

The Design of a Control Coupled Observer for the Longitudinal Control of Autonomous Vehicles

Seibum Ben Choi¹

This paper presents a distance observer that was developed for the longitudinal control of autonomous vehicles. The observer is implemented on a platoon of test vehicles as part of the California PATH research program. The experimental results show that the observer filters out the sensing error very effectively without any noticeable phase lag.

1 Introduction

Is it a dream to drive a car on a congestion-free and accident-free highway? There have been extended studies about Intelligent Transportation Systems (ITS) for decades as a way to realize this dream, and the California Partners for Advanced Transit and Highways (California PATH) has been developing Advanced Vehicle Control Systems (AVCS) required for ITS (Choi and Hedrick, 1995; Hedrick et al., 1991; Sheikholeslam and Desoer, 1991). AVCS ranges from Autonomous Intelligent Cruise Control (AICC) to the fully automated vehicle control system.

There already exist a few product AICC systems. However, the bandwidth of such systems is very low and the headway (the safe vehicle-to-vehicle distance to avoid collisions) is large (around 100 meters) (Fujita et al., 1995; Hashimoto et al., 1995). Therefore, these systems are almost useless on the busy urban traffic highway, and it is concluded that the bandwidth of the longitudinal vehicle control system should be increased significantly to increase the safety and reduce the headway. The major problem in increasing the bandwidth of the system is that the ride quality is deteriorating proportionally to the bandwidth.

For the purpose of the longitudinal control, the vehicle can be modeled as a lumped mass and, in that case, the remaining control issues to be considered are the sensing and the actuation (engine and brake control). There has been a lot of research conducted on the control of the engine and the brake torque with some optimistic results (Choi and Hedrick, 1995; Choi and Devlin, 1995). In addition to good actuation, good sensing of the states is the key to the success of the longitudinal control with both good ride quality and minimum spacing error.

This paper presents a range and range rate observer developed for the short distance platooning of the autonomous vehicles.

2 Speed Control Law

If a vehicle is assumed to be a lumped mass, and the dynamics of the drive train and the slip of the tires are neglected, the longitudinal control system can be normalized as:

$$\ddot{x} = u \quad (1)$$

where x is the position of the vehicle and u is the synthetic input. If the profiles of the position, the velocity, and the acceleration are defined as $x_d(t)$, $\dot{x}_d(t)$, and $\ddot{x}_d(t)$, then the goal is developing a stable and robust control law such that $x(t)$ is guaranteed to converge to $x_d(t)$. Define the tracking error as:

$$\epsilon = x - x_d \quad (2)$$

If the error satisfies:

$$\ddot{\epsilon} + 2\zeta\omega_n\dot{\epsilon} + \omega_n^2\epsilon = 0, \quad \zeta > 0, \omega_n > 0 \quad (3)$$

then the error converges to 0 asymptotically. Combining Eqs. (1), (2), and (3), the control law can be obtained as:

$$u = \ddot{x}_d - 2\zeta\omega_n\dot{\epsilon} - \omega_n^2\epsilon \quad (4)$$

The controls of the engine and the brake, to get the torque equivalent to the normalized control input given in Eq. (4), are mentioned in Choi and Devlin (1995).

3 Control Coupled Observer

The adaptive observer shown in Choi and Hedrick (1995) works well as long as the error on e_{meas} is limited only to the steady state off-set. However, another error on e_{meas} has been observed, which is too fast to be considered as an off-set, and yet is too slow to filter out. That is the error due to the variation of the effective radius of the tires matching with the suspension mode.

Define e_{meas} with measurement errors as:

$$e_{\text{meas}} = \epsilon + d_{e,ss} + d_{e,tr} \quad (5)$$

where $d_{e,tr}$ is the zero-mean transient error, and $d_{e,ss}$ is the steady-state off-set. It is necessary to get the exact value of the acceleration to estimate the velocity.

Therefore, a control coupled observer is suggested to estimate ϵ and $\dot{\epsilon}$, if the control law given in Eq. (4) is working properly, then the error ϵ will satisfy Eq. (3), and:

$$\ddot{\epsilon} = -2\zeta\omega_n\dot{\epsilon} - \omega_n^2\epsilon \quad (6)$$

Now, motivated by Eq. (6), define a synthetic relative acceleration a_s as:

$$a_s = -2\zeta\omega_n\dot{\epsilon} - \omega_n^2\epsilon \quad (7)$$

Using a_s and e_{meas} , define a synthetic relative velocity e' as:

$$e' = a_s + k'(e_{\text{meas}} - e'), \quad k' > 0 \quad (8)$$

and using e' , define a control coupled observer as:

$$\dot{\hat{\epsilon}} = e' + \hat{v}e_o + k(\epsilon_{\text{meas}} - \hat{\epsilon}), \quad k > 0 \quad (9)$$

$$\dot{e}_o = k_o \left[\frac{\dot{\epsilon}_{\text{meas}} - e'}{\hat{v}} - e_o \right], \quad k_o > 0 \quad (10)$$

where

$$\epsilon_{\text{meas}} = \epsilon + d_s \quad (11)$$

and d_s is assumed to be the zero-mean error of the distance measurement. Also using the observer output, define the control input as:

$$u = \ddot{x}_d - 2\zeta\omega_n\dot{\hat{\epsilon}} - \omega_n^2\hat{\epsilon} \quad (12)$$

The design of this observer depends on the selection of the synthetic acceleration a_s , and a_s on the control law. Therefore, this observer is coupled with the control law. Equations (9) and (11) can be written as:

$$\dot{\hat{\epsilon}} - \dot{\epsilon} = -k(\epsilon - \hat{\epsilon}) - \hat{v}e_o + (\dot{\hat{\epsilon}} - e') - kd_s \quad (13)$$

Combining Eqs. (1), (8), (11), and (12):

$$\ddot{\hat{\epsilon}} - \ddot{e}' = -k'(\dot{\hat{\epsilon}} - \dot{e}') - k'(d_{e,ss} + d_{e,tr}) \quad (14)$$

Equations (10), (13), and (14) can be written in a matrix form:

¹ Varsity Kelsey-Hayes, 12075 Tech Center Drive, Livonia, MI 48150.

Contributed by the Dynamic Systems and Control Division of THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS. Manuscript received by the Dynamic Systems and Control Division July 22, 1996. Associate Technical Editor: S. D. Fassois.

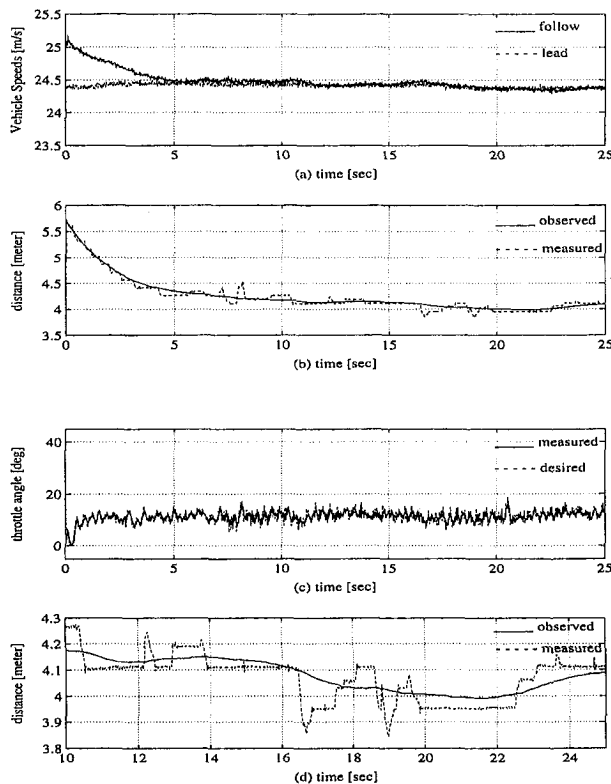


Fig. 1 Vehicle following test using a control coupled observer

$$\begin{bmatrix} \dot{\epsilon} - \dot{\hat{\epsilon}} \\ \dot{e}_o \\ \dot{\epsilon} - \dot{e}' \end{bmatrix} = \underbrace{\begin{bmatrix} -k & -\hat{v} & 1 \\ 0 & -k_o & k_o/\hat{v} \\ 0 & 0 & -k' \end{bmatrix}}_A \begin{bmatrix} \epsilon - \hat{\epsilon} \\ e_o \\ \epsilon - e' \end{bmatrix} + \begin{bmatrix} -kd_s \\ (k_o/\hat{v})\dot{d}_s \\ -k'(d_{e,ss} + d_{e,tr}) \end{bmatrix} \quad (15)$$

Since matrix A is Hurwitz, the observer is stable, and at the steady state, $\dot{\epsilon} - \dot{e}'$ converges to $d_{e,ss}$, therefore e_o to $d_{e,ss}/\hat{v}$ and finally $\hat{\epsilon}$ to ϵ . The transfer function from the transient error $d_{e,tr}$ to the observed distance is:

$$\frac{\hat{\epsilon}}{d_{e,tr}} = \frac{s^2}{(s^2 + 2\zeta\omega_n s + \omega_n^2)} \frac{sk'}{(s+k)(s+k_o)(s+k')} \quad (16)$$

while the characteristic function of the closed-loop system remains as:

$$s^2 + 2\zeta\omega_n s + \omega_n^2 = 0 \quad (17)$$

This observer can filter out the transient measurement error effectively, while keeping the closed-loop poles at the same location as in Eq. (3).

4 Experimental Work

4.1 Test Setup. The vehicle following tests were conducted using Lincoln Town Cars at various highway speeds. Each vehicle was equipped with a 33 MHz 80486 IBM-PC, a radar ranging system, a data communication system, and throttle and brake actuators.

4.2 Vehicle Following Test. This section describes the evaluation of the control coupled observer being implemented on the test vehicles.

Figure 1(a) shows the velocity of the leading and the following vehicle. Figure 1(b) shows the measured vehicle-to-vehicle

distance and the estimated distance by the control coupled observer described in Section 3. As the data shows, the observer filters out the noise very effectively. Therefore, as Fig. 1(c) shows, the throttle response of the following vehicle is quite smooth.

5 Conclusions

The distance observer for the longitudinal control of the autonomous vehicle has been developed. The vehicle following tests proved that the observer can reject the sensing error very effectively while minimizing the phase lag due to the filtering.

Due to the high performance filtering characteristics of the observer, the control law was able to choose the high feedback gains to minimize the space tracking error while keeping the throttle response, i.e., the ride quality, smooth enough.

References

- Choi, S. B., and Devlin, P., 1995, "Throttle and Brake Combined Control for Intelligent Vehicle Highway Systems," SAE 951897.
- Choi, S. B., and Hedrick, J. K., 1995, "Vehicle Longitudinal Control Using an Adaptive Observer for Automated Highway Systems," *Proceedings of American Control Conference*, Seattle, Washington.
- Fujita, Y., Akuzawa, K., and Sato, M., 1995, "Radar Brake System," *Proceedings of ITS America Annual Meeting*, Washington, D.C.
- Hashimoto, Y., Sasaki, K., and Kawai, M., 1995, "A Study of Brake Control for a Collision Avoidance System," *Proceedings of ITS America Annual Meeting*, Washington, D.C.
- Hedrick, J. K., McMahon, D. H., Narendran, V. K., and Swaroop, D., 1991, "Longitudinal Vehicle Controller Design for IVHS Systems," *Proceedings of American Control Conference*, pp. 3107-3112.
- Sheikholeslam, S., and Desoer, C. A., 1991, "A System Level Study of the Longitudinal Control of a Platoon of Vehicles," *ASME JOURNAL OF DYNAMIC SYSTEMS, MEASUREMENT, AND CONTROL*, Vol. 113.

Robust H_∞ State Feedback Control With Regional Pole Constraints: An Algebraic Riccati Equation Approach

Zidong Wang¹

This paper focuses on the controller design for uncertain linear continuous-time systems with H_∞ norm and circular pole constraints and addresses the following multiobjective simultaneous realization problem: designing a state feedback controller such that the closed-loop system, for all admissible parameter uncertainties, simultaneously satisfies the prespecified H_∞ norm constraint on the transfer function from disturbance input to output and the prespecified circular pole constraint on the closed-loop matrix. An effective, algebraic, modified Riccati equation approach is developed to solve this problem. The existence conditions, as well as the analytical expression of desired controllers, are derived. A numerical example is provided to show the directness and effectiveness of the present approach.

¹ Postdoctoral Research Fellow, Automatic Control Laboratory, Faculty of Electrical Engineering, Ruhr-University Bochum, D-44780 Bochum, Germany.

Contributed by the Dynamic Systems and Control Division of THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS. Manuscript received by the Dynamic Systems and Control Division January 2, 1997. Associate Technical Editor: E. A. Misawa.