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VirtuaLite, a new method for GPS INS Integration for the Agricultural Environment

Anthony Cole
University of New South Wales, Sydney, Australia
Ph: +61 2 9385 4185, Fax: +61 2 9313 7493, a.cole@student.unsw.edu.au

Jinling Wang
University of New South Wales, Sydney, Australia
Ph: +61 2 9385 4203, Fax: +61 2 9313 7493, jinling.wang@unsw.edu.au

Andrew G. Dempster
University of New South Wales, Sydney, Australia
Ph: +61 2 9385 6890, Fax: +61 2 9313 7493, a.dempster@unsw.edu.au

Chris Rizos
University of New South Wales, Sydney, Australia
Ph: +61 2 9385 4205, Fax: +61 2 9313 7493, c.rizos@unsw.edu.au

ABSTRACT

Agricultural applications, particularly row cropping applications which are the focus of this paper, are ideal candidates for automation through their continuous and repetitive nature, high dependence on manual labour and typically being conducted in locations that have a relatively unobstructed sky view. A key part of the automation process however, is determining the location of the machinery being automated. Traditionally, GPS and INS integration through either a loosely-coupled or tightly-coupled Kalman filter has been used to provide a robust positioning solution in both the long and short term. The innovative idea to bridge GPS outages presented in this paper will outline an alternate method for INS and GPS integration utilising the existing GPS infrastructure specifically for the agricultural environment. While the focus of this paper is on agricultural applications this technique could be extended into all fields utilising an integrated GPS and INS system to derive a position solution. This paper discusses the problems associated with this new approach as well as presenting initial simulation results. Furthermore, a preliminary comparison between these simulation results and a simulation based on the traditional method for bridging GPS outages using the variable fixed method.

KEYWORDS: Integration, GPS, INS, Machine Automation, Agriculture

1. INTRODUCTION

With the trend to a more urbanised population that is increasing rapidly, and a growing public concern with the environmental consequences of modern society's actions, agricultural producers are being subjected to pressures from two directions. These include the necessity to produce enough food to feed the growing population as well as a need to lessen the environmental impact of the food production process.

The combination of these factors is forcing agricultural operations to become more efficient in the way they use resources, for example in order to ensure that each application of the various chemicals used in food production is achieving the maximum benefit. One of the costs that are limiting the adoption of targeted farming practices are the associated intensive labour costs. Many agricultural tasks, however, are ideally suited for GPS-based automation in that they are highly repetitive, in regions of low population density, and usually are conducted in areas with good sky views. One of the main agricultural activities that could benefit from the introduction of automated farm machinery is crop farming, particularly for row crops. The use of precision machine automation has the potential to improve crop yield, decrease labour costs and reduce the environmental footprint of farming operations through the more efficient use of farming inputs (Bongiovanni and Lowenberg-Deboer, 2004).

The definition of "precision agriculture" is relatively imprecise. A definition taken from McBratney *et el.* (2005) states that precision agriculture is ''that kind of agriculture that increases the number of (correct) decisions per unit area of land per unit time with associated net benefits''. This definition implies that precision agriculture can be considered to be any technology that assists the farmer either by increasing the information available to him or allows better use of the information already available. In this paper, the focus is on the integration of GPS and INS, in a unique way, with the aim of assisting tractor operations with precise, reliable and accurate position information for use in row cropping operations.

Integrated GPS and INS systems have been in use for many years and offer a compelling advantage over GPS-only or INS-only systems for precise and robust positioning applications. GPS provides a high accuracy solution, however the low data rates can be a disadvantage. The dependence on the reception of satellite signals also means that a GPS solution can be affected by interference and signal blockages that can further reduce the availability of a reliable position solution. INS, on the other hand, has a high output data rate and good accuracy over short periods of time, but does suffer from time-dependent errors that cause the position solution to degrade with time. The combination of these two systems makes possible the generation of precise position information with good data rates and good long term accuracy and availability.

Current methods of integration have traditionally relied on the Kalman filter to integrate the outputs of the separate sensor systems, at various so-called integration "levels". There are three levels of integration. The integration of the two systems at the position output level, known as “loosely-coupled”, permits a basic integration that essentially treats each individual system as standalone. The drawbacks of such a system is that the position errors from the GPS system can be time correlated (Wendel & Trommer, 2004) and if an incomplete constellation is present, that is less than four trackable satellites, the system must disregard the GPS output and operate as the equivalent of a standalone INS system. Another drawback of such an integrated system is that many GPS receivers generate the position solution output through the implementation of a separate Kalman filter whose covariance structure is unknown. Using this navigation information in a loosely-coupled system can cause degradation in the quality of the final solution (Farrell *et el.* 1999).

The second level of integration, known as “tightly-coupled”, involves using the pseudorange and delta-range measurements from the GPS system directly in the navigation Kalman filter. This method of integration is more complex than the loosely-coupled approach, however it has the advantage of being able to utilise partial information from the GPS system such as occurs when less than four satellites are tracked. This form of integration is traditionally suited to operating environments that suffer from degraded GPS coverage. The final level of integration is known as “ultra-tight”, or “deeply-coupled” integration, where the I and Q signals from the tracking loops of the GPS receiver are combined with the position and velocity outputs of the INS. The primary advantage offered by this level of integration is the reduction of the tracking bandwidth, as the INS-derived Doppler aids the tracking loops in order to effectively remove the dynamics of the GPS signals (Babu and Wang, 2004).

The integration method presented here for the combined processing of INS and GPS measurements is a novel one. The basic idea of this method is to couple the output of the INS system to the GPS system *without* changing the GPS implementation. The proposed method transforms the INS-derived position solution into “virtual” satellite measurements, known as virtualites, which can be fed into the GPS receiver’s software and processed alongside the real GPS measurements.

The generation of a virtualite measurement is a multi-stage process that involves the creation of a virtual satellite (or “virtualite”), followed by the calculation of the virtual range measurements between the INS-derived position and the position(s) of the virtualite(s). There are many different aspects to this process and this paper will introduce this concept and present some preliminary results. The results of this integration method will also be compared to the results obtained using a traditional method of fixing one or more of the variables (usually height and/or clock bias) to its last known value.

2. VIRTUALITE IMPLEMENTATION

2.1 VIRTUALITE CREATION

The generation of the virtualite measurements is based on the range difference between the selected virtual satellite position and the INS-derived position. The errors involved in the INS solution are not transformed, and are minimised during the processing of the virtualite and GPS measurements through the selection of a weighting matrix that reflects the confidence of the INS-derived solution. The following equation shows the calculation of the pseudorange measurements for GPS, where p_{true} is the true range and p_M is the measured range, R_{cb} is the receiver clock bias, and *c* the speed of light in a vacuum:

$$p_{true} = p_M + R_{cb}c \qquad (1)$$

$$p_{true} = (x^i - x_r)^2 + (y^i - y_r)^2 + (z^i - z_r) + cR_{cb} \qquad (2)$$

Where superscript i indicates the coordinate for satellite position i and subscript r indicates the coordinate for the receiver's true position. *When* constructing a pseudorange measurement from the INS-derived position, the value of R_{cb} can be set to zero to give the following equation. We can also establish a relationship such that the true range value is equal to the computed range value for the virtualite plus the INS error value in the direction of the unit vector to the virtualite position ε_{VL}:

$$p_{true} = p_{VL} + \varepsilon_{VL} \qquad (3)$$

The least squares equation is:

$$l_k = A_k x_k + v_k \qquad (4)$$

where $l_k = \begin{bmatrix} p_M \\ p_{VL} \end{bmatrix}$ and is the measurement vector; A_k is the design matrix comprised of the partial derivatives; x_k is the state vector and v_k is the residual vector based on the predicted state vector. When the virtualite measurement vector is empty, the design matrix can be constructed in the normal way. However, when the virtualite measurement vector is not empty the design matrix needs to reflect the fact that the virtualite measurements are not subject to effects from the receiver clock bias, and therefore the corresponding term in the design matrix must be set to zero. The construction of the design matrix is shown below, with superscript i denoting position of the ith satellite and superscript j denoting the position of the jth virtualite:

$$A_k = \begin{bmatrix} \frac{x^i - x}{p_M} & \frac{y^i - y}{p_M} & \frac{z^i - z}{p_M} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ \frac{x^j - x}{p_{VL}} & \frac{y^j - y}{p_{VL}} & \frac{z^j - z}{p_{VL}} & 0 \\ \vdots & \vdots & \vdots & \vdots \end{bmatrix} \qquad (5)$$

2.2 VIRTUALITE PLACEMENT

As this implementation of virtualite is concerned with bridging GPS outages the placement of the virtualite position is dependent on the GPS satellites that are blocked. Each virtualite position is set to be the last known position of the satellite(s) that is (are) blocked. In this way, the virtualite position(s) is (are) set when the GPS satellite(s) is (are) first lost, and the position is updated via the apparent motion of the GPS satellite(s) as if it (they) was (were) still visible. Because the ranging measurements are created to the satellite position derived from the receiver's almanac, any orbital errors in the position of the real, obstructed satellite does not affect the generated virtual range measurements.

2.3 SIMULATION DESIGN

The implementation of the virtualite concept was implemented using Matlab, a powerful simulation tool for engineers and mathematicians. The approach used was to simulate both the GPS and the INS measurements, with the characteristics of the INS measurements established as shown in table 1. The INS system simulated comprised three gyros and three accelerometers with no alignment errors assumed. The GPS simulation assumed a single-frequency receiver outputting pseudorange and delta range measurements only. Figure 1 shows the schematic of the simulation process that was implemented for testing purposes.

	Value	Unit
Gyro Characteristics		
Bias Value	40	mg
Scale Factor	10	-
White Noise Std Deviation	10	$m/s^2/\sqrt{hr}$
Accelerometer Characteristics		
Bias Value	10	Deg/hr
Scale Factor	5	-
White Noise Std Deviation	1	$Deg/\sqrt{hr}$

Table 1: INS Characteristics

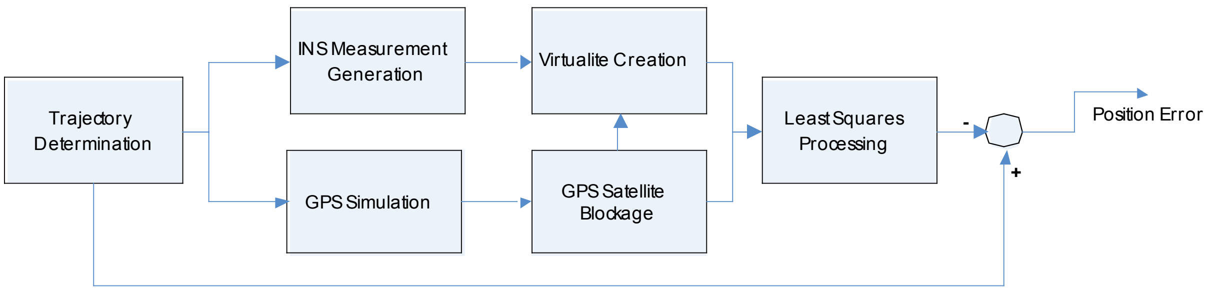


Figure 1: INS and GPS simulation diagram

3. RESULTS

The scenario examined in this paper seeks to use virtualites to bridge GPS outages when only a restricted constellation is visible. Figure 2 shows the ground track of the simulated tractor path. Each run is 500m long and the turns are constant velocity, constant radius turns. Figure 3 shows the number of satellites visible throughout the run under ideal tracking conditions.

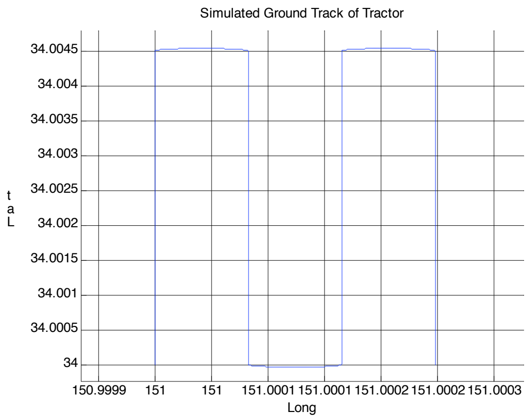


Figure 2: Simulated ground track of tractor

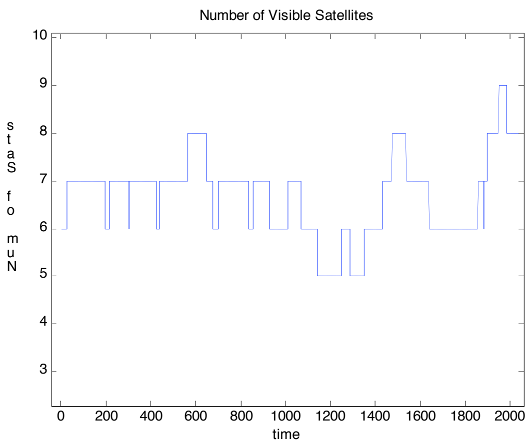


Figure 3: Number of visible satellites

As the condition examined in this paper is the situation where the number of visible GPS satellites drops below the minimum number four, the following three conditions are examined. The first is when the number of visible satellites drops to three and the resulting error is compared to the case where the height-fixed method is used to process a 3-satellite position solution. The second case is to examine the position error when only one satellite is trackable. This last case is a situation where a standard GPS position solution is not possible, allowing only the performance of the virtualite augmented system to be analysed.

3.1 LOW SATELLITE VISIBLE

In the case when three satellites are visible figure 4 shows the error derived from the traditional approach where the height value of the GPS solution is held constant. We can see that the error grows with time as the fixed variable position drifts from the true position. There are two intervals where the number of tracked satellites has fallen to three. The first is a short blockage of 25s during which the height doesn't vary, and the second is a longer blockage of 50s during which the ground height value varies considerably. Figure 5 shows the number of visible satellites during the run.

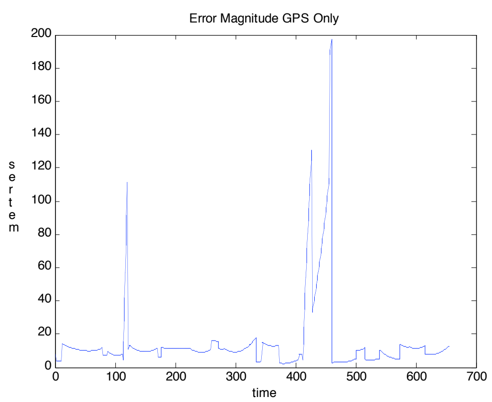


Figure 4: GPS error

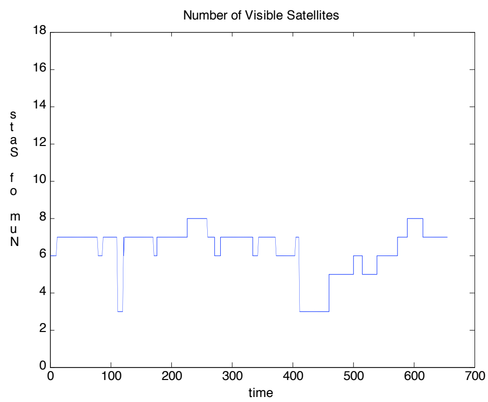
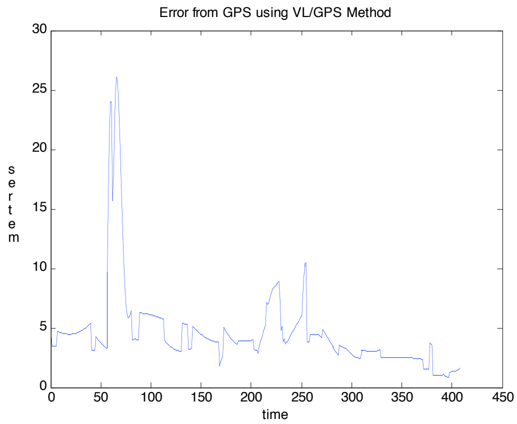


Figure 5: Number of visible satellites

Figure 6 shows the error from a combined virtualite solution where the blocked satellites are simulated from virtualites constructed from the INS-derived position solution. Figure 7 shows the number of virtualites in use at any one time and the total number of satellites and virtualites processed.



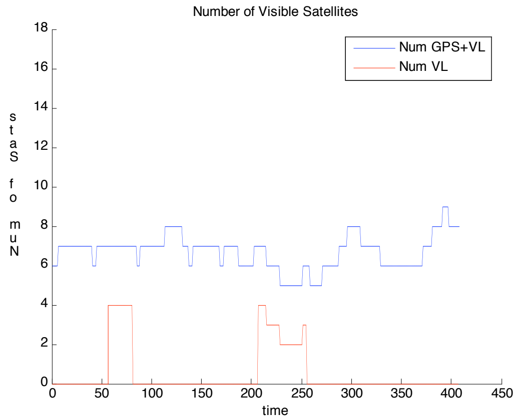
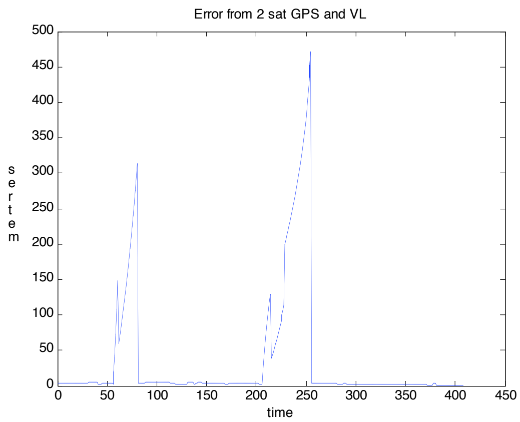


Figure 6: GPS error using VL for low satellite visibility

Figure 7: Number of visible satellites

We can see from figure 6 that the results when using the virtualite augmentation method are mixed, though positive. During the first outage, from 50s to 75s the error growth has been limited by using the virtualite concept, the absolute position error still grew to a maximum of approx 26m, an improvement on the 100m absolute position error using the variable fixed method. The second outage using the combined virtualite-GPS method performed significantly better than the variable fixed method in figure 4, with the absolute position error peaking at 10.5m. Figure 8 shows the error when only one GPS satellite is trackable and the remaining measurements are sourced from the virtualite method. We can see that while a position solution is achieved the error growth is very large. Figure 9 shows the number of trackable satellites as a total and the number of virtualites in use at a given time.



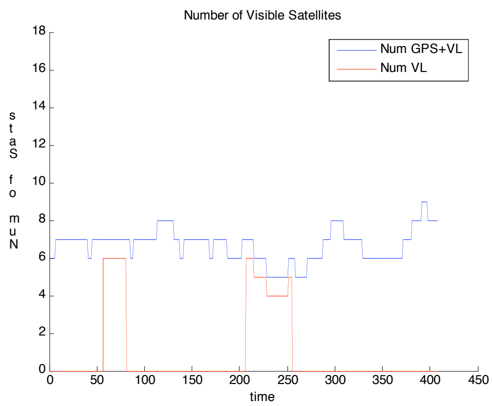


Figure 8: Error when only two GPS satellites trackable

Figure 9: Number of visible satellites and virtualites

4. CONCLUDING REMARKS

The results described above have demonstrated the validity of the virtualite concept as a method to bridge GPS outages. The simulations presented here have shown an improvement in the absolute position error when compared to the absolute position error obtained from using the traditional method of fixing height and solving for the remaining three unknowns. The resulting integrated solution also allows for the bias growth in the INS measurements to be partially contained when there is a satellite available.

As the results here show, the number of blocked satellites influences the utility of the virtualite solution. However, the more blocked satellites there are, the greater the number of virtual measurements that need to be generated. By having a situation where more virtualite measurements are generated, the net effect is to create a greater weighting on the virtual measurements and therefore onto the INS contributed component. This may lead to the introduction of a weighting matrix into the least squares solution in order to control the inevitable effect of having a large number of virtual measurements.

5. FUTURE WORK

The virtualite concept is still in its infancy and there are many directions this work can be taken in order to fully explore this concept. The most obvious is to extend this work to include real data such that the concept described here, indeed the validity of the simulation model, can be thoroughly tested under real world conditions. An important extension to this work would be to introduce a weighting mechanism such that the weight of the virtualite measurements, and therefore of the INS measurements, in the final position solution can be better controlled.

Another way in which this concept could be extended is to look at implementing a receiver clock model in order to predict the receiver clock bias into the next epoch. This would then allow the virtualite measurements to incorporate the receiver clock bias into the measurement generation.

There are also plans to extend this work into applications that have greater accuracy requirements and therefore utilise differential real-time kinematic GPS positioning.

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