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Study of the open and closed loop characteristics of a tractor and a single axle towed implement system

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Abstract

Accurate automatic guidance of towed implements is important for performing agricultural field operations and for gaining the ultimate benefit from such systems. The study of open and closed loop system responses of a vehicle-implement system can be helpful in the design of practical guidance controllers. Open loop analysis of the kinematic and dynamic models revealed that the higher order dynamics captured by the tractor and implement dynamic model had an impact on simulated responses at higher operating velocities and on higher input frequencies. In addition, a dynamic model with tire relaxation length dynamics was also studied. The various model responses were compared with the experimental responses. Closed loop system characteristics were studied by using a linear quadratic regulator (LQR) controller. The tractor position and heading and implement heading states along with respective rate states were fed back to close the loop. Steering dynamics were also added to the dynamic model closed loop analysis, which helped to achieve a realistic closed loop steering angle history. The closed loop system dynamics became faster as the forward velocity was increased. The open and closed loop response analysis performed in this work provided an understanding about the system at various forward velocities, which will help to design and develop efficient and robust tractor and towed implement guidance controller.

Keywords: Dynamic vehicle model; Implement guidance; Automatic guidance; LQR controller; Relaxation length

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1. Introduction

Increased and sustained agricultural productivity is a key to meeting globally increasing demands for food and energy. Automation of agricultural machinery is one of the ways to improve the efficiency and productivity of various field operations such as tillage, planting, chemical application, and harvesting. Accurate guidance of agricultural machinery while performing these field operations will result in reduced operation time, chemical inputs, and energy inputs thus reducing production costs and improving the timeliness of field operation [1]. Improved accuracy and reduced overlap in field operations will also reduce crop damage, soil compaction, and soil rutting as well as the adverse effects of the overlapped application of agricultural chemicals.

Off-road vehicle automation technology has been studied, developed and used in agriculture for several decades. A surge of relative position-based guidance system research occurred in the 1970s and 1980s [2–4] and continued into the 1990s and the new millennium [5,6]. Relative position-based guidance systems use a local co-ordinate system as a reference frame to define the navigation problem and use relatively short range sensing techniques such as vision-based guidance [7]. In the mid and late 1990s, emboldened by the successful application of Global Positioning System (GPS) in navigating airplanes and marine vehicles, researchers started applying high accuracy GPS signals to automatically guide agricultural equipment [8–11]. In contrast to relative position sensors, GPS provided absolute position and bearing measurements of agricultural vehicles. Due to its global availability, accuracy, ease of use, and relatively low cost,

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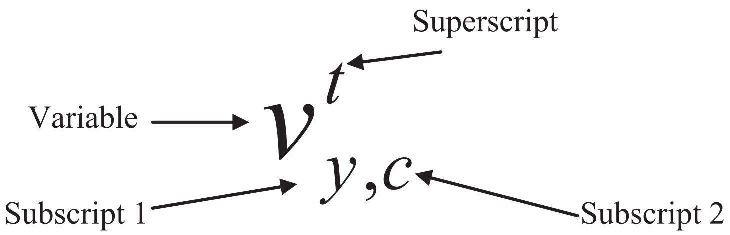
Nomenclature



Variable	the variable itself. Big or bold letter – vector or matrix, small letter – scalar
Superscript	denotes whether the variable is related to tractor or implement. t – tractor, i – implement
Subscript 1	specifies the co-ordinate axis the variable corresponds to. x – x-axis, y – y-axis, z – z-axis
Subscript 2	specifies the location the variable corresponds to. f – front tire axle, r – rear tire axle, c – center of gravity, p – toe pin (hitch point)

List of variables

α	side slip angle or the angle between the direction the tire is going and the direction it is facing. The velocity vector to the right of the tire is positive and reverse is negative
α_0	steady state side slip angle
γ	yaw-rate
δ	steering angle
λ	angle between tractor and implement headings
σ	relaxation length
φ	heading angle
a	distance between front axle and CG of tractor
A, B	empirical parameters of non-linear tire model
b	distance between rear axle and CG of tractor
c	distance between hitch point and CG of tractor
C_α	cornering stiffness
d	distance between hitch point and CG of implement
D, E, K	damping constant, input gain and inertial constant of the steering system
e	distance between rear axle and CG of implement
F	force
J	objective function for a linear quadratic regulator (LQR)
k	LQR controller gain
I	yaw moment of inertia
L	wheelbase
m	mass
n	size of state (square) matrix A
N	normal load to a tire
p	steering unit actuator input
Q	LQR controlled output penalty matrix
R	LQR control effort penalty matrix
r	turn radius of rear wheel
u	longitudinal velocity
v	lateral velocity
X–Y	world coordinates
x'–y'	vehicle coordinates
y	position of CG in y-axis of the world co-ordinate system
z	control state vector

GPS technology was key in bringing agricultural automation technology to a new level.

In the past decade, several researchers developed automatic steering controllers to guide agricultural vehicles along straight and curved paths [11–13]. In addition, manufacturers have commercialized navigation and automatic guidance technologies, and the adoption of these technologies has been growing steadily in recent years [14]. However, most automatic guidance controllers only use tractor mounted sensors. To extend agricultural automation, the capabilities of the automatic guidance systems must be extended to implements as well [15,16]. In the end, it is the implement which often performs the field operation and navigating the implement is equally or even more important than guiding the tractor [17,18].

Some researchers have investigated guidance controllers for tractor and implement systems. O'Connor et al. [8] and O'Connor [9] developed an automatic steering controller based on a kinematic model of a tractor and towed two-wheel implement. They designed a hybrid controller to provide a fast response to large errors. Bell [10] also developed a kinematic model of a tractor and towed implement system and designed an automatic tracking linear quadratic regulator (LQR) controller. Takigawa et al. [19] developed a trajectory control method for an agricultural vehicle and a mounted implement system. The feedback controller was designed based on a kinematic vehicle model. Karkee et al. [17] also developed a kinematic-model-based integrated position and heading feedback controller for a tractor and single axle towed implement system. One common element in all tractor