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Time-optimal guidance control for an agricultural robot with orientation constraints

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A B S T R A C T

This paper deals with time-optimal control for the row guidance system of an autonomous field robot with differential drive. The movement of the robot is concretely constrained by the plant cultivation environment. A time-optimal differential velocity profile is generated based on optimal control theory to eliminate any initial error or tracking deviation. To allow for an efficient implementation on a micro-processor, a substitute controller is suggested to perform the minimum-time guidance task. The substitute with a cascade structure is proposed using PID algorithms. The computational efficiency is consequently improved and the system is more convenient to be carried out on a micro-processor. The performance of the proposed substitute system is investigated through numerical studies by comparison with the time-optimal controller. Experiments are comprehensively conducted indoors and outdoors to evaluate the proposed row guidance regime. The results show the satisfactory performance and efficiency with a high precision of ± 3 cm in the field.

1. Introduction

In the past decades, autonomous agricultural machinery has been subjected to extensive studies due to labor shortage, food product quality and safety, as well as the environmental impact. Automatic harvesting machines were extensively studied for cucumber (Van Henten et al., 2003), cherry (Tanigaki et al., 2008) and white asparagus (Chatzimichali et al., 2009). Special autonomous robots were also suggested for greenhouse applications by Mehta et al. (2008) and Sànchez-Hermosilla et al. (2010). A number of researchers actively investigated automatic machines for weeding control based on machine vision and Real-time Kinematic Global Positioning Systems (RTK GPS). Considerable efforts have been made by Straten's group based on machine-vision and RTK GPS system in weeding control for sugar beet (Bakker et al., 2004, 2011). The main techniques for weeding control were thoroughly summarized by Slaughter et al. (2008). Autonomous differential-drive wheeled mobile robots are able to track almost all the possible desired paths, and have been widely used in well structured environment such as factories, warehouses and offices (Díaz del Río et al., 2001; Feng et al., 1993; Gracia and Tornero, 2008). In agricultural applications, differential-drive wheeled mobile robots have been also applied as platform or chassis to carry the associate apparatus like harvesting robot arm or spraying pistol for weeds (Åstrand and Baerveldt, 2002; Mehta et al., 2008; Van Henten et al., 2003; Xue et al., 2012). An automated row guidance control system is necessary for the autonomous agricultural robots to operate within rowed crops collision-freely to perform various tasks. Differently from the well-structured environment, the working environment of agricultural robots imposes varied constraints on the movements of the vehicles due to contact surface of loose soil and the specialties of crop cultivation features. The row guidance system of the autonomous agricultural robots is expected to be:

– Feasible: efficient and easy to be put into practice,
– Safe: avoiding dangerous motions and collisions with crops,
– High precision tracking: to operate safely within limited working space between rows,
– Low computational costs: to perform the real-time following algorithms on a single chip.

In this work we focus on the development and implementation of the time-optimal row guidance system of an autonomous field robot. The field mobile robot was developed as a platform for white asparagus harvesting. In contrast to the most often reported technologies in row identification based on machine-vision and RTK GPS which were summarized by Slaughter et al. (2008), the position of the target row for this robot is detected using sonar sensors benefiting from the erected cultivation bed. The up-erected cultivation bed of white asparagus provides a natural surface for the sonar sensors. This design not only relieves the computation effort

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of the processor in comparison with the machine-vision based application, but also reduces the investment. The study of this work is done based on our previous research (Dong et al., 2011). In that paper, a row guidance system based on conventional PID method was suggested for the prior try. The row following performance was verified in labor. However, since the robot movement is closely constrained by its working environment, the initial error and following deviation are expected to be eliminated as quickly as possible to achieve a stable operation. In this paper, we investigate firstly the simulation study of the time-optimal control problem of the row guidance system. Due to the very limited investment in the machine's cost, the realization of the time-optimal control is not feasible on a current micro-processor. Finally, we realize the guidance performance of the time-optimal control using a practical substitute system by improving the previous row guidance controller based on PID algorithms. The row following performance of the substitute system is extensively evaluated through comparison with the results of time-optimal control system in simulation studies, and further investigated experimentally in laboratory as well as in the field.

The outline of this paper is arranged as follows. The mechanical design of the harvesting robot platform is described in the following Section 2. In Section 3 the kinematic model of the robot and the environmental constraints are introduced. Section 4 is devoted to formulation of minimum time problem and controller development. Section 5 firstly details the establishment of the practical substitute system for time-optimal guidance control, and then illustrates the outcome of simulation and experimental tests. The concluding remarks and future work are given in Section 6.

2. Mechanical design

The agricultural wheeled mobile robot in this work is designed as a development platform of an autonomous field machine for white asparagus harvesting. White asparagus is cultivated in parallel trapezoidal beds that are heaped up about 60 cm over ground surface. The cultivation beds are built with 80 cm intervals and 100 cm wide at the bottom. The heaped beds are always covered with a film to keep the soil moisture in order to guarantee the product's quality. The field robot is demanded to operate by striding one bed at a time. It is also necessary for the robot to have sufficient place for the harvested white asparagus spears for future development. The platform is designed for both efficiency and cost effectiveness. The dimensions of the robot base is $310 \times 180 \times 160$ cm $(l/w/h)$. The platform frame has a hollow space room of $310 \times 160 \times 73$ cm $(l/w/h)$ under the machine. It has a weight of 450 kg with a maximal load capacity of 200 kg. The vehicle has a rolling system to guarantee mobility and maneuverability in an environment with considerable disturbance. The platform has two drive wheels at the front with a radius of 30 cm, which are independently actuated by two DC motors, and two casters with a radius of 15 cm at the rear. The maximal velocity of the vehicle is expected 50 cm/s by considering the upcoming development of harvesting function. A 450W DC motor (MY1020Z2, Zhejiang Unite Electric Motor Co., Ltd., China) was selected under the assumption that the vehicle travels on a sandy surface with a maximal slope of 5°. Sabertooth motor driver (2×50 HV) is applied to actuate both motors. The drive wheel is connected with the DC motor axis through a second-order chain gears with a ratio of 16:1 to improve the drive force and reduce the revolution speed. Steering is accomplished only by adjusting the differential velocities of the front drive wheels. Two rechargeable batteries ($12V38AH$) supply power. The identification of the actual position of the mobile robot is absolutely essential for the autonomous operation. By utilizing the features of the cultivation bed, two ultrasonic sensors (Parallax PING))))) with an angular aperture of 43° are applied to measure the front and rear side distances between robot and the target bed. The sensors are installed at the right side and vertically to the side surface of the cultivation bed, one of which is near the front drive wheel and the other near the rear. The revolution of the drive motor is sensed using an incremental optical encoder (Model 120E) with a resolution of 128 pulses per revolution. The signals of the sensors are processed by a PSoC CY8C55 processor on PSoC development board (CY8CKIT-001, Cypress Semiconductor Corporation, USA).

3. Mathematic model and environmental constraints

3.1. Kinematics

The platform of the differential drive agricultural robot is assumed to consist of rigid bodies and to move on a planar surface. The location of the robot (x,y) is represented by the center point P of the front axle in the initial coordinate system. θ is the orientation of the field robot. If the robot operates over a curvature path with an instantaneous angular speed ω, the velocities of the drive wheels v_L and v_R are given by:

$$v_L = v - \frac{L_b}{2}\omega \tag{1}$$

$$v_R = v + \frac{L_b}{2}\omega \tag{2}$$

where L_b denotes the base distance of the drive wheels, v the forward velocity of the robot at the point P. It is also assumed that the wheels are non-deformable and there is no slip between wheels and ground. The movement of the machine subjects to the non-integrable constraint

$$-\dot{x}\sin\theta + \dot{y}\cos\theta = 0 \tag{3}$$

In the initial coordinate system, the kinematic model of the field mobile robot is stated as:

$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} cos\theta & 0 \\ sin\theta & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} v \\ \omega \end{pmatrix} \tag{4}$$

3.2. Environmental constraints

The machine is demanded to drive by striding one row at a time (see Fig. 1). The interval space ($S_B = 80$ cm) between cultivation beds limits the robot movement on both lateral offset and orientation angle. The location of the robot with respect to its target row is supervised by the front and rear side distances denoted by S_f and S_r measured by the installed ultrasonic sensors SF and SR (shown in Fig. 1(a). Because of the symmetry of the spatial arrangement, only side distances on one side are essentially sensed. For the row guidance control, the robot is only permitted to drive forward. The desired location of the robot is set to $y = 0$ and $\theta = 0$. Therefore, under conditions:

–harvesting robot 180 cm wide,
–cultivation bed 100 cm wide at the bottom,
–interval space between beds 80 cm,
–free space between wheels is 160 cm wide,
–swivel radius of rear casters is 15 cm.

The reference side distance is set $S_{ref} = 30$ cm with a sufficient margin for rear casters. The rest free region for the robot in lateral direction is $S_{ref} \pm 15$ cm. Since the robot is only permitted to drive forward, it cannot proceed with some special initial positions like $S_f^{ub} = 45$ cm and $S_r^{ub} = 45$ cm or $S_f^{lb} = 15$ cm and $S_r^{lb} = 15$ cm. These