Nonlinear Control of a Robot-Trailer System Using a Hybrid Backstepping-linearizing Approach

by

Aditya Singh

A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
August 04, 2012

Keywords: Nonlinear control, backstepping, mobile robots

Approved by

John Y. Hung, Chair, Professor of Electrical and Computer Engineering
Thaddeus A. Roppel, Associate Professor of Electrical and Computer Engineering
Andrew J. Sinclair, Associate Professor of Aerospace Engineering

Abstract

In this work, the author develops a nonlinear controller to stabilize an autonomous wheeled robot and trailer system. A dynamic model based on robot-trailer kinematics that has previously proven sufficient for state feedback control is chosen for the ease of design. An iterative approach similar to backstepping is utilized to obtain the control input. In a manner reminiscent of feedback linearization, nonlinearities are cancelled at each step to obtain an equivalent linear system. This method is significantly different from integrator backstepping method as no signal differentiation is required. However, it is also different from the feedback linearization method as it does not require any coordinate transformation. This hybrid method is essentially a selective amalgamation of the two methods. In contrast to known state-of-the-art approaches, the proposed method stabilizes the system in both the forward and reverse motion directions, without modeling modifications. Simulation results suggest that the Hybrid Backstepping Controller(HBC)is sufficient for regulating the trailer to the desired path from any initial condition. Experimental results confirm that the Hybrid Backstepping Controller(HBC) can control the robot-trailer system and can regulate the trailer over a typical geophysical surveying path.

Acknowledgments

The author would like to thank the members of his committee Dr. John Y. Hung, Dr. Thaddeus A. Roppel and Dr. Andrew J. Sinclair for their guidance. The author would like to specially thank Dr. John Y. Hung for the invaluable advice and encouragement given during this research. This work would not have been possible without the funding and support provided by the U.S Army Corp of Engineers. Particular thanks goes to David Hodo, whose extensive previous work provided the basis for this research. Finally the author would like to thank Michael L. Payne for his invaluable support while performing the experiments.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Geophysical Surveying

Geophysical surveying is a field that has grown tremendously in the past decade.With survey areas estimated in the millions of acres in the continental USA alone [1] [2] unexploded ordnance (UXO) detection is a suitable field for robots. These surveys are carried out using a variety of sensitive sensor systems [3]. Currently these surveys are performed by highly-trained personnel towing sensors either manually (see Fig. 1.1) or by using a vehicle. These methods are both inefficient and costly for performing geophysical surveys. The nature of UXO surveying is such that it can expose the operator to significant dangers. Robotic systems [4], remotely-driven vehicles [5] and airborne surveying systems [6] are alternatives to the current method. Airborne surveying though fast has its own limitations. Remotely driven vehicles eliminate the danger to the operator, but it still requires an highly qualified operator to be present to perform the surveys. Robotic systems are potentially the best solution to the above problem. Geophysical surveying sometimes require a complete coverage of a desired region. There are several approaches used to achieve complete coverage. Coverage paths [7] and co-operative robotics [8] are a few methods to attain complete coverage. In [4] a linear controller is developed to perform geophysical surveying. As the dynamics of the linearized robot model are dependent on the point of linearization, the linear controller is insufficient for control over all operating conditions.

Figure 1.1: Geophysical surveying system towed by a human operator

1.2 Nonlinear Control Strategies

Several nonlinear controller strategies have been examined for mobile robotic system in the recent years. Several different non linear control laws have been proposed. These include -synthesis robust controller [9], adaptive backstepping control design [10], fuzzy logic control [11], role switching [12], different controller for kinematic and dynamic control inputs [13] and feedback linearization [14]. In [15] and [16] a global tracking law is developed for mobile robotic systems, but has constrained desired linear and angular velocities. In [17] and [10] these constraints are eliminated. However the backstepping method requires a lot of computational power thereby making it unsuitable for real time application.In [17] an unique method is proposed to get around this problem. A modular structure is proposed so that other dynamic control laws (like PID, feedback linearization) can be applied thereby reducing the computation effort. But none of these control laws are sufficient to control a robot-trailer system. The addition of a trailer behind the robot presents several unique challenges to the design of the control law, with one of the greatest challenge being that all forms of actuation are limited to the robot; it is a type of non-collocated control system.

1.3 An Innovative Approach

This thesis introduces an innovative nonlinear approach to design a control law for the robot-trailer system. The basic idea is to drive each state variable to a desired value or trajectory while cancelling the nonlinearity. To some degree, the control approach has semblance to feedback linearization. The design is first performed on the output state variable, and then repeated for remaining variables. Therefore, there is some likeness to the iterative nature of integrator backstepping. However, the described method requires no global coordinate transformation (escaping the chief difficulty of feedback linearization), nor any differentiation of signals (avoiding the drawback of integrator backstepping). This is similar to the control law proposed in [17]. However there are some major differences between the two methods. The controller proposed in [17] linearizes the kinematics and dynamics of the system and the controller also requires some co-ordinate transformation. The proposed control law neither linearizes the system nor requires any kind of co-ordinate transformation. The proposed control law stabilizes system dynamics in both the forward and the backward directions, without design model modifications. The above said control law is simulated and implemented on a robot-trailer system and has proven sufficient to control the system for any initial condition. This work has also been submitted for peer review to the 2012 IEEE International Conference on Industrial Electronics (IECON-2012, Montreal, Canada).

Chapter 2

System Model

Previous work has developed an autonomous robot-trailer system to tow geophysical sensor arrays using a linear controller [4, 18]. The author uses this system as a research platform to explore a innovative nonlinear control law to control the robot-trailer system. In this thesis, the robot is a four wheeled differential vehicle capable of making sharp turns. In fact, the vehicle can turn "in place" without any forward motion.

2.1 System Model

A mathematical model of the robot trailer system has to be derived before a controller can be designed. Previous work [4] has shown that a kinematic model(Fig 2.1) is sufficient to control the robot-trailer system. Dynamic effects such as moment of inertia, wheel slip and rolling friction are neglected for the slow speed that the system is run.

2.1.1 Parameter Definitions

A list of parameters and variables and their values used in this thesis is presented in Table 2.1 and Fig 2.1. (Note: The terms *easting* and *northing* are geographic Cartesian coordinates for a point.)

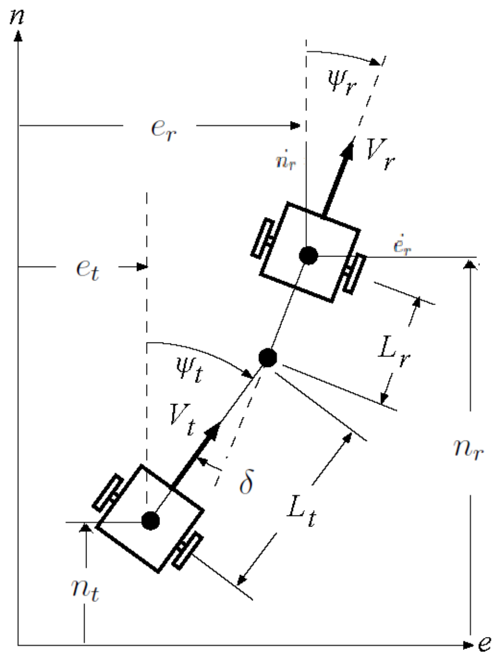

Figure 2.1: Kinematic model of the robot-trailer system

Table 2.1: Robot-trailer system parameters

Variable	Description	Value
L_t	Length of trailer tongue	3.3 m
L_r	Length of robot hitch	0 m
V_t	Velocity of trailer	
V_r	Velocity of robot	1 m/s
ψ_r	Heading of the robot	
e_r	Easting of the robot	
n_r	Northing of the robot	
ψ_t	Heading of the trailer	
e_t	Easting of the trailer	
n_t	Northing of the trailer	
ψ_{terr}	Heading error of trailer	
L_{err}	Lateral error from path of trailer	
δ	Hitch angle	
ω_r	Yaw rate of robot	

2.1.2 Kinematic Model

The system can be represented by the following state equations.

$$\dot{e_r} = V_r \sin(\psi_r) \tag{2.1}$$

$$\dot{n_r} = V_r \cos(\psi_r) \tag{2.2}$$

$$\dot{\psi}_r = \omega_r \tag{2.3}$$

$$\dot{\delta} = -\frac{V_r}{L_t}\sin(\delta) - \frac{L_r\omega_r}{L_t}\cos(\delta) - \omega_r \tag{2.4}$$

The vehicle model has two input - the angular velocity ω_r and linear velocity V_r. However as the goal is to control the trailer position, the following equations describe relationships between robot and trailer.

$$e_t = e_r - L_r \sin(\omega_r) - L_t \sin(\omega_r + \delta) \tag{2.5}$$

$$n_t = n_r - L_r \cos(\omega_r) - L_t \cos(\omega_r + \delta) \tag{2.6}$$

$$\psi_t = \psi_r - \delta \tag{2.7}$$

$$V_t = V_r \cos(\delta) - L_r\omega_r \sin(\delta) \tag{2.8}$$

The above equations give the relationship between robot variables and trailer variables. The set of equations is used to derive the dynamic equation of the trailer [19].

$$\dot{e_t} = V_t \sin(\psi_t) \tag{2.9}$$

$$\dot{n_t} = V_t \cos(\psi_t) \tag{2.10}$$

$$\dot{\psi}_t = -\frac{V_r}{L_t}\sin(\delta) - \frac{L_r\omega_r}{L_t}\cos(\delta) \tag{2.11}$$

$$\dot{\delta} = -\frac{V_r}{L_t}\sin(\delta) - \frac{L_r\omega_r}{L_t}\cos(\delta) - \omega_r \tag{2.12}$$

Chapter 3

Controller Design

3.1 Introduction

Path following control of robot-trailer system has been extensively studied in the past. Several types of nonlinear control have been developed that can control the robot on a desired path. But the application of nonlinear controller to the robot-trailer system has not been explored as much. In this thesis a new nonlinear control approach is tested to control the robot-trailer system to the path. This new approach is similar to the back stepping control, as the desired control input is backstepped through each integrator. However this approach differs significantly from the backstepping approach as no signal differentiation takes place. This approach also looks similar to feedback linearization method as it assumes a pseudo feedback at each step, but it differs from feedback linearization as there is no coordinate transformation. This is a novel approach that coalesces the desired features of the two approaches.

3.2 Controller Design

In this section, the control law for the robot-trailer system is derived. For path following the error model is required. The dynamic equation derived in Section 2.1.2 is used to derive the error model. For ease of controller implementation, the desired path at any moment in time is transformed by a nonlinear transformation to a path whose Universal Transverse Mercator (UTM) coordinates run from south to north. This ensures that the trailer lateral error is directly defined by the trailer easting e_t.

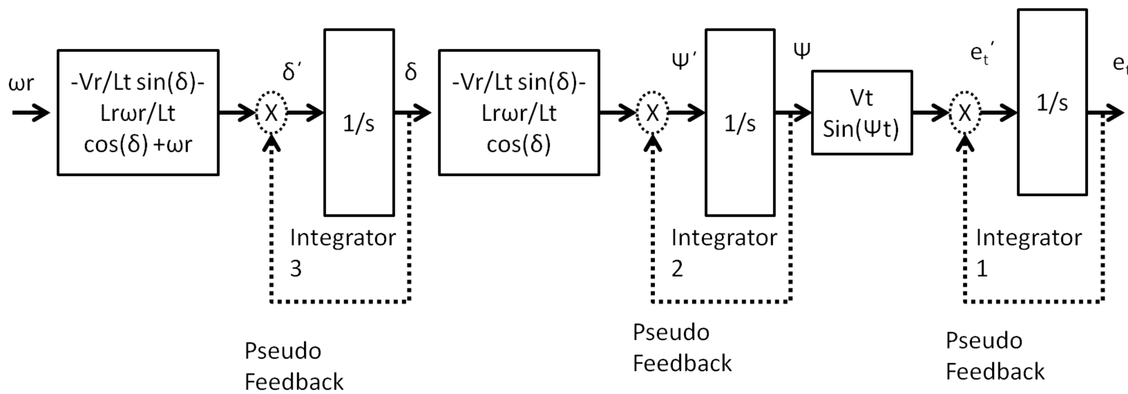

Figure 3.1: Block Diagram of the Robot-Trailer System

Hence, the error variables can be defined as follows.

$$L_{err} = e_{desired} - e_t \tag{3.1}$$

$$\psi_{terr} = \psi_{desired} - \frac{\psi_t}{k_2} \tag{3.2}$$

where k_2 is a gain.

The goal of the project is to control the trailer to the path, so only the lateral error and the heading error of the trailer are chosen as the controlled variables. This approach also provides more freedom to the robot as the robot does not need to follow the path. Velocity and yaw (turn) rate are the physically controllable variables of the robot. Though it is desired that the trailer velocity is 1 m/s, it was seen that while making tight turns, the robot speed tends to infinity. This is due to the fact that trailer speed is given by eqn (2.8), so for δ equal to 90 the robot speed goes to infinity. Hence the speed of the robot is fixed to 1 m/s. The trailer speed is 1 m/s on straight segments and slightly less than 1 m/s on mild turns. However when making tight turns having a fixed robot speed stops the system from becoming unstable. So only the yaw rate ω_r is a control input. The basic idea is to drive each integrator in Fig. 3.1 to a desired value while cancelling out the nonlinearities. This approach seems similar to integrator backstepping, but there is a major difference: Instead of taking the derivative at each integrator, a pseudo feedback is assumed across it. The proposed method eliminates the need for numerical differentiation (which is highly sensitive to small fluctuations in data) and coordinate transformation (which may not be possible in every case). The system model has three state variables, so the design requires three iterative steps.

Desired Input Calculation of First Integrator

In this step the value of the first integrator has to driven to the desired value (Lateral error). This done by assuming a pseudo feedback across integrator 1. This gives rise to the following equations.

$$\dot{e_t} = -L_{err} \tag{3.3}$$

Substituting (2.9) in (3.3) we get:

$$V_t \sin(\psi_{t1}) = -L_{err} \tag{3.4}$$

where ψ_{t1} is the desired heading to eliminate the heading error. Solving for ψ_{t1} gives:

$$\psi_{t1} = \sin^{-1}\left(\frac{-L_{err}}{V_t}\right) \tag{3.5}$$

For controlling the trailer on the path the heading error also has to be controlled. Let k_1 and k_2 be the gains on the heading error and the lateral error. The desired value of ψ_t is given by

$$\psi_{tdesired} = k_1\psi_{t1} + k_2\psi_{desired} \tag{3.6}$$

k_1 and k_2 can be chosen without any constraint as the $\sin^{-1}$ term limits the controller output. The value of $\sin^{-1}$ remains -1.517 for any value less than -1 and in the same way the value of $\sin^{-1}$ remains 1.517 for any value greater than 1. This implies that the controller keeps the desired control output to $+or-90°$ until the $\psi_{tdesired}$ value is between -1.517 and 1.517.

Desired Input Calculation of Second Integrator

In this step the value of the Second integrator has to driven to the desired value (obtained in previous step) . This done by assuming a pseudo feedback across integrator 2. This gives rise to the following equations.

$$\psi_{tfeedback} = k_1\psi_{t1} + k_2\psi_{desired} - \psi_t \tag{3.7}$$

or

$$\psi_{tfeedback} = k_1\psi_{t1} + k_2\left(\psi_{desired} - \frac{\psi_t}{k_2}\right). \tag{3.8}$$

Substituting (3.2) in (3.8) we get:

$$\psi_{tfeedback} = k_1\psi_{t1} + k_2\psi_{terr} \tag{3.9}$$

$$\dot{\psi}_t = -\psi_{tfeedback} \tag{3.10}$$

Substituting (2.11) in (3.10) we get:

$$\left(-\frac{V_r}{L_t}\right)\sin(\delta) - \frac{L_r\omega_r}{L_t}\cos(\delta) = -\psi_{tfeedback} \tag{3.11}$$

Recall the trigonometric identity

$$a\sin(x) + b\cos(x) = K\sin(x+\theta) \tag{3.12}$$

where

$$K = \sqrt{a^2 + b^2} \tag{3.13}$$

$$\theta = \sin^{-1}(\frac{b}{\sqrt{a^2 + b^2}}). \tag{3.14}$$

Applying (3.12) we can rewrite (3.11) as

$$K \sin(\delta_1 + \theta) = -\psi_{tfeedback} \tag{3.15}$$

where

$$K = \frac{1}{L_t}(\sqrt{{V_r}^2 + {L_r}^2{\omega_r}^2} \tag{3.16}$$

$$\theta = \sin^{-1}(\frac{V_r}{{V_r}^2 + {L_r}^2{\omega_r}^2})). \tag{3.17}$$

In (3.15), variable δ_1 is the desired value of the hitch angle δ. Solving for δ_1 we get

$$\delta_1 = \sin^{-1}(\frac{-\psi_{tfeedback}L_t}{\sqrt{{V_r}^2 + {L_r}^2{\omega_r}^2}}) - \sin^{-1}(\frac{V_r}{\sqrt{{V_r}^2 + {L_r}^2{\omega_r}^2}}) \tag{3.18}$$

which is the desired value of integrator 3.

Desired Input Calculation of Third Integrator

To drive the integrator 3 to its desired value, the hitch angle error δ_{err} is required. The δ_{err} is given by the following equation:

$$\begin{aligned}\delta_{err} = \sin^{-1}&\left(\frac{-\psi_{tfeedback}L_t}{\sqrt{{V_r}^2 + {L_r}^2{\omega_r}^2}}\right) \\ &- \sin^{-1}\left(\frac{V_r}{\sqrt{{V_r}^2 + {L_r}^2{\omega_r}^2}}\right) - \delta\end{aligned} \tag{3.19}$$

Assuming that there exists a pseudo feedback across integrator 3, we get:

$$\dot{\delta} = -\delta_{err}. \tag{3.20}$$

Substituting (2.4) in (3.20) we get:

$$-\frac{V_r}{L_t}\sin(\delta) - \frac{L_r\omega_r}{L_t}\cos(\delta) - \omega_r = -\delta_{err} \tag{3.21}$$

Solving for ω_r we get:

$$\omega_r = \delta_{err} - \frac{V_r}{L_t}\sin(\delta) - \frac{L_r\omega_r}{L_t}\cos(\delta) \tag{3.22}$$

Substituting (3.19) in (3.22) we get

$$\begin{aligned}\omega_r = \sin^{-1}\left(\frac{-\psi_{tfeedback}L_t}{\sqrt{{V_r}^2 + {L_r}^2{\omega_r}^2}}\right) - \sin^{-1}\left(\frac{V_r}{\sqrt{{V_r}^2 + {L_r}^2{\omega_r}^2}}\right) \\ -\delta - \frac{V_r}{L_t}\sin(\delta) - \frac{L_r\omega_r}{L_t}\cos(\delta)\end{aligned} \tag{3.23}$$

Substituting (3.9) in (3.23) we get:

$$\begin{aligned}\omega_r = \sin^{-1}\left(\frac{-k_1\psi_t 1 - k_2\psi_{terr}}{\sqrt{{V_r}^2 + {L_r}^2{\omega_r}^2}}L_t\right) - \sin^{-1}\left(\frac{V_r}{\sqrt{{V_r}^2 + {L_r}^2{\omega_r}^2}}\right) \\ -\delta - \frac{V_r}{L_t}\sin(\delta) - \frac{L_r\omega_r}{L_t}\cos(\delta)\end{aligned} \tag{3.24}$$

Finally substituting (3.5) in (3.24) yields the control input in terms of lateral error and heading error:

$$\begin{aligned}\omega_r = \sin^{-1}\left(\frac{-k_1(\sin^{-1}(\frac{-L_{err}}{V_t})) - k_2\psi_{terr}}{\sqrt{{V_r}^2 + {L_r}^2{\omega_r}^2}}\right) \\ - \sin^{-1}\left(\frac{V_r}{\sqrt{{V_r}^2 + {L_r}^2{\omega_r}^2}}L_t\right) - \delta - \frac{V_r}{L_t}\sin(\delta) \\ - \frac{L_r\omega_r}{L_t}\cos(\delta)\end{aligned} \tag{3.25}$$

Since the arcsine function $\sin^{-1}$ is valid over the interval $(-\frac{\pi}{2}, \frac{\pi}{2})$, the sign of lateral error has to be flipped when the robot faces in the opposite direction.

3.2.1 Controller Gains

To calculate the controller gains the Butterworth gains and Linear Quadratic Regulator (LQR) gains were examined [20]. After examining both the methods it was observed that better control was obtained using LQR method. Hence LQR method was chosen to obtain the value of k_1 and k_2. For LQR calculations the system is assumed to be a three state linear system. This assumption is made as all the nonlinearities of the system are cancelled. It was seen that with different weights placed on the two states, different output characteristics can be obtained. For example if the weight on lateral error is greater than that on the heading error, the trailer regulates faster to the path but oscillates on the path. In contrast, if the weight on the heading error is greater than lateral error, the system does better line following but takes a long time for the system to regulate onto the path if the initial errors are large. Hence two different gains were calculated. Gain 1 was calculated with greater weight placed on lateral error while Gain 2 was calculated with greater weight placed on heading error.

Using the *lqr()* command in MATLAB®, LQR gains k_1 and k_2 were calculated for different weight matrices. The Q matrix for Gain 1

$$Q_x = \begin{bmatrix} 100 & 0 & 0 \\ 0 & 10 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad R_u = \begin{bmatrix} 1 \end{bmatrix} \tag{3.26}$$

which resulted in closed loop poles at

$$s_1 = -2.0563 \tag{3.27}$$

$$s_2 = -1.2746 + \jmath 1.7996 \tag{3.28}$$

$$s_3 = -1.2746 - \jmath 1.7996. \tag{3.29}$$

The following gains are obtained k_1=10 k_2=10 The Q matrix for Gain 2

$$Q_x = \begin{bmatrix} 10 & 0 & 0 \\ 0 & 100 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad R_u = \begin{bmatrix} 1 \end{bmatrix} \tag{3.30}$$

which resulted in closed loop poles at

$$s_1 = -0.3164 \tag{3.31}$$

$$s_2 = -2.2853 + \jmath 2.1847 \tag{3.32}$$

$$s_3 = -2.2853 - \jmath 2.1847. \tag{3.33}$$

The following gains are obtained k_1=3.1623 k_2=11.4415

3.2.2 Gain Scheduling

As discussed in the previous section, it was observed that the controller gains that provided the best path following did not produce the fastest regulation to the path when the initial error were large. Gain scheduling was performed to retain the best characteristics of Gain 1 and Gain 2 [21]. Another design issue was to obtain the gain scheduling point. As the controller and the system were non linear the linear methods (like Nyquist criteria) to determine the stability could not be used to obtain the scheduling point. Hence by experimental and simulation result it was seen that the scheduling point was to be set at 4 meters (lateral Error) for the Gain 2 to be able to smoothly bring the trailer on the path without any oscillation

3.3 Simulation of the Controller

To test the validity of the control approach, the system is simulated with the proposed Hybrid Backstepping Controller(HBC). The system was simulated for various initial conditions. The system was simulated with fixed gains and also using gain scheduling. The system was simulated for approximately 50 seconds.

Fixed gain performance

As can be seen in Fig. 3.2, the robot and trailer have an initial orientation that is 270° from the path and the lateral error is 6 m. It can be seen that the robot and trailer take a long north distance to regulate onto the path but is able to follow the path better when it reaches the path. In Fig. 3.3, the lateral error and heading error of the system is plotted. It can be seen that the system does not have any steady state error and the system shows good tracking.

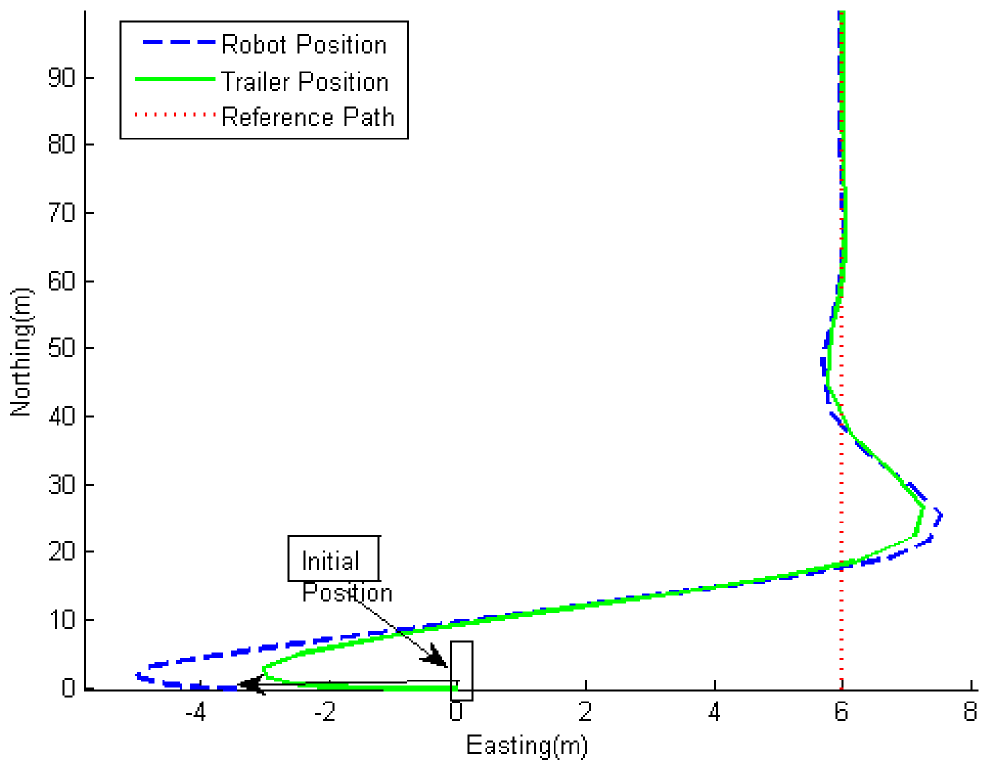

Figure 3.2: System position with fixed gains (simulated)

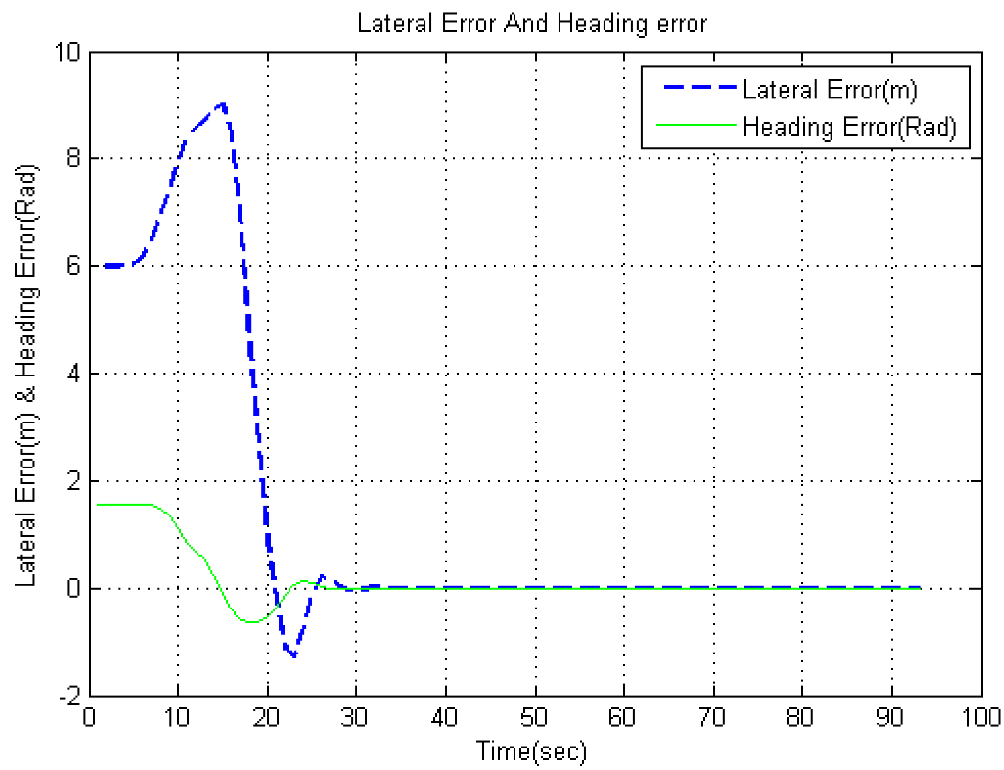

Figure 3.3: Lateral error and heading error (simulated)

Gain scheduled performance

Now the simulation is run with gain scheduling. In Fig. 3.4, the initial position is same as in Fig. 3.2. But it can be clearly seen that the robot-trailer system makes a sharper turn and regulates quicker to the path. The path following is as good as before but the regulation to the path is faster than with a fixed gain.

Trailer backing performance

One of the greatest features of this control law is that it can control the trailer in both directions without any design modifications. In contrast, other known methods require some additional design modifications. For example [22] introduces a virtual robot that pulls the robot in the reverse direction. In Fig. 3.5, the backing performance of the controller is demonstrated. Initially the robot and trailer have an orientation of 135° to the path. The initial lateral error is 6 m. It can be seen that

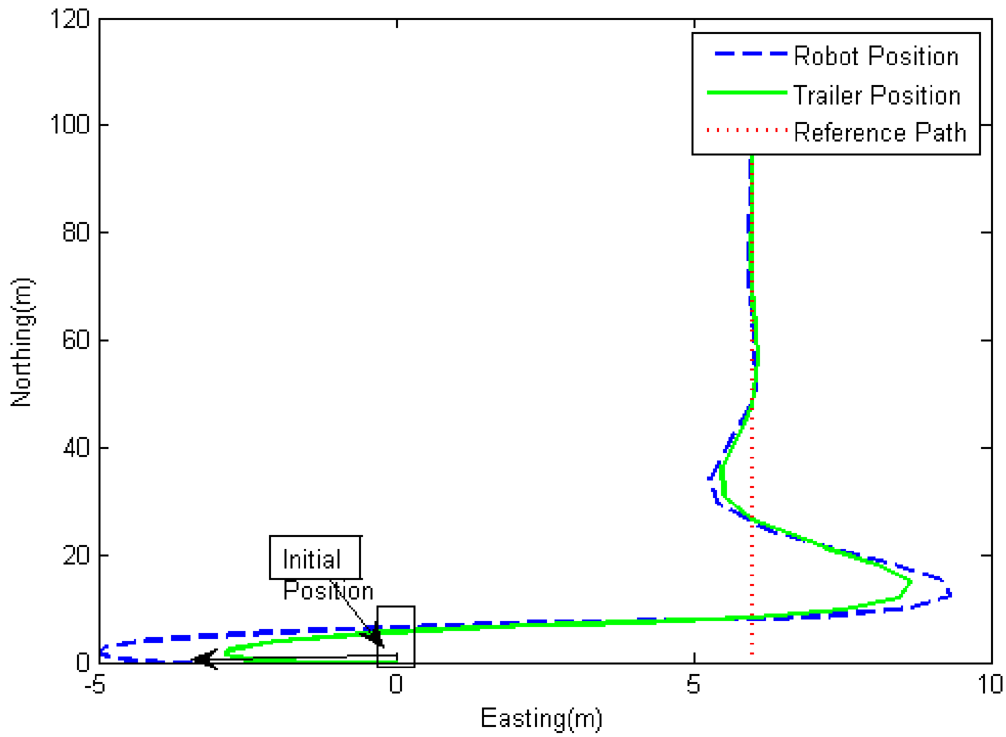

Figure 3.4: System Position with Gain Scheduling (simulated)

the controller is sufficient to control the system while backing the trailer onto the path.

3.4 Conclusion

These simulations show that the Hybrid Backstepping Controller(HBC) is sufficient in controlling the system for any initial condition. Further more they demonstrate that gain scheduling provides more dynamic control than fixed gains. The simulation also suggest that the controller is dexterous at backing the trailer onto the path.

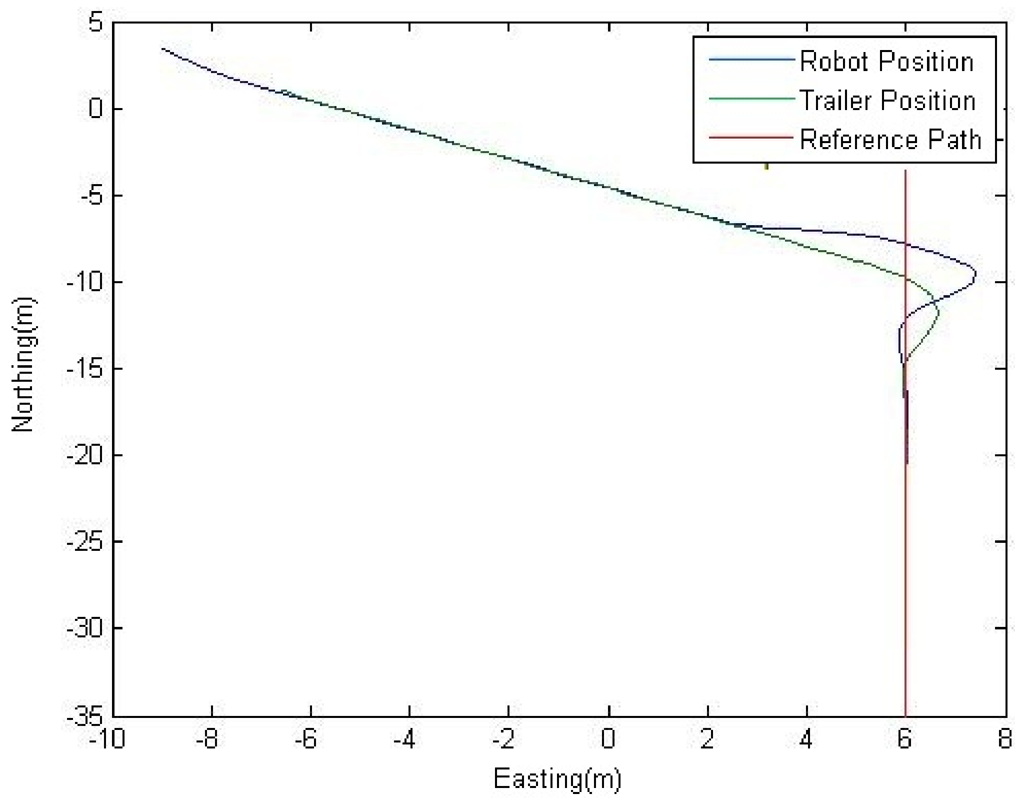

Figure 3.5: Backing of trailer (Simulated)

Chapter 4

Experimental Results

4.1 The Robot-trailer System

The Autonomous Robot-Trailer system used for this research is built on a Segway Robotics Mobility Platform (RMP) 400. This is a four-wheeled, differential-drive robot capable of carrying ample payload [23]. The RMP 400 communicates using a Universal Serial Bus (USB) interface. The inputs to RMP 400 are turn and velocity command that are sent in counts. The RMP 400 has inbuilt speed and yaw controller that controls the speed of individual motors. A NovAtel SPAN™ Global Navigation Satellite System/Inertial Navigation System (GNSS/INS) is present on the robot [24]. Using real-time kinematic (RTK) position corrections from a base station,the GNSS/INS provides accurate knowledge of the vehicle position and orientation [25]. Another Novatel Global Positioning System(GPS) antenna is mounted on the trailer. This provides the position information of the trailer. The position and velocity obtained from the GPS are very accurate [26]. A rotary encoder positioned at the trailer hitch of the vehicle provides the angle of the trailer with respect to the robot. The orientation of the trailer is calculated from the orientation of the robot provided by the GNSS/INS and the hitch angle provided by the rotary encoder. This provides more accurate orientation than the orientation provided by the trailer GPS alone. To minimise the electromagnetic interference to geophysical sensors , the trailer is constructed using fiberglass. For the purpose of this research the orientation from the trailer GPS, hitch angle information from the rotary encoder and the orientation information calculated from the hitch angle and the orientation information from the GNSS/INS is used.

Figure 4.1: Autonomous geophysical surveying system described in this thesis

Figure 4.1 shows the robot-trailer system. As it can be seen in the figure the robot-trailer system has a hitch at the center of the robot; hence the robot hitch length (L_r) is zero.The linear controller [4] previously developed on this robot trailer system provides the scope for a direct comparison between the two controllers.

4.2 Experimental Setup

Experiments were performed at Auburn University Solar House field. Several different paths and initial conditions were chosen to demonstrate the capabilities of the Hybrid Backstepping Controller(HBC) to regulate the robot-trailer system to the desired survey lines.

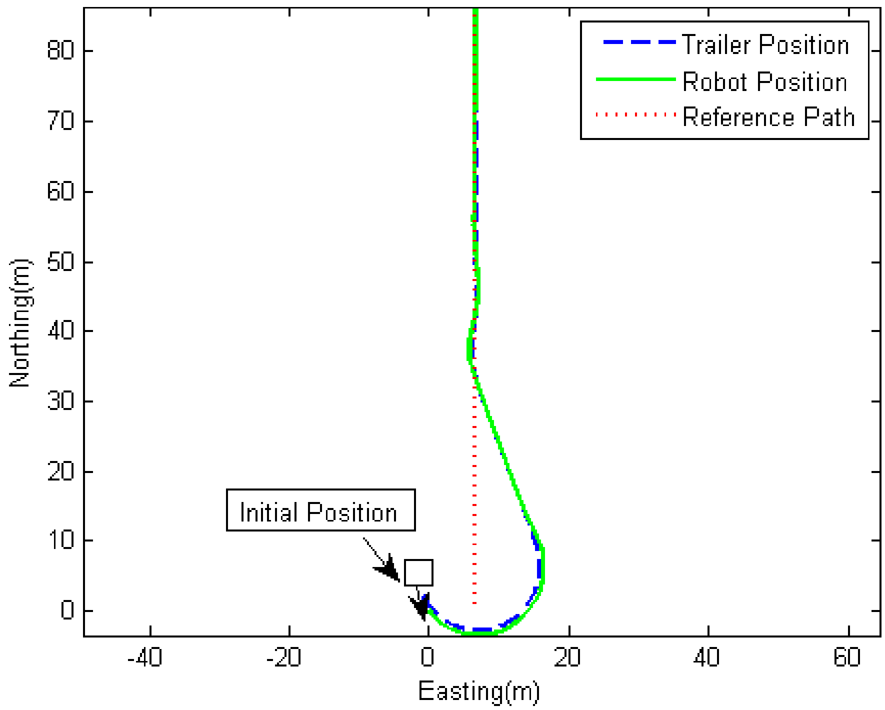

Figure 4.2: Robot-Trailer Position with fixed gains (experimental)

4.3 Different Initial Conditions

The effectiveness of the control law is tested for different initial conditions. This is done to show the versatility of this control law in controlling the robot-trailer system to the path. Fixed gain performance is also compared to the Gain scheduling performance.

Fixed gain performance

In Fig. 4.2, the robot and trailer have an initial orientation of 180° with respect to the desired heading and the trailer has a lateral error of 9 m. It can be seen that robot-trailer system shows good tracking of the path with minimal steady state error. It can be seen that controller automatically performs both clockwise turns (see Fig. 3.2) as well as counterclockwise turns (see Fig. 4.2), depending on the shortest route to the path.

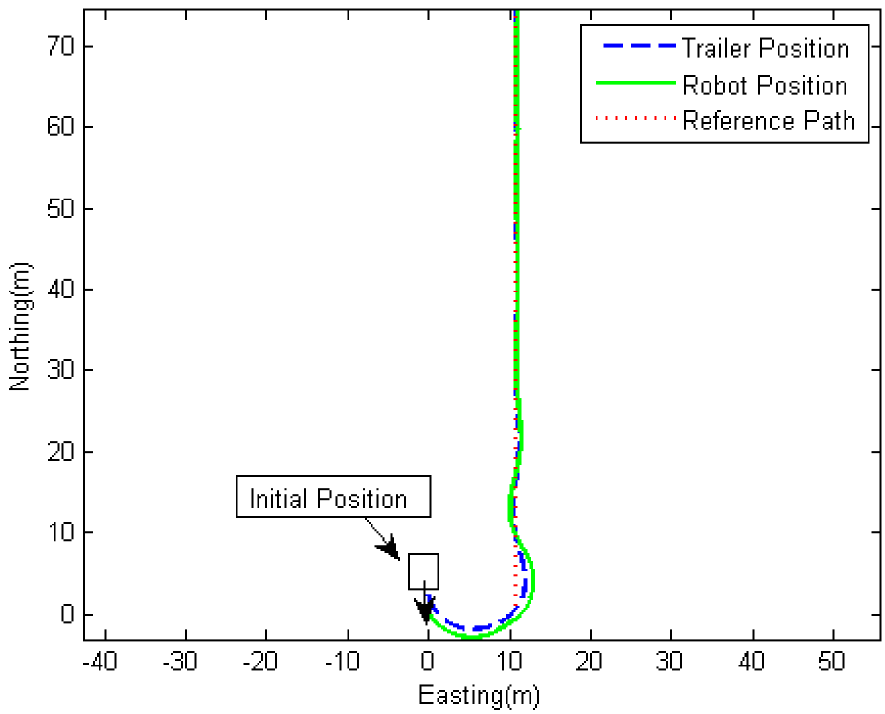

Figure 4.3: Robot-Trailer Position with Gain Scheduling (experimental)

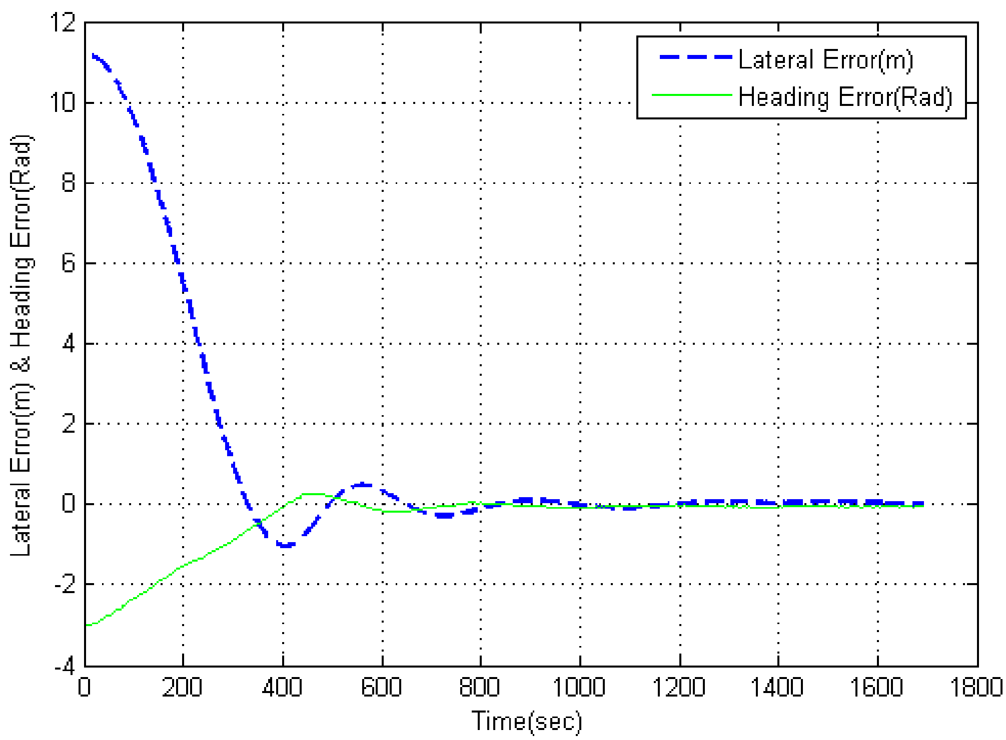

Figure 4.4: Lateral Error And Heading Error (experimental)

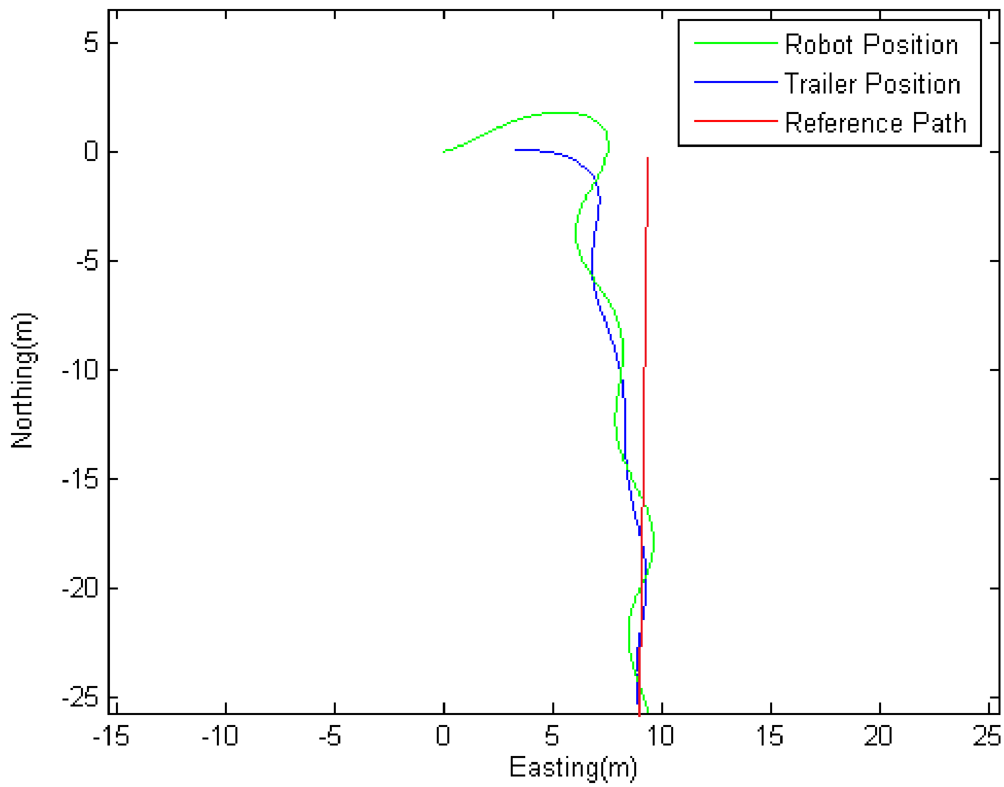

Figure 4.5: Backing of the trailer (experimental)

Gain scheduled performance

In Fig. 4.3, the robot and trailer have an initial orientation of 180° with respect to the desired path – the same condition as for the fixed gain experiment. However, the initial lateral error is increased from 9 m to 10 m. It can be seen that with gain scheduling the robot-trailer system makes a sharper turn and is able to get on the desired path faster than in the fixed-gain case (compare to Fig. 4.2). Fig. 4.4 shows the plot of lateral error and heading error for the gain-scheduled case. It can be seen that the Hybrid Backstepping Controller(HBC) seems to control the system well. The robot and trailer are initially located at $(0, 0)$ and $(0, 3.3)$, respectively. Their initial headings are 270° from the path. The robot-trailer system moves to the right and downward in the plot.

Trailer backing performance

In Fig. 4.5, the trailer backing performance of the controller is shown. Though the controller is able to back the trailer onto the path there are some oscillations in the position. The oscillation of the trailer is about 0.50 m. It is also seen that the amplitude of the oscillations reduce slowly.

4.4 Path Following

The path following capability of the controller is examined in this case. The trailer is place on the path with a very small lateral error and a small heading error. It can be seen in the Figure 4.6 that the system is able to follow the desired path. It is capable of making the turns.

In Figure 4.6 it can be seen that the controller is able to control the robot trailer system on the path. It can be further seen that the controller is able to make the turns. Hence the controller appears to be able to perform path following.

4.5 Comparison with Linear Controller

To put the performance of the Hybrid Backstepping Controller(HBC) into perspective, the performance of the Hybrid Backstepping Controller(HBC) is compared to the full state feedback controller.

4.5.1 Different Initial Conditions

The two controllers are examined for different initial conditions. It is apparent that the Hybrid Backstepping Controller(HBC) can control the system over a wide range of initial conditions where the linear controller is inadequate.

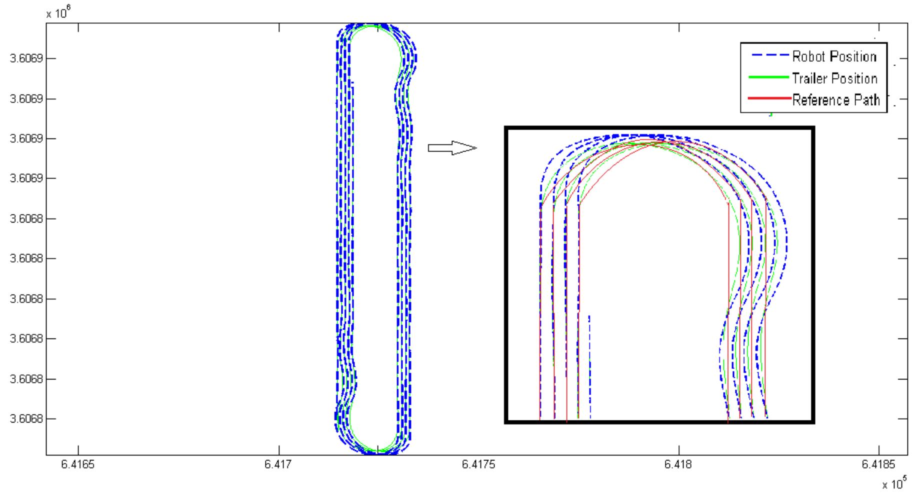

Figure 4.6: Plot of Robot and Trailer path

Table 4.1: Comparison of the two controllers for different initial conditions

Initial Condition	Full State Feedback	HBC
With very small heading and lateral error	Can perform path following	Can perform path following
With large lateral error and very small heading error	Causes the system to become unstable if lateral error is greater than two meters	Can regulate the system back onto the path for any lateral error.
With large heading error and very small lateral error	Causes the system to become unstable if heading error is greater than 30 degrees.	Can regulate the system back onto the path for any heading error.
With large lateral and heading error	Causes the system to become unstable thereby causing the trailer to jackknife	Can regulate the system back onto the path without jackknifing the trailer.
With initial orientation of the robot in opposite direction to the path	Causes the trailer to jackknife	Can smoothly turn the robot-trailer around without jackknifing the trailer
Backing the trailer onto the path	Cannot control the trailer in reverse direction	Can back the trailer onto the path.

Table 4.2: Comparison of the two controllers while path following

Characteristic	Full State Feedback	HBC
Settling time	Shorter	larger
lateral error	Similar	Similar
Heading error	Similar	Similar
Lateral error coming out of a turn	Slightly Smaller	Slightly Greater
Heading error coming out of a turn	Similar	Similar

4.5.2 Path Following

In this section the path following capability of the two controllers is examined. The nonlinear and linear controller is used to control the system on the same path to get a direct comparison of path following performance. The initial lateral and heading error are kept very small. Fig 4.7 shows the path following performance of the linear controller and Fig 4.8 shows the path following performance of the non linear controller. It can be seen that though both controllers are able to control the trailer on the path, but the Hybrid Backstepping Controller(HBC) takes longer to stabilize after coming out of the turn. In Fig 4.9 the comparison of the lateral error for the two controller is shown. It can be seen that both the controllers have similar type of lateral error characteristics. However it can be seen that the lateral error after coming out of the turn for the Hybrid Backstepping Controller(HBC) is not as good as that of the linear controller. Fig 4.10 shows the heading error of the two controller. The heading error characteristics are similar for the two controllers. However the performance of the linear controller while path following is better than that of the Hybrid Backstepping Controller(HBC).

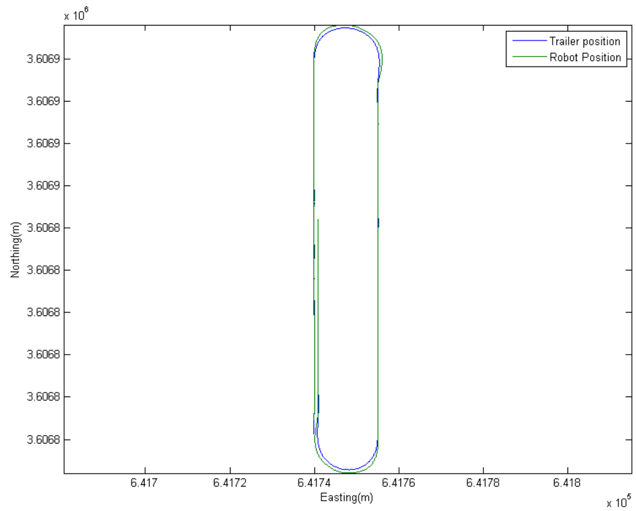

Figure 4.7: Plot of robot-trailer with Linear controller

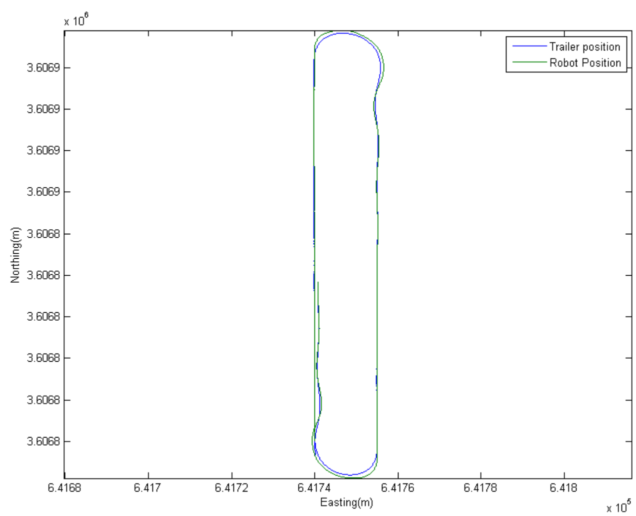

Figure 4.8: Plot of robot-trailer with HBC

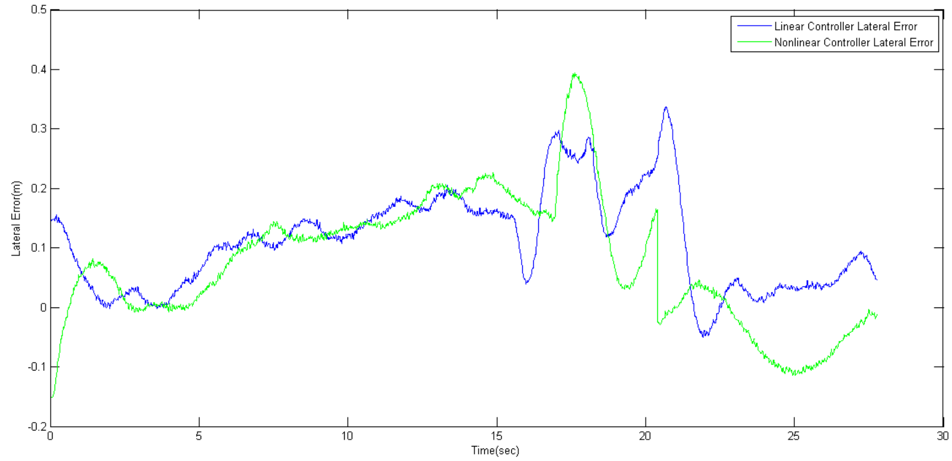

Figure 4.9: Comparison of Lateral error

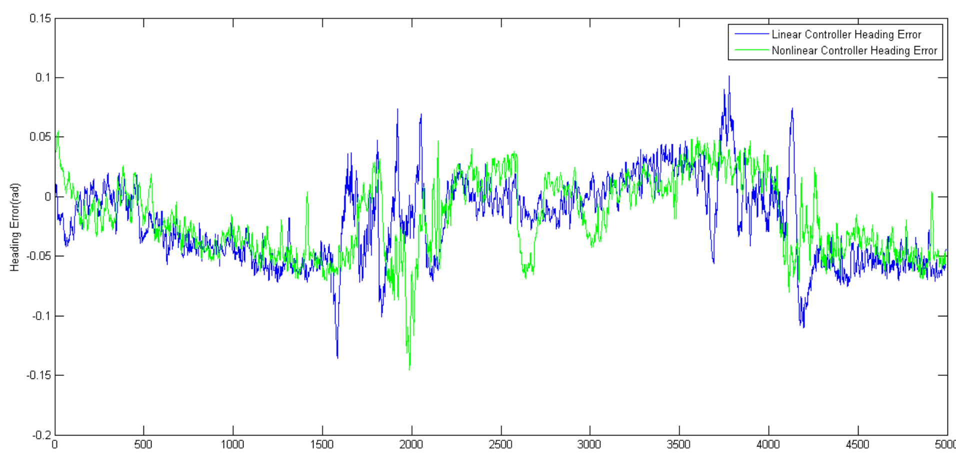

Figure 4.10: Comparison of Heading error

Chapter 5

Conclusions

The conclusions drawn from the simulations are verified by the experimental results. The innovative nonlinear controller presented in this thesis is shown to be sufficient to control the robot-trailer system. The selective amalgamation of the integrator backstepping method and feedback linearization not only avoids the design difficulties of both the approaches but also provides excellent control. The Hybrid Backstepping Controller(HBC) is seen adequate in controlling the robot-trailer system on the path. It is also seen that the Hybrid Backstepping Controller(HBC) is capable of controlling the robot-trailer system from any initial condition. In contrast to the state-of-art-methods, this control law is able to control the system in both the forward and reverse direction without any modification.The author believes that this hybrid control law can be applied to other systems with similar success.

5.1 Effectiveness of the Hybrid Backstepping Controller(HBC)

While path following

The Hybrid Backstepping Controller(HBC) is able to control the robot-trailer system on the path and is able to make sharper turns than the state feedback controller. However it is seen that the while coming out of turns, Hybrid Backstepping Controller(HBC) takes longer to regulate the system onto the path. This is an undesirable characteristic. The author believes that this can be corrected by fine tuning the gains.

For different initial condition

The Hybrid Backstepping Controller(HBC) is capable to handle any initial condition. It is capable of handling any initial heading or lateral error, while the linear controller is only capable of controlling if the heading and lateral error are small. This is a very desirable characteristic of the controller. This gives the system freedom that is not possible with the linear controller.

While backing trailer

The simulation suggested that the Hybrid Backstepping Controller(HBC) will smoothly back the trailer onto the path. However the experimental data showed that though Hybrid Backstepping Controller(HBC) is able to back the trailer onto the path there are some oscillations and it would take a long time for the oscillations to die down. Different gains were tried to make the system converge quickly, however the optimal gain could not be found. The author believes that this is due to the unmodeled dynamic effects present in the experimental setup. Despite the deficiencies, the Hybrid Backstepping Controller(HBC) is able to control the system over a wide variety of conditions.

5.2 Future Work

The Hybrid Backstepping Controller(HBC) has been shown to control the robot-trailer system accurately on the path and also control from any initial condition. However several improvements can be made to the controller to improve path following ability and backing capabilities of the trailer.

5.2.1 Full dynamic model

As discussed in Chapter 2, the dynamic model used is only based on kinematics of the system. While a kinematic model is seen to be sufficient for linear controller to control the system on the path, the exclusion of dynamic effects can have a pronounced effect on the controller performance while backing the trailer. This is due to the fact that while backing the trailer, the system is inherently unstable and the unmodeled dynamics further reduces the effectiveness of the controller. Future work will include the modeling of dynamics like wheel slip, moment of inertia and rolling friction. Future work will also incorporate the delays in the system. Modeling these dynamics should improve the ability of the controller to control the robot-trailer system while backing the trailer.

5.2.2 Choosing Controller Gains

Butterworth gains and LQR method were examined for this thesis. The LQR tuning should be improved for better path following control. Different weight values were examined during the design process, but better gains are required to reduce the oscillations after the turns. Optimal gains for backing the trailer on to the path need to be investigated. Some other methods for choosing controller gains should also be examined.

5.2.3 Gain Scheduling

A more complex gain scheduling should also be examined, as it is apparent the gain sets currently used do not provide as good path following as the linear controller. It is the authors belief that a separate gain should be used while path following. This would improve the path following performance of the controller. However the gains that provide the best path following may not be able to regulate the system onto the path fast enough when the errors are large. Hence by having more sets of gains all the desired features can be retained. Proposed three set gains can be seen in Table 5.1

Table 5.1: Proposed gain scheduling

Gain	Schedule	Lateral error values
Gain 1	For large lateral errors	> 4 meters
Gain 2	For medium lateral errors	0.5 meters to 4 meters
Gain 3 (Similar to Linear gain values)	For small lateral errors	< 0.5 meters

5.2.4 Design of a Nonlinear Estimator

The nonlinear controller used in this thesis require all the state variables. However this also introduces multiple sources of measurement noise. For example the hitch angle values obtained from the rotary encoder has more noise than the GPS values: this introduces error in the controller. This problem can be reduced by estimating some of the states that cannot be measured as accurately as others.

5.2.5 Effectiveness on other problems

The effectiveness of the control law should be verified on other types of vehicles like Ackermann drive robot trailer system. The author believes that the control law should be sufficient to control the Ackermann drive robot. But it would be interesting to study the effect of the constraints that Ackermann drive places on the control of the system.

Bibliography

[1] J. S. Foster, "Report of the defense science board task force on unexeploded ordnance (UXO) clearance, active range UXO clearance, and explosive ordnance disposal (EOD) programs," Defense Science Board, Office of the Under Secretary of Defense, Washington, DC, Tech. Rep., April 1998.

[2] B. Delaney and D. Etter, "Report of the Defense Science Board Task Force on Unexploded Ordnance," *Defense Sci. Board, Washington, DC, Final Tech. Rep. A*, vol. 79914, 2003.

[3] H. Nelson and J. McDonald, "Multisensor towed array detection system for UXO detection," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 39, no. 6, pp. 1139–1145, 2001.

[4] D. Hodo, "Development of an autonomous mobile robot-trailer system for UXO detection," Master's thesis, Auburn University, 2007.

[5] H. Zafrir, Y. Bregman, D. Wolf, and S. Hershler, "Super-sensitive, real time and wide coverage, all terrain ground robotic and hand held systems for mine and UXO detection and mapping," in *Second International Conference on the Detection of Abandoned Land Mines*, Oct. 1998, pp. 208 –212.

[6] A. Fijany, J. Collier, and A. Citak, "Recent advances in unexploded ordnance (UXO) detection using airborne ground penetrating SAR," in *Proceedings of 1999 IEEE Aerospace Conference*, vol. 3, 1999, pp. 429 –441 vol.3.

[7] H. Choset, "Coverage for robotics—A survey of recent results," *Annals of Mathematics and Artificial Intelligence*, vol. 31, no. 1, pp. 113–126, 2001.

[8] A. Karimoddini, H. Lin, B. Chen, and T. H. Lee, "Developments in hybrid modeling and control of unmanned aerial vehicles," in *Control and Automation, 2009. ICCA 2009. IEEE International Conference on*, dec. 2009, pp. 228 –233.

[9] G. Yin, N. Chen, and P. Li, "Improving handling stability performance of four-wheel steering vehicle via 956;-synthesis robust control," *IEEE Transactions on Vehicular Technology,*, vol. 56, no. 5, pp. 2432 –2439, sept. 2007.

[10] D. Nganga-Kouya and F. Okou, "Adaptive backstepping control of a wheeled mobile robot," in *17th Mediterranean Conference on Control and Automation, 2009. MED '09*, June 2009, pp. 85 –91.

[11] Y.-C. Chang and B.-S. Chen, "Adaptive tracking control design of nonholonomic mechanical systems," in *Proceedings of the 35th IEEE Decision and Control, 1996.,*, vol. 4, dec 1996, pp. 4739 –4744 vol.4.

[12] H. C.-H. Hsu and A. Liu, "A flexible architecture for navigation control of a mobile robot," *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans,*, vol. 37, no. 3, pp. 310 –318, may 2007.

[13] J. Crowley, "Asynchronous control of orientation and displacement in a robot vehicle," in *Proceedings of IEEE International Conference on Robotics and Automation, 1989.*, may 1989, pp. 1277 –1282 vol.3.

[14] G. Gamage, G. Mann, and R. Gosine, "Formation control of multiple nonholonomic mobile robots via dynamic feedback linearization," in *International Conference on Advanced Robotics, 2009. ICAR 2009.*, june 2009, pp. 1 –6.

[15] Z.-P. JIANGdagger and H. NIJMEIJER, "Tracking control of mobile robots: A case study in backstepping," *Automatica*, vol. 33, no. 7, pp. 1393 – 1399, 1997. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0005109897000551

[16] Z.-P. Jiang, E. Lefeber, and H. Nijmeijer, "Saturated stabilization and tracking of a nonholonomic mobile robot," *Systems & Control Letters*, vol. 42, no. 5, pp. 327 – 332, 2001. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0167691100001043

[17] D. Chwa, "Tracking Control of Differential-Drive Wheeled Mobile Robots Using a Backstepping-Like Feedback Linearization," *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans*, vol. 40, no. 6, pp. 1285 –1295, nov. 2010.

[18] D. W. Hodo, J. Y. Hung, D. M. Bevly, and S. Millhouse, "Effects of sensor placement and errors on path following control of a mobile robot-trailer system," in *2007 American Control Conference (ACC'07)*. IEEE, 2007, pp. 2165–2170.

[19] D. W. Hodo, J. Y. Hung, D. M. Bevly, and D. S. Millhouse, "Analysis of Trailer Position Error in an Autonomous Robot-Trailer System With Sensor Noise," in *IEEE International Symposium on Industrial Electronics (ISIE 2007)*. IEEE, 2007, pp. 2107–2112.

[20] W. L. Brogan, *Modern Control Theory*. Prentice Hall, 1991. [Online]. Available: http://books.google.com/books?id=OPFQAAAAMAAJ

[21] K. Astrom and B. Wittenmark, *Adaptive control*. Addison-Wesley Longman Publishing Co., Inc., 1994.

[22] F. Lamiraux, S. Sekhavat, and J. Laumond, "Motion planning and control for Hilare pulling a trailer," *IEEE Transactions on Robotics and Automation*, vol. 15, no. 4, pp. 640–652, 1999.

[23] H. Nguyen, "Segway robotic mobility platform," DTIC Document, Tech. Rep., 2004.

[24] S. Kennedy, J. Hamilton, and H. Martell, "Architecture and system performance of SPAN - NovAtel's GPS/INS solution," *Proceedings of IEEE/ION PLANS 2006*, pp. 23–25, 2006.

[25] J. Weston and D. Titterton, "Modern inertial navigation technology and its application," *Electronics Communication Engineering Journal*, vol. 12, no. 2, pp. 49 –64, Apr. 2000.

[26] D. Bevly, J. Gerdes, C. Wilson, and G. Zhang, "The use of GPS based velocity measurements for improved vehicle state estimation," in *Proceedings of the 2000 American Control Conference*, vol. 4, 2000, pp. 2538 –2542 vol.4.