where k is a constant proportional to differential acceleration of drive velocities.

Direction of the curve is the integral of curvature, namely,

$$\theta(s) = k*s^2/2 .$$

Thus, the trajectory is expressed by the Fresnel equations:

$$x = \int_0^s \cos(k*s^2/2) ds$$

$$y = \int_0^s \sin(k*s^2/2) ds$$

The (x,y) locus above is known in geometry as a Clothoid curve. Continuing a Clothoid through a number of complete revolutions of theta yield the Cornu Spiral, illustrated in [Rektorys 69] and [Kanayama 85]. Their relation to two wheel differential drive robots is summarized below.

Velocity transitions are efficiently executed in the Labmate by commands to set acceleration to a fixed value. If one wheel is accelerated at the same rate that the other is decelerated,

$$V1'(t) = V1 - at$$

and

$$V2'(t) = V2 + at.$$

Thus, average velocity remains constant, namely

$$(V1' + V2')/2 = (V1 + V2)/2 = V .$$

Curvature, $1/R$, is

$$(V2' - V1')/2hV = (V2 - V1 + 2at)/2hV .$$

If the starting trajectory is a straight line, then

$$V1 = V2$$

and curvature is

$$at/hV = aD/hV**2.$$

Thus curvature is proportional to distance travelled D and the trajectory is indeed a Clothoid Curve. Note that the rate of change of curvature is proportional to acceleration " a ". It can be shown that all clothoid curves are similar. The Fresnel integrals do not have a closed form solution. Since all Clothoids are similar, a one dimensional table of values of the integral can be computed numerically for x and y as functions of s . Results can then be scaled by acceleration " a ".

Figure 5-7 illustrates the transition from one straight line segment to another using Clothoid and circular arcs. Segment A is a straight line deceleration which reduces the velocity the necessary amount to achieve the desired curvature of the central arc, specified in advance under user choice as $1/R$. Segment B is a clothoid which transitions curvature to $1/R$. Lookup in the Clothoid table yields the value of x and y at which that curvature is achieved. The direction θ of the tangent at this point is the value of an integral of curvature which started accumulating when B started. The circular arc C commences and goes until θ is forty-five degrees. Then C' is traversed, duplicating the duration and velocity values used in C. Then follows a clothoid arc B', opposite in sign of acceleration to B. Similarly, A' is the time-mirror image of A.

The values and times for the segments in figure 5-7 can be computed for arbitrary line segments to be blended. Once R , a , V_{max} and V are given, the lengths of all segments are uniquely determined. Figure 5-8 illustrates the history of differential drive wheel velocities which yield a path such as illustrated in figure 5-7. Arcs A, B, C, C', B' A' correspond in both figures.

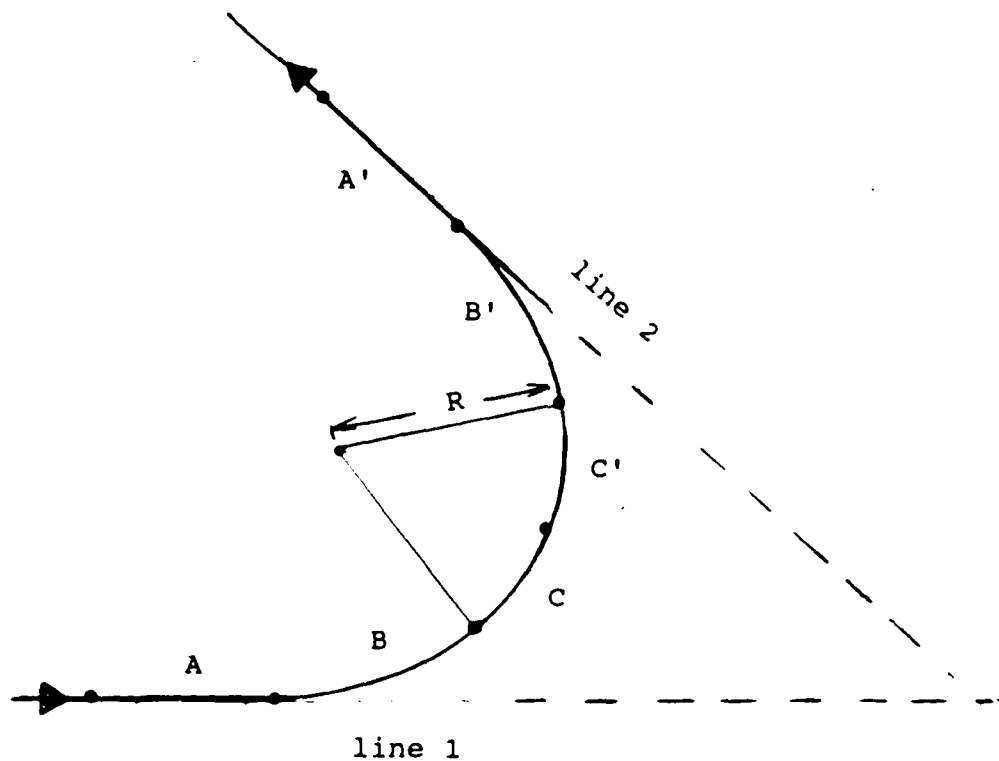


Figure 5-7. Clothoid Blending of Two Straight Lines

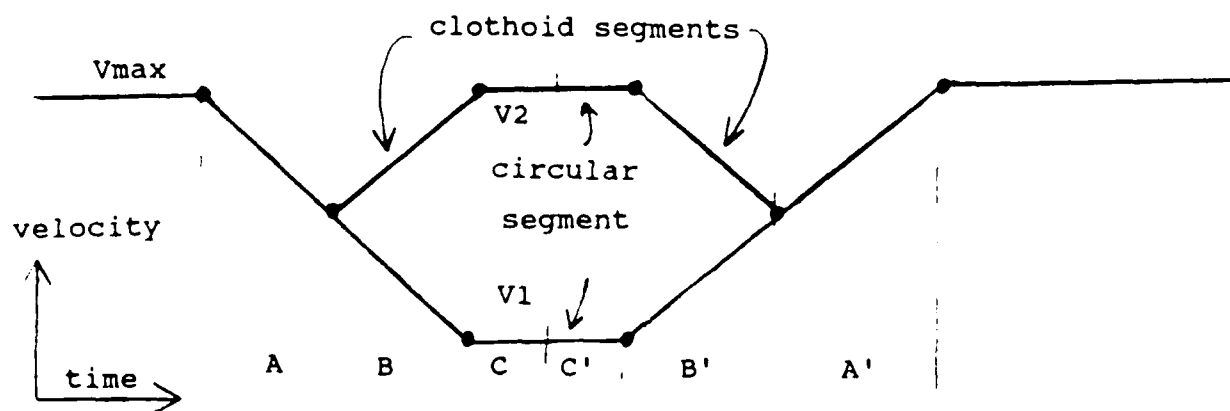


Figure 5-8. Wheel Velocity Profile for Clothoid Blend

5.2.2 Trajectory Control by Sensory Feedback

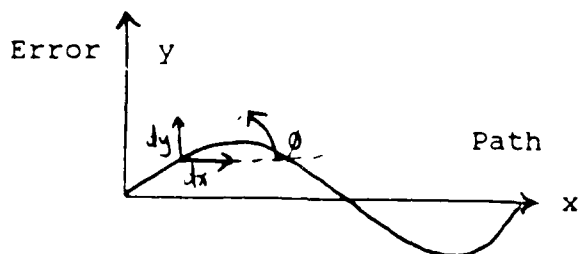
To navigate without reference to a map, it is possible to maneuver with reference to sensor observations of the environment. This includes visually tracking beacons, tracking a path on the floor or maintaining fixed distance to a lateral wall while travelling down a hallway. Point-to-point control based on successive observations is a simple approach. Continuous motion control can be achieved by treating sensor measurements as feedback signals. Analysis follows.

[NOTE: The bulk of the recent publication on mobile robots is contained in proceedings of two annual conferences: The IEEE Robotics and Automation Conference and SPIE fall conferences on vision and robotics. The reader is referred to those proceedings since 1985 for further background reading.]

To continuously servo on an external reference signal, such as the error in tracking a wire guide or a wall or a road, it is necessary to develop a way to continuously adjust the motion of the vehicle to correct any errors in path position. This is the use of the JOG command. JOG slows down one wheel and speeds up the other to initiate a rate of turn of the vehicle without changing the average straight line velocity. Small errors can thus be corrected in straight line motion without using dead reckoning turns. JOG commands can be sent to the vehicle control at rapid rates, including during execution of another JOG, so a continuous control mechanism is provided to change behavior.

Assume a higher level supervisory computer running a navigation system for the vehicle using a sensor system that measures vehicle position with respect to some external reference. We will develop a theory of steering based on servoing against the error in that external measurement. This formulation is based on fundamental wire following technology for automated guided vehicles (AGV's) that goes back several decades and on more recent work on steering autonomous vehicles such as [Wallace 85] or [Crowley 86].

Consider the actual path of the vehicle about the desired path to be a space harmonic wave of wave number k . Assuming that the steering function is able to keep the amplitude of the disturbance small (a few centimeters deviation from the desired path over meters of travel) then we will use small angle approximations for trigonometric functions in the following equations.



$$\sin \phi \approx \phi = dy/dx$$

Path following error = y

Trajectory $y = A \sin(kx)$

$$k = 2\pi/\lambda$$

A servo system would then be represented as

$$d\phi/dt = -Ky \quad (1)$$

$$d\phi/dt = d\phi/dx * dx/dt = v d\phi/dx = v d^2y/dx^2$$

$$\frac{d^2y}{dx^2} = -\frac{K}{v} y \quad (2)$$

This is an undamped oscillation which does occur for position sensing at the differential point of the vehicle (the mid point between the drive wheels about which the vehicle turns). Damping can be provided in two ways. First, if the error measurement is made in front of the differential point a distance a, then the sensed error is

$$D = y + a \sin \phi \approx y + a\phi$$

$$dD/dt = -KD = -Ky - Ka\phi$$

so the equation of motion is:

$$v \frac{d^2y}{dx^2} + Ka \frac{dy}{dx} + Ky = 0 \quad (3)$$

which is the equation of a damped harmonic oscillation (for positive a). If the location of the sensor is variable, a can be adjusted to provide whatever vehicle dynamics are desired. If a is fixed or limited (by the physical size of Labmate, for example), then an explicit damping term may be desired:

$$d\phi/dt = -K_p D - K_d dD/dt \quad (4)$$

Which leads to the dynamic behavior described by

$$(v + K_d av) \frac{d^2 y}{dx^2} + (K_p a + K_d v) \frac{dy}{dx} + K_p y = 0 \quad (5)$$

Experience at TRC has shown that an explicit damping term is usually desirable for visually smooth path control.

Control of the vehicle is accomplished as follows:

1. Calculate error (in cm or mm) and rate of change of error (in cm/sec or mm/sec).
2. Multiply by proportional and damping term gains (units of gain are deg/sec per cm and deg/sec per cm/sec, or equivalently in terms of mm and mm/sec)
3. Calculate $d\theta/dt$ according to equation (1) or (4) above.
4. Truncate to integer degrees/sec.
5. Send a JOG command to the vehicle using this parameter.
6. Repeat (useful loop rates are 50-500 msec.)

Wallace discusses the same concept for road following with a slightly different formulation, but the same result. An interesting simplification is that if the direction of the vehicle can always be pointed at the desired path at a fixed distance in front of the vehicle, the system is unconditionally stable. This is a "little red wagon" type of steering system. Considering dynamics leads to equations similar to those above, critical damping occurring at

$$g = RK = 4v/R$$

This is the same as our equation (3) above with $a = R$ and no explicit damping term. The conclusion is that once the vehicle dynamics are set, gain should be varied with velocity to hold those dynamics.

5.3 Managing Position Uncertainty

Position inference based on wheel encoders is subject to digitization error and wheel slippage errors. Both tend to accumulate with time. Reference to sensor data can correct such accumulated errors, but sensor data is also uncertain because of finite sensor resolution and variations in measurement environment. Magnitudes of uncertainty from all sources can be statistically quantified by experiments.

Crowley (1987) has analyzed the strengths and weaknesses of a variety of approaches to position uncertainty for mobile robots. He suggests that the best solution to the problem of estimating uncertainty is to treat position uncertainty in a two dimensional maneuvering space as a bivariate normal distribution. The algebra of combining uncertainty can be expressed in the formalism of Kalman filtering. In some cases compounding uncertainty worsens error. In other cases, the uncertainty can be significantly reduced by combining measurements. This multivariate phenomenon is analogous to the familiar one-dimensional example of reduction of estimated variance by a factor of $1/n$ for n samples of a statistical variable.

Figure 5-9 illustrates the reduction in uncertainty derived from two gross measurements of position based on visual beacon measurements. The location of the vehicle is precisely known in vehicle position 1 (solid dot in center of vehicle). From position 1 a beacon is observed. The large ellipse characterizes the distribution of uncertainty, say at the level of one standard deviation. Range measurement is based roughly on visual subtense and is therefore not as precise as bearing measurement. The robot vehicle then moves to position 2. Encoder based estimates of this position are subject to the uncertainty indicated by the dashed circle drawn within the outline of the vehicle. The beacon observation uncertainty from position 2 is indicated by the solid ellipse so labelled. The circumscribing dashed ellipse indicates the compounding of the visual observation with the uncertainty of the encoder based estimate of position. The hatched ellipse at the intersection of the beacon observation ellipses indicates the net compounded and reduced uncertainty of estimate of beacon position, relative to the initially known position 1 of the robot vehicle.

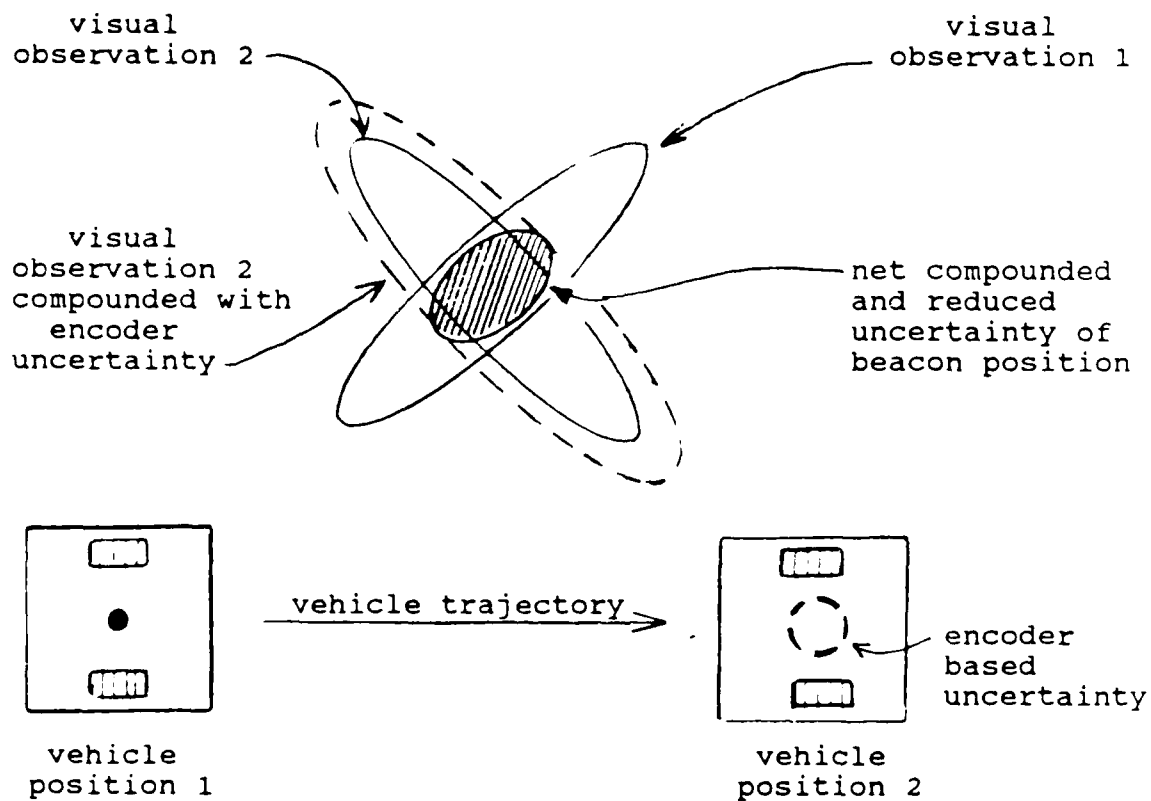


Figure 5-9. Reduction of Uncertainty from Two Measurements

Net uncertainty can be continuously updated in real time using Crowley's method. Computation is relatively simple, consisting of adding, inverting, or multiplying bivariate covariance matrices. Figure 5-10 illustrates the matrix operations which correspond to the growth and shrinking of uncertainty, respectively. The capital lambda symbols are 2-by-2 covariance matrices characterizing geometric uncertainty on the 2-D maneuvering space of the robot. Geometric constraints such as the straightness of walls and the invariance of environmental positions of fixed objects can be used to refine and reduce uncertainty in a predictable manner. This type of position uncertainty management is critical to sensor based navigation, whether or not a map is used as the basis of navigation.

Compounding

Uncertainty:

$$\Lambda_{om} = \Lambda_o + \Lambda_m$$

Reducing

Uncertainty:

$$\Lambda_n = [\Lambda_m^{-1} + \Lambda_o^{-1}]^{-1}$$

Figure 5-10. Combining Uncertainties

6.0 Communications

The fourth objective in the proposal was to define a communications system for the vehicle against design requirements. Progress has been made in this area, but due to a lack of definition of requirements here, no final solution has been chosen. Instead, a range of options will be offered to the user to select the most appropriate for a given application.

Radio Frequency (RF), infrared, and wire or fiber optic cable have been evaluated for use in communicating with LABMATE. The communications rate, usable range, and cost of the system will dictate which method is most appropriate for a particular application.

6.1 Radio Frequency Communications Technology

RF is suitable for video, analog, and digital information transmission. The use of RF for video transmissions will be covered later in this section. Digital and analog information is usually transmitted in the 45 Mhz to 900 Mhz frequency range. Digital data can be transmitted at rates up to 9600 baud over several hundred feet to several thousand feet. The range is significantly reduced if buildings or walls are between the transmitter and receiver. Also, the receiver module must be shielded from external sources of EMI/RFI generated by computers and switching power supplies. Ineffective isolation of the receiver will result in loss of sensitivity and possible susceptibility to unwanted signals.

An FCC license is required if the power output is higher than approximately forty milliwatts. This process can be complicated and take as long as ninety days. Forty milliwatts of power will give a range of several hundred feet. Five hundred milliwatts of power will yield a range of several thousand feet.

The price range for this equipment will be between \$2000 to \$12,000 depending upon communication range, speed and whether a simplex or full duplex link is required. Repco Inc. manufactures a full line of commercial grade RF modems for transmitting serial digital data. Rematron Inc. manufactures a line of RF telemetry modules for transmitting analog and digital data.

A very nice wireless modem from ASR in Japan was discovered costing only \$1000 and providing 9600 baud full duplex communication. Unfortunately, this unit operates in the 120 MHz aircraft communication band and cannot be licensed in the United States. Robosoft in France has bought several of these units and is trying to engineer a version to run at an acceptable frequency band. TRC will maintain contact with Robosoft to see if this produces a useful solution.

6.2 Infrared Communications Technology

A system using infrared technology can be developed which would allow communications with Labmate anywhere an infrared transceiver module could be located. This approach is being used by TRC in an elevator control application. A mobile robot calls an elevator car by communicating with an infrared transceiver located in the ceiling. Once inside the elevator the robot communicates with another infrared transceiver to select the destination floor. All ceiling mounted transceivers are wired to a central elevator control computer.

A typical infrared transmitter uses a gallium aluminum arsenide (wavelength of 880 nm.) or gallium arsenide (wavelength of 920 nm.) light emitting diode. The diode is pulsed at about 40 kilohertz providing a carrier which is either amplitude, pulse code, or pulse width modulated. Using the high frequency carrier enables the receiver to filter noise from TV's, lights, and other sources which emit infrared radiation as well as visible light.

The receiver incorporates a PIN photodiode to detect the transmitted signal because it has the required response time that is not available in phototransistors. An IR pass lens is used to filter out the visible light spectrum because, although the photodiode's response peaks at IR wavelengths, it responds in lesser degrees to radiation from 500 to 1100 nm.; often the lens is built right into the diode component.

The receiver is generally a much more complex device than the transmitter. It not only has to contend with demodulating the transmitter's signal, but must do so over a wide range of power sensitivity. At very close range (e.g. one inch) the receiver must adjust the sensitivity with a DC emitter to avoid diode saturation. At long ranges (10-30 feet depending on beam angle), a very high sensitivity and high noise rejection is required to assure signal detection.

Codenoll Technology Corporation markets a very high end "line-of-sight" communication link that uses IR to transfer data at 100 Mbaud for distances of up to 400 feet. TRC has developed a low cost IR transceiver prototype that provides a 2400 baud remote communication link to a mobile service robot. The link has performed well at distances of 30 feet with a field of view of plus/minus thirty degrees. Further modifications are expected to increase the baud rate to 9600 and provide more symmetric reception and transmission envelopes.

6.3 Wire and Fiber Optic Communications Technology

A cable link to the Labmate is normally only usable over a short distance (of the order of a few meters) before the cable becomes entangled with the vehicle or objects in the room. A solution to this problem can be found in a spring loaded reel which feeds and retracts the cable automatically.

The military is using a similar approach to control a remotely piloted missile. A video image for targeting purposes is transmitted back to the operator via a fiber optic cable attached to the missile. The cable is automatically fed by a constant tension reel.

This type of mechanism is being used by TRC to feed the AC power cord on a prototype vacuum cleaner. In place of the power cable we can have a RS-232 cable and/or video cable. A fiber optic cable can also be used if light weight or long lengths (greater than thirty feet) of cable are required.

Fiber optic systems are capable of transmitting video, audio, digital and analog signals. Digital information can be transmitted at speeds up to 10 megabits per second over a 1000 meter distance. Analog systems have a five megahertz bandwidth with fifty db of dynamic range over a 3000 meter distance. Audio combined with composite or NTSC video signals can also be sent over 3000 meter distances. The electronics cost for a simplex link should be under \$1000. Cable costs would be approximately one dollar per foot. Math Associates Inc. offers a broad range of fiber optic components.

6.4 Video Communications Link

This is the area that provides the greatest engineering problems and the fewest defined requirements.

Off the shelf equipment designed for television broadcasting is available at a price.

For example, a 250 mW transmitter and matching receiver operating at 2 GHz is available from Broadcast Microwave Services for \$13,000. This would provide single channel video with an audio subcarrier which could be used for sensor data.

Besides the transmitter and receiver, antennas are needed. Antennas include omnidirectional and fixed or steered dishes. BMS sells an autotracking antenna system to track on news helicopters that would be suitable for many outdoor mobile robot projects.

Experiments with stereo TV would require two channels to transmit video. For such an application, the video links become by far the dominant cost of the system.

Choices available to the researcher are thus one or two microwave channels or a cable link to off-board vision processing or on-board vision processing. No one approach represents any sizable market for a commercial product. Custom engineering services or engineering by the research group itself seem the only solutions.

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8.0 Phase II Plans

TRC has achieved success during Phase I in designing a low cost mobile robot to support research in AI. We have discussed requirements with numerous researchers, we have introduced a basic vehicle as a commercial product at the lower end of the target price range, and we have identified additional useful developments.

TRC intends to submit a Phase II proposal to continue work on developing a low cost mobile robot to advance research in artificial intelligence and engineering of mobile robot systems.

The basic approach that we are planning for a Phase II proposal is as follows:

1. The most significant outcome of the Phase I work is an understanding of vehicle control and the development of the lower level hardware and software of a vehicle control system. We believe we are in a cost leadership position in controls at the moment. The lower level control issues and how they support higher level navigation are very important and we intend to publish and disseminate this information during Phase II.

2. A viable mechanical design has been developed and packaged for sale. Additional options for greater application utility and cost reduction engineering are needed. Specifically, power support and communications support subsystems need to be provided to the researcher. These options would be 110 V from an inverter and 9600 baud bidirectional radio or IR links. Additional options would include more battery capacity, three degrees of freedom of motion provided by independent wheel steering or an independent turret, and a camera subsystem with pan, tilt, and possibly zoom and iris control, and mechanical packaging for all of these options.

3. There is no consensus on requirements for a single vehicle that would meet all research objectives. The feedback on LABMATE is good to excellent, but LABMATE does not support all research programs. Therefore, a range of vehicles with a common control system will provide the greatest impetus to research and will allow sharing of software and comparing of results. CMU, in providing inputs for this report, requested an outdoor version of LABMATE, noting that Terregator takes a large crew to run experiments. A version of LABMATE that could run on sidewalks and over curbs would meet this need.

A gasoline powered vehicle for extended all terrain use, and a very small indoor vehicle for student use would round out a family of vehicles. Concepts will be developed and evaluated during Phase II.

4. There is no consensus on arms. TRC is working on several designs that could be added to a mobile base. A better approach would be to provide the researcher directions for mounting a PUMA arm on the base, since the PUMA is the most widely used research arm. Alternatively or additionally, when the DARPA ARM (Advanced Research Manipulator) is available, it could be mounted on a LABMATE base for experimentation. Development of a support and mounting kit for one or both of these approaches will be evaluated during Phase II.

5. One area of interest identified by several universities and many industrial researchers is the coordinated control of multiple vehicles. This problem arises in all military applications, including tank (or anti-tank) squadrons, aircraft squadrons, and ship and submarine fleets. TRC intends to organize a Workshop during Phase II to address sensor and control requirements for multiple vehicle control. It is recommended that DARPA supply multiple identical vehicles to several research groups and organize a competition to focus attention on vehicle control problems. Either a military competition (e.g. Laser Tag between tank squadrons) or non-military competition (e.g. soccer with teams of robot vehicles as proposed by Professor Meystel) could be undertaken. Limiting bandwidth to the human control team keeps the focus on autonomous control rather than supervisory control.

These themes will be developed for the Phase II proposal.