

# Lateral Control of an Articulated Bus for Lane Guidance and Curbside Precision Docking

Fanping Bu, Han-Shue Tan, and Jihua Huang

**Abstract**—This paper presents the design, implementation, and field testing of a lane assist system that provides lane guidance and curbside precision docking functions for a 60 ft articulated bus. The challenges in this lateral control design include the extra lightly-damped mode from the articulated section, the relatively large disturbance due to the sharp S-curves for precision docking, and the uncertainties introduced by public roads and live traffic. To tackle these challenges, the control problem is formulated as a mixed  $H_2/H_\infty$  synthesis problem and solved by LMI optimization. Extensive field tests were conducted in live traffic and the results show adequate and consistent performances.

## I. INTRODUCTION

Compared with urban light rail systems, Bus Rapid Transit (BRT) systems can provide high quality, high capacity bus transit service on easily identifiable route structures with higher modification flexibility at a lower development and implementation cost. BRT services can be greatly improved with the addition of electronic guidance technologies. Buses equipped with lateral guidance systems can be operated at higher speeds on narrow lanes, facilitating greater rider satisfaction as well as cost effectiveness. Precision docking capability allows the bus to dock at the bus stations within an accuracy measured in centimeters, facilitating fast loading and unloading of passengers with special needs and thereby reducing waiting time and improving ease of access for all passengers.

Electronic guidance systems have been developed in multiple countries. Toyota has developed an Intelligent Multimode Transit System (IMTS) [1] which consists of automatically driven buses on exclusive tracks using magnetic sensing system. The IMTS system was demonstrated at the 2005 World Exposition in Nagoya, Japan with platooning, lane guidance and precision docking functions. In [2], a lane support system retrofitted on a Metro Transit bus was demonstrated to steer a 9.5 ft wide bus along a 10 ft wide “bus only shoulder” in the Minneapolis/St. Paul Metro Area with a mean error of 5.6 cm (2.2 in), a STD of 13 cm (5.1 in) and a maximum lateral error of 45 cm (17.7 in) at 35 mph. The CIVIS bus developed by IRISBUS and MATRA Transport International (subsequently taken over by Siemens) uses a

vision-based control/guidance system. The bus position is estimated by detecting stripes painted in the center of the lane. CIVIS buses were introduced to everyday operation in several cities such as Clermont-Ferrand and Rouen in France as well as Las Vegas, Nevada, primarily for precision docking rather than lane guidance. Most of the precision docking maneuvers were conducted along a relatively gentle curve. The major constraints of snow and ice preclude its application in northern parts of US and all of Canada [3]. Since 2003, the PATH research team has been working on the development of lane guidance and precision docking systems for transit buses. Several public demonstrations were held in Washington DC, San Diego, and San Francisco with transit buses to show the basic performance and feasibility for the lane guidance and precision docking technology.

This paper presents the design of a lane assist system that provides lane guidance and performs typical curbside precision docking for a 60 ft articulated bus, together with the results of extensive field testing in live traffic environment. The motivation of this research is three-folded. Firstly, most lane assist functions in the existing systems were developed for 40 ft single-unit buses; only limited lane assist functions were developed and demonstrated for a 60ft articulated bus, although the 60 ft articulated buses are widely used in public transit because of their greater capacity. Due to an extra degree-of-freedom (DOF) introduced by the trailer section, the development of lane assist functions, especially curbside precision docking, for a 60 ft articulated bus is more difficult. More specifically, the additional DOF introduces a lightly damped mode that will create oscillating responses if not handled properly. Secondly, most tests and demonstrations of the previously developed (lane guidance and precision docking) systems were conducted in controlled environments<sup>1</sup>. Compared with controlled demonstration environments, public streets, where BRT will operate, usually have large road crown angles (especially along the edge of the road), uneven road way with potholes, sewage and storm drain covers. Those road surface conditions can generate large disturbances from control point of view especially along an aggressive lane change trajectory (S-curve) just before the station stop. More importantly, live traffic on public streets, including pedestrians, bikers, and vehicles cutting into the test track

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<sup>1</sup> CIVIS buses do operate on public roads; however, they adopt vision-based sensing, which requires frequent repainting of the lane stripes. This research is to develop magnetic-sensing based lateral guidance and precision docking system (but only along relatively gentle docking curves). Similarly, the lane support system in [2] does not include precision docking function.

could interrupt the operation of the bus with a lane assist system. Therefore, a more sophisticated lane assist system, which can be quickly turned off or on at any stage of the operation, is required for bus operations using lane assist systems on public streets. Thirdly, most previous demonstrations were a several-day event, so the durability of such systems over long periods of time with heavy use is still unknown. Typically, only limited demonstration runs were conducted due to the necessary busy scheduling of such events.

Therefore, it is the purpose of this research to develop lane guidance and precision docking functions for a 60 ft articulated bus and to conduct extensive field testing in live traffic environment. The challenges unique to this lateral control design include the extra lightly-damped DOF from the articulated section, the relatively large disturbance due to the sharp S-curves for the curbside precision docking, and the uncertainties introduced by public roads and live traffic. To tackle these challenges, the control problem is formulated as a mixed  $H_2/H_\infty$  synthesis problem and solved by LMI optimization. Extensive field tests have been conducted in live traffic and the results show adequate and consistent performances.

This paper is organized as follows: Section II describe the system design and the dynamic model of an articulated bus, Section III presents the design of the lateral controller based on the mixed  $H_2/H_\infty$  approach, Section IV describes the field test track and Section V details the experimental results. Conclusions are provided in Section VI.

## II. SYSTEM DESIGN AND MODELING

### A. System Design

The bus lane assist system adopts magnetic sensing technology, in which magnetometers mounted on the bus measure the magnetic field strength of magnetic markers installed under roadway and the lane position is determined based on the measured magnetic field strength. A PC104 computer with a data acquisition unit is the “brain” of the system, which processes information and determines control and guidance actions. Lane positioning sensors include two set of magnetometer bars mounted under tractor unit. Vehicle speed is read from vehicle’s J1939 bus. A yaw rate gyro measuring vehicle rate is used as a supplemental sensor. An add-on DC motor on the steering column serves as the steering actuator. A Human Machine Interface (HMI) unit, consisting of local electronic circuits, a toggle switch, LED displays, and an audible device, provides the operator with essential information and commands for automation.

### B. Dynamic Model of Articulated Bus

With an additional degree-of-freedom (DOF) introduced by trailer section, the dynamics of a 60 ft articulated bus is different from that of a 40 ft single section bus. This is especially true when the articulated bus makes lane changes and docks at the station. Initial closed-loop testing using a lateral control designed for a 40 ft single-unit bus shows that the articulated section exhibits significant oscillations when

the bus enters or exits a lane change with relatively high speeds (e.g. higher than 15 mph). Therefore, the lateral dynamics of the articulated bus needs to be studied before a high performance robust lateral controller can be designed for the articulated bus.

The dynamic model of a 60 ft articulated bus can be developed based on Kane’s equation [4]. If we assume a small steering angle and a small articulation angle, the lateral dynamics of an articulated bus can be written as:

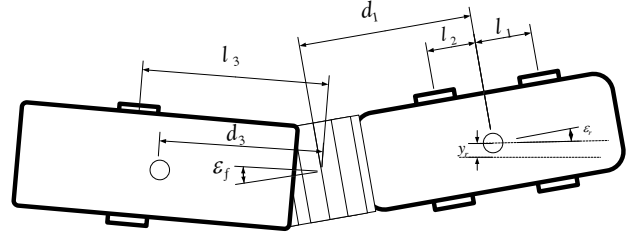


Fig. 1 Configuration of an articulated bus

$$M\ddot{q} + C\dot{q} + F = E_1\dot{\epsilon}_d + E_2\ddot{\epsilon}_d \quad (1)$$

where  $q = [y_r \ \epsilon_r \ \epsilon_f]^T$  and  $y_r$  represents the lateral displacement of the bus front section CG with respect to the lane center line,  $\epsilon_r$  is the yaw angle of bus front section with respect to the lane center line,  $\epsilon_f$  is the articulation angle shown in Fig. 1.  $\dot{\epsilon}_d = v\rho$  is the angular velocity of road reference frame, where  $v$  is vehicle longitudinal speed and  $\rho$  is the road curvature. The matrices are defined as follows with the assumption of small articulation angle.

$$M = \begin{bmatrix} m_1 + m_2 & -m_2(d_1 + d_3) & -m_2d_3 \\ -m_2(d_1 + d_3) & M_{22} & M_{23} \\ -m_2d_3 & M_{23} & I_{z2} + m_2d_3^2 \end{bmatrix}, \quad (2)$$

$$\text{with } \begin{cases} M_{22} = I_{z1} + I_{z2} + m_2(d_1 + d_3)^2 \\ M_{23} = I_{z2} + m_2d_3^2 + m_2d_1d_3 \end{cases}$$

$$C = \begin{bmatrix} 0 & (m_1 + m_2)v & 0 \\ 0 & -m_2(d_1 + d_3)v & 0 \\ 0 & -m_2d_3v & 0 \end{bmatrix} \quad (3)$$

$$F = H\dot{q} + Kq + G\delta \quad (4)$$

$$H = \frac{2}{v} \begin{bmatrix} H_{11} & H_{12} & -C_{at}l_3 \\ H_{12} & H_{22} & C_{at}(d_1 + l_3)l_3 \\ -C_{at}l_3 & C_{at}(d_1 + l_3)l_3 & C_{at}l_3^2 \end{bmatrix} \quad (5)$$

$$\text{with } \begin{cases} H_{11} = C_{af} + C_{ar} + C_{at} \\ H_{12} = C_{af}l_1 - C_{ar}l_2 - C_{at}(d_1 + l_3) \\ H_{22} = C_{af}l_1^2 + C_{ar}l_2^2 + C_{at}(d_1 + l_3)^2 \end{cases}$$

$$K = 2 \begin{bmatrix} 0 & 0 & -C_{at} \\ 0 & 0 & C_{at}(d_1 + l_3) \\ 0 & 0 & C_{at}l_3 \end{bmatrix} \quad (6)$$

$$G = -[C_{af} \ C_{af}l_1 \ 0]^T \quad (7)$$

$$E_1 = \begin{bmatrix} -(m_1 + m_2)v - \frac{2}{v}(C_{af}l_1 - C_{ar}l_2 + C_{at}(d_1 + l_3)) \\ m_2(d_1 + d_3)v - \frac{2}{v}H_{22} \\ m_2d_3v - \frac{2}{v}C_{at}l_3(d_1 + l_3) \end{bmatrix} \quad (8)$$

$$E_2 = \begin{bmatrix} m_2(d_1 + d_3) \\ -M_{22} \\ -M_{23} \end{bmatrix} \quad (9)$$

where  $\delta$  is front wheel steering angle.  $m_1$  and  $m_2$  represent the mass of the bus's front and rear (articulated) sections;  $I_{z1}$  and  $I_{z2}$  represent moment of inertia of the bus's front and rear sections, respectively.  $C_{\alpha f}$ ,  $C_{\alpha r}$  and  $C_{\alpha t}$  represent cornering stiffness of bus front tires, rear tires and trailer tires respectively. If we choose  $x = [y_r \ \varepsilon_r \ \varepsilon_f \ \dot{y}_r \ \dot{\varepsilon}_r \ \dot{\varepsilon}_f]^T$  as the state, steering angle  $\delta$  as the system control input, and  $d = [\dot{\varepsilon}_d \ \dot{\varepsilon}_d]^T$  as the disturbance, the lateral dynamics of the articulate bus can be written in the state space as:

$$\dot{x} = Ax + B\delta + Ed + n \quad (10)$$

Where

$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}(C + H) \end{bmatrix},$$

$$B = \begin{bmatrix} 0 \\ -M^{-1}G \end{bmatrix}, \quad E = \begin{bmatrix} 0 & 0 \\ M^{-1}E_1 & M^{-1}E_2 \end{bmatrix},$$

and  $n$  represents the disturbances that cannot be modeled exactly, which can be generated by conditions such as road crown angle, holes, and unevenness on the road surface.

### C. Frequency Responses

Figs. 2 to 4 show the frequency responses from the vehicle (front wheel) steering angle to vehicle lateral acceleration, front section yaw rate, and trailer section yaw rate at different longitudinal speeds. As vehicle longitudinal speed increases, resonant peaks appear at around 0.3Hz, especially for the trailer section yaw rate (Fig. 4). This explains the significant oscillations exhibited in the articulated section during our initial testing.

## III. LATERAL CONTROLLER DESIGN

The objective of the lateral controller is to keep the lateral error in front of the bus,  $y_h = y_r + \varepsilon_r d_4$  (where  $d_4$  is the look-ahead distance), small by using the front wheel steering angle  $\delta$  as the control input. There are several difficulties inherent in the design of this controller. First, the lightly-damped mode introduced by the bus's articulated section tends to cause oscillations when the bus enters and exits a lane change maneuver with relatively high speeds (e.g. higher than 15 mph). Secondly, the system is subject to large external disturbances ( $d = [\dot{\varepsilon}_d \ \dot{\varepsilon}_d]^T$  with  $\dot{\varepsilon}_d = v\rho$ ) during a docking maneuver due to the relatively sharp curves (or short lane changes) for entering and exiting the stations. Third, the controller needs to be robust to multiple uncertainties, such as changes in road surface conditions (including road crown angle, potholes, etc) and external load changes from passenger loading and unloading.

Various control techniques can be employed to design the feedback controller; we choose the mixed  $H_2/H_\infty$  synthesis for both performance and robustness. The generalized  $H_2$  norm facilitates the incorporation of performance requirements such as disturbance rejection, which is important especially for bus docking operations. Moreover, since the generalized  $H_2$  norm represents the system gain from  $L_2$  to  $L_\infty$ , its value can be interpreted as the worst time-

domain amplification of the disturbance input with finite energy. In addition, the  $H_\infty$  criterion provides a natural expression for the system robustness [4].

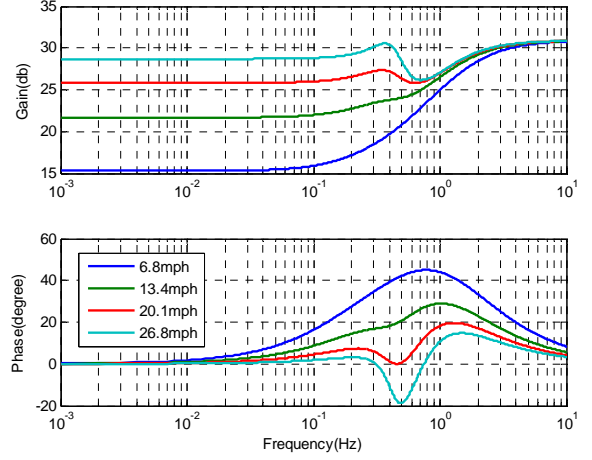


Fig. 2 Frequency response from front wheel steering angle to lateral acceleration

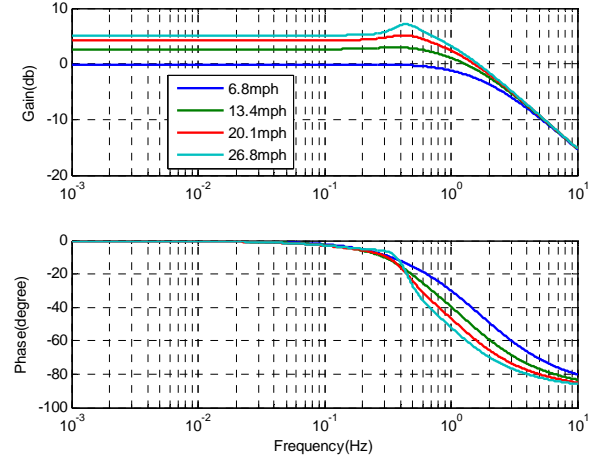


Fig. 3 Frequency response from front wheel steering angle to front section yaw rate

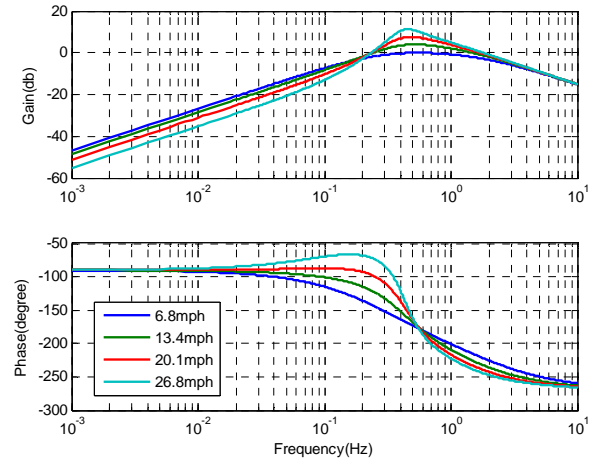


Fig. 4 Frequency Response from steering angle to trailer section yaw rate

The mixed  $H_2/H_\infty$  synthesis can be formulated as shown in Fig. 5, where  $G(s)$  represents the open-loop lateral dynamics of the articulated bus and  $K(s)$  represents the controller to be synthesized.  $\rho$  is the road curvature and  $n$  is the lump uncertainties in (10).  $W_\rho$ ,  $W_n$ ,  $W_\delta$  and  $W_{y_h}$  are the weighting functions used in the control design.

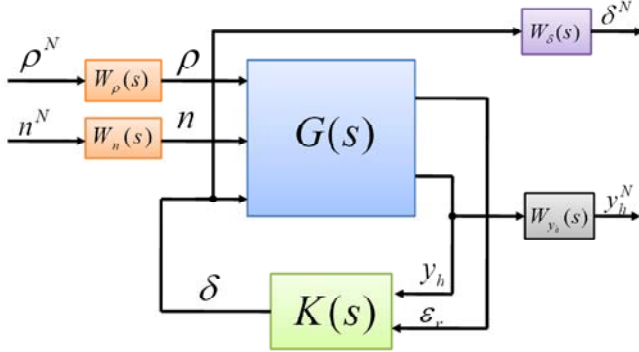


Fig. 5 Controller design configuration

For description purpose, let's denote:

$$\begin{cases} y_h^N = T_1(s)(\rho^N, n^N)^T \\ \delta^N = T_2(s)(\rho^N, n^N)^T \end{cases}, \quad (11)$$

where  $T_1$  and  $T_2$  are the transfer functions from the disturbance to the weighted lateral deviation  $y_h^N$  at a look ahead distance  $d_4$  and to the weighted front wheel steering angle  $\delta^N$ , respectively. As mentioned earlier, minimizing the  $H_2$  norm of  $T_1$  imposes the performance requirement of disturbance rejection, while minimizing  $H_\infty$  norm of  $T_2$  increases the system robustness against unstructured additive uncertainties. Hence,  $T_1$  and  $T_2$  represent two channels with different roles in the above control design.

In the traditional  $H_2$  or  $H_\infty$  design, those two channels are usually combined together with different weighting functions and optimization is performed on either  $H_2$  or  $H_\infty$  norm. An LMI-based multi-objective strategy, however, can treat each channel separately with different norm criteria. Such a design technique provides more design flexibility compared with the traditional design and is therefore adopted for the design of the lateral controller.

Accordingly, the control objective is to minimize  $\|T_1\|_2$  subjected to  $\|T_2\|_\infty$ , which can be interpreted as maximizing system disturbance rejection performance with guaranteed system robustness against unstructured additive uncertainties. This sort of mixed  $H_2/H_\infty$  synthesis problem can be solved via LMI optimization [5]. In practice, bus lateral dynamics can be regarded as a linear parameter-varying system with respect to the vehicle longitudinal speed  $v$ . Due to the large mass and the requirements for passenger comfort, the longitudinal acceleration during operation is generally small. A practical approach for the synthesis is to design the controller at several speed grid points and use interpolation for implementation. Fig. 6 and Fig. 7 show the final lateral controller<sup>2</sup> at two different speeds:

<sup>2</sup> Dynamics of the steering actuator has been combined with the dynamics of the articulated bus in the mixed  $H_2/H_\infty$  synthesis for the controller design.

$$\delta = K(s)[y_h \quad \varepsilon_r]^T = K_1(s)y_h + K_2(s)\varepsilon_r, \quad (12)$$

where  $y_h$  ( $y_h = y_r + \varepsilon_r d_4$ ) is the lateral error in front of the bus and  $\varepsilon_r$  is the yaw angle of bus front section with respect to the lane center line, as mentioned before.

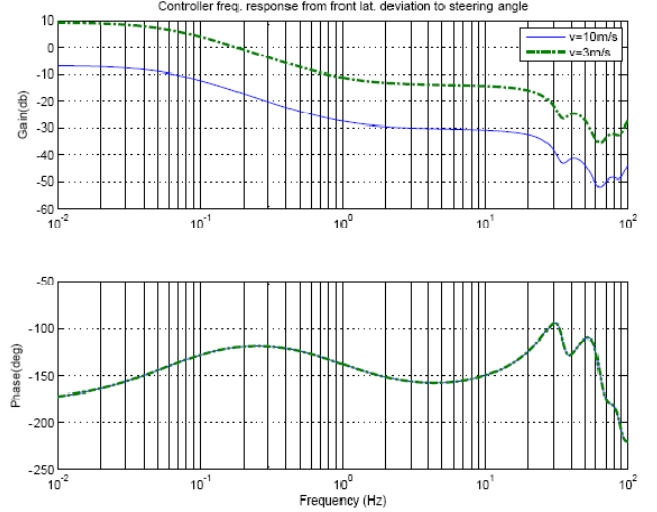


Fig. 6 The lateral controller  $K_1(s)$

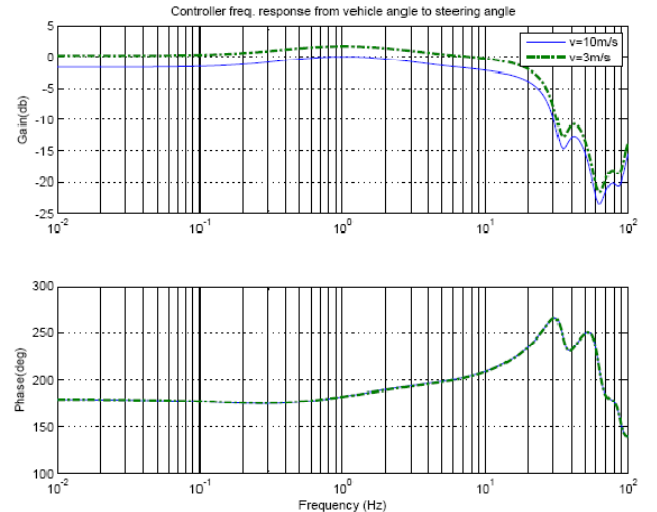


Fig. 7 The lateral controller  $K_2(s)$

#### IV. FIELD TEST TRACK

Southbound East.14<sup>th</sup> Street in San Leandro, California, was selected as the field testing site. The total length of this route is about 0.9 mile. There are three bus stops along the test route; each of them requires the bus to make a full lane change before stopping at the platform due to street parking. Fig. 8 shows the map of the test route.

In order to install magnets, a detailed test track was designed for the surveyor and track layouts were then finalized with iteration between the surveyor and researchers. For example, the track parameters for the second station are as follows:

- S-curve-in: 24 m long (lane change at  $\sim 1.3$  times bus length) with about 2.91 m lateral offset (from  $(s - 57.4)$  m to  $(s - 33.4)$  m, where  $s$  is the bus sign location)

- Straight docking line: 25 m long and 1.36 m to the curb (from (s – 33.4) m to (s – 8.4) m)
- S-curve-out: 24m long with about 3.18 m lateral offset (from (s – 8.4) m to (s + 15.6) m)

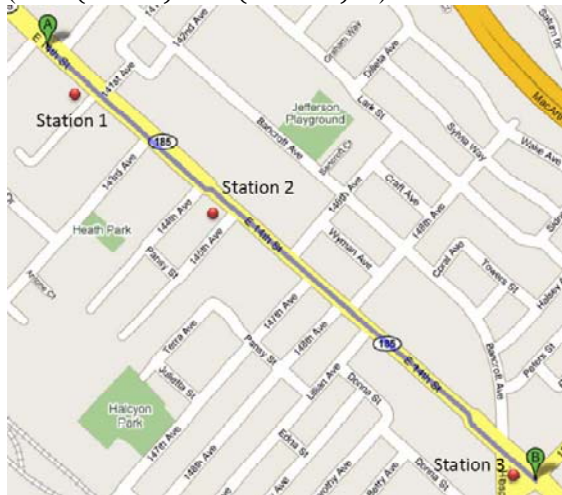


Fig. 8 Map of the test route

Magnets were then installed with a spacing of 1 m. Figs. 9 and 10 show the road crown angle, the uneven road surface, manhole, and storm drain, all of which are disturbances to the lateral controller.



Fig. 9 Left: road Crown right before Station #2 (4.75-4.15 deg); Right: Road Crown from the Crossroad (144 Ave.)



Fig. 10 Manhole and Storm Drain in front of Station #1

## V. FIELD TEST RESULTS

In addition to multiple demonstrations to transit agencies, 192 test runs with automated steering were safely conducted along the E-14 Street test track with the 3 stations. Among them, 95 runs were conducted after the system was finalized and under the normal bus operational environment. 35 runs out of the 95 runs had the data recording of the complete runs for further analysis. During each test run, the vehicle speed was controlled by the bus operator while the steering was under automated control on the 0.9-mile route.

### A. Lane Guidance Performance

Fig. 11 shows the time traces of the front and rear lateral positions and vehicle speed for one automated test run. The time “0” corresponds to the time when the bus detected the first magnets right before 139<sup>th</sup> Ave. and the traces ended just before 150<sup>th</sup> Ave. The bus is under automated steering control except between time=194.5 s and time=203 s when a manual override occurred to avoid a bicyclist in the lane. It is worthwhile to notice that the vehicle trajectory was smooth before and after the manual/auto transition. As shown in the figure, the lateral tracking error under automatic control never exceeded 10 cm except the relatively large initial error when the driver switched the control from manual to automatic. The speed trace shows the time the bus stopped at each station and for traffic lights.

Figs. 12 to 14 show plots that combined all the data of the 35 runs whose data was saved for each complete run. These figures use magnet numbers as the x-axis so that all the information is on the same scale for easy comparison. Fig. 12 shows the locations of the magnetic track, the static and the dynamic trajectories (for guiding the bus to the track after manual to automatic transition), and the front and rear bus positions (under automatic or manual control). The rear positions (rear sensor bar roughly under the middle door) basically followed the front positions but typically with somewhat smaller magnitudes.

Fig. 13 further illustrates the tracking errors between the desired trajectories and the front bus locations. After combining all the tracking errors from all 35 sets of data, the tracking error standard deviation, when the bus is under automated control, is 10.52 cm. The STD of the tracking error became 7.2 cm when we exclude all tracking data under S-curves. It is therefore fair to access that a typical value of the lane-guidance performance is within 7.5 cm (excluding S-curve maneuvers).

### B. Precision Docking Performance

As an example, the precision docking performances for all 35 recorded runs along the first automated docking stations is shown in Fig. 14. The standard deviation of the tracking error when the bus was at the final approach to the docking station (at magnet #115 to #130) after aggregating the 35 sets of data is 0.98 cm and the STD of the tracking error at the bus stop is 0.6 cm. The 35 recorded run data also shows that for Station #2 the standard deviation of the tracking error when the bus was at the final approach to the docking station is 1.0 cm and the STD of the tracking error at the bus stop is 0.69 cm. Similarly, for Station #3, the standard deviation of the tracking error when the bus was at the final approach to the docking station (at magnet #1225 to #1240) from all 35 sets of data is 1.22 cm and the STD of the tracking error at the bus stop is 0.76 cm. These results demonstrate the good repeatability of the docking performance.

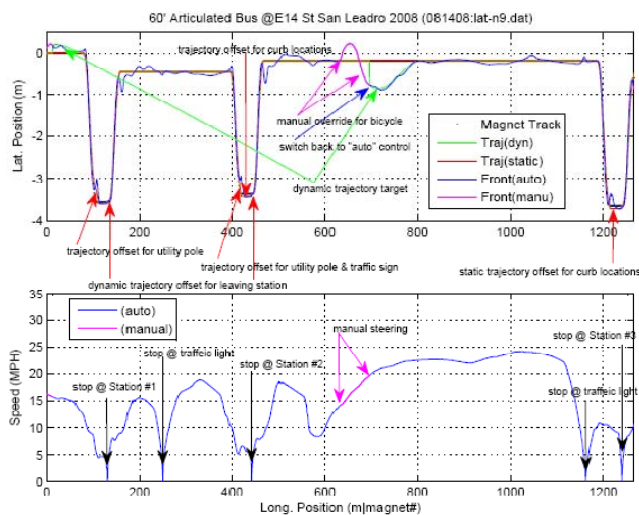


Fig. 11 Single Run Example: front position and speed

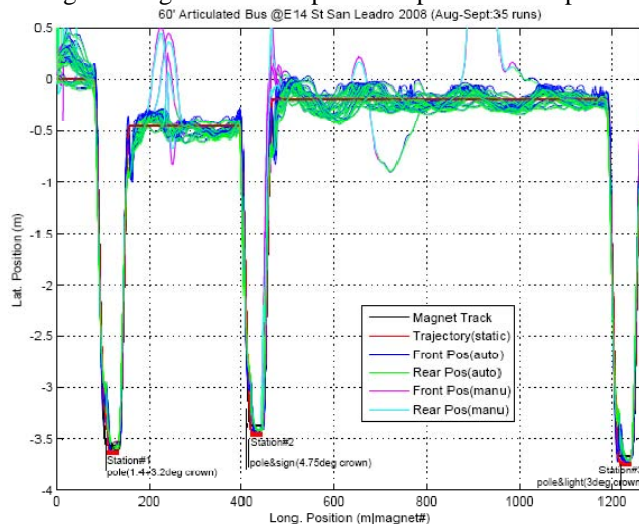


Fig. 12 Front/Rear Lateral Positions (35 Field Test Runs)

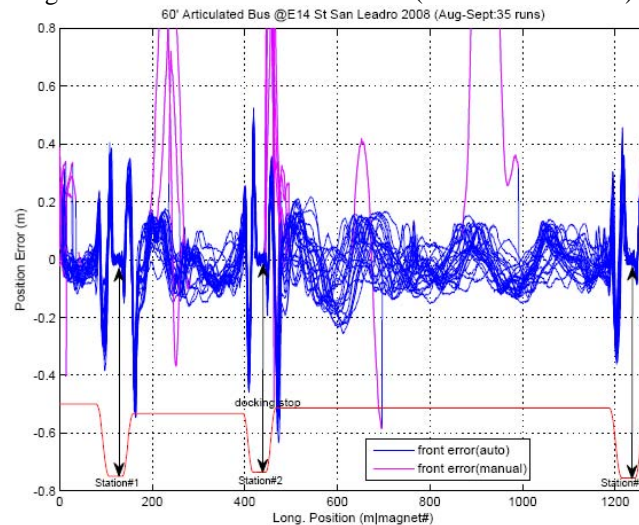


Fig. 13 Lateral Position Errors (35 Field Test Runs)

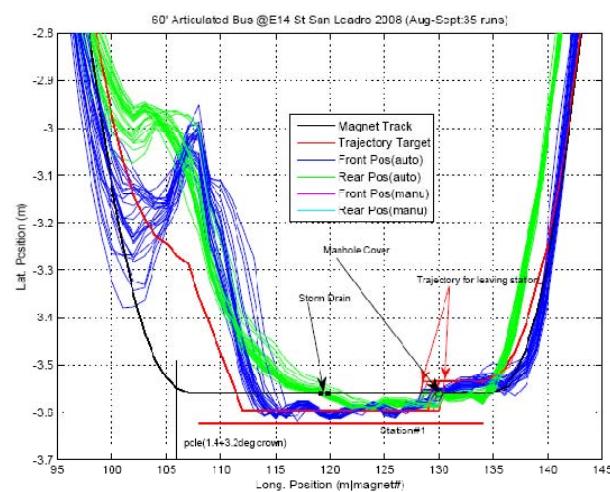


Fig.14 Lateral Positions at Station #1 (35 Field Test Runs)

## VI. CONCLUSION

This paper presents the design, implementation, and field tests of a lateral controller for the lane guidance and curbside precision docking of a 60 ft articulated bus. The unique challenges in this lateral control design include the extra lightly-damped DOF from the articulated section, the relatively large disturbance due to the sharp S-curves for precision docking, and the uncertainties introduced by public roads and live traffic. To tackle these challenges, the control problem is formulated as a mixed  $H_2/H_\infty$  synthesis problem and solved by LMI optimization.

192 test runs with automated steering were safely conducted in live traffic along the 0.9-mile field test track with 3 automated precision docking stations on Southbound East.14<sup>th</sup> Street in San Leandro, California. Among the 92 test runs with the finalized lateral controller, 35 test runs were recorded for the whole run and the test results show adequate and consistent performances.

## ACKNOWLEDGMENT

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