Computers and Electronics in Agriculture
20 (1998) 185–197

Computers
and electronics
in agriculture

Centimetre-precision guidance of moving implements in the open field: a simulation based on GPS measurements

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Received 7 July 1997; received in revised form 24 November 1997; accepted 17 February 1998

Abstract

High quality and sustainable agricultural production in the open field will be supported by centimetre-precision guidance of agricultural implements. In this paper, a complete guidance system is proposed and simulated using real sensor data obtained from a real time kinematic (RTK) differential global positioning system (DGPS). This type of the satellite navigation system became available commercially in 1997 and is claimed to reach cm accuracy. It uses real time kinematics to improve the accuracy of a position fix by phase comparison of the carrier signal. The simulation primarily aims to investigate the accuracy of the guidance system that can be obtained with RTK DGPS. Using real DGPS measurement errors the simulated system showed a tracking error less than 0.005 m when the PID-controller had settled. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: GPS; Guidance; Simulation; Agricultural implements

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PII S0168-1699(98)00016-7

1. Introduction

Arable fields are spatially variable in factors such as fertility, moisture content and weed infestation. The most common way to describe spatial variability is to interpolate from spot measurements in a sampling grid, resulting in a patchwork-like map when visualised.

It may be important to distinguish between those spots or bands in the field where the crop grows, and the area where no crop or crop roots are present, at least in the first months of crop growth. These so called inter-row bands are often far wider than the crop rows in this period of time (until the canopy closes). The inter-row bands should preferably have far worse growing conditions, to minimise weed emergence and development, than the bands where the crop plants are sowed or planted. Nevertheless, in normal practice, the inter-row bands are cultivated and fertilised just as the crop rows.

A control system that is capable of placing inputs and seeds exactly and exclusively on desired, predetermined spots, would increase the overall effectiveness of nutrient uptake and save inputs as well as protect the environment (De Wit, 1953). He describes an increase in the percentage of nitrogen uptake by the crop plants, when fertiliser is applied in the crop rows only, leaving less nutrients exposed to potential leaching to ground water.

In addition the control system may be used to increase the quality of operations such as ploughing and ridging potatoes. Therefore it has the potential to increase the sustainability of production.

The main objective of the research was to build, analyse and evaluate a guidance system for agricultural implements. The starting point of the research was to fine-tune an implement exactly to a predetermined path which was already approximately followed by a standard tractor powering the implement. The main elements in this system were a digital map containing the coordinates that described the path, a sensor to measure the actual position of the tractor and a control system to steer the implement onto the path. The control system consisted of an actuator, rigidly connected to the back of the tractor, with a moving part on which the implement could be rigidly connected. The moving part moved perpendicular to the direction of driving of the tractor and was actuated by a hydraulic cylinder. The control system used the measurements of the actual tractor position to determine the desired side shift of the implement onto the path stored in the digital map. To realise the desired side shift the controller used measurements of the actual side shift as described in Section 2.

In 1997, satellite navigation systems called RTK DGPS (real time kinematic differential GPS) became available commercially. The manufacturer claimed sub-centimetre accuracy at a 1-s interval, or ± 3-cm accuracy at a 200-ms interval. Latency will not exceed these 200 ms, and the time to which the position measurement refers is included in the output message. Using actual data of the RTK DGPS position sensor (Trimble 7400 Msi), to represent measurements of the actual position of the tractor, the simulation results of the guidance system are presented in this paper. The objective of the simulations was to determine the

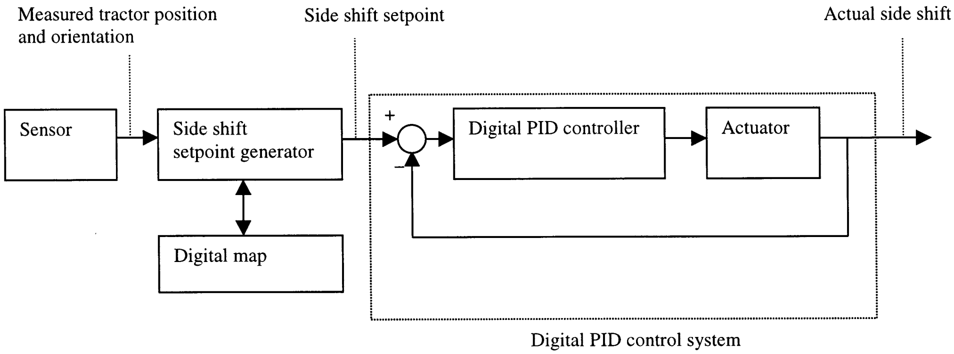


Fig. 1. The guidance system.

accuracy of a guidance system that can be obtained using this satellite navigation system. The work was initiated by Van Erp (1995) who generated a simulation model of the implement guidance system in which he used artificial sensor data.

2. Description of the simulated guidance system

2.1. Introduction

Fig. 1 represents a block scheme of the implement guidance system. The RTK DGPS sensor, which measured the tractor position and heading, was used, together with a digital map, which stored the path the implement had to track, to calculate the desired side shift. A digital PID control system was used to realise the desired side shift. The control system consisted of a digital PID-controller and the actuator which could side shift the implement.

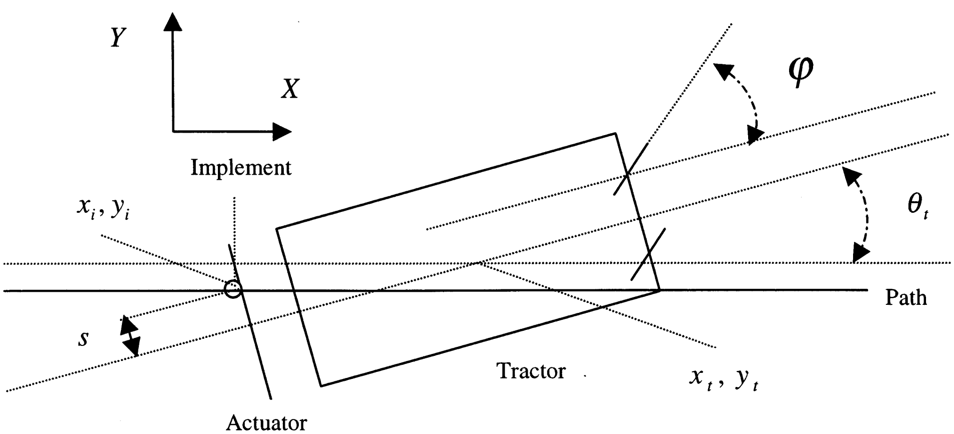


Fig. 2. Tractor actuator implement configuration.

Fig. 2 schematically represents the tractor–implement configuration. The path that the implement had to track is described by successive points that the implement has to pass. The straight lines connecting these points are crop row orientated and represent the path. At any moment in time only one of these straight lines is considered to be the path. The coordinate system in which the computations will be made is such that the positive x-axis runs parallel to this straight line (Van Zuydam, 1997). In our simulation, and in Fig. 2, the path was only one single straight line. If multiple straight lines determine the path, the coordinate system in which the computations are made changes with the changing of the lines.

The RTK DGPS position sensor was mounted on the tractor, and its measurements were used to calculate the coordinates x_i, y_i of the centre of the actuator. In Fig. 2, it was assumed that the sensor was mounted in the middle of the tractor, with coordinates x_t, y_t, but, without loss of generality, they may be assumed to be anywhere else on the tractor.

To simulate deviations that occur during driving, the tractor was steered such that the movement of the centre of the actuator was close to a sine wave. In the ideal situation the centre of the actuator moved along the path. If the coordinates x_i, y_i in Fig. 2 deviated from the path, the actuator was used to side shift the implement onto the path (s in Fig. 2).

Control was performed by a digital PID-controller. The actuator moved the implement perpendicular to the direction of driving, within a certain range, called the capture range. The deviation of the implement, which followed the desired path, had to be within this capture range, which was chosen to be ± 20 cm.

The way in which the guidance system is simulated is shown in Fig. 3. The dynamic model of the tractor is based on an existing model of a fire truck (Bushnell et al., 1993) and has three state variables, x_t and y_t, the coordinates of the middle of the tractor, and θ_t, which is the heading of the tractor. There are two control inputs v, the velocity of the tractor and ϕ, the angle between the front wheels and the central line of the tractor which is determined through steering (see Fig. 2). The path followed by the centre of the actuator is generated by varying the steer angle ϕ. The velocity v is kept constant.

In the left part of Fig. 3, a side shift setpoint is calculated, based on the RTK DGPS sensor information. The simulated RTK DGPS sensor data consist of the simulated (true) position and heading of the middle of the tractor disturbed by a measurement error signal obtained from an experiment with an RTK DGPS sensor. The PID-controller setpoint results in an actual side shift of the implement. The output of the simulation model is the tracking error, the difference between the desired and the actual side shift of the implement, which is one-dimensional. The mean absolute error (MAE) is used to compare different simulation runs.

2.2. The tractor model

The tractor model generates the path that the tractor follows and is given by,

$$\dot{x}_t = v \cos \theta \tag{1}$$

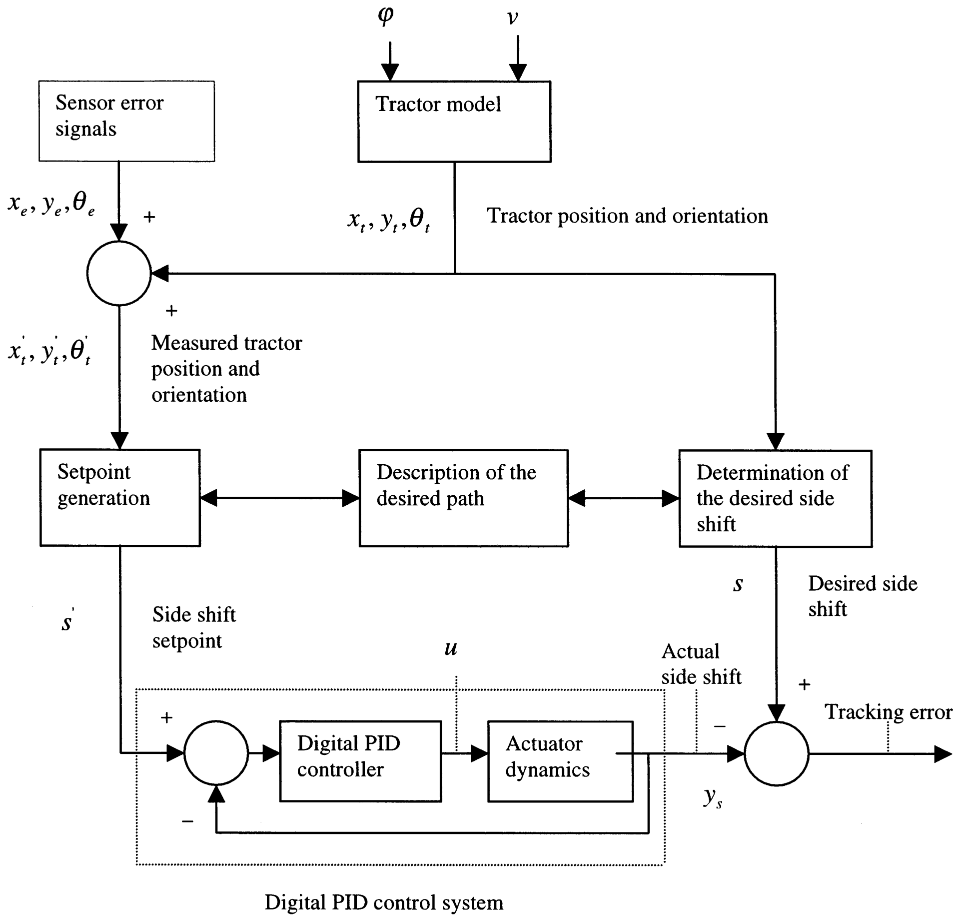


Fig. 3. Simulation of the guidance system.

$$\dot{y}_t = v \sin \theta \tag{2}$$

$$\dot{\theta}_t = v \frac{\tan \theta}{l} \tag{3}$$

The state variables x_t and y_t are the coordinates (in m) of the middle of the tractor. The state variable θ_t is the heading of the tractor, in radians, with respect to the x-axis (see Fig. 2). The heading is also measured by the position sensor. Together they form what is called the state vector of the tractor model, i.e. $[x_t\, y_t\, \theta_t]^T$.

Furthermore the parameter l is the wheel-base, the distance (in m) between the front and the rear axle of the tractor. The control variable v is the velocity (in m/s) of the tractor–actuator–implement combination and is assumed to be constant. The control variable ϕ is the steer angle (in radians) measured with respect to centre line of the tractor (see Fig. 1). Together they form the control vector $[v\ \phi]^T$. The initial state, the control and the parameter were chosen as follows,

$$[x_t\ y_t\ \theta_t]^T = [0\ 0\ 0.018]^T \tag{4}$$

$$[v(t)\ \phi(t)]^T = [2\ 0.006\ \sin(t_k/100)]^T, \quad t\in[t_k\ t_{k+1}], \quad t_k = kt_s,$$
$$k = 0, 1, 2,\ldots, 599, \quad t_s = 0.2 \tag{5}$$

$$l = 2.7 \tag{6}$$

In Eq. (5), t denotes the time measured in s, t_k are the sampling instants at which the controls are updated and t_s is the sampling period. As a result of this choice, the path followed by the centre of the actuator is a sine-wave with a period of about 50 m and an amplitude of about 15 cm, that starts at the origin. This sine-wave is assumed to represent the movement when someone tries to drive a tractor with a length of approximately 4 m along a straight line with a constant velocity.

2.3. GPS measurements used to generate the measurement error signal

The measurement error signal, used to simulate RTK DGPS measurement disturbances, is generated using static measurements obtained with the RTK DGPS receiver (Van Zuydam et al., 1997). With 5 Hz position updates the technical data indicate a 3 cm + 2 ppm (times baseline length) horizontal accuracy. Latency of the signal does not exceed 200 ms, and the time to which the position measurement refers is included in the output message.

In the experiment, the receiver was placed in a stationary position and the output, containing the position and orientation of the receiver, was monitored for several minutes. The local position and orientation of the receiver were assumed to be equal to the mean of the corresponding measurements. By subtracting this mean position from all the measured positions, the measurement error signal was obtained. By doing so the mean is assumed to be the true position. Experience with GPS indicates that this is not so. So in practice there is an additional offset-error which adds to the simulation error computed in this study. The measurement frequency was 5 Hz and 771 position fixes were obtained. Statistical analysis of these fixes gave the following results. The variance in the x-direction equalled $7.38\cdot10^{-5}$ m^2 and the variance in the y-direction equalled $1.22\cdot10^{-4}$ m^2, where the x- and y-axis were taken from the coordinate system of the GPS system. Within this system the y-axis was parallel to the equator (west–east) and the x-axis ran parallel with the Greenwich meridian (south–north). The associated mean absolute error of the x- and y-coordinates were respectively $6.37\cdot10^{-3}$ m and $9.19\cdot10^{-3}$ m. Fig. 4A and B depict the measurement error signal and for the and coordinates respectively. Based on technical data of the RTK DGPS sensor the measurement error signal of the heading was generated randomly assuming the maximum

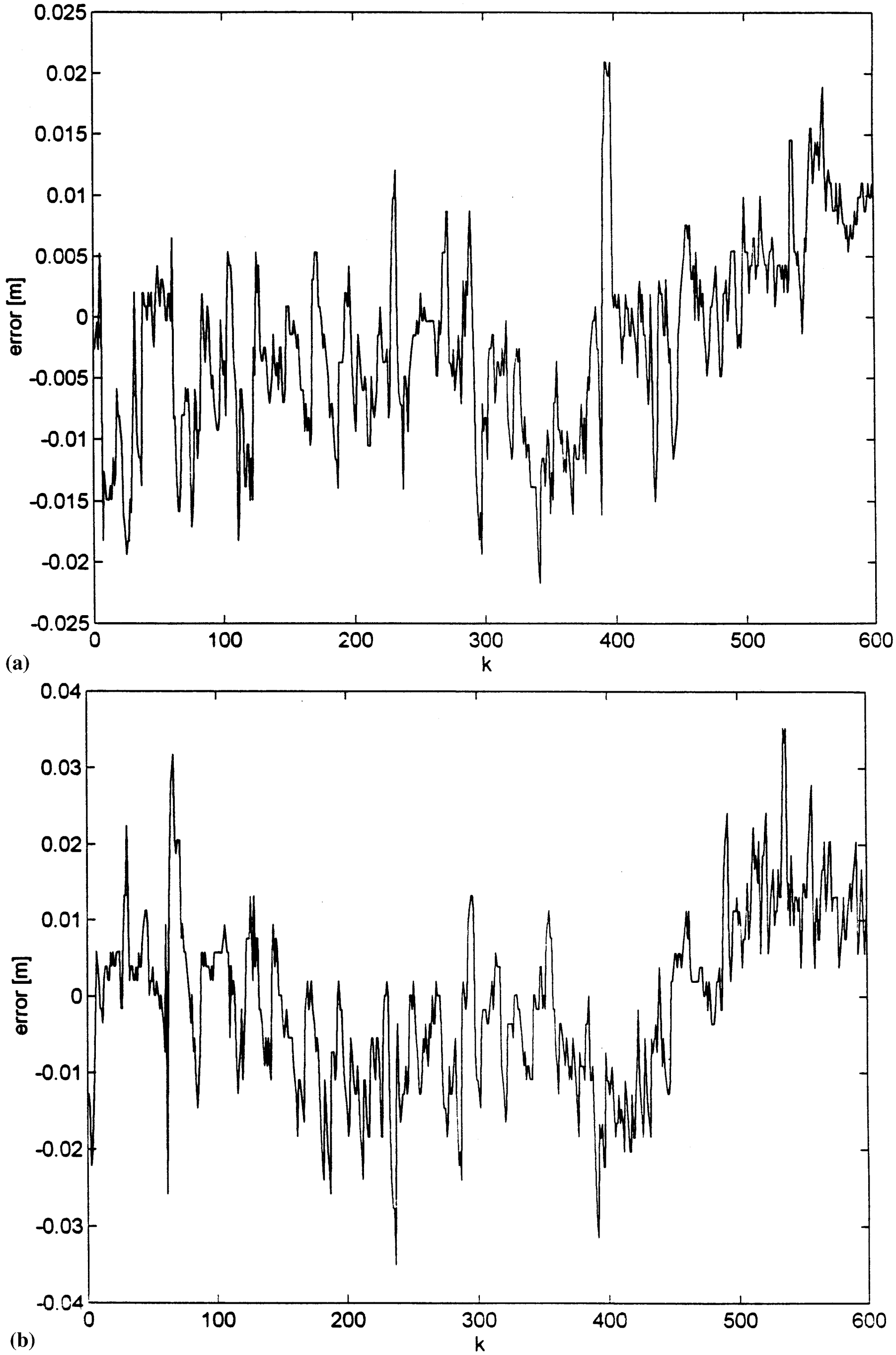
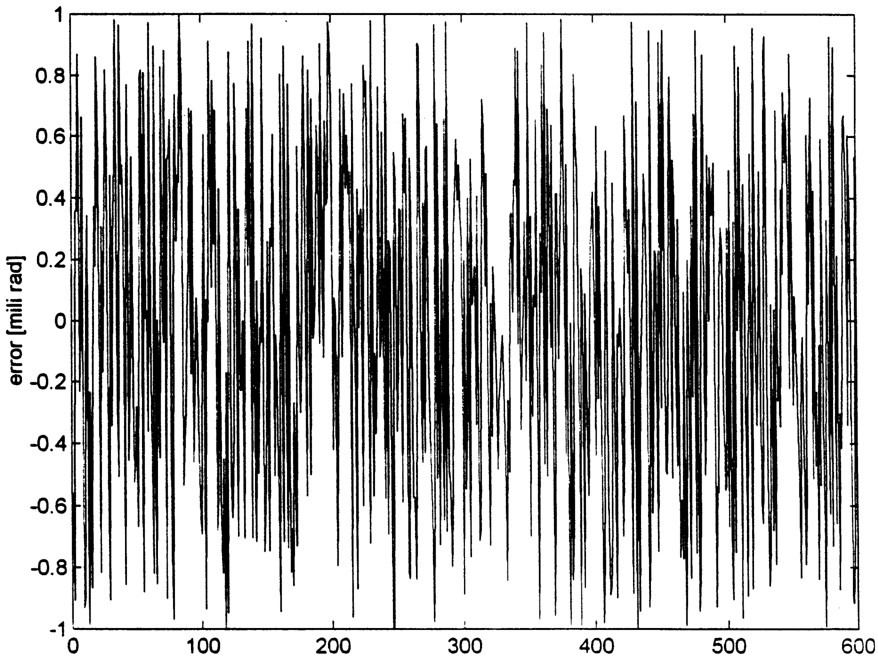


Fig. 4. (a) Measurement error x-coordinate (x_e); (b) measurement error y-coordinate (y_e); (c) measurement error heading (θ).



(c)

Fig. 4. (*Continued*)

disturbance to be 0.001 rad. The resulting measurement error signal is depicted in Fig. 4C. Summarising, the simulated RTK DGPS measurements are constructed as follows

$$x'_t = x_t + x_e \tag{7.1}$$

$$y'_t = y_t + y_e \tag{7.2}$$

$$\theta'_t = \theta_t + \theta_e \tag{7.3}$$

where $'$ refers to measurements.

2.4. Setpoint generation and determination of the desired shift

To determine the side shift setpoint, based on the RTK DGPS measurements, first the measurements obtained from the RTK DGPS receiver had to be transformed into the coordinate system of which the x-axis coincides with (part of) the path, i.e. into x'_t, y'_t and θ'_t. Then the desired position on the path, at each sampling instant, was computed as the intersection of the line along which the implement is side shifted and the path. To formalise this, from Fig. 2 observe that the relation between the coordinates of the middle of the tractor x_t, y_t and the coordinates of the centre of the actuator, denoted by x_i, y_i, are given by,

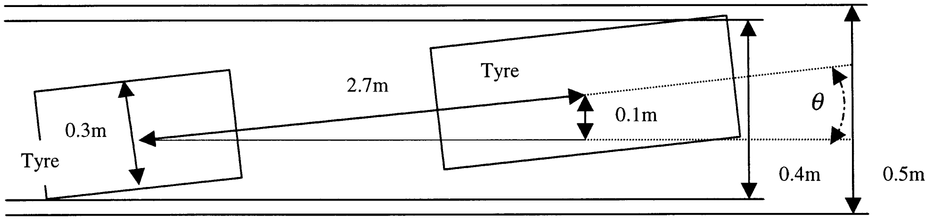


Fig. 5. Inter-row band and maximum oblique angle of the tractor.

$$x_i = x_t - a\cos\theta \tag{8.1}$$

$$y_i = y_t - a\sin\theta \tag{8.2}$$

where a is the distance between the middle of the tractor and the centre of the actuator ($a = 1.25$ m). Using the relations in Eqs. (8.1) and (8.2) from the RTK DGPS measurements x_t', y_t' of x_t, y_t the estimated coordinates x_i', y_i' of x_i, y_i were computed. Then the side shift setpoint, calculated from the RTK DGPS measurements, was given by

$$s' = \frac{y_i'}{\cos\theta} \tag{9}$$

This side shift s' will place the implement exactly on the path only if the measurements are undisturbed.

The following example demonstrates that the angle θ, in practice, is very close to zero. In that case Eq. (9) may be approximated with

$$s' = y_i' \tag{10}$$

In the worst case situation, the tractor stands as oblique as possible within an inter-row band. Fig. 5 shows this, assuming the width of the inter-row band to be 50 cm. The tire width is said to be 30 cm. In practice, the tractor driver can not steer his vehicle within 5 cm of a crop row, so only 40 cm passable ground is left between two crop rows. Then the maximum deviation of the front wheel is 10 cm (less in practice because of the oblique positioning of the front wheels). With a wheel-base of 2.7 m, the maximum oblique angle θ will be 0.037 rad. In the worst case situation in Fig. 3, with, the outcome of Eq. (9) is $s' = 15.00$ while the outcome of Eq. (10) is $s' = 14.99$. Clearly this difference is negligible compared to the error caused by RTK DGPS sensor errors.

2.5. PID-controller settings and the dynamics of the side shift

Control is performed by a digital PID feedback controller as described by Stephanopoulos (1984):

$$u(t) = u_k, \quad t \in [t_k, t_{k+1}], \tag{11.1}$$

$$u_k = K_c\left(1 + \frac{t_s}{\tau_i} + \frac{\tau_D}{t_s}\right)\varepsilon_k - K_c\left(1 + \frac{2\tau_D}{t_s}\right)\varepsilon_{k-1} + K_c\frac{\tau_D}{t_s}\varepsilon_{k-2} + u_{k-1},$$
$$k = 0, 1, 2, \ldots, 599 \tag{11.2}$$

with,

$$K_c = 0.5, \quad \tau_i = 25, \quad \tau_D = 5 \tag{11.3}$$

In Eq. (11.2) ε_k, is the difference between the actual shift and the setpoint at the sampling instant t_k. Furthermore K_c, τ_i and τ_D are the gain and integration and differentiation time constants of the digital PID-controller respectively. Their values, given by Eq. (11.3), were determined through experimentation. They constitute a trade off between minimising the settling time and minimising the overshoot of the PID control system to a step response, whilst preserving stability (Stephanopoulos, 1984). Observe that Eq. (11.1) assumes infinite computing power because the control at time t_k is computed from measurements at time t_k. As long as the computation time is small compared to the sampling time, t_s, this is a reasonable assumption. Otherwise adjustments have to be made.

The actuator is assumed to be rigidly connected to the tractor. A double integrator is used as a simplification of the dynamics describing the side shift,

$$\ddot{y}_s = u \tag{12}$$

where y_s is the side shift of the implement in m with respect to the centre of the actuator and u is the control coming out of the digital PID-controller.

3. Simulation

In practice, the following factors affect the tracking error:

- RTK DGPS measurement errors.
- Side shift measurement errors.
- Deviations between the calculated and actual shift caused by the PID control system.
- The connection between the tractor, actuator and implement is not stiff.

In the simulation only the first and third factor were taken into account. The errors caused by the second factor may be neglected if accurate sensors to measure the side shift are used (e.g. optical encoders) and if the actuator is sufficiently stiff and rigidly connected to the tractor. Then the side shift can be measured up to about 1 mm accuracy. The fourth component might in practice cause errors of the same order of magnitude as the first. With respect to the RTK DGPS sensor errors, it is important to note that they consist of position measurement errors, and, if the sensor (tractor) is moving, of errors due to latency, i.e. the fact that the position changes during its computation. Now the errors caused by latency are not simulated because the measurement error signal was obtained from true RTK DGPS measurements with the sensor at a fixed position. Also the construction of the measurement error signals, and, used in the simulation, presumed that there are no

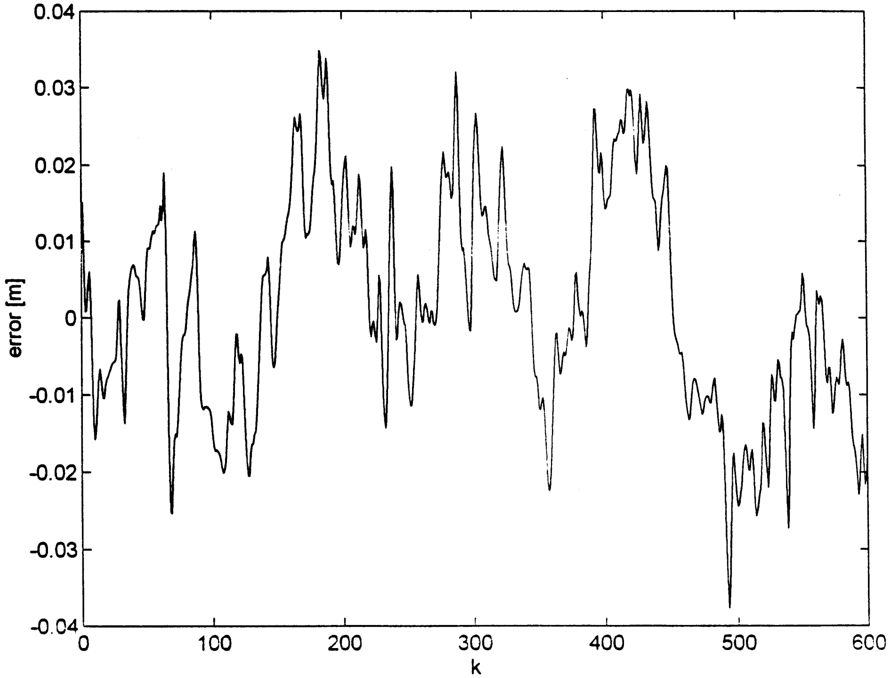


Fig. 6. Tracking error.

offsets. In practice there will be offset-errors which add to the simulation errors computed in this paper. Fig. 6 shows the tracking error. The MAE turned out to be $1.17 \cdot 10^{-2}$ m.

The errors caused by the PID control system relate to the settling-time, the overshoot and the varying setpoint and were found through simulation with undisturbed sensor data, i.e. with the measurement error signals x_e, y_e and θ_e set to zero. The tracking error which resulted from this simulation is shown in Fig. 7. The MAE was $2.62 \cdot 10^{-3}$ m. After the PID-controller had settled the errors were less then 0.5 cm.

With respect to the measured x_t coordinate of the tractor, i.e. x_t' observe that, through Eqs. (8.1), (8.2) and (9) and since θ is very close to zero, x_t' almost fully determines the desired position on the path. This position in turn determines the desired side shift. Thus the measurement error signal x_e has almost no direct influence on the tracking error in Fig. 6. For reasons described at the end of Section 2.4, the influence of the measurement error θ_e in the heading θ_t is negligible. The tracking error is determined primarily by y_e, i.e. errors in the measured y_t coordinate, and errors of the digital PID control system. Because of Eqs. (8.1), (8.2) and (9) and the equal order of the errors in Fig. 4b and Fig. 6, we can conclude that the tracking error of the guidance system is mainly determined by the RTK DGPS sensor errors.

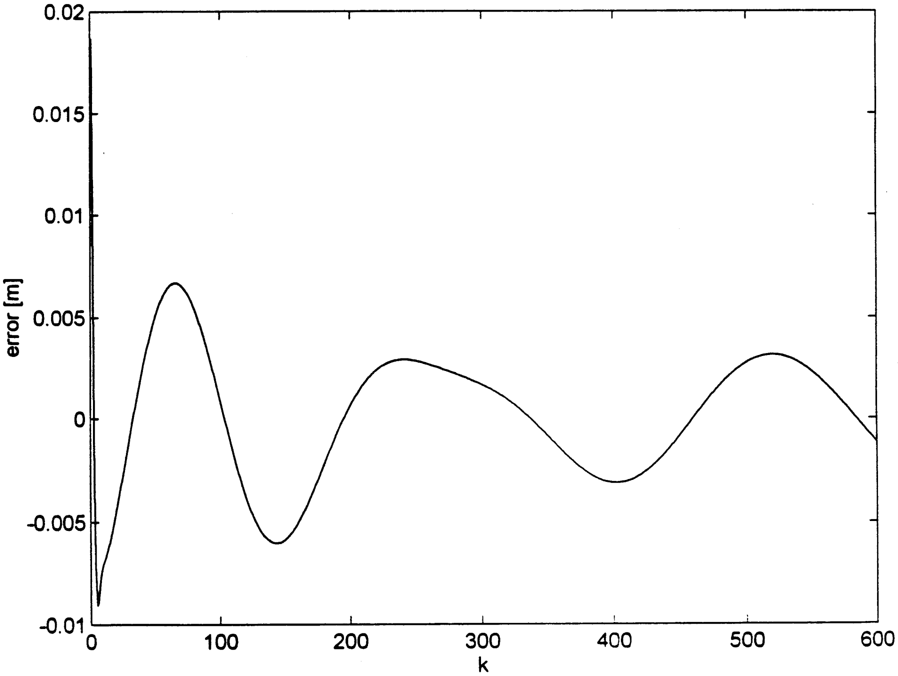


Fig. 7. Tracking error.

Applying a Chebyshev filter to try to improve the x_t and y_t measurements in our simulation resulted in an increase of the MAE tracking error ($1.29 \cdot 10^{-2}$ m). Most probably this is caused by the delay introduced by the filter which affects the tracking error, again because the sensor (tractor) is moving.

4. Conclusions and discussion

RTK DGPS gives position fixes with a few centimetres inaccuracy with current equipment, even in mobile applications. Given these errors, simulation revealed that inter-row guidance is possible using RTK DGPS.

Further research concerning the errors that will occur in practice is needed. The errors caused by offset and sensor latency have not been considered. From the technical data they are expected to be of the same order of magnitude as the tracking errors computed in this paper. Experiments with a moving sensor have to be performed to investigate this issue. The dynamics of the side shift, if powered by a hydraulic cylinder, are different from the double integrator dynamics assumed in the simulation. The side shift dynamics influence the PID control system error, and also need further investigation. Using a filter to try to improve the RTK DGPS measurement data automatically introduces a delay. Instead of a filter, an estimator could be applied, which in principal will not suffer from a delay, due to the use of a dynamic model. Then the possible improvement depends on the accuracy of the dynamic model.

One of the goals of the research is to actually design and build an actuator that can carry and control an implement. Based on the results of this paper, an actuator is currently being built, and will be tested in field experiments using the RTK DGPS sensor.

The control of the implement position, as described in this paper, has the advantage that the control system does not need any information concerning the tractor dynamics and is more or less independent of the way in which the tractor is driven. On the other hand, given the independence from the way in which the tractor is driven, the way in which the desired path is travelled in time is not controlled by the system. Theoretically, successive desired positions on the path, calculated from the RTK DGPS measurements, can be opposite to the direction of driving. Knowing the length of the tractor and its speed and turning circle, this situation will not occur in practice. However, several practical applications, such as spraying, also demand control over the way in which the path is travelled in time. Then the control system must also incorporate a dynamic model of the tractor and preferably be able to control the tractor driving. In that case, other approaches to control system design, which make more explicit use of dynamic models, such as optimal control, may be more appropriate.

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