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Evaluating the Performance of a Vehicle Pose Measurement System

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Abstract
A method is presented for evaluating the performance of a vehicle pose measurement system (e.g., GPS, inertial sensors, etc.). The method supports evaluations of the system on a vehicle moving at high speeds. An example is provided to illustrate the method.

Keywords
Vehicle, pose, position, measurement, accuracy, uncertainty, GPS, IMU

1 Introduction

Precise knowledge of the pose of a moving ground vehicle is important in such applications as navigation, safety, robotics, metrology and surveying. Vehicle pose measurement (VPM) system manufacturers typically state the accuracy of their systems under static conditions, that is, with the system stationary over time. Latency and synchronization errors are difficult to detect under static conditions. In this paper, a method is described for evaluating the performance of a VPM's ability to measure the position of a moving vehicle. The method requires that the VPM have a synchronization interface, which we call a sync pulse interface. This interface is often incorporated in a VPM to support photogrammetry applications where a camera's vertical sync latches a pose measurement. In the method presented in this paper, a photo emitter/detector sensor that senses energy reflected off a reflective target generates a sync pulse. By mounting the photo sensor on the vehicle and placing a reflective target on the ground, pulses are generated whenever the vehicle drives directly over the target. Repeated measurements of the target as the vehicle drives by are used to determine the repeatability in the VPM's measurement of the target location.

The National Institute of Standards and Technology (NIST) Intelligent Systems Division is pursuing work in several areas of intelligent vehicles, including research in autonomous mobility and development of performance measurement techniques. Various testbed vehicles are used in support of several projects, and each has been, or will be, outfitted with a VPM system. These systems are used in at least two distinctive ways. For autonomous vehicles, the VPM is a principal component of a real-time navigation system, providing necessary information for the vehicle to move through the environment. A somewhat different need is met by the ability of the VPM system to capture appropriate information in real-time that can be combined with other sources of information after the fact to generate more precise pose information than is available in real-time. This meets a metrology need, providing improved accuracy to evaluate performance of the vehicle itself and its various sensors.

This paper describes a method to determine or confirm the performance of an implemented VPM on a testbed vehicle. Since the VPM examined in this paper is intended for metrology applications, steps are included in the method to post process the data to obtain the highest possible accuracy. The method described could also be used to obtain real-time performance information. This is accomplished by analyzing the real-time solutions as opposed to the post-processed solutions. The method consists of a way to precisely trigger vehicle position measurements, a procedure for collecting data and a way to analyze the repeatability in the vehicle position measurements. Although VPMs are capable of providing a full position and orientation solution, this current effort addresses only the position measurement capability. In the following sections, the method is described in the context of evaluating a specific VPM, though the described method is applicable to any VPM that supports a trigger mechanism.

 

Figure 1 Note the downward looking photo sensor, the retroreflector on the ground and the vertical rod to guide the driver.

2 Test Procedures

The vehicle used in the evaluation is a full size passenger sedan. The installed VPM is a system that integrates a dual frequency carrier phase Global Positioning System (GPS), a secondary GPS, an inertial measurement unit (IMU) consisting of accelerometers and fiber optic gyros, a wheel encoder, and a system control and data collection computer. This system is configured to capture and provide solutions at a 200 Hz data rate. In addition, it is configured to capture all data required for later post processing.

The system is augmented with an external photo sensor connected to the sync pulse interface. When triggered, the result is the notation in a file of an event occurrence, along with the time of the event with microsecond time precision. Since triggers will be caused during vehicle motion, latency in the assertion of this signal will be reflected in position errors in the resulting data. For this reason, a low latency photo sensor (300 ms) was employed. During post processing, pose solutions are determined for selected events of interest. The sensor was mounted slightly in front of the vehicle bumper, in line with the vehicle driver position. A vertical rod above the sensor assists the driver in steering the sensor over a target while driving. The target is a simple retroreflective surface, constructed by affixing a layer of retroreflector material (available in sheets) to an aluminum disk. A disk of 15.24 cm (6 in) diameter is used. This size was selected as large enough to enable the driver to successfully steer the vehicle over it at speeds of interest most of the time, even in a grassy and somewhat bumpy field, but small enough to keep the target detection points close to a surveyed point. In this test a National Geodetic Survey (NGS) survey marker, flush with the ground, is used. The retroreflector is simply centered on top of it.

The configuration of the photo sensor, its mounting, and target is shown in Figure 1.

To evaluate the VPM's measurement performance, the vehicle is driven over the target from a variety of directions while collecting all data necessary to compute, via post processing, the position of the sensor at the time of target crossing. In the analysis phase, the repeatability of the measurements of the target's radius and the location of the target with respect to the survey marker produce a measure of performance of the VPM system.

The position solutions are computed for the location of the sensor (actually for a point on the ground directly below the sensor). This requires a transformation of coordinate frames between the VPM system and the position of interest below the sensor. This transformation depends on knowledge of the translations and rotations between the two reference frames. In the case of this implementation, translation and rotation measurements between the IMU reference frame and the sensor reference frame are needed. These measurements are entered into the VPM system. Determination of the translation and rotation parameters is performed in two steps.

The first is a best-effort measurement of the (x, y, z) distances between the IMU and the point below the sensor. Performing these measurements is physically awkward because of the location of the IMU in the vehicle trunk and the sensor location at the front bumper. An attempt was made to mount the IMU to align with the major vehicle axes as well.

Since these measurements are difficult and somewhat prone to error, data is also collected during the test run which is used to calibrate the system by adjusting the translation and rotation parameters as required. Several events are triggered by driving the vehicle sensor over the target as slowly ("creep") as possible and as well centered laterally as possible. These creep events are collected for approaches to the target from four directions. The slow speed is intended to eliminate any significant data latency errors. Positions of events collected in this manner should conform to the edge of the target, and the calibration parameters are adjusted slightly to yield solutions consistent with the known target diameter. This "creep" data also helps detect any movement of the sensor that may have occurred between tests.

After collecting the initial creep calibration data, the vehicle was driven over the target at a number of speeds and from a number of directions. Speeds were limited to about 10.6 m/s (≈20 mph) due to the roughness of the grassy field where these tests were performed. (The sensor/retroreflector system has been tested successfully at highway speeds on a roadway as well.) Approximately 40 events and their associated data were collected in this way, including a second set of creep points after completion of the vehicle at-speed runs.

3 Post Processing

Since the purpose of this test was to determine the maximum accuracy possible from the VPM, post processing was conducted on the data. If the purpose of a test is to evaluate the real-time performance of a VPM, then this step would not be performed.

The data logged on the vehicle during the test is retrieved, and the real-time navigation solution, though not the subject of this paper, is examined to confirm the existence of good data depicting an appropriate vehicle trajectory. The raw data is then post processed to obtain the more precise solution for the events of interest.

To enhance the quality of the solution, differential GPS post processing is used. A detailed explanation of this processing is beyond the scope of this paper, but the approach essentially makes use of information collected from another nearby GPS receiver (base station) at an accurately known location to remove (during post processing) certain kinds of errors from the reported position of the rover (our vehicle).

For these tests, we used a National Geodetic Survey (NGS) Continuously Operating Reference Station (CORS) located in Gaithersburg, MD known as GAIT. The NGS, an office of NOAA's National Ocean Service, coordinates a network of continuously operating reference stations (CORS) that provide GPS carrier phase and code range measurements in support of 3-dimensional positioning activities throughout the United States and its territories. (See http://www.ngs.noaa.gov/CORS/)

The reference station data for station GAIT is downloaded from the NGS for the appropriate period during which we performed the test, and used by post processing software to enhance the GPS solution. Further post processing is performed to integrate this GPS solution with the raw data from the VPM system sensors (IMU and wheel encoder). Smoothing algorithms are executed, and interpolation of navigation solutions for the recorded events is performed. The result is a file with a full navigation solution for each event. The solution information in this file is analyzed below.

4 Analysis

Two types of VPM measurement errors are estimated: target (i.e., reflector) location and target radius. The estimated location error is derived as the difference between the surveyed (static) location of the target and VPM measured (dynamic) location of the target. The estimated radius error is the difference between the known radius of the target and VPM measured radius of the target. The location error may be left uncalculated if survey data is not available. The following process is used to compute uncertainties.

1. <u>Put event points in a convenient local coordinate system.</u> First, the event points (VPM-measured coordinates of target's edge) are transformed from latitude and longitude coordinates into UTM coordinates (see velvet.tec.army.mil/access/milgov/fact_sheet/geotrans.html) so that errors may be expressed in meters. Second, if available, the known location of the target is subtracted from each event point. This places the event points in a coordinate system whose origin is the surveyed location of the target.

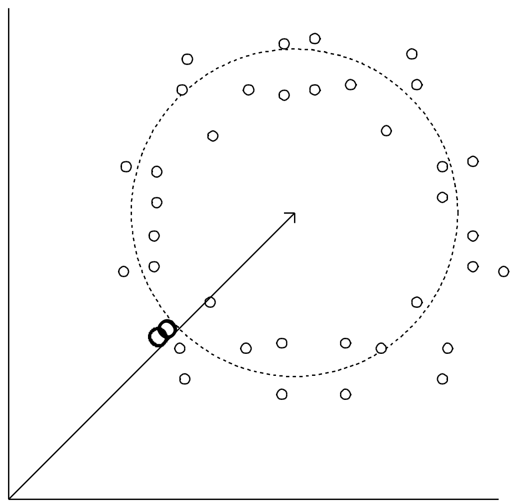

Figure 2. Example measurement points surrounding the target's edge.

2. <u>Determine the target location error.</u> A circle is fit to the event points. The fit produces an offset vector, **O**, indicating the center of the circle. Figure 2 shows an example set of data points with the offset vector to the center of the circle. If the origin of the coordinate system is the surveyed location of the target, then the magnitude of **O**, e_l, describes the estimated target location error.

3. <u>Determine the target radius error and uncertainty.</u> First, the offset vector of the circle is subtracted from each event point. This places the event points into a coordinate system with the center of the circle at the origin (see Figure 3). Then the distance of each event point from the origin, d_i, is computed. These distances are the measured radii of the target. The mean and standard deviation of the radius measurements, μ_r and S_r, are computed. The estimated target radius error, e_l, is the difference between the mean of the target radius measurements and the target radius measured by hand. Choosing a 95 % level of confidence, the component of the expanded uncertainty due to data scatter in the radius measurement is:

$$u_r = kS_r \qquad (1)$$

Where $k = 2$ for $N \geq 30$ and k equal to a t-factor obtained from a t-distribution for $N < 30$.

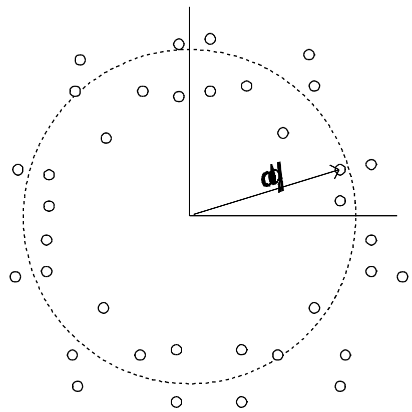

Figure 3. Measurements points translated such that center of circle is at origin. The distance of each point is the measured radius of the target

Figure 4 shows a plot of the event points collected when the vehicle traveled over a circular target with a radius of 7.62 cm (3 in). The origin of the plot coincides with the survey marker's coordinates, in this case, the coordinates of the NGS survey marker where the target was placed. The large circle is the target drawn to scale. Each event point is plotted as a small circle with an attached velocity vector (origin of vector is inside of small circle and points away from circle in direction of travel). The vectors are scaled to fit to the plot. The largest velocity vector is labeled 10.6 m/s to provide a scale for comparison (label is at end of vector opposite small circle shown on left side of plot). The results of the analysis of these measurements indicate a location error of 0.3 cm, an estimated radius error of 0.2 cm and a radius uncertainty of 1.3 cm (95 % level of confidence).

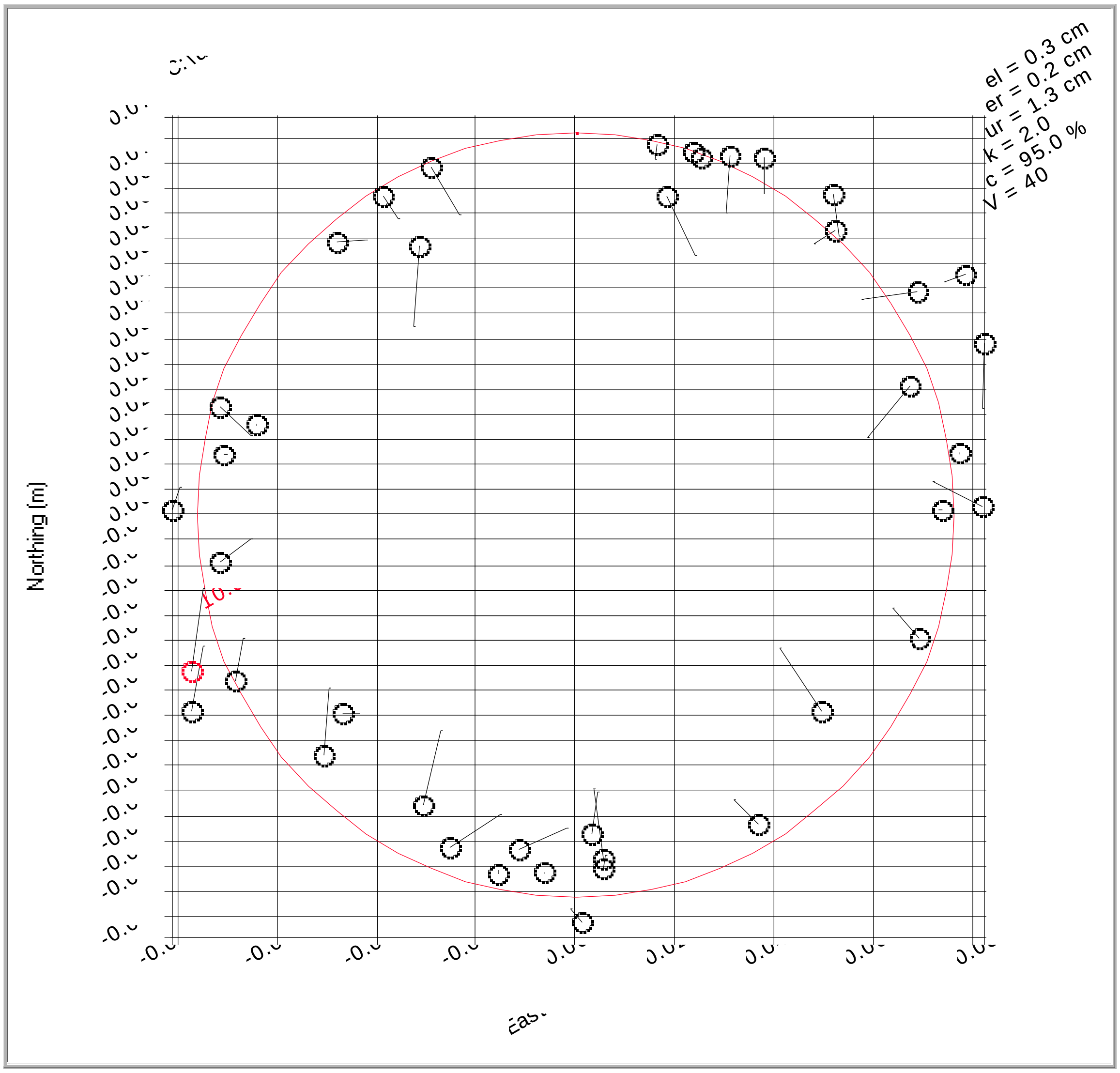

Figure 4 Plot of event points (shown as small circles) triggered when vehicle is driven over the edge of a circular target (large circle) with a radius of 7.62 cm. Vectors at each event point are vehicle velocity at event point. The largest velocity was 10.6 m/s (left side of target).

5 Conclusions

Further work is needed in several areas. This effort, an initial step in developing a performance measurement capability, focused only on vehicle position information in x and y. Height (z) data was collected but the data has not yet been analyzed. The testing methodology needs to be expanded to include orientation (roll, pitch, yaw) capabilities of VPM systems as well. That information, along with position information, is critical in registering the data received from intelligent vehicle sensors such as cameras and laser scanners, and directly affects the correctness of the model of the world being maintained by the vehicle computers. In addition, the scope of the work here included differential post processing of GPS data and further post processing of all the navigation sensor data. This is appropriate for metrology purposes. For navigation of intelligent vehicles, the real-time solution is important, and methods for determining the quality of the real-time navigation solution should be explored. Further, a real-time navigation solution may make use of real-time differential GPS corrections received by the vehicle during operation. The method described here can be used to examine position determination performance for those types of systems as well, and should be extended to characterize orientation measurement performance. Further, these tests were conducted with good GPS satellite coverage. While gaps in satellite coverage occurred, a test specifically excluding satellite info for prescribed periods would enable performance analysis of the VPM systems when they rely more on their inertial components.

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