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AUTONOMOUS LAND NAVIGATION: A DEMONSTRATION OF RETROTRAVERSE

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P. R. Klarer

Sandia National Laboratories
Advanced Technology Division 5267
P.O. Box 5800
Albuquerque, New Mexico 87185
(505) 846-2974

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ABSTRACT

This paper describes a hardware and software system developed to perform autonomous navigation of a land vehicle in a structured environment. The vehicle used for development and testing of the system was the Jeep Cherokee Mobile Robotics Testbed Vehicle developed at Sandia National Laboratories in Albuquerque. Since obstacle detection/avoidance has not yet been incorporated into the system, a structured environment is postulated that presumes the paths to be traversed are obstacle-free. The system performs path planning and execution (following) based on maps constructed using the vehicle's navigation system and onboard map-maker. The system configuration allows a map to be generated and stored during teleoperation of the vehicle, which may then be inverted and autonomously followed to perform a "retrotraverse" back to the path start point. The system software, hardware, and performance data are discussed.

INTRODUCTION

Autonomous navigation for land vehicles is currently a subject of research at several major government and academic institutions around the world. Most efforts are directed towards solving navigation through the use of vision-based systems to plan and execute path traverses, and to detect and avoid obstacles [1],[2],[3]. Alternatively, the system developed at Sandia National Laboratories relies on a set of road maps stored in onboard computer memory as lists of x,y points. This method inherently introduces structure to the operating environment by defining traversable paths and enabling that information to be stored and recalled at will. In particular, this allows any path to be recalled and inverted (used in reverse order from that in which it was originally stored), so that the path may be followed from the end point back to the original start point. The technique is referred to as "retrotraverse", and has particular usefulness in proposed battlefield robotics applications [4]. The utility of a retrotraverse capability is evident in any hazardous environment where the possibility of a communications dropout exists. Upon confirmation by the vehicle's onboard computer that communication with the remote control facility has

failed, the retrotraverse will bring the vehicle back to the start point autonomously and eliminate the need to retrieve the vehicle using another robot or humans. This technique uses sensors and sensor fusion to estimate the vehicle's position and orientation, but as yet provides no obstacle detection capability. As part of a phased development plan, obstacle detection and avoidance are left for future work, and the mapped roads are assumed to be free of obstacles. This work is a continuation of previous efforts to perform retrotraverse [5]. The following describes a system for autonomous land vehicle navigation which incorporates position estimation, map making, and path following, in software and hardware onboard the vehicle.

SOFTWARE

The autonomous navigation software resides entirely onboard the vehicle, and performs four major tasks: current position estimation, map making, path retrieval, and path following. Data from several sensors are combined using sensor fusion techniques to improve the signal to noise ratio and to improve accuracy, most significantly regarding vehicle heading data. An accurate knowledge of the vehicle's orientation is critical for navigation, since heading errors tend to propogate position errors in all aspects of autonomous navigation.

Position Estimation

Position is estimated by calculating the vehicle's position and orientation in a two dimensional (x,y) internal world model using a dead reckoning navigation algorithm [6]. Periodically updating that estimate with true position data from an external microwave beacon system using a weighted sum method reduces positional errors to less than 1 meter, regardless of distance travelled [7]. The beacons are located at known surveyed locations on the vehicle test range, and an onboard computer translates distance information from each beacon to the vehicle into an x,y location. In this way accumulation of position errors in the dead reckoning system are periodically eliminated.

Map Making

Mapping the roads or trails that the vehicle is expected to travel autonomously is accomplished using the vehicle's navigation system. The system tracks vehicle location as the roads are driven, either through teleoperation or by an onboard human operator, and saves the data to onboard memory or diskette. Data in the form of x,y position and current vehicle heading are sampled every 2 meters as the vehicle moves, and are stored as a two dimensional array in memory by the map maker. Any points that have special significance are marked by entering a coded value into the array in place of the heading data. Road intersections, landmarks, or other special features of the point's location may be stored in this way. The array is then saved to diskette as a file, and may be reloaded at any time. A system of interconnected roads may be mapped and loaded into computer memory from diskette at startup. Maps may be loaded to or from diskette as needed, and available computer Random Access Memory (RAM) allows over 150 kilometers of road maps to be accessed by the navigation system at any time.

Path Retrieval

Path retrieval is simply the process of recalling a previously stored map from diskette or RAM and inverting the list for use by the path follower. Inverting the list consists of placing the end of the path at the head of the path follow list, and copying the path data to the follow list in reverse order from that in which it was originally stored. This assumes that the vehicle is located at or near the end of the path, and that the task of returning to the original start point is to be performed. This technique is referred to as "retrotraverse". This method for defining a path to be followed is just a simplified special case of the methods used for autonomous navigation in a structured environment [8]. In addition to inverting the path list, a velocity profile for the vehicle is planned using a set of performance criteria to determine the desired vehicle speed, and the result is stored next to the x,y and heading data in the continuous path follow list at each point along the road. The performance criteria mentioned above includes a maximum allowed lateral acceleration of the vehicle while turning, which can be translated into either a velocity limit for a given steering angle or a steering angle limit for a given velocity, depending on the particular circumstance. In this case, the turn radius required to negotiate the road is calculated and used to determine the maximum allowed velocity that doesn't violate the lateral acceleration limit. The resulting desired target velocity is used by a cruise control algorithm that controls the brake/throttle actuator during the retrotraverse (autonomous pathfollowing). The end result of all this is a continuous list of x,y points spaced 2 meters apart, proceeding from the start point to the destination, which was the vehicle's original start point at the beginning of the mission. Compass heading and desired velocity at each point along the path is included as well, so that the path follower has target values to compare with actual data during pathfollowing.

Path Following

Path following is accomplished by comparing the current estimate of vehicle position with the path, and steering the vehicle in the appropriate direction. The objective is to cause the computed lateral error between the closest point on the path and the vehicle's position to decrease to zero, using a classical closed-loop control algorithm.

The difference between the current vehicle heading and the bearing angle of the current road segment is computed to derive the steering angle required to simply parallel the road. If the lateral error distance from the path to the vehicle is outside the defined deadband limit, an additional convergence angle must be calculated to bring the vehicle closer to the road.

Sequential lateral error measurements are subtracted to derive a lateral "closing velocity" figure that reflects the rate of the vehicle's convergence with the intended path. A desired target closing velocity is computed by scaling the current computed lateral error, and the difference between the desired and actual closing velocities produces an error signal which is used to perturb the steering angle and alter the convergence rate.

The current steering angle is used with the aformentioned performance criteria to limit the desired velocity figure stored in the path follow list, and the resulting velocity figure is passed to the autonomous cruise control function.

The cruise control samples the vehicle's forward velocity at a constant rate and compares actual vehicle velocity with the current desired target figure. The difference between the target and actual velocities generates an error signal which is used to alter the brake/throttle actuator's position appropriately.

HARDWARE

Hardware employed for this phase of development include the Jeep Cherokee Mobile Robotics Testbed Vehicle (Fig. 1), with its array of navigation sensors and systems, state-of-health sensors, actuators, and video equipment [9]. The vehicle has three onboard computers, one of which is integral to a commercially available microwave beacon system. Of the two other onboard computers, one is devoted to the vehicle hardware interface, and the other provides high level navigation control and interfaces with a remote control/driving station. The remote control station provides an operator interface to the vehicle in either teleoperation or autonomous modes, and the capability for multi-vehicle control has been incorporated as well.

TEST AND PERFORMANCE DATA

Test data to date show that the path follower can hold the vehicle to within an average of +-0.48 meters (lateral error) of the intended path, with an average standard deviation error of 0.9 meters, while continuously moving at speeds up to 7 KPH over path lengths of up to 1.6 kilometers each. The following table summarizes some of the hardware and software performance characteristics.

ITEM	PERFORMANCE / DATA
Control Program :	Written in ANSI standard C language. Program size == approx. 60 kilobytes. Main loop time == approx. 0.07 seconds on 8-bit CPU at 6.1 MHz clock.
Positional Accuracy :	The microwave beacon system's accuracy specification is +- 1 meter. Data fusion of beacon position and dead reckoning reduce this to approx. +- 0.5 meters.
Operating range :	The maximum operating range is limited by the radio links for data, video, and the microwave beacon system. This varies according to power settings and terrain but typical maximum ranges are from 5 kilometers to as high as 80 kilometers.
Performance criteria:	These are software constants intended to be adjustable by the researcher, and are used to vary the pathfollower's gain and response characteristics. The following values were those used during system testing. Maximum allowed lateral acceleration: 0.098 meters/second/second Maximum allowed longitudinal acceleration: 0.3353 meters/second/second Maximum allowed change in successive steering angles (represented as the unity sum of a percentage of the new angle plus a percentage of the previous steering angle): 70% of new angle plus 30% of current steering angle Deadband width for path convergence: 0.2 meters

The system is currently operating over a 1.7 kilometer course of dirt roads and jeep trails at Sandia National Laboratories' Robotic Vehicle Range, and development of this and similar systems is ongoing.

FUTURE WORK/ONGOING WORK

It should be noted that this retrotraverse technique applies to any "learned" path, not just the path that leads "home". A set of paths may be saved to memory as they are driven, and may be recalled for autonomous following at any time. A specific application of this would be a set of paths that connect a "hiding position" to a "firing position", as well as a path that leads "home" for a battlefield robot such as the Sandia-developed FIRE ANT demonstrator (Fig. 2) or the Sandia-developed DIXIE demonstrator vehicle (Fig. 3).

The next phase of development for this system will be to integrate the hardware and software to a small vehicle such as the FIRE ANT, DIXIE, or TOMSS vehicles currently under development at Sandia National Laboratories.

Obstacle detection and avoidance features are currently under development. The intended approach is to use an array of ultrasonic ranging transducers to provide detection of obstacles, although negative obstacles such as potholes and ditches will require a different type of sensor. Candidate sensors for that task include millimeter-wave radar and scanning laser radar.

A vision system does exist on the development vehicle, although it is currently used only for teleoperation and/or observation by a human operator located at a remote control console. The use of triangulation or trilateration techniques that incorporate vision and/or laser ranging devices is underway. A unique hardware solution to vision-based path following is also being considered, as is a neural network approach to image interpretation, although the techniques are not currently mature enough to test on the vehicle.

The autonomous cruise control feature used while path following may be an attractive feature to augment teleoperation of the vehicle, and evaluation of its utility in that mode of operation is underway.

The current self-imposed limit for vehicle velocity is 7 kilometers per hour. The major issue to resolve before velocities much over 15 kph are attempted is smoothing of the steering correction functions in the path follower to minimize oscillation of the vehicle trajectory around the nominal intended path.

As previously stated, the accurate determination of vehicle orientation is critical to all aspects of autonomous navigation, and ongoing work in this area is intended to improve performance. New sensors for orientation in all three axes are under evaluation, as are some new inertial sensors. New sensor fusion techniques are being evaluated as well, with the idea that a combination of medium accuracy sensors and data fusion can be used to derive accurate data without the need for expensive and delicate sensing devices.

The current limit of 1.6 kilometers for an individual path length is arbitrary, and as stated above, the capacity for up to 150 kilometers of map data is the computer's actual storage limit. The entire 150 kilometer capacity may be used for a single path to traverse, however some other means of position updating will have to be used since the beacon system currently employed has a limited operational range. As more Global Positioning System (GPS) satellites are brought into service, they may eventually provide a means to take advantage of the long distance capabilities of the retrotraverse system.

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