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Stable and robust vehicle steering control using an overhead guide in greenhouse tasks

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ABSTRACT

We have developed an autonomous vehicle steering control algorithm to aid with harvesting and spraying tasks in greenhouses to alleviate the problem of shortage of workers. We use an overhead guide constructed in the greenhouse to mark the desired path of the vehicle. A rigid bar is then connected from the guide to the vehicle. The vehicle steers and corrects itself by sensing the angle and distance of the vehicle from the guide. The control algorithm was developed for a two-dimensional kinematic vehicle model which was found to be valid for low-speed vehicles. The steering control was examined by numerical simulation in order to investigate the effects of parameters such as control-point location on stability deviations of the vehicle path. The asymptotic stability of the system was verified analytically and confirmed using numerical simulations. The control system was then simulated using a multibody dynamics simulation in conditions that better simulated an agricultural environment, thus confirming that the control system also maintained stability under rough conditions. Finally, in accordance with the control algorithm and the simulations, a proof-of-concept prototype of the vehicle was developed and the control algorithm was successfully deployed on a set of experiments.

1. Introduction

Growing vegetables is a laborious task which requires many manual workers. Moreover, some types of work in the greenhouse (spraying, carrying loads, etc.) can impair the health of the workers, which is one of the reasons for a shortage of workers for these tasks.

As an example, of all the tasks in a cucumber greenhouse, spraying and harvesting require the greatest labor input. In the Western World, each acre requires approximately 320 working days per year, of which harvesting occupies approximately 160 days and spraying about 24 days (Gan-Mor et al., 2005).

Another example of a time-consuming operation is transporting produce from the greenhouse to the packing house. Gan-Mor et al. (1994) showed that the use of a motorized collecting cart, steered autonomously with the aid of ground rails, reduced the time of work by 50%. Furthermore, there was a 400% difference in the harvesting efficiency with the use of conveyance carts as previously described (Mashov haklaot, 2012).

Cultivating and ploughing activities are required at the end of each growing season; in fact, some crops such as cucumbers and flowers, have several growing cycles per year. Therefore, farmers in some countries insist that all equipment connected to the ground be easily removed and replaced and, accordingly, they reject any solution for transporting and steering that involves ground rails.

In order to overcome the above mentioned problem and to allow the clearing of the ground between cultivation, an additional transport technology is used via an overhead monorail. The disadvantage of this method is that the weight of the vehicle necessitates a strong rail, whose high cost renders the system uneconomical.

In light of the methods summarized above it can be seen that the cost of the system external to the vehicle is a limiting factor. For this reason, and in light of technological developments of recent years, attempts are being made to devise a steering control that would enable the vehicle to drive autonomously without an auxiliary component. Some of the methods involve steering controlled via ultrasonic sensors (González et al., 2009; Singh et al., 2005), using a laser rangefinder for navigation in orchards (Bergerman et al., 2012), a combination of a LIDAR together with image processing (Younse, 2005), or computer vision algorithms for selective vineyard spraying (Berenstein et al., 2010).

The change in environment caused by the growth of crops during the season and the change in the greenhouse layout over the

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production period disrupts map-building based on onboard sensors and reduces the robustness of these algorithms. Therefore, there are difficulties in developing these systems to be commercially.

In the present study we propose an autonomous vehicle steered with the aid of an overhead guide. The main advantages of this method compared with those described above are: the overhead guide allows cultivation of the ground between growing the cycles; it requires simple sensors hooked to small processors and the weight of the vehicle is carried by the ground. Thus, the cost of the overhead guide rails minimized. The cost of a simple rail that provides guidance to a sensing system as described in the present report is approximately 1.6 $/m, including the supporting mechanism. For 1.6 m row intervals it amounts to 3000 $/acre. Considering that the minimal wage in the western world is more than 8 $/hr and that only 50% of the above mentioned labor savings in harvest can be attributed to the rail; the rail cost can be returned in less than 2 years. Furthermore, it is possible to make the solution more economical by using inexpensive rails which are made of plastic or even simple cables.

In a previous unpublished study conducted in cooperation with the present authors, a mechanical control linked to an overhead guide rail was developed and tested. In the previous study a mechanical steering powered by a pendulum was used. The pendulum weight imposed a steering torque on the front wheel to minimize the vehicle's deviation from a desired path. A major weakness of that system was that the control gain was constant and was kept unchanged during the operation. In addition the system was sensitive to the vehicle weight and the soil type along the vehicle's path.

Another study, in an orchard, tested whether it was possible to navigate a vehicle by reference to an overhead guide by measuring only the offset from the rail, without taking into consideration the vehicle's orientation (Shin et al., 2002); the results showed that if the ground was not flat or if the vehicle began with a relatively large orientation offset, the vehicle might become unstable.

The purpose of the present study was to develop a prototype autonomous vehicle capable of spraying in a greenhouse or helping in the harvest process while using overhead rail for guidance and ground travel. To maintain the above described requirements the control and steering systems should be stable, robust and economic. The present study also validates experimentally that dedicated control algorithms devised via simulation can minimize the autonomous vehicle deviations from the predetermined path.

This paper comprises the following sections. Section 2 describes the vehicle kinematic model and equations of motion. Section 3 describes the development of the steering-control algorithm. In Sections 4 and 5, we describe different types of simulations to examine the system's stability and optimization of the vehicle's path. Section 6 presents the experiments conducted on the prototype vehicle, and the comparison between the experimental and simulation results.

2. Vehicle kinematic model

2.1. Vehicle modeling

The 3-D model of the vehicle and its components are shown in Fig. 1. We assumed that the ground slope was constant and known and, for simplicity, we initially assumed the ground to be horizontal. Furthermore, the fork-to-rail connection was defined as a two-degrees-of-freedom connection, which could translate along and rotate about the rail (Fig. 1A). In light of these assumptions, the vehicle's three degrees of freedom relative to the rail are shown in Fig. 2. Specifically, θ is the angle that represents the orientation of the vehicle relative to the rail, ϕ is the steering angle, and φ is the angle between the guidance arm and the vertical.

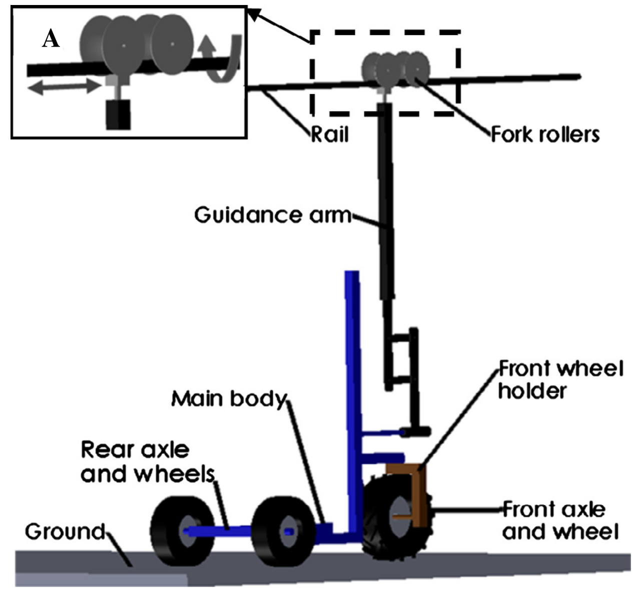

Fig. 1. Vehicle 3-D model. Inset A represents the two degrees of freedom between the fork and the rail.

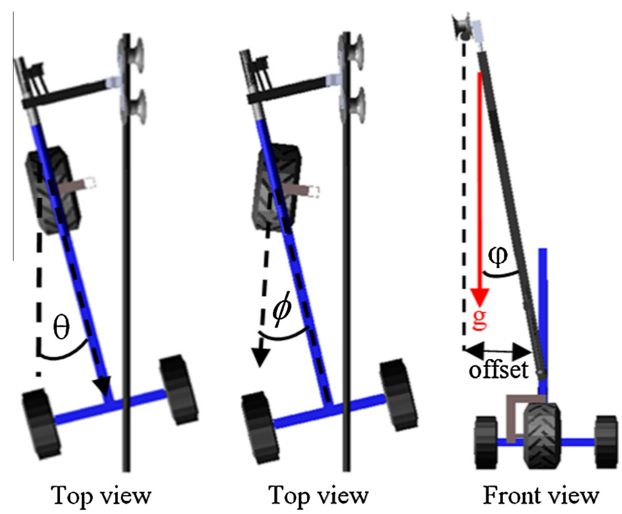

Fig. 2. Vehicle angle representation: θ is the orientation angle, ϕ is the steering angle, and φ is the guidance arm tilt angle.

2.2. Kinematic model equations

The two-dimensional, planar model of the vehicle in the horizontal plane is based on the work of De Luca et al. (1998). The kinematic equations of the vehicle were derived under the assumption that motion in the horizontal plane with low vehicle speeds has no skidding. Moreover, using the kinematic model, we disregard the existing forces in the system. In Section 5.2 we show that these assumptions are indeed adequate under greenhouse environments.

For simplicity, the two wheels on the rear axle are assumed to merge into a single wheel located at the midpoint of the axle. The front wheel is the only one being steered. Fig. 3 (right-hand panel) depicts the top view of the two-dimensional model in the horizontal plane.