speed, and this would remove some of the responsibility from the harvester operator.

5 Conclusions

A method of assessing cane loss has been described in which an audio transducer directly detects cane billet impacts on the blade of the primary extractor fan. The signals from this transducer bridge the gap between the moving fan to the stationary frame of the harvester via a passively coupled rotating transformer.

Field trials of these detecting and recording processes have successfully been conducted on a mechanical cane harvester in Bundaberg. A sample of the raw waveform has been presented here, and post-processing techniques that may be used to discriminate between billets and trash have been illustrated and discussed. The most successful of the signal processing techniques is described and the output waveform is illustrated. This method could be implemented digitally with a micro-controller in 'real-time', and the measure of cane loss that is quantified could be implemented to control the fan speed.

The methods described here show promise of providing an accurate real-time assessment of cane loss.

Acknowledgements

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Low cost GPS for the Autonomous Robot Farmhand

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Abstract

An autonomous robot has been proposed to perform precision agricultural tasks. In addition to vision guidance and odometry, it will require GPS navigation with an accuracy of ten centimetres or better. This paper describes two complementary methods of employing signals from a pair of low-cost receivers to achieve this accuracy. The method has potential for application to more general tractor guidance.

Keywords:
GPS, carrier pseudorange, autonomous robot, agricultural.

1 Introduction

A scarce resource in farming is the farmer's own time. Machinery tends to grow ever larger and faster so that the farmer can attend to many rows simultaneously in a minimum of time. An alternative method which has been the subject of much research is to make the machinery autonomous and unmanned. For the reasons below, it is not fruitful to seek to achieve autonomous operation by upgrading existing machinery by the addition of guidance and supervisory systems. It is preferable to build on the concept of smaller machines in which task and control structure are integrated at the outset.

Manufacturers are unwilling for tractors to be unmanned. Small modifications to the existing vision guidance system [1, 2] developed by the National Centre for Engineering in Agriculture (NCEA) would make autonomous operation feasible, but the consequences of a system failure would carry an unacceptable level of risk with the fear of litigation. Even human-supervised operation has problems that might not be expected. A guidance upgrade to a large tractor will imply that its supplier has an obligation to maintain it, something likely to be outside the supplier's expertise. This will deter suppliers unless their financial mark-up is very large indeed, adding further to the high cost of present guidance systems.

A relatively small autonomous vehicle can answer many of these problems. Although not entirely devoid of risk, its threat can be made more easily acceptable. Since it now makes few demands on the farmer's time and can work day and night, it can operate at a much lower speed. A safety-bumper can therefore be provided to cause an emergency stop, presenting no greater risks than are already accepted for unmanned machines which move components in factories.

If it is engineered as an integrated unit, the distributor can approach the maintenance problem in the same way as the High Street vendor of a computer system. A replacement can be loaned while the machine is repaired at a centre with the necessary expertise.

A small mobile of this type has the potential to make a great impact on farming methods. To be viable, however, it is essential to use guidance techniques which are robust yet economical. Odometry and magnetic compass signals are of low cost and are easy to interface. The vision techniques developed for tractor guidance can be adapted at modest cost to give accurate location relative to the crop.

To move to a location where a vision lock can be achieved, a further navigation system is needed which can achieve sub-metre accuracy. A target accuracy of such a system might be some ten centimetres. 'OEM' GPS receivers cost only one or two hundred dollars, but suffer errors of one to five metres at best. Precision GPS is at present a very expensive option.

Some initial experiments at the NCEA are looking very promising for combining the signals from two OEM receivers to achieve a precise differential solution. One receiver is fixed and its raw pseudorange data are transmitted to the mobile robot, where its data are combined with that of the second unit in a computer on which the solution is performed.

Indeed, the signals from a single base unit can be received by any number of mobiles to perform differential calculations using a single receiver in each mobile.

2 Carrier phase differential GPS methods for accurate navigation

2.1 Background to GPS

In a GPS receiver, distances (termed 'pseudoranges') are estimated from the visible satellites using very accurate clocks and correlators of pseudorandom sequences. Low cost receivers use the L1 band transmission of pseudorandom sequences at about one megaherz bit-rate. The cycle length of these sequences is 1023 bits taking just 1 ms and they are termed 'coarse acquisition'. Highly priced systems as employed by surveyors use also the L2 band transmission at a bit-rate of 10 MHz. [4]

What is conventionally known as differential GPS or DGPS is not truly differential. A fixed base station receives signals from the visible satellites. Using its accurately known position it back-calculates the range errors in the received signals. The major contributions to these errors are atmospheric effects and the much greater 'selective availability' error which was until recently added deliberately to the transmitted signal.

The correction is transmitted as an 'RTCM signal', typically at a rate of 200 bits per second. Coastguards around the world transmit such signals gratis on long-wave radio, while agencies use satellite and FM radio signals and charge a substantial fee for their use. Now that 'selective availability' has ceased, the typical error of 80 metres of an uncorrected receiver has reduced to the three metres of one with RTCM compensation. In a corrected receiver, the cessation of selective availability will hardly have been noticeable.

The receiver process is remarkable in that all satellite transmissions are on the same frequency, spread only by the doppler effect. To separate these superimposed signals, the receiver replicates the perceived signal of each satellite, complete with its pseudorandom sequence and the doppler-shifted carrier signal onto which it is modulated. These signals are phase-locked with the received carrier signals, so a second set of data describes the range as measured by the carrier wave.

The accuracy of three metres in the conventional 'code phase' fix represents one percent of the 300 metre wavelength of one bit of the modulating signal. The wavelength of the carrier signal is a mere 20 cm and the jitter in the measured phase-shift is some eight millimetres for the receiver used in these experiments.

The code range is measured unambiguously, since the entire sequence corresponds to a speed-of-light distance of 300 km. In contrast, although the carrier phase measurement includes a count of the cycles through which it has changed, its starting value could be at any multiple of a half wavelength. To exploit the precision of the carrier range, it is therefore necessary to solve the problem of the 'ambiguity'.

2.2 Peer-differential GPS

By combining the pseudorange data from two receivers, many of the errors cancel out. The difference of the pseudoranges for a given satellite will represent the separation between the receivers, resolved in the direction of the satellite. The difference of the carrier ranges will have in effect a single ambiguity error.

One way to solve the ambiguity problem is to know the initial displacement of the receivers and calculate the ambiguities to fit. The signal from a given satellite can remain in lock for many minutes and during that time the ambiguity remains the same. At first, maybe eight satellites are in view and locked. From the initial displacement and the measured signals, eight ambiguities are calculated and movement can commence.

As time proceeds, some satellites set and others rise. Whenever slip occurs and lock is lost the satellite must be deleted from the solution. A new satellite cannot be added, since its ambiguity is unknown. Eventually the number of survivors falls below four and the solution ceases. Four satellites must be used, since clock errors in the receivers make it necessary to solve for x, y, z and t.

The nub of the navigation problem can be posed as two questions:

1. How can an accurate initial absolute location be found without a known landmark?
2. How can the quality of the fix be made to survive loss of lock?

Answers are offered in the next two sections.

2.3 Time-differential methods.

At the heart of the least-squares method used for solving for position is the vector equation

$$p = Hx$$

where **p** is the vector of pseudoranges and **x** is a four-element vector, being three of position and one of time. H is a matrix of direction cosines of the satellite directions, the 't' column containing values of c, the velocity of light.

The estimated position which minimises a sum of squares of error is given by

$$x = (H'H)^{-1}H'\mathbf{p}$$

The procedure for obtaining a solution is as follows.

- For each receiver in turn:
  - Read the data messages giving satellite ID and pseudorange.
  - In a table, update the entry corresponding to the satellite ID (an integer in the range 0 to 31) with the new range.
  - Set a flag to indicate that the data is valid for that satellite and receiver.
  - If slip has ocurred in either receiver, clear the 'locked' flag for that satellite.
  - Receive also the computed time-of-origin of the measurements.
  - When these correspond (in alternate messsages) calculate differences for all satellites which are valid in both data sets.
  - For each of these satellites, calculate a row of the matrix H as follows:
    - The ephemeris of this satellite gives full orbital data sufficient to calculate its position with great accuracy.
    - Further calculation using the location of the fixed receiver gives the direction cosines.
    - If the satellite is new to the constellation, its ephemeris can be requested from either receiver.
- Calculate the four-by-four matrix of the product of the transpose of H and H.
- Invert this matrix
- Calculate the product of the transpose of H with the range differences (corrected for ambiguity)
- Finally, multiply these to give the estimate of position and clock error.
- For carrier range calculations, usable satellites are restricted to those which are locked and the range differences are corrected by the ambiguity estimates.

The relationship between position and carrier pseudorange can be writen in more detail as

$$p = Hx + p_0$$

where p_0 represents the ambiguity. If the time derivative is taken, p_0 disappears:

$$dp/dt = H\,dx/dt + dH/dt\,\mathbf{x}$$

If the 'mobile' receiver does not move, this becomes

$$dp/dt = dH/dt\,\mathbf{x}$$

This can be solved in exactly the same way as before, since the derivative of H can be calculated and is no more likely to have degenerate rank than H. The position is found from the rates of change of the pseudoranges as the satellites move in the sky - to which we have given the nickname "The sundial effect".

A fatal loss of lock can therefore be remedied by remaining stationary for a few minutes while a new absolute fix is found. The figures below show the unedited results of the first set of data recorded.

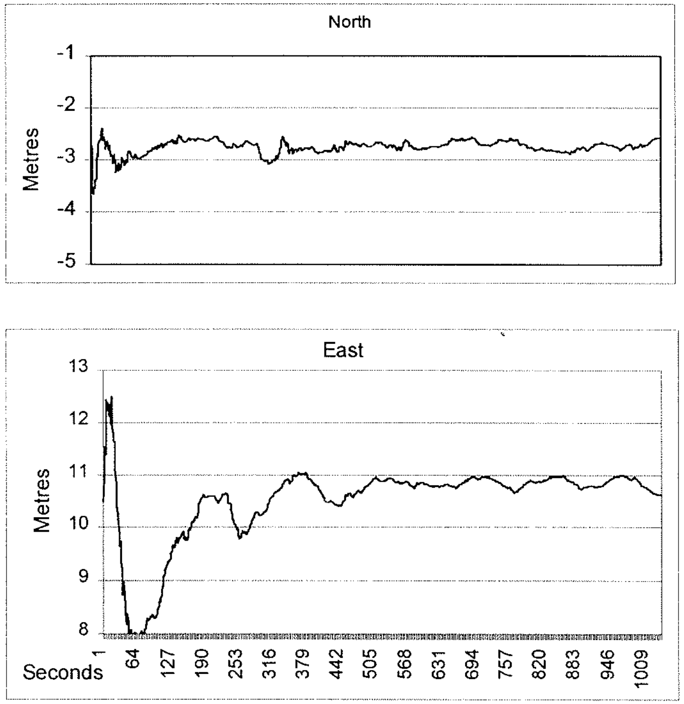

Fig 1. Absolute location using a time-difference method.

2.4 'Repair' of lost lock

The signals delivered by the receivers give pseudorange measured in cycles and phase and also the slip status. Ambiguity can be stored as an integer number of half cycles. When just four ranges are used in the solution, the solution is 'exact' - though not necessarily free from error. If the satellites are in syzygy the rank of H collapses and the matrix inversion cannot be performed. When more are used, the equations are over-specified and the solution represents a compromise. The 'sum of squares' which is used in the minimisation process gives a measure of the consistency of the equations.

When lock is lost temporarily, or if a new satellite becomes usable, the solution given by the surviving channels can be used to estimate a new ambiguity. These estimates are smoothed over, say, twenty values at one-second intervals and then applied to the 'rehabilitated' channel. With a 'jitter' of less than ten percent of a half-wavelength, the correct integer value will most probably be selected and the repair should then be perfect.

If the initial set of ambiguities is in error or if the direction cosines are ill-conditioned the solution can be in error. Each newly calculated ambiguity then has a probability of introducing an additional error of the order of five centimetres.

The graphs below show the unedited results of the first test recorded, representing many losses of lock and repairs. Modifications had been made to the software to allow loss-of-lock errors to be introduced into each channel in turn and in these graphs all channels had been interrupted and repaired at least once.

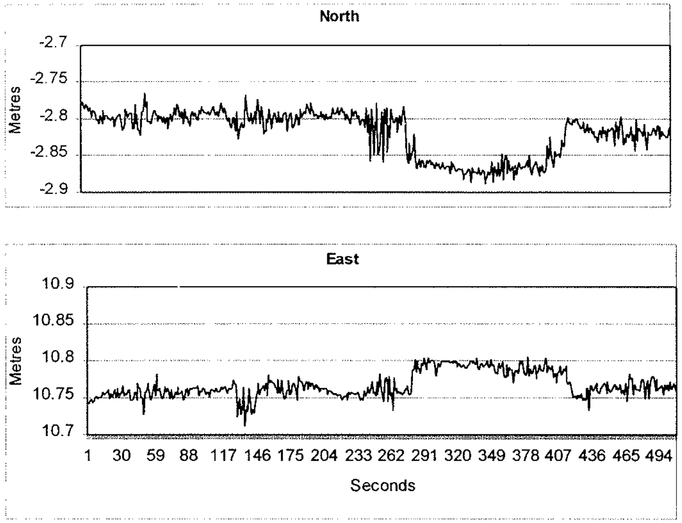

Fig 2. Results over eight minutes of 'repaired lock'.

One conclusion which can be drawn is that the initial ambiguity values were not accurately set up. About 285 seconds into the run, a channel came on line with an incorrect value, pulling the solution about 7 cm to the south-east. At time 410 it dropped out again and the solution reverted to its former location.

If the initial ambiguity can be set exactly, whenever a channel is 'repaired' the quantisation of the ambiguity can pull the new value to the 'exact' correction. Attention will be concentrated on achieving and detecting an exact 'lock' with the aid of the 'sundial' method.

3. Conclusions

The results presented here show that the 'sundial' method is already close to giving the accuracy needed for exact ambiguity determination. Since the tests were performed near tall buildings, multipathing could be blamed for the remaining errors. In open fields, the method might already be of sufficient quality - the next set of tests will be performed in that situation.

A further line of investigation will concern development based on the 'sundial' method to allow ambiguity to be corrected while the vehicle is in motion.

With the combination of vision and GPS, the possibility of an autonomous farming mobile of true commercial value is close to a reality.

Acknowledgments

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