GLOBAL-LOCAL NAVIGATION USING A GPS

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ABSTRACT
The purpose of this paper is to describe the use of Global Positioning Systems (GPS) as the geographic information and navigational system for a ground based mobile robot. Several low cost wireless systems are now available for a variety of innovative automobile applications including location, messaging and tracking and security. The GPS system is interfaced to the Bearcat mobile robot that also has a local positioning system. A mapping program is used to define a desired route. Then GPS information may be displayed for verification. However, the GPS information is also used to update the control points of the mobile robot using a reinforcement learning method. Local position updates are also used when found in the environment. The significance of the method is in extending the use of GPS to local vehicle control that requires more resolution that is available from the raw data using the adaptive control method.

INTRODUCTION
The GPS is a worldwide radio-navigation system formed from a constellation of 24 satellites and their ground stations. While there are millions of civilian users of GPS world-wide, the system was originally designed for and is operated by the U. S. Department of Defense (DOD). Nowadays, the GPS is finding its usage into cars, airplanes, ships and could be applied to all other moving facilities. There are five stations around the world (Hawaii, Ascension Island, Diego Garcia, Kwajalein, and Colorado Springs.) monitoring the GPS satellites, checking both their operational functions and their exact position in space. The ground station transmits corrections for the satellite's ephemeris constants and clock offsets back to the satellites. The satellites can then incorporate these updates in the signals they send to the surface of the earth and can be read by GPS receivers. It functions just like assigning each patch of land a unique address. GPS satellites provide specially coded signals that can be
processed in a GPS receiver, enabling the receiver to compute altitude, longitude, height, velocity and time. Precise positioning could be achieved by using GPS receivers at different locations providing corrections and reference positioning data for remote receivers. Time and frequency dissemination, based on the precise clocks on board the satellites and controlled by the monitor stations, is another use for GPS. Astronomical observatories, telecommunications facilities, and laboratory standards can be set to precise time signals or controlled to accurate frequencies by special purpose GPS receivers.

Generally, at least four satellite signals should be read to determine precisely one position on earth. The determination of position and time from satellites is shown in Figure 1.

The University of Cincinnati Robotics Research Center has been working on improving the ability of automated guided vehicles for several years. Each year, some new features are added to extend the robot’s functionality. Navigation and positioning are crucial to mobile robot navigation and yet the process has always been quite cumbersome. Over the years the Cincinnati Robotics team has successfully developed vision systems and sonar sensors on their robot Bearcat II to trace landmarks so that the robot could understand where it is. However, this is highly unreliable as it is worked only in local area and also subject to movement or destruction by environmental factors. The quest for greater and greater navigation accuracy has spawned the idea of employing GPS technology to improve the robot navigation functionality. The mobile robot was also brought to the AUVS world wide mobile robot Contest in Detroit, June, 2001.
At the small end of the scale there are robots just a few centimeters in size, which will require high precision navigation over a small range (due to energy supply constraints), while operating in a relatively tame environment. At the other end of the scale there are jumbo jet aircraft and ocean going liners, each with some sort of auto-pilot navigation, which requires accuracy to a number of meters (or tens of meters), over a huge (i.e. global) range, in somewhat more rugged conditions. We use three terms to help in categorizing this scale of requirements:

- Global navigation, which is the ability to determine one's position in absolute or map-referenced terms, and to move to a desired destination point.
- Local navigation, the ability to determine one's position relative to objects (stationary or moving) in the environment, and to interact with them correctly.
- Personal navigation, which involves being aware of the positioning of the various parts that make up oneself, in relation to each other and in handling objects.

Though these aspects are distinct, they are often related. For example, local navigation capabilities also support global navigation in a mapped environment, since knowing one's position relative to a known mapped feature determines one's absolute position.

GPS MECHANISMS

The nominal GPS Operational Constellation consists of 24 satellites that orbit the earth in 6 planes. The orbit altitude is such that the satellites repeat the same track and configuration over any point approximately each 24 hours (4 minutes earlier each day). There are six orbital planes (with four satellites in each), equally positioned in space (60 degrees apart), and inclined at about fifty-five degrees with respect to the equatorial plane. This constellation provides the user with between five and eight satellites visible from any point on the earth.
Figure 2 - GPS Constellation

GPS receivers convert the satellite signals into position, velocity, and time estimates. Four satellites are required to compute the four dimensions of latitude, longitude, height and time. GPS receivers are used for navigation, positioning, time dissemination, and other research. Navigation in three dimensions is the primary function of GPS. Navigation receivers can be made for all moving objects on earth such as vehicles, aircraft, ships, and for hand carrying by individuals.

The basis of GPS calculation is to solve the triangulation from the GPS satellites. The GPS receiver measures distance using the travel time of radio signals in space, which needs extremely accurate timing. We also have to know exactly where the satellites themselves are in space (i.e. height of their orbits). The delays during signal transmission through the atmosphere also need to be considered. The idea behind GPS is to use satellites in space as reference points for locations on earth. A position is computed from distance measurements from at least three satellites. Distance to a satellite is determined by measuring how much time a radio signal takes to reach us from that satellite. To make the measurement we assume that both the satellite and our receiver are generating the same pseudo-random codes at the same time. By comparing how late the satellite's pseudo-random code appears compared to the receiver's code, then the time it took to reach us could be determined. Multiply that travel time by the speed of light and the distance can be computed. Accurate timing is the key to measuring distance to satellites. Receiver clocks do not have to be that accurate because an extra satellite range measurement can remove errors. The basic orbits of satellites are quite exact but in order to make it reliable the GPS satellites are constantly monitored by the Department of Defense (DoD). They use precise radar to check each satellite's exact altitude, position and speed. The
errors they're checking are called "ephemeris errors" because they affect the satellite's orbit or "ephemeris." These errors are generated by gravitational pulls from the moon and sun and by the pressure of solar radiation on the satellites. The errors are usually very slight but if you want high level accuracy they must be taken into account. Once the DoD has measured a satellite's precise position, they relay that information back up to the satellite itself. The satellite then includes this new corrected position information in the timing signals it is broadcasting. So a GPS signal is more than just pseudo-random code for timing purposes. It also contains a navigation message with ephemeris information as well. The ionosphere and atmosphere around the earth cause delays in the GPS signal that translate into position errors. Some errors can be factored out with mathematics and modeling. The configuration of the satellites in the sky can magnify other errors. Differential GPS can eliminate almost all errors.

NAVIGATIONAL CHALLENGE PROBLEM

For the International Ground Robotics Contest navigation contest, five fixed base points are set as the target position, which are about 100 yards apart. The GPS is used to get the original position, then tracking is used to move the robot from one point to the next, updating the new base with every pass. The GPS receiver outputs position (latitude, longitude, height) and velocity information at a rate of 1 second per output to 255 seconds per output. The accuracy of the output varies between 5 feet to 25 feet. The normal robot speed is about 5 feet /second, and the motion command delay is about 0.5 second. The main issue in controlling with GPS feedback is to maximize the accuracy. In order to do this, several sample data should be accumulated and then the average and variance computed through a least squares method. Also, since the contest field has limited distance, errors due to the earth arc may be ignored. However, when the robot is in motion, the sampling historical data are taken not for a fixed spot. This could be fixed by adding shifts of the robot over time to the historical data, which could then be processed as if they are sampled at the same spot over a period of time.

The goal of the GPS navigational challenge is for the Bearcat robot to navigate to a given sequence of predefined waypoints while avoiding obstacles. The robot is provided with the grid coordinates of the points in Cartesian and longitude/latitude coordinates. The robot navigates to each successive target point based on GPS satellite position data. Arrival at a target point is defined as approaching within five feet of the target point.

NAVIGATIONAL CHALLENGE SOLUTION APPROACH

The methodology behind the Bearcat navigational challenge problem was to select a commercially available GPS unit and utilize the built in features of the unit to provide a solution to the GPS navigational problem. This approach relies on the GPS unit’s navigational processing features and reduces the computational load that the robot CPU must perform to navigate the course. The advantage of this method is that it reduces the computational load on the
robot computer CPU freeing valuable processing time for other duties. This method is also beneficial in that it relies on the GPS navigational algorithms developed by the GPS unit manufacturer. The GPS unit manufacturer has invested in the development and optimized these GPS navigation algorithms, which reduces development time for the robot navigation algorithm. The major disadvantage to this approach is the GPS units built in algorithms are proprietary and undocumented. The GPS unit was selected based on the criteria that its embedded software be upgradeable as newer versions become available from the manufacturer. The ability to upgrade the GPS unit’s software provides our robot with the most recent algorithms as they become available.

The basic criteria used in the selection of the GPS unit are Waas capability, RS-232 serial port input/output ability, external antenna, external power capability, and embedded navigation features. Waas capability improves the accuracy of the standard GPS signals to 3 meters. The RS-232 input/output capability allows the robot computer to interface with the GPS unit and process the navigational data from the GPS unit. The NMEA (National Marine Electronics Association) data format interface is the sole format used to exchange data between the robot and the GPS unit although the GPS unit is capable of other data interface methods. An external antenna option was selected for the robot because it provides more accurate reception of GPS satellite signals and a variety of mounting options than the internal antenna. External power capability ensures that the GPS unit always has a constant source of regulated power from the robots power system. The main navigational features of the GPS unit used in the solution of the GPS navigational problem are the ability to input/output NMEA messages, set target waypoints, and calculate bearing/range information to the target waypoint. Based on these selection criteria the Garmin GPS 76 was chosen as the unit to provide GPS navigational ability to the robot. The Garmin GPS 76 provides all of the above-mentioned features in addition to other features not used in the current navigation algorithm.

DESCRIPTION OF NAVIGATIONAL CHALLENGE ALGORITHM

The basic solution selected to solve the navigational challenge problem is to model the problem as a basic closed feedback control loop. This model has an input command, feedback signal, error signal, and output transfer function characteristics. The input command is the target waypoint destination. A feedback signal is provided by the GPS unit position information. The GPS unit uses the current position information and calculates the bearing and range from the target waypoint to determine the error. The bearing and range to the target waypoint create the error signal. Correction signals are generated to reduce the error to a certain tolerance based on the bearing angle error signal generated by the GPS unit. The correction signals consist of turn right, turn left, forward motion, or stop. These corrective commands are sent to the robot motion control system, which translates these commands into motor control voltages that steer and propel the robot on the course. Once the bearing angle error and target range have been reduced to the required tolerance the command is
considered complete and the robot has arrived at its target destination waypoint. At this point the next target waypoint is selected and the process is repeated until all target waypoints in the database have been reached.

The robot may not always be able to reach its intended target waypoint directly because of obstacles on the path. To handle this situation, a laser scanner is used to detect obstacles on the path and control of the robot is transferred to the obstacle avoidance routine once an obstacle is detected. The obstacle avoidance routine is basically the same feedback control loop used for the GPS navigation except that the target waypoint command is replaced with the target point that will guide the robot around the path obstacle. The obstacle avoidance routine is recursively repeated so that each new obstacle detected during the obstacle avoidance routine becomes the new target waypoint. This allows the robot to avoid any new obstacles detected during obstacle avoidance mode. Once the robot successfully avoids the obstacles, the original target waypoint is restored and the navigational feedback control loop is resumed.

**ALGORITHM IMPLEMENTATION**

The physical implementation of GPS navigation feedback control loop consists of the Garmin 76 GPS unit, the robot motion control system, laser scanner, and the robot computer.

The command portion of the feedback control loop is implemented as a text file, which contains a list of the latitude/longitude and Cartesian grid coordinates of the waypoints. The route that the robot will take to reach each waypoint is determined by the sequential order of the waypoint records in the file. The first record is the first point in the route and the second record is the second point, etc. All records are read from the waypoints file during the initialization stage of the program and stored in an array in memory. This method improves performance because the file read operation is only performed once at the beginning of the program. Each target waypoint is sequentially selected from the waypoint coordinate array and the target coordinates are formatted into a NMEA $GPWPL (Waypoint Location) sentence that is transmitted to the Garmin 76 GPS unit via the RS-232 port interface. The NMEA $GPWPL sentence has the following format:

```
Waypoint Location (WPL) 4917.16,N,12310.64,W,003*65
Latitude of waypoint 4917.16,N
Longitude of waypoint 12310.64,W
Waypoint ID 003
```

This message is sent to the Garmin 76 GPS unit and it sets the active target waypoint in the GPS unit’s memory, this is the command signal. Once set, the waypoint coordinate is used by the GPS unit to calculate bearing and range to the target waypoint. The Garmin 76 unit must be set to NMEA interface mode and navigate to waypoint mode with the target waypoint name (ID) selected. Once in NMEA mode, the Garmin 76 unit transmits various NMEA sentences with GPS navigational data. The feedback and error signal information are
transmitted in the NMEA $GPRMB (Recommended minimum navigation information) sentence which has the following format:

RMB - Recommended minimum navigation information (sent by nav. receiver when a destination waypoint is active)

RMB,A,0.66,L,003,004,4917.24,N,12309.57,W,001.3,052.5,000.5,V*0B
A             Data status A = OK, V = warning
0.66,L        Cross-track error (nautical miles, 9.9 max.),
               Steer Left to correct (or R = right)
003           Origin waypoint ID
004           Destination waypoint ID
4917.24,N     Destination waypoint latitude 49 deg. 17.24 min. N
12309.57,W    Destination waypoint longitude 123 deg. 09.57 min. W
001.3         Range to destination, nautical miles
052.5         True bearing to destination
000.5         Velocity towards destination, knots
V             Arrival alarm A = arrived, V = not arrived
*0B           Mandatory checksum

The $GPRMB ASCII sentence transmitted by the Garmin 76 is parsed to obtain the bearing and range to destination waypoint data, this is the error signal. A turn left or turn right correction signal is sent to the robot motion control system based on the bearing to target value. The robot turns to the commanded correction angle until the GPS unit bearing error feedback signal is within the selected tolerance. The command is defined as complete once the range to the destination waypoint is within the selected range tolerance. After arriving at the target waypoint the next target waypoint record is selected and the process is completed.

The Garmin 76 GPS unit is represented in the navigation code by a C++ GPS class that packages member functions into a single GPS object that can be used in the C++ code to implement the feedback control loop. The primary member functions defined in the GPS class are:

void readGpsData(void); // Reads gps data from the serial port parses the input string and sets the private gps data members with the current gps data.

void SelectWaypoint(int select); // Select an Active Waypoint from the Waypoint coordinate array. Takes waypoint number as a parameter

void InputWaypoints(void); // Read in waypoint latitude and longitude from waypoints data file.

void CreateWaypointFile(void); // Creates waypoints data file by prompting user for input then writes to a file using a waypoint data structure.
The laser scanner also provides feedback and error signals when the robot is in obstacle avoidance mode. It serves a similar function as the Garmin 76 unit in navigation mode but it sends an error feedback signal to turn the robot until the obstacle is no longer in the forward path of the robot.

The robot computer handles the communications interface with the Garmin 76, laser scanner, and motion control system devices. It is also responsible for running the digital feedback control algorithm code and sending the correction commands to the robot motion control system.

**TEST SETUP AND RESULTS**

A test field was created to test the GPS navigation algorithm. The test field consisted of an open outdoor area with four target waypoints marked on the ground. The latitude and longitude of each target waypoint was determined using the handheld GPS unit and recorded. Each target waypoint was input into a file using the GPS navigation computer program.

The first test involved manually navigating the robot to the target waypoint location. The angle and distance information displayed by the GPS navigation computer program was used to determine the steering direction information to the operator piloting the robot. For example, if the GPS navigation computer program displayed the angle error as –65 degrees then the –65-degree value was manually input into the robot steering command prompt. This command turns the robot right 65 degrees. Once the turn angle was manually set, the robot was given the command to move a line distance equal to the range to the target waypoint as displayed by the GPS navigation computer program.

The manual test was performed to verify the GPS unit interface and output data. The results of the test showed that the GPS navigation computer program algorithm components functioned properly and manually navigated the robot to the target waypoint location. An error of twelve feet short of the target waypoint location was observed. The distance error observed in the manual experimental test is approximately equal to the advertised accuracy of the GPS unit in Waas mode.

**CONCLUSIONS**

The GPS is an excellent positioning system. However, the direct use of GPS on automated guided vehicles in manufacturing is currently limited. Although the GPS technology has been used successfully in many military and geographic applications1-39, the use of this technology in manufacturing and medicine has been limited. One reason is that low cost systems are only accurate to about 2 meters. Whereas, manufacturing accuracies on the order of 0.001 meter or better are needed. In medicine, even greater accuracies down to 0.000001 may be needed in an operation such as brain surgery.

The large potential of GPS navigation can be realized if it can be combined with local sensor measurements. The GPS can enhance the robot’s navigation
ability. Compared to other methods, the GPS has poor accuracy but covers the entire earth, is weather-proof and simple to use. The biggest obstacle in this application now is the accuracy of the GPS. However, this can be improved by also using two or more ground-based receivers. One ground based receiver monitors the variations in the GPS signal and communicates those variations to the other receiver. The second receiver can then correct its calculations for better accuracy. In the future, one can combine the GPS signal with local sensors such as the existing vision and laser scanner signals to allow a robot to move from one point to the next and at the same time avoid obstacles on the course. The success of this integration of GPS in the mobile robot will soon make possible the accurate automated guided vehicle operations in many manufacturing applications.

Knowing the location of objects such as packages or work pieces is one of the fundamental problems in manufacturing, warehousing and distribution. Having the right material in the right place at the right time is a key to manufacturing success. The use of GPS combined with local beacon should have a variety of application in material handling, storage and retrieval. Further combinations of the location technology with existing identification sensors such as bar code scanner and smart tags could lead to significant improvements in productivity and quality.

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