Development of Vision Based Steering System for Unmanned Vehicle Using Robust Control

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Abstract: In this paper, the automatic steering system for unmanned vehicle was developed. The vision system is used for the lane detection system. This paper defines two modes for detecting lanes on a road. First is searching mode and the other is recognition mode. We use inverse perspective transform and a linear approximation filter for accurate lane detections. The PD control theory is used for the design of the controller to compare with H_∞ control theory. The H_∞ control theory is used for the design of the controller to reduce the disturbance. The performance of the PD controller and H_∞ controller is compared in simulations and tests. The PD controller is easy to tune in the test site. The H_∞ controller is robust for the disturbances in the test results.

Keywords: lane detection, preprocessing, unmanned vehicle, inverse perspective, steering control,, H_∞ control

1. INTRODUCTION

For the actual autonomous driving on the road, both Lateral and Longitudinal Control are necessary. Longitudinal Control is to keep the distance between two vehicles appropriately. All of the autonomous cruising, regulation of distance between two vehicles, and prevention of accidents are possible by controlling the acceleration of the vehicles.

There have been done the studies on longitudinal control of the vehicles using PID, feedback-linearizing, adaptive, or fuzzy-sliding mode methods. Lateral control method is to steer automatically to drive the vehicles along the lanes and make riders feel comfortable. It is necessary to keep or change from the lane where the vehicles are located. The system controls the direction of the vehicle using the measured displacements between the vehicle and the reference lane.

The dynamic equations of Lateral Control theory contain mass of the vehicle, inertial moments, forward velocities, stiffness of the tires, and friction between tires and roads, the parameters that is variable in the actual case. As a result, these factors are supposed to be uncertainties of the systems. Therefore robust control method is needed to compensate the uncertainties. There are two types of systems to measure the information needed for the guidance, Look-ahead and Look-down system. Look-ahead system, for instance vision system, is placed in front part of the vehicles to measure the displacement between the reference and the vehicle. It shows similar patterns to those of human's.

This paper is for autonomous steering vehicle systems. In this paper, the studies to select the suitable guidance lane and sensor system have been done. The controllers designed in this study have been estimated their performance in experiments. In the experiments a generic vehicle has been used because there is no special vehicles for UCT(Unmanned Container Transporter).

In chapter II, dynamic equations and simple modeling of the vehicle have been derived, assuming that the vehicle is a mass and spring system. In chapter III, Both H_∞ and PID controller have been designed and simulated. In chapter IV, theories and algorithms used for vision system has been stated. The examinations of steering-control systems and their results have been represented in chapter V. Finally in chapter VI, the conclusions based on all the results of experiments have been noted and the directions of newly suggested research.

2. MODELING OF THE VEHICLE

6 D.O.F. nonlinear dynamic equations of the vehicle are so complicated that it is not proper for the controller needed in this paper. Thus linearized simple model that contains lateral movement and yawing has been used to design the controller.

A simple dynamic equation of vehicle is obtained with several simplifications. To simplify the vehicle model, ignore the vertical movements, rolling, and pitching because

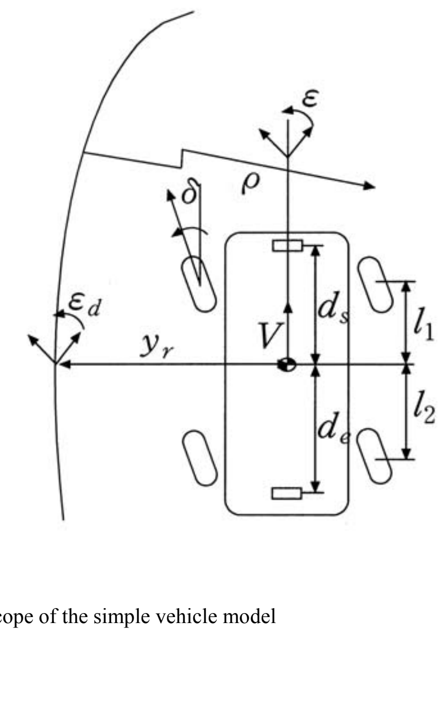

Fig.1. Scope of the simple vehicle model

the control of steering is merely influenced by them. And assume the small yaw angle and constant longitudinal velocity to linearize the system. 4 state variables are needed to express the lateral and yawing movements each two variables. Fig.1 shows the simple vehicle model.

Simplifications including assumption of small lateral displacement (y_r), yaw angle ($\varepsilon - \varepsilon_d$), and yaw rate ($\dot{\varepsilon}$) yield the following state space equation.

$$\frac{d}{dt}\begin{bmatrix} y_r \\ \dot{y}_r \\ \varepsilon - \varepsilon_d \\ \dot{\varepsilon} - \dot{\varepsilon}_d \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & \frac{A_1}{V} & -A_1 & \frac{A_2}{V} \\ 0 & 0 & 0 & 1 \\ 0 & \frac{A_3}{V} & -A_3 & \frac{A_4}{V} \end{bmatrix}\begin{bmatrix} y_r \\ \dot{y}_r \\ \varepsilon - \varepsilon_d \\ \dot{\varepsilon} - \dot{\varepsilon}_d \end{bmatrix} + \begin{bmatrix} 0 \\ B_1 \\ 0 \\ B_2 \end{bmatrix}\delta + \begin{bmatrix} 0 \\ A_2 - V^2 \\ 0 \\ A_4 \end{bmatrix}\frac{1}{\rho} \quad (1)$$

, where

$$A_1 = \frac{-2(C_{sf} + C_{sr})}{m}, \quad A_2 = \frac{2(C_{sr} l_2 + C_{sf} l_1)}{m},$$

$$A_3 = \frac{2(C_{sr} l_2 + C_{sf} l_1)}{I_z}, \quad A_4 = \frac{-2(C_{sf} l_1^2 + C_{sr} l_2^2)}{I_z},$$

$$B_1 = \frac{2C_{sf}}{m}, \quad B_2 = \frac{2 l_1 C_{sf}}{I_z},$$

$$d_1 = \frac{F_{wy}}{m} - \frac{V^2}{\rho} + \frac{A_2}{V}\dot{\varepsilon}_d = \frac{A_2 - V^2}{\rho},$$

$$d_2 = \frac{A_4}{V}\dot{\varepsilon}_d - \ddot{\varepsilon}_d = \frac{A_4}{\rho}$$

When the sensor is displaced as much as d_s from the center of the mass in the vehicle, the output of the sensor is expressed by

$$y_s(t) = y_r + d_s(\varepsilon - \varepsilon_d) = [1 \quad 0 \quad d_s \quad 0]\underline{x}(t) \quad (2)$$

3. DESIGN AND SIMULATIONS OF THE STEERING CONTROL SYSTEM

3.1 Design of PD controller

In this section the PD controller that is very common in the industrial fields is designed using the dynamic equations of the vehicle deprived in chapter II. If the reference input is set to zero, the error has to be decreased to zero in order to control the vehicle to track the guidance lane well. Design specification is to make steady state error under 0.1, overshoot under 10%, and settling time within 2 seconds. PD controller is prone to raise the noise in high frequency. But maximum overshoot is decreased by proper damping ratio. PD controller is one of the most common methods of control in the industrial fields. Moreover during the experiments it offers the easy way to coordinate the gain values.

3.2 Design of H∞ controller

Deprive a state equation and two output equations from (1) to construct the generalized plant to design H∞ controller.

$$\begin{aligned} \dot{x} &= Ax + B_1 w + B_2 u \\ z &= C_1 x + D_{12} u \\ y &= C_2 x + D_{21} w \end{aligned} \quad (3)$$

Letting w_y a disturbance of y_r, w_ε a disturbance of y_ε, w_{sy} a disturbance of the sensor to y_r, and $w_{s\varepsilon}$ a disturbance of the sensor to y_ε yield the following system equations.

$$\frac{d}{dt}\begin{bmatrix} y_r \\ \dot{y}_r \\ \varepsilon - \varepsilon_d \\ \dot{\varepsilon} - \dot{\varepsilon}_d \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & \frac{A_1}{V} & -A_1 & \frac{A_2}{V} \\ 0 & 0 & 0 & 1 \\ 0 & \frac{A_3}{V} & -A_3 & \frac{A_4}{V} \end{bmatrix}\begin{bmatrix} y_r \\ \dot{y}_r \\ \varepsilon - \varepsilon_d \\ \dot{\varepsilon} - \dot{\varepsilon}_d \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ A_2 - V^2 & b_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ A_4 & 0 & b_{12} & 0 & 0 \end{bmatrix}\begin{bmatrix} \frac{1}{\rho} \\ w_y \\ w_\varepsilon \\ w_{sy} \\ w_{s\varepsilon} \end{bmatrix} + \begin{bmatrix} 0 \\ B_1 \\ 0 \\ B_2 \end{bmatrix}\delta \quad (4)$$

$$z = \begin{bmatrix} c_{11} & 0 & 0 & 0 \\ 0 & c_{22} & 0 & 0 \\ 0 & 0 & c_{33} & 0 \\ 0 & 0 & 0 & c_{44} \\ 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} y_r \\ \dot{y}_r \\ \varepsilon - \varepsilon_d \\ \dot{\varepsilon} - \dot{\varepsilon}_d \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ d_{12} \end{bmatrix}\delta \quad (5)$$

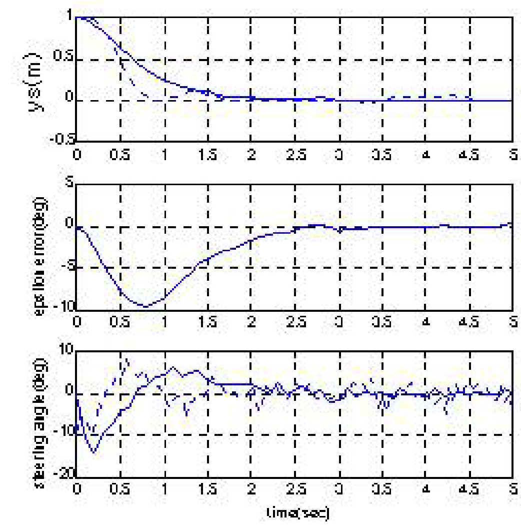

Fig.2. Simulation results(5m/s, 1m offset)

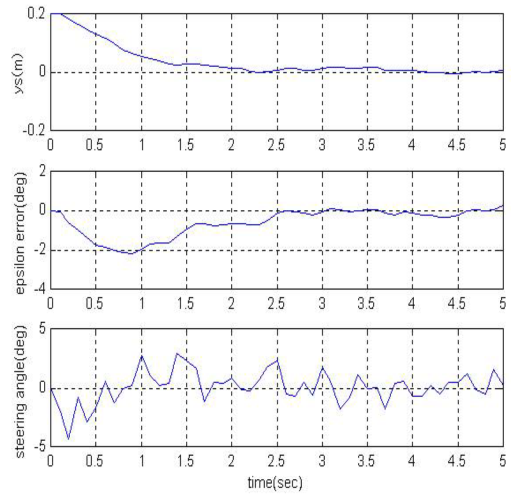

Fig.4. Simulation results (4m/s, 0.2m offset)

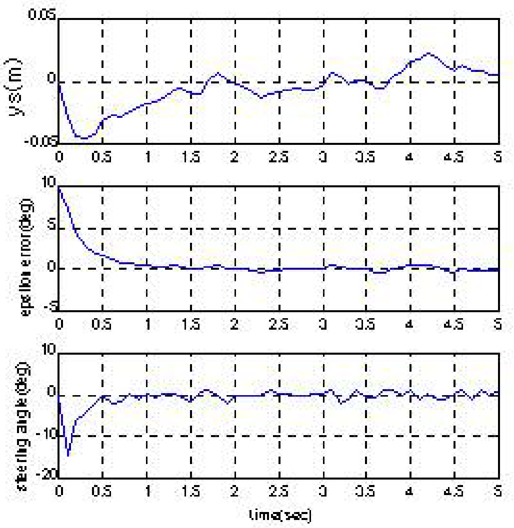

Fig.3. Simulation results(5m/s, 10° offset)

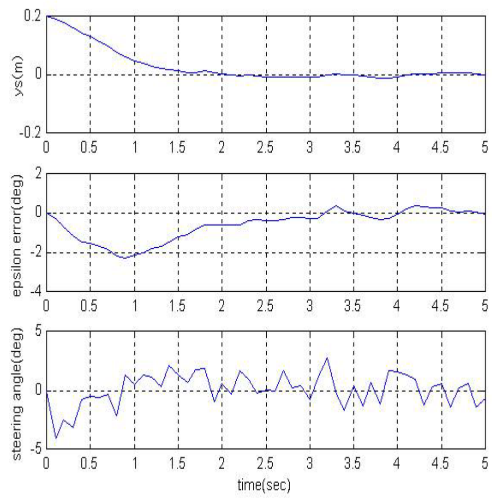

Fig.5. Simulation results(4m/s, 0.2m offset, 80kg)

$$y=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 0 & d_s & 0\end{bmatrix}\begin{bmatrix}y_r\\ \dot{y}_r\\ \varepsilon-\varepsilon_d\\ \dot{\varepsilon}-\dot{\varepsilon}_d\end{bmatrix}+\begin{bmatrix}0 & 0 & 0 & d_{21} & 0\\ 0 & 0 & 0 & 0 & d_{22}\end{bmatrix}\begin{bmatrix}\frac{1}{\rho}\\ w_y\\ w_\varepsilon\\ w_{sy}\\ w_{s\varepsilon}\end{bmatrix} \quad (6)$$

3.3 Results of the simulations

Fig.2 shows the result of the simulation in which H_∞ controller(a dotted line) and PD controller(a solid line) have been used with 1*m* offset and 5 ㎧ velocity to experiment the performance of the vehicle. PD controller has smaller settling time and H_∞ is more robust to the disturbances. In the case of H_∞, the error is almost zero after 2.5 seconds pass away. But in the case of using PD controller, the steady state error is occurred. As a result the vehicle shows a good tracking performance in the simulation. Fig.3 shows that the experiment made with 10° offset and 5 ㎧ velocity. The error satisfies the design specification as ±0.02*m*. The error is converged to zero within 1.5 seconds. The simulation shown in Fig.3 is made with 4 ㎧ velocity, 0.2*m* offset, and fixed γ determined by the former experiment with 5 ㎧ velocity. They are the same conditions to those of the actual experiment. Comparing to Fig.4, the maximum displacement of yaw angle is about -10° in Fig.2 and that of Fig.4's in the condition of smaller velocity and offset is about -2°. Fig.5 shows the simulation with additional mass of 80 ㎏. It is also the same condition to that of the actual experiment. There is no difference from the former case, that is, the controller is very robust to the mass variations as discussed before.

4. THEORIES FOR LANE DETECTION

4.1 Road model

Road model provides the method to estimate the border of the road and the edge of the lane. To set the road model, following assumptions are needed.

1) All the environments of the roads are predictable.
2) The lanes and borders of the roads are continuous.
3) The border of the road are continuous both in time and in space. Broken border represents the abnormal situations such as crossroad.
4) Curvature of the curved road is also continuous in time.
5) The lanes on both sides of the roads are parallel in the world coordinate system.
6) All the roads are on a same plane.

4.2 Preprocessing and lane recognition algorithm

The Sobel operator is used to determine the edge of the lane. Generally a differential operator makes even the noise outstand. But the Sobel operator makes the differences of the brightness of the image clear by itself and has the effects to make them smooth. To improve the quality, histogram distribution is applied to the input image. The ultimate object of that is to create the uniformly distributed histogram. As a result, the image maintains the proper brightness. Thus it is very effective when the image has the detailed part in the dark range. Modifying the distributions of the brightness of the images improves the total contrast balance.

Fig. 6 shows the overview of the proposed lane recognition algorithm.

Implementation of the vision system through full range is inefficient for real time processing. Thus defining a part of the image as the searching range is recommended for decreasing computations. From now on, the defined region is represented ROI(Region of Interest). This paper defines the two for detecting lanes on a road. The first is searching mode that is searching the lane without any prior information of a road. The second is recognition mode, which is able to reduce the size and change the position of a searching range by predicting the position of a lane, though the acquired information in a previous frame. If the system could not recognize the current lane, former information replaces the current. And the system is changed to the searching mode and finds the edge again. When the curvature of the road is very large, lane on one side can be out of the view. In this case, the lane that is out of the view is predicted using the other lane and the width of the load obtained by the former frame.

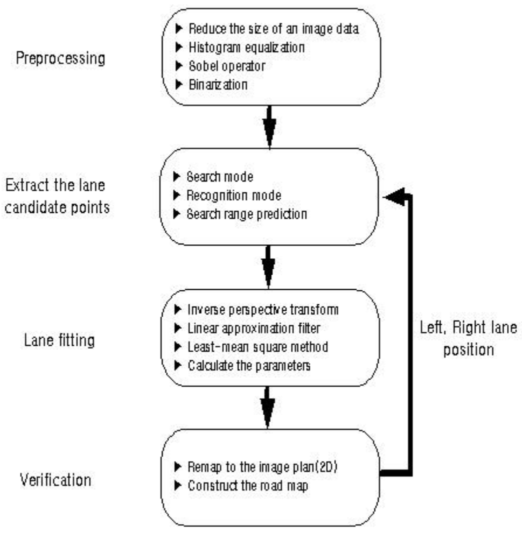

Fig.6. Overview of the proposed lane recognition algorithm

4.3 Inverse perspective transform, linear approximation filter, and curve approximation

A perspective input image must be transformed to a non-perspective world coordinate image.

Equations for inverse perspective transform is

$$X = \frac{A(-x\cos\theta\sin\alpha + f\sin\alpha) - B\cos\theta(-y\sin\alpha + f\cos\alpha)}{f(y\sin\alpha - f\cos\alpha)} \quad (7)$$

$$Y = \frac{B\sin\theta(y\sin\alpha - f\cos\alpha) - A(x\sin\theta\sin\alpha + f\cos\theta)}{f(y\sin\alpha - f\cos\alpha)} \quad (8)$$

, where

$$A = yZ_0\cos\alpha + yf + fZ_0\sin\alpha$$
$$B = xZ_0\cos\alpha + xf \quad (9)$$

Since there is no information about prior frame in an initial searching mode, the initial frame is prone to a noise such as shadows and back lights. Though noises are reduced by setting up an ROI and predicting in a recognition mode, the process contains incorrect edges caused by bad road conditions, lane-blocking. These ununiform edges occur large errors during estimating lane. To remove these factors linear approximation filter is used in this paper.

Curve approximation is to determine the minimum order polynomials that approximate the points with flexibility. Least square method is very simple and rapid way to approximate the points. The lane and borders of the road are approximated to quadratic polynomials with noise-removed edges based on the road model stated in previous sections. In (10) an equation of circle is obtained to quadratic equation and it is approximated using least square method.

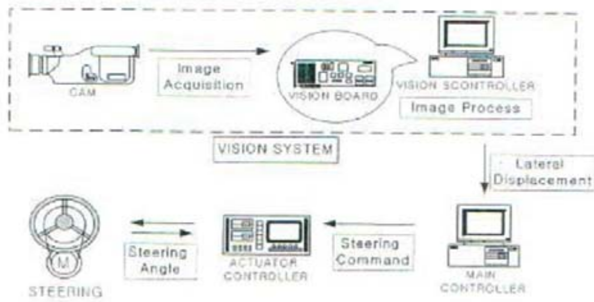

Fig.7. Schematic of total system

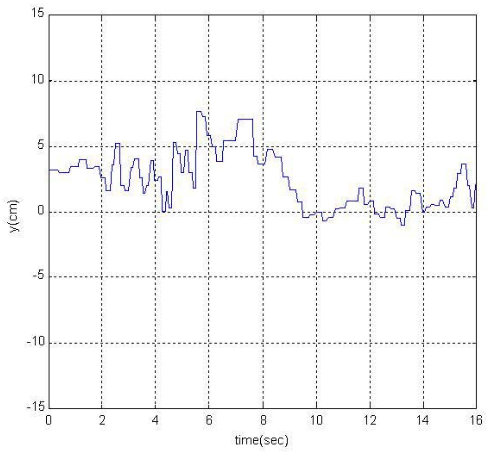

Fig.8.Test result (PD, 4m/s, straight course)

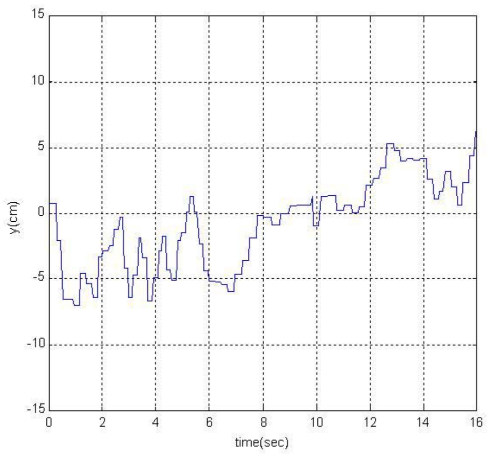

Fig.9. Test result (PD, 4m/s, curved course)

$$X = a_1 + a_2 Y + a_3 Y^2 \tag{10}$$

5. EXPERIMENTS ON THE STEERING CONTROL SYSTEM

5.1 Configurations of the experiment vehicle

Fig. 7 shows the configuration of the vehicle for experiments. The steering actuator made by Baekdu Electronics co. is connected to the steering wheel with 1:1 rotational ratio using belt and pulley. The actuator is a geared D.C. motor with 64:1 gear ratio.

The main computer (Pentium-III 900㎒ industrial) and another computer for process of the image information (Pentium-III 1.7㎓ personal) are installed in the trunk.

The control software has been programmed using C++ language.

The CCD camera has been installed behind the windshield to win the image information.

The power supplier is an additional battery of 12V 160AH installed in the vehicle. The battery provides the power of 220V to the control system through the converter of 1 ㎾.

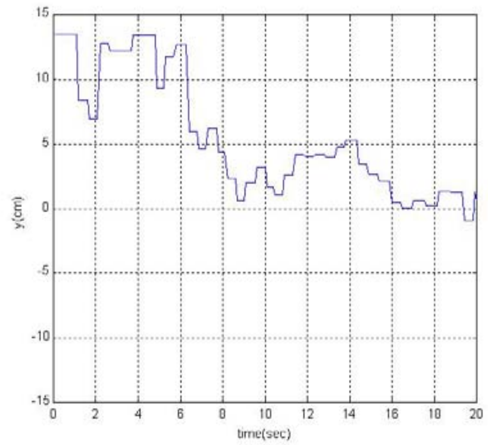

Fig.10. Test result (H_∞, 13cm offset, 4m/s, straight course)

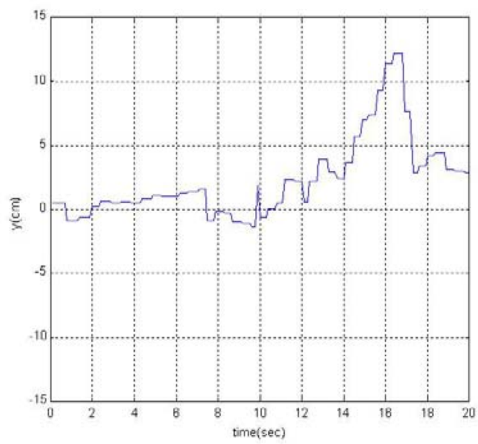

Fig.11. Test result (H_∞, 4m/s, curved course with 80kg)

5.2 Results of the experiments

Fig.8 is a result of the experiment using PD controller. Since the system ran recklessly with the gains determined in simulations when the error is slightly large, the gains must have been corrected with the result of the former experiment. The vehicle seems to vibrate because of the noise occurring in itself. But vibration of 3～5cm is too small for riders to feel because the size of vehicle is much larger than the range of the vibration. The sensor seems to have the same vibration caused by outer noise.

Fig.9 is a result of the experiment using PD controller in curved way. At the beginning, the vehicle tracked well the guidance lanes. After 12sec, it was prone to run off the lane as error increased. Most of the controllers have been diverged in the experiment using $H\infty$ controller designed in simulations. In these cases, the experiments have been made again with the modified controllers determined in the way stated in previous sections.

Fig.10 shows the result of the experiment with 4㎧ speed and 13cm lateral offset in straight way. The vehicle is converged to the guidance lanes.

The result shown in Fig.11 is made by the experiment with 4㎧ speed and 80㎏ additional mass in the way of straight or curved. As shown in this experiment an additional mass of one human's has no effects to the vehicle of large mass.

6. CONCLUSIONS

In this paper steering system for unmanned vehicle has been developed and tested using vision sensor and $H\infty$ controller.

First, $H\infty$ controller has been designed to guarantee the robustness to the modeling errors, noises and disturbances such as mass, velocity, cornering stiffness, and frictions. And it has been compared with PID controller with simulations.

Second, the Vision system has been developed to recognize the lane that does not need any infrastructures and is able to increase the preciseness using various methods. And the inverse perspective transform has been used to improve the performances of the vision system in noisy road images. Setting up the searching range decreased the amount of the computation and prevented noises from unnecessary ranges. It also saved the processing time. When the strength of the outlines on one side was different from the other, threshold values was renewed by prior information independently to improve the adaptive ability. The mean filter has been used for robustness on the noise and light variations. The Hough transform algorithm through the prior information also has been used to prevent the situation that the system keeps extracting the incorrect lane information when the partial strong noise caused by defect of the road exists.

Third, the developed system has been tested on the road made for experiments. $H\infty$ controller has been shown the robust performance on modeling errors and disturbances such as noise.

The unsolved problems appeared from the experiments are stated in following.

Recognition of the lane and determination of the directions in a crossover, a road crossing, and a branch road have to be developed. They are able to be solved using a method to predict the path to the destination achieved by GPS.

And the curvature of the lane supposed to disturbances has to be measured and used to control the steering system through the vision sensor or another sensor. A displacement angle between the lane and the vehicle can be used for the control system. Using the displacement angel measured by vision sensor has been tried in the experiments but the measured values contained too much vibrations and incorrectness to apply. Thus other sensors such as gyroscope are recommended.

For the complete ITS, the vision computer for the process of the image information has been used to share the computational load. And additional interface card was needed.

Considering the commercial production, the vision computer has to be combined to the main computer and all the sensors have to be modularized to save the costs and be convenient easy to install.

Finally since the single sensor is not able to guarantee the reliableness and stability, additional sensors such as MR and MPC sensors, GPS, and gyroscopes are necessary.

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