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Vision-GPS Fusion for Guidance of an Autonomous Vehicle in Row Crops

Thomas Bak, *Aalborg University*

BIOGRAPHY

Thomas Bak is Associate Professor of Control Engineering with Aalborg University, Denmark, where he is part of the Intelligent Autonomous Systems group. His research is focused on estimation, sensor fusion and hybrid systems. Dr. Bak received his Ph.D. in Electrical and Electronic Engineering from Aalborg University, Denmark in 1998.

ABSTRACT

This paper presents a real-time localization system for an autonomous vehicle passing through 0.25 m wide crop rows at 6 km/h. Localization is achieved by fusion of measurements from a row guidance sensor and a GPS receiver.

Conventional agricultural practice applies inputs such as herbicide at a constant rate ignoring the spatial variability in weed, soil, and crop. Sensing with a guided vehicle allow cost effective mapping of field variability and inputs may be adjusted accordingly.

Essential to such a vehicle is real-time localization. GPS allow precise absolute sensing but it is not practical to guide the vehicle relative to the crop rows on an absolute coordinate. A row guidance sensor is therefore included to sense the position relative to the rows.

The vehicle path in the field is re-planned online in order to allow for crop row irregularities sensed by the row sensor. The path generation is thus controlled by location relative to the local field while the actual path execution is carried out in absolute GPS coordinates. The solution is a system that fuse data from a relative and an absolute measurement system while ensuring accurate row operation at high work rates.

INTRODUCTION

Most arable fields have inherent spatial variability in weed, soil, and crop properties, but conventional agricultural practice applies inputs such as herbicide and fertilizer at a constant rate. This is not only inefficient in terms of cost but also has an undesirable environmental impact. If the variability in weeds can be measured and mapped, inputs can be varied according to a defined strategy providing environmental and economic benefits. Studies in [3] and [5] show that 50 to 80% of the costs for herbicides can be saved when treating only patches where weeds actually grow.

The ability to manage weed infestations in a spatially precise manner rely on efficient weed mapping techniques, the ability to predict the change in patch location over time and the appropriate technology for site-specific weed management.

This paper discuss a cost-effective ways for sampling weed populations based on a guided vehicle with a vision system. Because such a vehicles can work continuously without an operator, it is able to carry out operations, which have been too expensive or impossible so far. Essential to the operation of such a vehicle are means for real-time in field localization. GPS allow precise absolute sensing of the position in the field, but it is not practical to guide the vehicle between crop rows on an absolute coordinate. Row guidance sensors (see e.g. [1]), however, allow sensing of the position relative to the crop rows. The objective of the work described here is to develop a localization system that incorporate the GPS information with the crop row guidance measurements thereby enabling inter row operation in 0.25 m wide crop rows at 6 km/h without causing crop damage. Rather than viewing vision based perception and GPS as competing sensor modalities, they are considered complementary.

Weed parameter sensing is undertaken using advanced vision technology that samples the field at defined locations. These locations may be dynamically redefined in order to allow e.g. gradients in the weed pressure to sample at a decreased spatial distance. The sampling points define a path in the field, which is to be executed by the vehicle. The path may be re-planned online in order to allow for crop row irregularities. The re-planning is based on the row guidance measurements ensuring accurate row operation at high work rates with minimal damage to the crop.

A Carrier-Phase Differential GPS (CDGPS) system provides absolute position and servers as a reference to the closed loop control system. The path generation is thus influenced by location relative to the rows while the actual path execution is carried out in absolute GPS coordinates.

The benefits are obvious outside the row crops where the row guidance camera provide no useful information. The absolute localization of the vehicle is, however, also beneficial for the field parameter sampling and field map generation.

The solution is a system that fuse data from a relative and an absolute measurement system. It allows autonomous operation and precise localization of the vehicle in the row crop, but also avoid having to switch from an relative to an absolute guidance in and out of the rows.

This paper concentrates on the engineering aspects of the research and evaluation of an experimental system.

EXPERIMENTAL SYSTEM

The experimental vehicle is a complete electro-mechanical system that includes a mechanical concept [4] and suitable vehicle electronics and control systems to properly actuate the mechanical subsystem. A new experimental system is currently being developed and will be used in the spring of 2002.

Figure 1 outlines the mechanical structure. The structure was designed specifically for agricultural use with good ground clearance, slim wheels, and four wheel drive and steering for in-row driving.

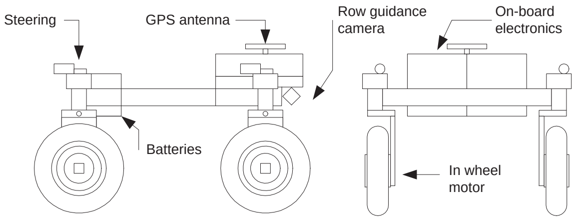

Figure 1: *Mechanical structure of vehicle. The row guidance camera is mounted at the front of the vehicle.*

Vehicle localization is achieved based on information from a Topcon Legacy GPS receiver, wheel and steering encoders, a Honeywell HMR3000 magnetometer, a KVH E-Core 2000 fiber optic gyro. Actuation is achieved using four Heinzmann brushless hub wheel electric motors.

A ECO-DAN row guidance system is mounted on the front implements toolbar and serves as point of reference in relation to the plant rows. The image processing is based on analysis of more than 25 frames per second, each covering a width of 50-75 cm. A new signal, regarding the implements position relative to the plant rows, is generated every 7 cm at 6 km/h. As the basic method in the image processing is segmentation of vegetation from background it is a requirement that the plant rows form visible living green line.

The electronics architecture was built around a PC/104 computer system running Linux as shown in Figure 2. Communication with the vehicle was achieved through a wireless link to a base station. On the base station a Matlab/Simulink graphical interface allows the user to modify parameters in the vehicle control software and provide new path segments and points.

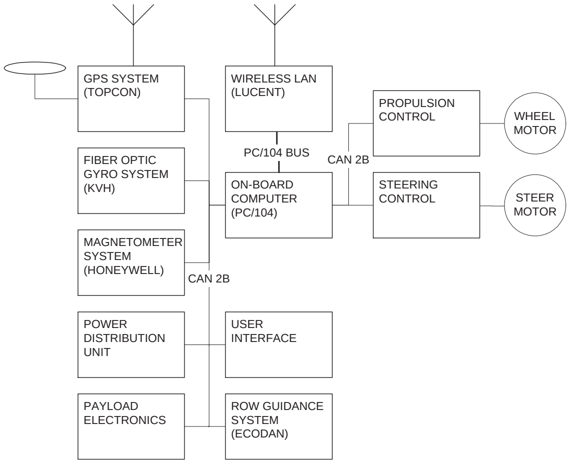

Figure 2: *Vehicle electronics. The on-board electronics communicate with a base station (not shown) through a wireless Ethernet link.*

The on-board PC/104 main processors communicate with various sensors (such as GPS, row guidance system, and a fiber-optic gyro) and with the four steering and four wheel actuators. Intelligent network nodes handle all sensors and actuators which are linked to the main computer on two separate CAN 2.0b busses. The steering and propulsion nodes include PWM drivers and local velocity control.

The software implementing control, localization, planning, and reasoning algorithms resides on the PC/104. The code was automatically generated under Matlab/Simulink on the base station computer and transferred to the onboard computer. This allowed rapid prototyping, and relative simple deployment on a rather complex electromechanical system.

The four-level, hierarchical control scheme used for the vehicle guidance system is shown in Figure 3.

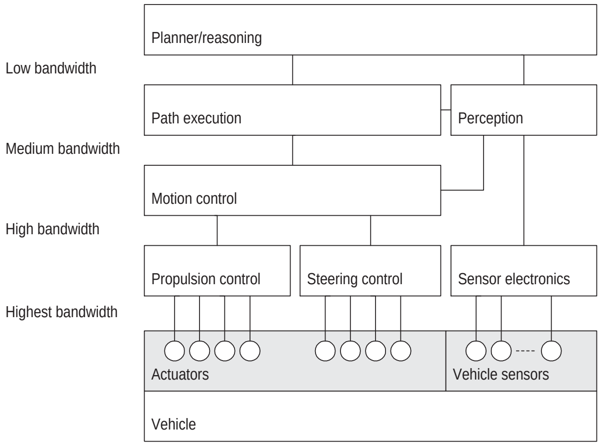

Figure 3: *Hierarchical guidance system architecture. Note that the actuator modules contain some propulsion/steering specific sensors e.g. encoders. Other sensors, such as GPS are located in the vehicle sensor module.*

Information flow in the system demonstrates increased abstraction with decreasing bandwidth. In the low-level (high bandwidth) controller voltage and current commands are generated by PWM modules and send to the vehicle actuators. Information sources at this level are hall sensor outputs that describe the motor speeds. At the next level up in the hierarchy, the motion controller communicates motor set points to the low-level controller based on an specification of the instantaneous rotation point and velocity specified by the path execution. At the path execution level information from GPS, gyro, encoders, and magnetometer are fused by the perception block and used to close the loop. The path execution generate low-level set points to force the vehicle to track the desired path. Finally, the path planner operates at the coarsest resolution and, correspondingly, the lowest bandwidth. Information feedback at this level includes pose estimates from the perception as well as row guidance camera measurements.

The normal operating mode for the vehicle is the closed-loop control mode. This mode is used to follow a path prescribed by the path planning using feedback of the vehicleŠs estimated pose.

In order to test the use of such a vehicle under agricultural conditions a test field was planted with a winter cereal crop at the Danish Institute of Agricultural Sciences center in Bygholm. The individual plant rows were separated 25 cm. The planting was carried out under normal agricultural practice. CDGPS measurements of the plant row start and and points were taken after the sowing to give an indication of the row layout.

In the spring of 2001 a weed sampling strategy was devised based on the assumed row layout. Three weed sampling points were identified in three separate rows as illustrated in Figure 4. Measurements of row irregularities were not made and there is therefore no objective measure of the performance of the system described here. Such measurements are, however, planned for the spring of 2002.

AUTONOMOUS GUIDANCE

The aim of the vehicle guidance algorithms are to determine and execute an appropriate path for the vehicle taking account of the irregularities in the crop rows and thereby reduce crop damage. Irregularities as shown in Figure 5 are caused by transverse motion of the sowing machine during planting and/or introduced as the crop is growing. The result of relying solely on the precise by global coordinates from the GPS receiver are obvious; crops are damaged by the wheels.

The combination of the absolute precision of the GPS system with the relative position information from the row guidance has several benefits. All navigation is carried out in GPS coordinates and transfer at the end of rows from a local coordinate to an absolute is hence avoided. In addition the global coordinates are required for specification and determination of the weed sampling points.

The fusion task is undertaken by the path planning algorithm (see Figure 3).

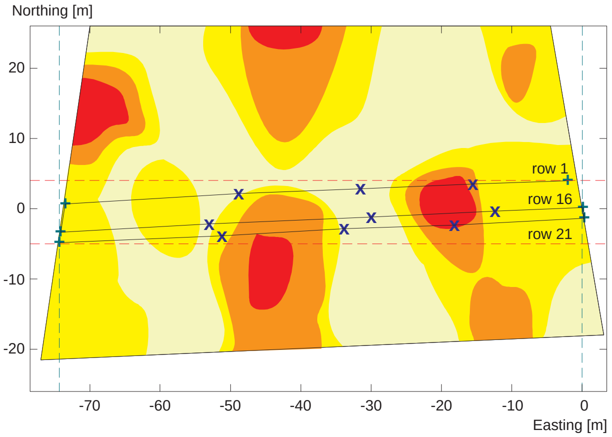

Figure 4: *Weed sampling point layout on field in Bygholm. Rows 1, 16 and 21 are sampled. Three sampling points (x) in each row. The assumed start and end points of rows is indicated by a $+$. An example weed population density is indicated.*

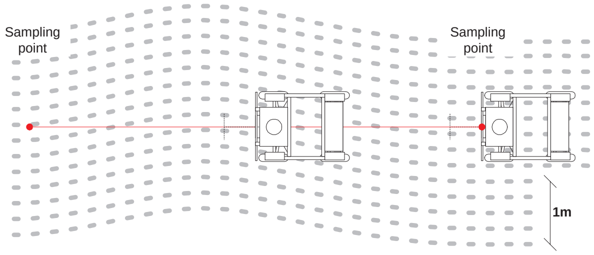

Figure 5: *Crop row irregularity cause the vehicle to damage crops when driving on an absolute reference.*

The main input to the path planning are the predefined weed sampling points as specified by the user, current vehicle pose from perception and information from the row guidance system. The row guidance system provide offsets of the vehicle relative to the rows in terms of a x_h and ξ correction regarding the vehicles position relative to the plant rows as shown in Figure 6.

The path planning is one of two control loops comprising the high level control system of the vehicle, see Figure 7. A *high-bandwidth* inner loop (path execution) provides pose stabilization and vehicle position control based entirely on information from the CDGPS, magnetometer, gyro, and wheel/steering system fused in a Kalman Filter. A *low-bandwidth* outer loop provides path commands to the inner loop based on the vision data and feedback from the CDGPS.

In its current form, the merger of these two loops is accomplished by converting the corrections observed by the row guidance system (i.e. rows relative to vehicle) into path segments expressed in global GPS coordinates that can be processed by the path execution loop.

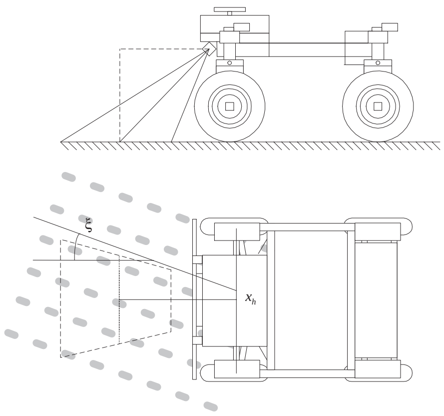

Figure 6: *The image processing is based on analysis of more than 25 frames per second, each covering an area of 50×75 cm. At a speed of 1.5 m/sec a new signal, regarding the vehicles position relative to the plant rows, is generated every 6 cm.*

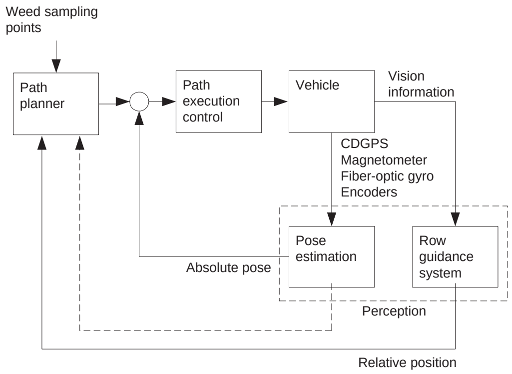

Figure 7: *Two control loops constitutes the high level control; the inner loop is Path execution, the outer loop Path planning.*

Path Execution

The path execution algorithms are concerned with the problem of tracking the path. It compares the desired path to the actual path and computes appropriate signals to be used by the motion control that handles wheel movement. This computation is done on the basis of errors in the vehicleŠs pose. It effectively generates commands to the motion control in terms of velocities and instantaneous rotation point setpoints in response to errors in the path tracking.

The path execution problem is illustrated in Figure 8 where R is the orthogonal project of the vehicle point P onto the path. The signed distance between P and R is denoted d. The error in orientation is defined as

$$\theta_{err} = \theta - \theta_r \tag{1}$$

where θ_r is the orientation reference. The basis for the path execution control is the following globally stable non-linear control law [2]

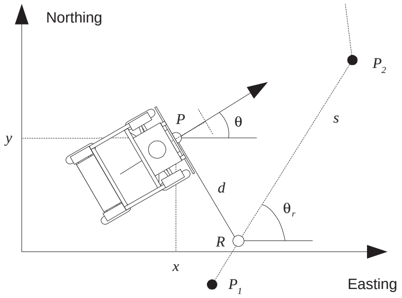

Figure 8: *Path execution problem. The path is defined by the points P_1 and P_2 .*

$$\omega = \begin{cases} -L_1 v d, & \theta_{err} = 0 \\ -L_1 v \frac{\sin(2\theta_{err})}{2\theta_{err}} - L_2 |v| \theta_{err} & \text{otherwise} \end{cases} \tag{2}$$

where the forward velocity v is specified by the operator. The controller gains L_1 and L_2 are specified to give a desired distance response (see [2]). The controller specifies the angular velocity ω input to the system such that the distance to the path and the orientation error tends to zero. The traveled distance along the path is not considered in this solution.

In the system described here the instantaneous center of rotation is locked on the axis joining the front wheels. This simplifies the motion control, but effectively locks the front wheel steering. Advantages is thus not taken of the 4 wheel steering capabilities of the vehicle. The aim here has been to establish a first attempt of path execution.

Path Planning

The path planner shown in Figure 7 creates path commands for the inner loop to track. It has three basic modes of operation:

- A GPS-based mode, where the path planning generates reference path segments based on operator input.
- A row guidance mode where the row guidance camera is used as reference for path replanning. Two submodes exist
  - A averaging mode, where the row camera signals are averaged in order to avoid path execution loop interaction.
  - A transfer mode, where the vehicle is transferred to a new path segment.

In the GPS-based mode, the path planner create reference path segments, in terms of a specification of the line passing through the points P_1 and P_2 in Figure 8. The P_1 and P_2 are specified by the operator and represents weed sampling points or intermediate points used for navigation in the field.

From the general equation of a line, the segment specification determines, a, b, and c as well as an reference for the orientation, θ_r. This allows the path execution to calculate the distance error as

$$d = ax + by - c \tag{3}$$

where x and y is the estimated global position. The error in orientation is given by Eq. 1. In the current implementation the GPS based mode is mainly used outside the rows and during initial acquisition of a row.

The second, row guidance mode is used to account for crop row irregularities. The same basic functionality is used, but the points P_1 and P_2 may be re-programmed based on row guidance information. The input from the row guidance system is the angle ξ and the offset x_h as indicated in Figure 6. It is clear that the correction specified by the row guidance system is a function of crop row irregularity but also of the error in the path tracking loop.

Brute force adjustment of the path according to crop row guidance could thus lead to stability problems. A number of measures are hence taken to minimize the interaction:

- The bandwidth of the path planning loop is reduced approximately 10 times lower that of the path execution loop (approximately 10 Hz at nominal speed).
- An 1 Hz update rate (corresponding to approximately 1.5m at nominal speed) of the path planner is used for simple averaging of the row guidance information in order to reduce the effect of tracking errors.

Assuming that dominant row irregularity is slow changing relative to the vehicle, the angular error is averaged over the 1 sec interval resulting in $\hat{\xi}$. The average translational velocity $\hat{v}$ over the interval is used to determine the average offset

$$\widehat{x_h} = \frac{1}{k}\left(x_h(n) + \sum_{i=n-k-1}^{n-1} x_h(i) + \sin(\widehat{\xi})\hat{v}(n-i)T\right)$$

where T=1/25 sec is the row guidance system sampling interval.

The term $\widehat{x_h}$ is now assumed to represent the lateral displacement of the vehicle and $\hat{\xi}$ is assumed to represent its angular heading relative to the crop row. A predetermined limit is put on the corrections, thereby avoiding continuous replanning.

The replanning is carried out in two steps. First a new path segment is generated by rotation and translation of the previous path corresponding to $\widehat{x_h}$ and $\hat{\xi}$.

Secondly a transfer path is generated. This is done in order to avoid step inputs on the d error calculation in the path execution. The transfer path should transfer the vehicle to the correct row within 1 meter as seen in Figure 9.

As soon as the vehicle has reached point P_{new} the path previously generated is the basis for the vehicle path tracking. As the vehicle d error gets below a specified limit, the row guidance mode is reentered and the averaging starts over.

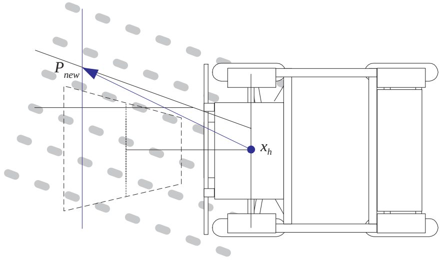

Figure 9: *Replanning of the path. The path segment is redefined according to the row guidance estimates.*

The row guidance mode is typically entered in the rows, where straight path can be assumed and after that the variance on the path error d has decreased below a set limit.

The solution is a system that minimize loop interaction while taking account of date from both a relative and an absolute measurement system. It allows precise operation and localization of the vehicle in row crops.

EXPERIMENTS

A number of experiments have been carried out to demonstrate the performance in a row crop. Actual weed sampling has not been carried out and the focus here is on the performance of the path following. The real test of the system is, of course, the accuracy with which it follows the crop-rows. As an absolute measurement of the row crops have not been performed objective criteria for accessing the performance of the row tracking are not available. The focus here is thus on the performance of the two closed loop systems described and their coupling and transient responses.

In the first experiment the vehicle was started in row 16 as described in Figure 4. The row guidance path planning mode was started. The vehicle was forced to drive in a 0 deg angle the first two meters, thereby artificially generating an offset of approximately 10 cm. At 2 meters the path planning generated a transfer path and the original path was re-acquired. The result is The result is show in Figure 10.

Figure 11 shows the actual performance of the vehicle on a test run were the row guidance mode was enabled. The plotted vehicle path is based on the raw GPS measurements. The vehicle is started in row 16 heading west in the GPS-based mode. That is the vehicle should track the predetermined path regardless of the actual rows. After row 16 the vehicle turned and started traveling down row 1. The row guidance mode was disabled at the second sampling point in the top row (-50 meters Easting). The vehicle was stopped at the end of row 1.

Figure 11 is an indication that the path execution as predicted is stable and that the row guidance has no effect on the stability in this case. Closer inspection (see Figure 12) indicates that the row guidance has had some effect.

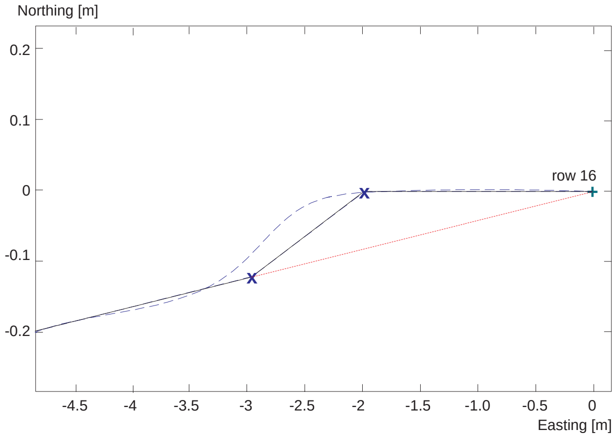

Figure 10: *Performance of path execution and planning. The vehicle starts at (0,0) and no correction to the orientation is performed the first two meters. At 2 meter a transfer is generated .*

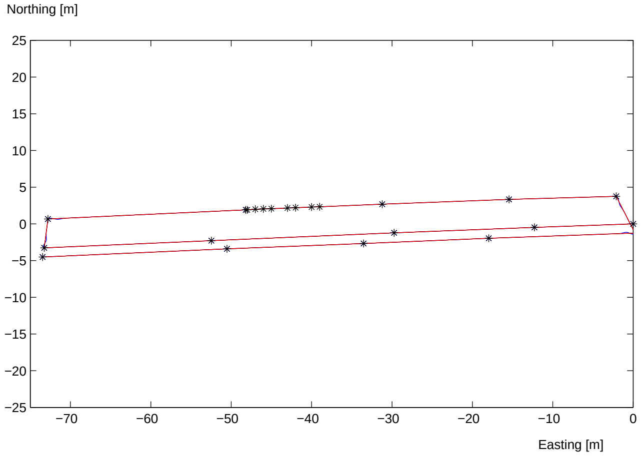

Figure 11: *Performance of path execution and planning. Vehicle starts at (0,0) and heads west along row 16 without row guidance. At approximately -50 meters in row 1, row guidance was enabled.*

A sampling point at -48.2 meters generates a number of samples as the vehicle is standing still. The path planning generates a number of modifications to the predefined path as indicated by the x symbols in Figure 12. The vehicle tracks the new path segments as indicated by the d error in the center and bottom of Figure 12. The error relative to the new segments is clearly lower and close to the precision of GPS.

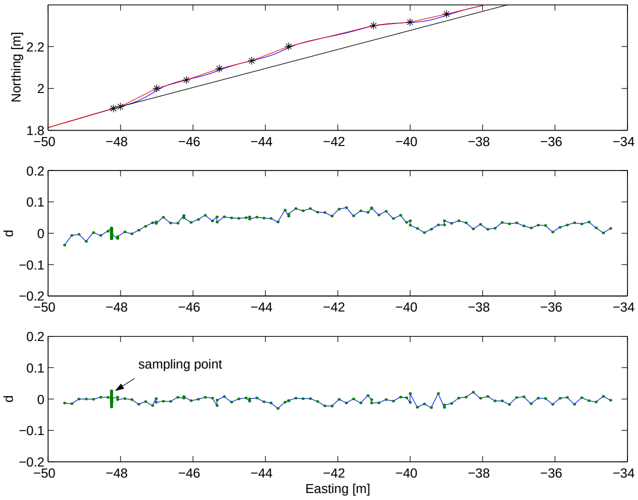

Figure 12: *Performance of path execution in row 1. The* x *indicate path points partly generated by path planning. The figures are decimated to 1 sec intervals. Center plot illustrates the error* d *relative to the original predefined path. The bottom plot illustrates the* d *relative to the original re-planned path .*

CONCLUSION

These combined results demonstrate the feasibility of vision-GPS fusion for guidance of an autonomous vehicle in row crops. Structure and electronics of an experimental vehicle was explained and the control system architecture outlined. Special focus was put on the path execution and path planning algorithms. In the path planning two modes were described. A GPS-based mode, where the vehicle path segments are predefined and a row guidance mode where the vehicle adapts to irregular crop rows. Path tracking that incorporate the row guidance system involves a transfer mode, that causes the vehicle to transfer to the new path that follows the crop row layout detected by the camera.

A demonstration was given in a row crop that demonstrated the functionality of the system and its ability to adapt to rows of crops. As an absolute measurement of the actual row crops have not been performed, objective criteria for accessing the performance of the row tracking are not available.

Additional work on the system is underway and a new vehicle is being developed for the spring 2002. Studies are also currently being performed to optimize the performance of the combined path execution and planning. Proper use of the four wheel steering is also being addressed.

The solution presented here, however, demonstrates the fusion of data from a relative and an absolute measurement system. It allows autonomous operation and precise localization of the vehicle in the row crop minimizing the damage to the crop.

ACKNOWLEDGEMENTS

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