EVALUATION OF AN INTEGRATED INERTIAL NAVIGATION SYSTEM AND GLOBAL POSITIONING SYSTEM UNDER LESS THAN OPTIMAL CONDITIONS

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ABSTRACT

Accurate real time position data is required for an outdoor autonomous ground vehicle to successfully navigate a pre-planned path. Two commonly used positioning systems for the navigation of an outdoor autonomous ground vehicle are an Inertial Navigation System (INS) and a Global Positioning System (GPS). The INS offers position data at a 10 Hz rate but tends to drift over time. The GPS offers position data without drift but at a 1 Hz rate. Through the use of an external Kalman filter, the integration of these two independent positioning systems offers accurate real time position data at a 10 Hz rate. Although the INS data is continually drifting, the Kalman filter is able to maintain an accurate navigation solution by using the GPS data. Since the Kalman filter depends on GPS to maintain its accuracy, the loss of or inaccurate GPS data will result in a less accurate filter solution. The focus of this paper is to evaluate the accuracy of the Kalman filter solution during these circumstances. Test results have shown that the Kalman filter was able to maintain position accuracies of approximately two meters or less for a period of five minutes after the loss of GPS data and was able to smooth through momentary inaccurate GPS data .

KEYWORDS: Global Positioning, Inertial Navigation, Kalman Filter, Autonomous Navigation, Unexploded Ordnance.

INTRODUCTION

An engineering program has been established at Wright Laboratory, Tyndall Air Force Base, Florida. The objective of this program is the autonomous cleanup of various Department of Defense facilities containing buried unexploded ordnance (UXO). Autonomous operation removes the human operator from a potentially hazardous environment and offers quality control by insuring that 100% of the site is efficiently searched.[1]

Removing buried munitions is a two step process. First, the buried munitions must be located. This is accomplished by an Autonomous Survey Vehicle (ASV) towing a sensor package across 100% of the area to be surveyed. As the ASV navigates, it collects and stores time-tagged position data as well as data form the sensor package. This data is then post-processed to determine the locations of the buried ordnance. Second, the buried munitions must be uncovered. This is accomplished by an autonomous excavator. The autonomous excavator navigates to each identified ordnance and removes it.[2]

The Center for Intelligent Machines and Robotics (CIMAR), at the University of Florida, has been contracted to develop the navigation system for these vehicles required to locate and remove the buried ordnance. A Kawasaki Mule 500 all-terrain vehicle was modified for computer control in order to be used as a Navigation Test Vehicle (NTV) (Fig. 1). Computer control was realized by mounting actuators and encoders on the vehicle's steering wheel, throttle, brake and transmission. Closed loop control of each actuator was then obtained by means of a VME based computer running under the VxWorks operating system. Autonomous navigation was accomplished by first calculating a survey path based on the coordinates of the survey site boundaries.[3] Figure 2 shows a typical path generated for the NTV to navigate. The vehicle's position relative to this path is then determined by utilizing an external Kalman filter which integrates the position data from an Inertial Navigation System (INS) and a Global Positioning System (GPS).[4]

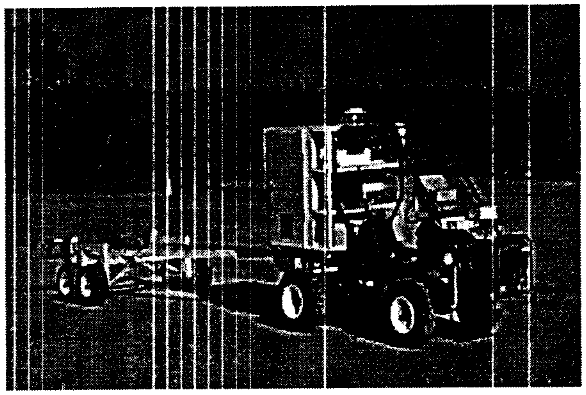

Figure 1. Navigation Test Vehicle.

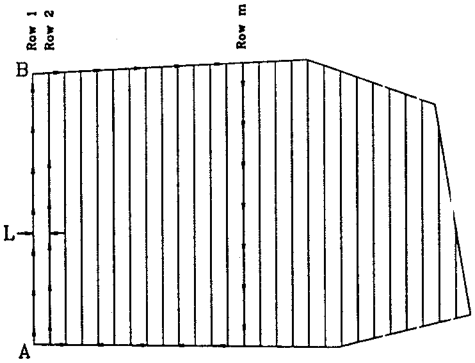

Figure 2. Planning of Survey Path

The INS used on the NTV is the H-726 Modular Azimuth Positioning System (MAPS) marketed by Honeywell Inc., Clearwater, Florida. The MAPS is a completely self-contained and strapped down system. It requires only an initial position at the start of operation. It then uses three ring laser gyros and three accelerometers to calculate a position solution relative to the initial position. This solution is made available to the controlling computer at a rate of 10 Hz.[5]

A problem encountered with INS is that the position solution tends to drift over time from the actual position due to measurement and system errors. In order to reduce the amount of drift, the MAPS can make use of zero-velocity updates (ZUPT) at a determined interval, typically every four minutes. This is not an acceptable solution since stopping the vehicle every four minutes is undesirable. Figure 3 shows the results of a dynamic test of the MAPS position data. The error in the MAPS position was calculated by comparing it to a post processed GPS position.[6]

The GPS used by the NTV consists of two Z-12 receivers marketed by Ashtech Inc.,Sunnyvale, California. The Z-12 receiver is designed to make full use of the Navstar Global Positioning System. It has twelve independent channels and can track all of the

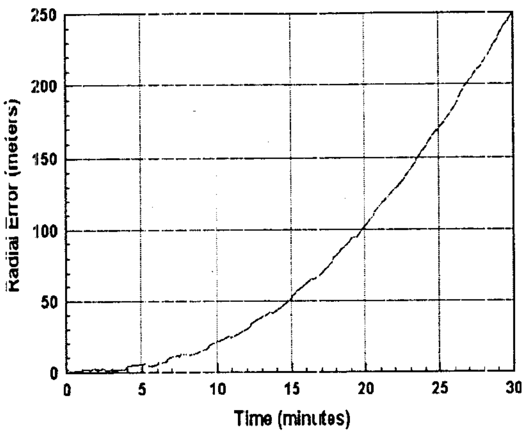

Figure 3. Dynamic MAPS Position Test

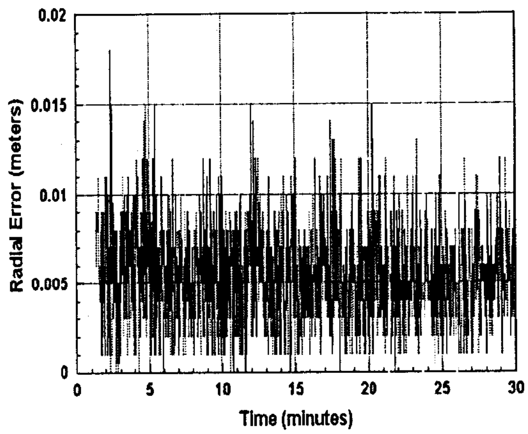

Figure 4. Dynamic GPS Position Test

satellites in view automatically. Data from the Z-12 is made available to the controlling computer at a rate of 1 Hz.[6]

The two GPS receivers operate in a carrier phase differential mode. In this mode, position can be calculated with centimeter level accuracy. Figure 4 shows a dynamic test of the real time differential GPS position data. The error in the real time differential GPS position was calculated by comparing it to a post processed GPS position.[6]

An external Kalman filter is used to integrate the INS and GPS position data to calculate a navigation solution. The filter includes nine states for the INS's position, position rate and tilt errors. Since the filter is being used for a ground vehicle, it is implemented in a local level geodetic frame. As a result, other INS errors can be included as process noise terms in the filter as tuning parameters. The filter processes the Differential GPS data by alternating between position and position change.[4]

The filter assumes that the position data from the GPS is accurate to within two-tenths of a meter. It uses this data to build a model of the INS position, position rate and tilt errors. By building this model of the INS errors, the filter has the ability to check the quality of the GPS data before it processes the data and it can continue to calculate an accurate position in the event of the loss of GPS data.

Under normal circumstances, GPS data is accurate within the two-tenths of a meter accuracy requirement. However, there are circumstances where GPS is unable to meet these requirements. First, GPS requires line of sight with at least four orbiting satellites in order to calculate a position. Tall trees and buildings are two examples where the NTV may not have line-of-sight with at least four satellites. Second, the accuracy of the calculated position depends on the changing geometry of the satellites in view. Third, the accuracy of the calculated position also depends on the amount of multi-path (reflected signals) which results from the surrounding environment.

The focus of this paper is an evaluation of the external Kalman filter during circumstances where there is a loss of GPS data and where there is inaccurate GPS data. The following sections will discuss the tests done in order to evaluate the Kalman filter navigation solution and the results derived from these tests.

TEMPORARY LOSS OF GPS DATA

Temporary loss of GPS data can occur when the NTV is in a place which does not allow a direct line-of-sight with at least four orbiting satellites. In order to test the filter's capability to maintain an accurate position solution during a temporary loss of GPS data, the following test was performed. Three areas within a survey site were marked off and the location of these areas were measured using GPS. The NTV was then allowed to autonomously navigate the survey site. Any time the vehicle entered any of the three marked areas, the GPS data was withheld from the Kalman filter.

Figure 5 shows the results of this test, where CALC is the calculated filter solution. In order for comparison, Figure 6 shows the same survey without any loss of GPS data. Table I shows the statistical results of these two surveys. From this test, it has been shown that the temporary loss of GPS data does not reduce the accuracy of the Kalman filter navigation solution.

TABLE I. Deviation of Real Time Data from Post Processed GPS Data.

	Temporary GPS loss		No GPS loss	
	CALC	GPS	CALC	GPS
Average Deviation (m)	0.23	0.02	0.23	0.03
Maximum Deviation (m)	1.19	1.12	1.54	1.86
Standard Deviation (m)	0.17	0.09	0.18	0.13

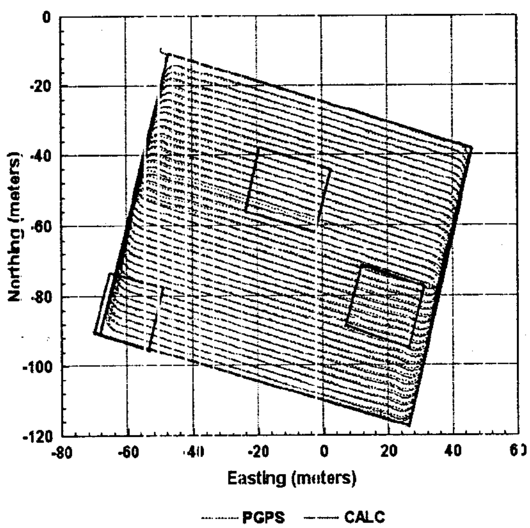

Figure 5. Temporary GPS Loss Test

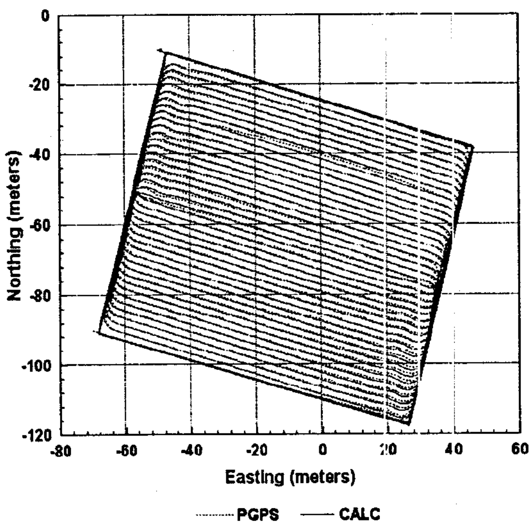

Figure 6. No GPS Loss Test

COMPLETE LOSS OF GPS DATA

Complete loss of GPS data is less likely to occur than a temporary loss. A complete loss of GPS data could occur when communication between the remote receiver and the base receiver fails. In order to test the filter's ability to maintain position accuracy after the loss of GPS data, the following tests were performed. The NTV was allowed to navigate autonomously for fifteen minutes. During this time, the filter constructed a model of the INS errors. After fifteen minutes, the GPS data was withheld from the filter. The NTV was allowed to continue to navigate for an additional ten minutes. For the next two tests, the NTV was allowed to autonomously navigate and construct its INS error model for thirty and forty-five minutes, respectively, before the GPS data was withheld from the filter.

The results of these tests are shown in Figure 7. In each of the tests, the filter was able to maintain an accuracy of four meters or less for two minutes after the loss of GPS data. Also from figure 7, it is apparent that the longer the filter has to construct its INS error model, the longer its navigation solution remains accurate after the loss of GPS data.

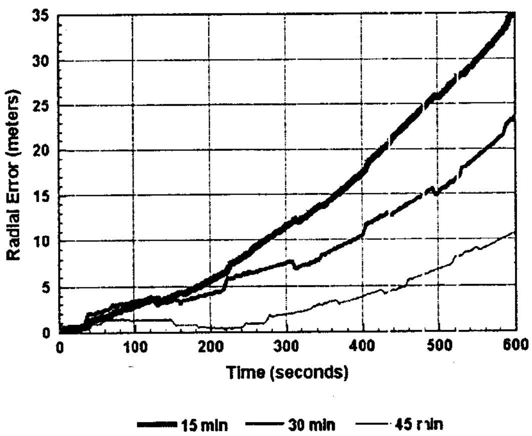

Figure 7. Complete GPS Loss Test

INACCURATE GPS DATA

Inaccurate GPS data could occur due to the changing geometry of the orbiting satellites. It could also occur in a high multi-path environment. In order to test the Kalman filter's ability to reject inaccurate GPS data, the following test was performed. The NTV was allowed to navigate a survey site autonomously. Approximately every two minutes error was introduced, by means of software, into one of the GPS positions. No error was introduced to the GPS data before or after this position. The amount of error was slowly increased from one-half meter to nine meters.

The results of this test are shown in figure 8. The filter was able to smooth through the inaccurate GPS position data. However, the filter did not reject all of the inaccurate GPS position data. The filter may require some additional fine tuning of its parameters so that all of the inaccurate GPS position data will be rejected.

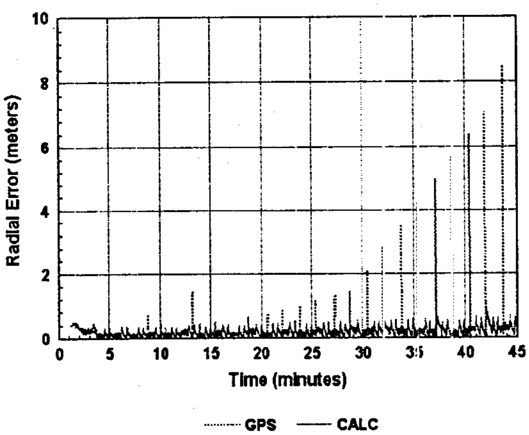

Figure 8. Inaccurate GPS Test

CONCLUSION

MAPS and GPS are two positioning systems which can be used to navigate an outdoor autonomous ground vehicle. Both positioning systems have inherent weaknesses that make it difficult to use one of them independent of another positioning system for the purpose of autonomous navigation. MAPS position data has been shown to drift over time due to measurement and system errors. GPS data is available at a rate of only 1 Hz. Also, GPS requires line-of-sight with at least four satellites and its accuracy depends on the satellite geometry and the amount of multi-path it experiences.

The integration of the MAPS and GPS position data, through the use of a Kalman filter, helps overcome the weaknesses of the two systems operating independently. The Kalman filter constructs a model of the INS error from the GPS position data. From the use of this error model and new MAPS position data, the filter is able to provide accurate position in between the GPS position data. With this model it is also able to provide an accurate position in the event of the loss of GPS data. It has been shown that the filter is able to provide an accurate position when there is a temporary loss of GPS data. It has also been shown that it is able to provide a position accurate to within four meters for two minutes after a complete loss of GPS. Finally it has been shown that the filter has the ability to smooth through inaccurate GPS data due to multi-path or poor satellite geometry.

The Kalman filter's integration of MAPS and GPS position data provides an accurate real time navigation solution. This navigation solution makes it possible to effectively control the NTV autonomously.

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