High Precision GPS Guidance of Mobile Robots

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Abstract

The use of GPS for guidance of mobile robots has been reported as achieved in a number of useful proximate scenarios such as stevadoring, formation movement or search and agricultural positioning. Standard DGPS can be used to get an accuracy of under one metre sometimes leaving fine motor adjustments by humans to complete a task. Pay a lot more, and the precision improves but the cost is high in any commercial terms for the mass market. We report high precision GPS-guided movement based on the use of readily available low-cost receivers. Accuracies of better than 5 cms maintained over minutes have been demonstrated and are being improved upon. The guidance algorithms were adjusted to allow for the retention of orientation when approaching close to a destination. The introduction of the Galileo[1] system will improve the efficacy and usefulness of this method as we move from 24 to 30 satellites.

1 Introduction

The use of GPS for navigating in open air is well established and proven. Extra-terrestrial applications are now being explored for navigating on the surface of the planet Mars [LeMaster and Rock, 2003]. Most applications are satisfied by accuracies of order 2 to 10 meters. However, there are classes of problems where better accuracy is the key to autonomous movement. Examples are in autonomous construction, storage of precious and maybe small items, fork lift manoevering and generically for agricultural picking of fruit [Billingsley, 2000; Benner and Fassbender, 1999; Cordesses et al, 1999; Elkaim et al, 1997; Reid, 1998]. The limitation of GPS to open air use has now been bypassed by the advent of factory GPS that works in an enclosed space to accuracies of order centimeters or better depending on layout, radio shadow and the multiplicity of beacons viewable by a receiver [Hedges and Moon, 2002].

The typical operational mode of GPS is to decode pseudoranges from all viewable satellites in the sky in the one receiver and then calculate the absolute position on earth. This calculation is subject to errors mainly from inaccuracies in calculating satellite position, ionospheric delay in the signal paths and clock synchronisation. Systematic errors can be significantly reduced by using two receivers that are essentially local to one another and comparing real-time data from both.

2 GPS differential systems

There are numerous ways to operate in differential mode when using GPS satellite information. The most straightforward methods rely on having a base station receiver and a mobile receiver, then analysing differences between the signals received in real time at each receiver [Stone et al, 1999]. Some techniques look for averaging and Kalman filtering to make an optimal choice of position. Other techniques rely upon counting cycles of wavelength and phase shift then arriving at a least mean square answer to the positional error found.

There is a common misconception concerning the GPS system usually called differential. In DGPS, a fixed station is merely used to estimate errors in the data transmitted by each satellite and it distributes this to other receivers in the form of a low-bandwidth RTCM correction signal. In contrast, the method described here is more worthy of the name differential. It gathers raw measurement data from two receivers and compares carrier phase data to obtain accuracies normally associated with the much more costly Real Time Kinematics (RTK) systems. Indeed both RTK systems and as here reported obtain resolution from phase-tracking, relying on the accuracy of measurement of a fraction of a 20 cm carrier cycle rather than of the 300 metres (or 30 metres for P-code receivers) corresponding to one bit of the transmitted pseudo-random binary

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[1] http://europa.eu.int/comm/dgs/energy_transport/galileo/intro/future_en.htm

sequence.

When invoking the use of two separated receivers, enough satellites have to be mutually available to compare raw data or fixes. Figure 1 shows how satellite reception can be spasmodic and difficult to work with. The availability of each satellite is indicated by the line being present.

A consequence of the reliance on taking differences of the raw readings is that only those satellites that are adequately measured by both receivers can be used. Moreover, the displacement is inferred from the aggegated phase changes of a sequence of readings. If a reading is lost in the chain, some means has therefore to be found to repair the fix by reinitialising to an estimated position based on the one a second ago.

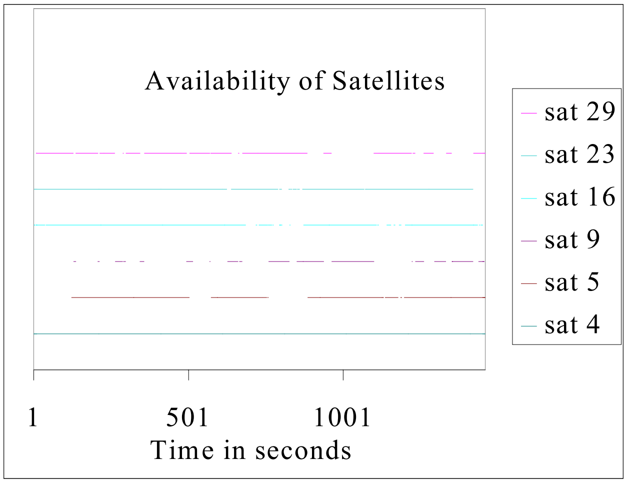

Figure 1 The availability of satellite signals on a GPS receiver.

3 Synchronisation of data

A schematic of how general differential GPS systems work is shown in Figure 2.

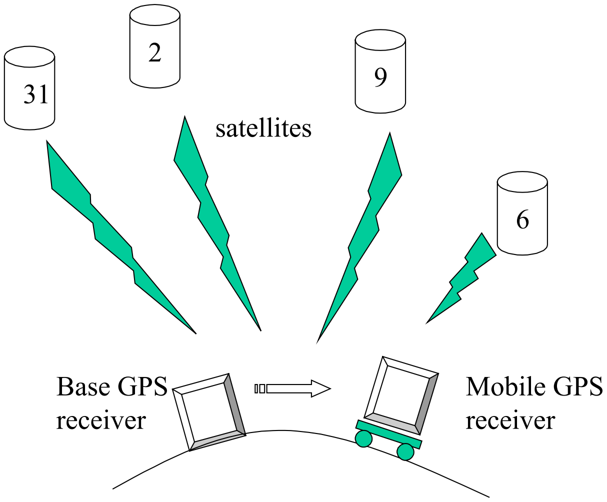

Figure 2 Schematic of general differential GPS.

Two receivers are used to obtain distance information from viewable satellites. The technique relies upon two key conditions being met namely:

- A minimum set of 4 satellites are available to both receivers, even if other satellites are selectively available to each receiver.
- One base receiver output can be radioed to another mobile receiver.

The time stamps of data received can be synchronised to make real time calculations meaningful. There are a number of commercial products that work with these boundary conditions as mentioned in [Stone et al,1999] but this feature is not incorporated into the more common low-cost receivers.

4 Generic accuracy of single receiver

There are several major manufacturers of OEM GPS receivers that are all characterised in producing much the same type of data extracted from satellite transmission. Calculations based on a low cost receiver are normally made available every second and posted out from the receiver at an unpredictable time delay after real-time fixing has taken place. If the fix is valid at time kT, where k is the kth iteration of the universal clock and T is normally an interval of one second, the result will not be offered till kT + ~0.5 seconds. Further to this delay, the internal processing of the receiver will occasionally interrupt the continuity of the output, to permit real time internal machinations such as signal input, such that transmission is begun at say kT + ~0.5s, then may stop for a few hundred milliseconds and then resume to completion. The time delay is incurred by the receiver performing the transformations on the pseudorange data to arrive at an absolute position. The generic accuracy of the low cost receivers treated as a single independant fix is shown in Figure 3. The accuracy is of order a few meters with occasional excursions to greater than 10 meters.

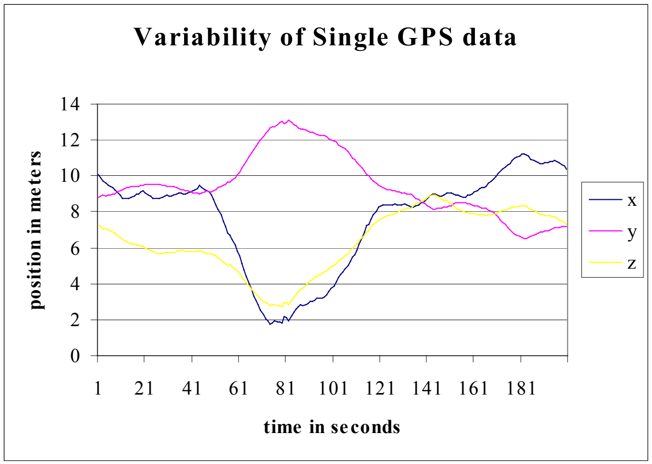

Figure 3 Short term stability of one GPS receiver

5 Real-time use of GPS fixes

Once it has been possible to obtain a fix of some accuracy, the question arises as to how that information should be blended with other sources determining position. In using a mobile robot, there is a case for relying to some extent on odometry if the application allows it, even when the terrain may be uneven. Should the GPS fail for any reason, odometry will still offer an approximate position albeit one that has cumulative error and cannot be relied upon for long. If the GPS is intermittantly reliable, odometry may well bridge the gaps and sensor fusing both results offers a more trustable system.

With this viewpoint in mind, a simulation to explore the extent to which odometry and GPS could be used in tandem was made using MATLAB.

6 MATLAB Steerage Prediction

Steerage of a vehicle along a track using a blend of GPS and odometric modelling was achieved in MATLAB simulation and relied upon two sources of information to predict where the vehicle is and in which direction the vehicle is to be steered. Firstly, for odometry, a laser Doppler or encoder distance measuring device and the steering angle of the vehicle are notionally sampled every 0.1 seconds. Secondly, GPS fixes are deemed to arrive at one-second intervals from the processing of signals from two Garmin receivers and can be related to their time-equivalent odometric counterparts. Thirdly, the desired steering angle is determined and, in practice, would be output back to the vehicle. A desired track is pre-chosen. Since GPS is normally quite good but has gross hiccups every so often, blending of the two predictions was made on the basis of looking at the difference between the predicted and actual GPS input as a new GPS input arrives. A simple Kalman filter in the form of a blending coefficient β was calculated so as to use relative proportions of GPS and odometry depending on which was most trustworthy at the time. The coeficient took the form of:

$$\beta = \exp(K.D)$$

where K is a proportionality constant and D is the Euclidian distance from the actual to the predicted position of the mobile robot.

For odometry, the incremental path is assumed circular with radius r over a 0.1 second interval between arrivals of input, the distance gone from the last input 0.1 seconds earlier. For GPS, the assumed position comes from extrapolating GPS data according to a 3rd order polynomial from the last four GPS inputs with a presumption that data is well behaved, if correct, because the vehicle only changes its parameters in a smooth manner. The model is very sensitive to changes in velocity, acceleration and rate of change of acceleration. Predictions of GPS position between the arrivals of data take place at 0.1 second intervals. Directional information is also calculated based on the last two predictions 0.1 seconds apart.

As already noted, the model predictions rely upon information that is up to 4 seconds out of date. Odometry update is actioned every 0.1s. GPS update is actioned every second, at which point, new coefficients for the 3rd order polynomial are calculated along with a new blending coefficient. At each second interval, the odometry prediction is also put back to the current blended position.

Variance was introduced into each input stream of data to test how realistically predictions of position were made. Previous tests using the mobile robot with odometry alone had generated data that showed accuracy could be maintained to 0.1% in distance travelled on each wheel once calibrated, including turning. GPS differential data received could be maintained to an accuracy of ± 5 mm. between sequential fixes and was pseudo-Gaussian.

Figure 4 shows a typical result where odometry is generally dominating. At iteration 500, a large perturbation on GPS, indicated by the arrow (say a satellite dropping out), is introduced. The effect can be clearly seen on the GPS prediction before settling down again. β is reduced to near zero and odometry relied upon until GPS recovers. This is intuitively correct since odometry has a better accuracy over short distances.

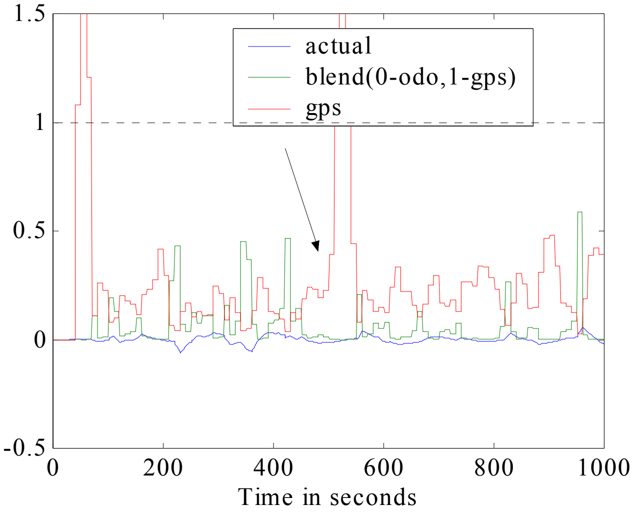

Figure 4 Predictions of determining actual position by blending GPS and odometry data

7 Experimental Results

The high precision fixes from using a differential GPS technique in the manner described here do not of themselves generate absolute results that have better accuracy than for low cost receivers. However, the technique can rely upon the establishment of waypoints that have been previously calibrated and surveyed to high precision. Using such points, relative accuracy in the sub-centimeter range is achievable and can be recalibrated against known points from time to time.

As the first stage of autonomous navigation, a mobile robot platform has been used to test the ability for accurate steerage relying on GPS alone, see Figure 5. The use of odometry to enhance short-term accuracy as depicted in the MATLAB model was to be used after the generic accuracy of differential GPS had been established. The robot is a flexible test bed for a number of applications and is capable of positioning wheel movement down to 10 microns. The accuracy of movement by odometry is readily determined on level ground and can be matched to GPS derived data at a later stage, testing the predictions made.

A GPS base station received carrier phase information and retransmitted it to a mobile robot platform either by direct connection or over Ethernet. A series of destinations was fed into the steerage program that started from a notional (0,0,0) datum facing due north. The program calculated a steerage vector based on an algorithm that reconciled the actual heading and position with the desired values.

Figure 5 Autonomous mobile robot GPS test platform

Figure 6 shows two methods of steering to achieve the desired goal including a desired orientation. Position A is the current position, B is the desired position and the vector A to B has been determined to be the final orientation facing forward. In such a scenario, the approach to a destination point has to be through a way point that lines up orientation or an absolute spot turn needs to take place once arriving at the destination along the vector from the previous destination.

In Figure 6, the upper diagram shows the goal as a simple attractor that stands independent of orientation. Movement completes when the robot reaches the goal. This type of control suffers from noise in the GPS fix never allowing the goal to be reached, causing hunting and loss of orientation. The lower diagram shows an adjustment that forces the line of travel back onto the original vector through a second control term. The goal is changed to a pseudo-goal that is beyond the real goal in the expected vectoral line of travel. As the goal is approached, the velocity is reduced proportionately so that zero velocity is reached when reaching within a pass band of B but orientation is not changed. The general form of the algorithm is:

$$V_{L(kt+1)} = V_{L(kT)} + K_1(\theta_D\ \theta_A) + \mathrm{sgn}(\theta_D\ \theta_A).K_2.E$$
$$V_{R(kt+1)} = V_{R(kT)} - K_1(\theta_D\ \theta_A) - \mathrm{sgn}(\theta_D\ \theta_A).K_2.E$$

where:

$V_{L(kT)}$, $V_{R(kT)}$ are the current velocities of the two drive wheels,

$V_{L(kt+1)}$, $V_{R(kt+1)}$ are the new velocities on the two drive wheels,

θ_D, θ_A are the desired and current steerage directions

K_1 is the proportional coefficient on steerage deviation

K_2 is the proportional coefficient on track deviation

E is the perpendicular distance from the current position to the line of the track

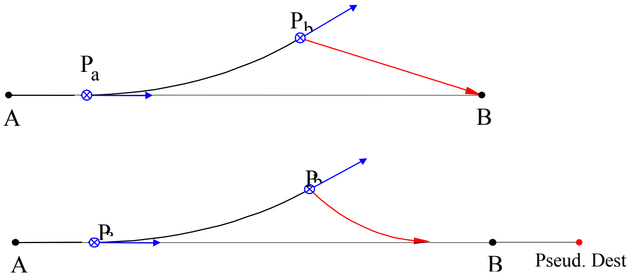

Figure 6 Goal-seeking behaviour

The accuracy of using two receivers in the manner proposed relies on the stability of reception from satellites. If the common sets of satellites used in the calculations change, there is a possibility that the cycle counts are not optimized and the datum will be shifted. Figure 7 shows what happens when the set of satellites common to both receivers change. The zero datum was fixed some time prior to the data shown and a small amount of drift is evident. There are 3 changes of satellite combination shown and the break points are clearly evident. Methods for tracking and compensating for drift as well as maintaining datums for each possible set of common satellite data are topics of ongoing reseach.

A number of tests were made to check on how well the system could drive the position of the robot under GPS control alone. Since accuracies of better than +/-5cm were possible, the receiver on the mobile robot was positioned such that it was exactly above the mid position between the two driving wheels. This meant the GPS fix equated directly to the local (x,y) center (0,0) for calculations of movement and direction. The base station receiver could be placed anywhere within say a 50 meter radius of the test area and maintaining radio contact.

Prior to the testing, a check was made to ensure that the satellites were stable in the sky and that the common sets of satellites used by each receiver were going to remain the same for the duration of the test. This can be achieved by reference to almanac data predicting availability of satellites at any given time for a position on the earth's surface.

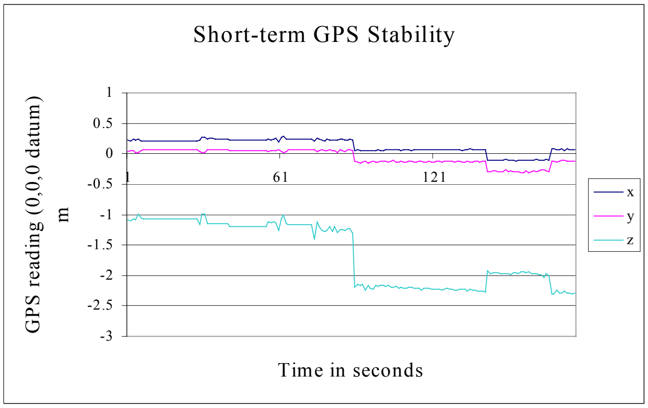

Figure 7 Short-term stability of GPS fixes when using 4+ stable satellites.

A first test was made that forced the mobile robot to turn almost back on itself. Figure 8 shows the result of steering 3 meters East and then aiming for a position 1 meter South of the start position. The control method used here was that described in Figure 6 upper diagram with a deadband around the destinations of 0.25 meters to prevent hunting. In travelling East, it can be seen a systematic error to the South of the path is only overcome towards the first destination. The full poential accuracy is not realised in that the robot stops 0.25 meters short of its destinations.

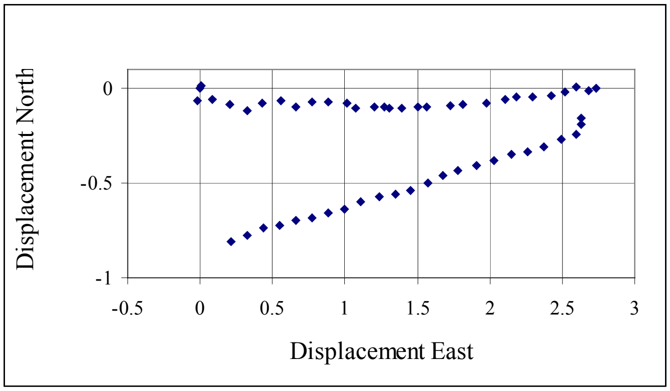

Figure 8 Path following involving a near double back, East 3 meters then to 1 meter South from start.

A second test commanded the robot to steer East for 2 meters and then North for 3 meters using a control scenario as depicted in Figure 6, lower diagram. Figure 9 shows the path followed by the mobile robot. At most times, the path is within 5 cms of the planned path with a few excursions outside this tolerance. There is evidence that, as the final destination is approached, the vectoral behaviour has brought the mobile robot back onto track after some perturbation has occurred.

A third test, again using the control scenario of Figure 6 lower diagram, attempted to steer the robot, precisely 5 meters due East. Figure 10 shows the resultant path. The error along the path is consistently below 10 centimeters and often below 5 centimeters. The robot has also stopped within 5 centimeters of its prescribed destination.

8 Discussion

The improved accuracy of position information has consequences for assumptions on placing the GPS receiver on the mobile robot. The ground upon which the tests were conducted was levelled concrete and supported the assumption that the centre of measurement on the mobile robot remained at the center point on the ground between the two driving wheels albeit some 40 centimeters above it. This assumption will not be valid if the robot travels across sloping ground, in which case, the 3D offset of the GPS receiver would have to be included in the calculation of position.

The assumption of real time positioning is not valid in any case since the data is delayed at least 500 milliseconds before it is made available by low cost GPS receivers. With such improved positional accuracy as demonstrated here, some form of Kalman filtering would now be necessary to predict the position if accurate delays on the data were also available from a real time clock synchronised to the satellite output.

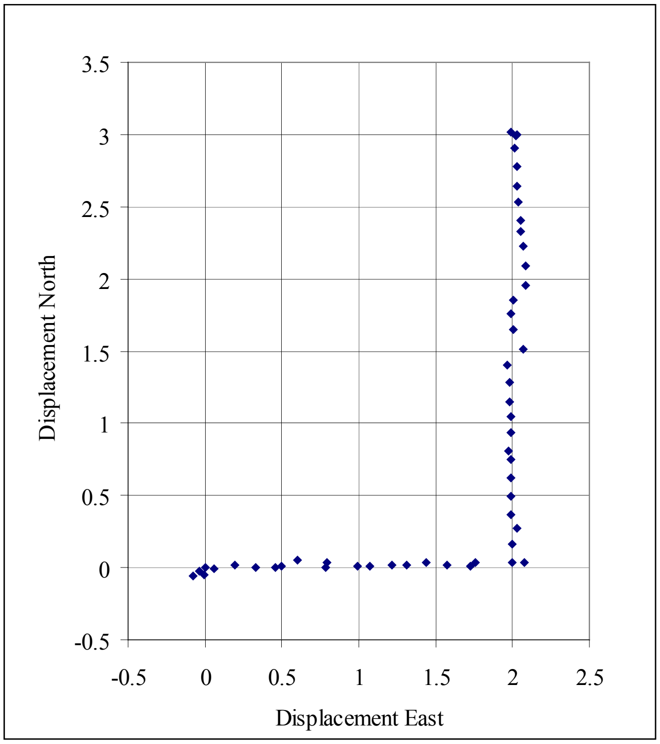

Figure 9 Steerage path under GPS, East 2 meters then North 3 meters

8 Future Work

A number of issues have been highlighted that increase in significance as accuracy of placement improves. The first issue to be addressed next will be to adopt sensor fusion of odometry and GPS in practice. Secondly, ongoing work in improving the use of available satellites will make the GPS data streams more reliable. There is a need to separate out the issues of wanting 24 hour usage and being able to work at times predicited by the almanac to be conducive and reliable. Thirdly, some form of transformation to accurately record the position of the GPS receiver with respect to an on-board datum on the mobile robot is now needed if ground tracking over non-level terrain is to benefit from the potential accuracy available. Fourthly, the delay due to processing in the GPS receiver has been set aside and will have to be taken into account if high speed use is envisaged.

9 Conclusions

Autonomous control of a mobile robot down to centimeter accuracy, relying solely on low cost GPS receivers has been achieved and demonstrated on a versatile test platform. Limitations of the technique so far, namely choice of satellite data to use, non real-time fixes and offsets of receiver placement, have been identified along with some possible ways of overcoming them.

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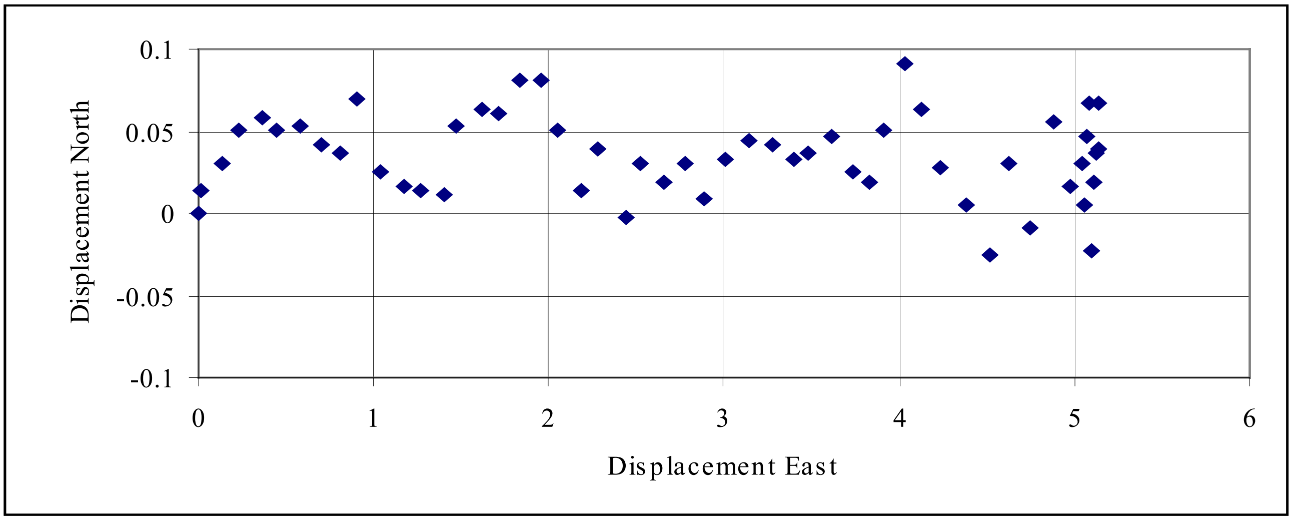

Figure 10 Steering the robot 5 meters due East.