Bus Transit: Why Automated Buses?

• **Automated buses: light-rail like performance at a lower cost**
  – Right-of-way purchase costs are high and increasing ➔ narrow lanes
  – Transit agencies seek **safe** and **cost-effective** transit systems
    • Reduce accidents
    • Reduce operating and maintenance costs
    • Reduce driver workload and turnover
  – Transit customers demand **high-quality** transit service
    • Smooth ride and level boarding for faster travel and reduced dwell time

- Narrow lane (3.04m wide for 2.58m wide bus)
- Curvy: 36 curves; 8 of them have radii less than 100m (the smallest is 46m)
- Sharp docking curves (with radii of 25~35m)
- Speed reaches above 40mph (64.4km/h); docking at above 20mph (32.2km/h)
Background

• Project motivations
  – Caltrans/PATH have led research on vehicle automation for the past 25 years.
    • Research results show magnetic guidance can provide performance features similar to light rail systems.
    • Operation data in real-world environment needs to be collected in order to move toward deployment.
  – Transit agencies are looking for proven technologies
    • VAA system has been wanted by transit agencies interested in BRT.
    • FTA is taking the lead for the deployment of VAA.
  – Field operational test of VAA systems is a necessary step toward deployment.

• Participants
  – FTA, Caltrans, transit operators (AC Transit & Lane Transit District), UCB/PATH, industrial subcontractors

• Project goals
  – Demonstrate (in revenue service) the technical merits and feasibility of VAA technology applications
  – Access benefits and costs
Scope: A Large Step Toward Deployment

- Complexity in contractual arrangements with project partners
- Substantial new hardware and software developments for better integrating with different transit buses and for improving reliability and safety
- Product-like components and subsystems
- Safety (no margin for error)
- Infrastructure preparation: design and installation
- Close collaboration with transit agencies and drivers
- Real-world operation scenarios
- Real-time data collection and independent evaluation
- Deployment in revenue service
Automated Steering Bus for Revenue Service
Precision Docking + Lane Guidance

- EmX Line LTD, Eugene, OR
- 4-km segment, 6 stations
- Magnetic-based position sensing

Revenue service started on 6/10/2013
Automated Steering Bus
Operational Requirements: Performance

• Precision docking
  – Gap to platform: within 7.62cm (ADA requirements) $\rightarrow$ STD < 1.27cm (achieved 0.8cm)
    • S-curve docking (complete within an intersection – can enter above 32km/h)
    • Without touching platform or curb, despite of the variations in driver’s speed profile

• Lane keeping
  – 8.5-ft wide bus on a 10-ft lane $\rightarrow$ STD < 7.6 cm (achieved 7.2cm)
    • 36 curves (sharpest radius = 46m) + docking curves (sharpest radius = 25m)

• Ride comfort
  – Ride comfort should be compatible to that from drivers
    • The lateral acceleration: $a_y < 0.12g + \frac{v^2}{R}$
    • The lateral jerk: $j_y < 0.24g/s$

• Simple and easy to operate

• Control system requirements
  – Robust high-performance controller that can avoid lateral collision with the curb or platform
  – Smooth and immediate transition between automated and manual controls
Automated Steering Bus
Operational Requirements: Safety

• Safety design focuses on functional safety
  – Absence of unacceptable/unreasonable risk to individuals caused by failures
  – ISO 26262 (Hazard analysis & risk assessment → safety goals → safety concept)

• The safety concept during design include three dimensions
  – Redundancy (Complexity, independence, propagation, human elements, costs)
  – Fault detection abilities
  – Fault management capability

• Safety design of the automated steering bus includes
  – Design redundancy in every component (except steering actuator)
  – Fault detection for every (known) fault; redundancy in fault detections
  – Fault tolerant control to sustain automatic operation for 3 (5) seconds
  – Automatically turned off steering actuator for critical system faults

• Fault testing and safety validation

• Control system requirements
  – Fault tolerant controller that can sustain control for a few seconds after a failure occurs so as to provide sufficient time for driver to take over steering function
  – Immediate transition among various automated and manual controls when initiated by driver or fault management functions
Automated Steering Bus
Operational Requirements: Deployment

• Revenue service elevates design requirements of automated control
  – Apply product development methodologies (reliability + maintainability)
    • Prefer to use embedded controllers and sensors
  – Emphasize on safety design (redundancy + fault detection/management)

• Deployment requires professional installation
  – Installation should not degrade bus normal operations
  – Normal maintenance should be straightforward (visual inspection, automatic diagnosis, fault reporting, data collection)
  – Most repairs could be conducted by transit personnel (plug & play)

• Deployment requires the handling of all operational modes
  – Work in all possible operational conditions and scenarios (different drivers, speeds, weather, traffic conditions, transition methods, ...)
  – Detect and manage all (known) faults

• Revenue service demands addressing any (new) issues
  – Resolve any technical issue discovered
  – Work through operational and other issues (e.g., policy, legal, institutional) with transit agencies
  – Need to address customers’ satisfaction (agencies, operators, passengers, ...)
LTD Automated Bus (New Flyer, 60’)
Automated System Installation/Configuration

- J1939 connection
- Buzzer (2)
- Indicators (2 sets)
- Switch & button
- Instrument Cabinet (25x15x38) cm
- Control computer (2)
- Actuator controller
- HMI controller (2)
- GPS
- Yaw rate gyro
- Front & rear magnetometer sensor bars (2)
- Steering actuator
- Magnetometer sensor boards
VAA LTD Testing (Final Tests: 4/14/13 Run#18 EB)

- Revenue service started: 6/10/2013
- 400+ round trips (~800 miles) with LTD operators and under VAA control before revenue service started
Performance: Controller Design

- Robust high-performance steering control
  - New high-performance controller has been developed based on how drivers steer, and transformed for a look-down sensing system
  - High-gain control enables high accuracy and robustness against vehicle dynamics (speed + road) variations

- Fault-tolerant control
  - Kalman-filter-based observers provide accurate, robust estimations based on “redundant” sensor suits: front sensor, rear sensor, yaw rate gyro
  - Combining the high-performance steering controller with an appropriate observer based on fault detection provides fault tolerance while ensuring robustness against false switching

- Transition control
  - Dynamic initial conditioning is applied to the high-performance controller to ensure smoothness during all control transitions (manual/auto, controllers, computers)
  - Dynamic initial conditioning provides a uniformed transition structure, and the integrity of the high-performance controllers remain intact
Safety: System Redundancy Design

- Redundancy in all major subsystems (except steering actuator)
  - Redundancy in vehicle position sensing subsystem
    - Two sets of magnetometers + gyro
  - Redundancy in control computer
    - Two control computers with independent power
    - Two HMI processors act as watchdogs for control computers
  - Redundancy in HMI subsystem
    - Two HMI embedded systems with independent power supplies
    - Two sets of LEDs and buzzer, each controlled by one HMI
    - Two independent sets of input wiring for switches
  - Driver serves as a redundant steering actuator
    - One actuator due to resource and schedule limitations
    - A small motor with limited torque capability is selected for safety
    - The detection and management of steering actuator faults is critical ("redundant fault detections" were developed)
    - Driver is required to monitor the system operation and to override when the system provides warning
Safety: Redundancy Architecture

- Engine/Transmission
- Pneumatic Brake System
- Power Steering

Existing Bus Systems

VAA System

Bus Driver

HMI Processor#1
- HMI & I/O processing
- System watchdog

HMI Processor#2
- HMI & I/O Processor
- System watchdog

Control Computer #1
- Controls & transitions
- HMI & db management
- Decisions & state machines
- Fault detection & management

Control Computer #2
- Controls & transitions
- HMI & db management
- Decisions & state machines
- Fault detection & management

GPS/INS Computer
- DGPS/INS Processing
- Map

Steering Actuator
- Servo + Fault detect/respond

Steering Actuator #2
- Servo + Fault detect/respond

Front Sensor
- Signal processing
- Fault detection

Vehicle Sensor
- Yaw Gyro

Rear Sensor
- Signal processing
- Fault detection

LED, Sound

Switch/button

HMI devices

Serial/Ethernet

Dedicated CAN

J1939

Bus gateway

04/2009

DRISI
Safety: Fault Detection

• Multi-level fault detection
  – Component level
    • Components: magnetic sensor bars, steering actuator, HMI, gyro, speed
    • Self diagnostic fault detections: sensor/data characteristics, command consistency, data channel performance, timing performance, processor watchdog
  – Subsystem level
    • Subsystems: positioning and signal processing, actuating and servo, HMI & watchdog, CAN communication network, control computer and algorithms
    • Logic based fault detections: heartbeat, communication and command consistency, message format and data rate
    • Algorithm based fault detections: servo error, coding error, position estimation error, curvature estimation error, state machine error, ...
  – System level
    • Systems: location and position estimations, actuator and driver operations, automated control and transition, redundancy operations, fault detection and management
    • Logic based fault detections: state machines, command authority, coding sequence
    • Performance based fault detection: location based information, observer/measurement comparisons, timing consistency, missing or inconsistent measurements
    • System-level “relationship” fault detection: based on physics and mathematics
    • Cross check fault detection: commands, positions, estimations, locations, states, faults
    • Operational fault detection: reverse under automation, end-of-magnet, ...
    • Additional layer of fault detections to protest against (unforeseen) system errors as well as human operational or coding errors

Over 70 different fault detection functions (system, subsystem, component, driver levels) are executed throughout the system (~130 fault detections, if counting redundancy)
Three-level fault management strategy

- **Benign-fault operation**
  - The automated system is capable of tolerating the fault *without noticeable impact* on the system performance
  - Examples: failure of one HMI, one control computer
  - System warns the driver (blink red LED and beep slow to fast) to take over the control

- **Fault-tolerant operation**
  - The automated system is capable of maintaining the operation (for at least 3 seconds) at a reduced level of efficiency
  - Examples: failure in one or both magnetometer sensor bar, gyro, one actuator sensor
  - System warns the driver (blink red LED and beep slow to fast) to take over the control

- **Emergency operation (Driver immediate take-over required)**
  - In cases where the automated system can no longer perform its desired functions or the performance degradation is unacceptable, driver’s take-over is expected
  - Example: critical failure of the steering actuator
  - System warns the driver (blink red LED and beep fast) to immediately take over control
Safety: Rigorous Testing

• Four-level testing
  – Component testing, component integration testing, system testing, field operational testing

• Comprehensive fault testing (included in system testing)
  – Basic fault testing scenarios include 47 individual fault scenarios for various sensor’s, actuator’s, communication’s, computer’s, algorithm’s faults and inconsistencies
  – Prepared various embedded software and control computer software to generate the faults specified in the fault test scenario suit
  – Conducted the comprehensive fault testing included 178 test runs with 47 individual fault scenarios and their combinations for the final system
  – All faults were detected successfully; fault testing on EmX became part of the driver training (over 25 drivers had been trained)
Safety: Comprehensive Fault Testing

- Created a fault test suit containing 47 fault scenarios based on FMEA:
  - Sensor bars (8), actuator (7), yaw rate (4), CAN and power (8), HMI (2), control computers (9), operators and procedure (7), operations (2)
Safety: Fault Testing Example

Fault Test @ EmX (by Shutting down power of Front, Rear Sensors, Actuator, and Computer)

LED/Sound (m)

- Green LED
- Blue LED
- Red LED
- Sound/Buzzer

Results of Multiple Fault Detection Mechanisms

- Front Sensor Faults Detected
- Rear Sensor Faults Detected
- Actuator Faults Detected
- Control Computer Faults Detected

Lat. Disp. (m)

- E11 Sharp Turn
- Agate Docking
- Rear Sensor Noises

Steer Cmd. (deg)

- Primary Computer Transition
- Primary = CC#1
- Primary = CC#2
- CC#1 Restart
- Actuator Self Calibration

Time (sec)

18
Precision Docking Performance

- Data collected during revenue service (6/2013 ~ 8/2013)
- Docking accuracies: within 2cm (STD <1 cm) to the desired lateral position
Lane Keeping Performance (I)

- Data collected during revenue service (6/2013 ~ 8/2013)
- Lateral positions: 7.1 cm STD (auto) vs. 16.7 cm STD (manual)
Lane Keeping Performance (II)

- Speed: compatible; manual driving achieving maximum speeds 1~1.5 m/s higher
- Steering: compatible, with automated steering more consistent

Steering angle exceeded 100° over 20 locations
Lessons Learned:
Safety Design is a Complex and Iterative Process

• Safety design is the critical element for deploying an automated bus
  – Redundancy is central to safety design; achieving “economical” redundancy is not necessarily straight forward
  – Fault detection and warning are essential to safety operations
  – Fault-tolerant controls are critical to keep bus in track until operator takes over

• Safety design & testing is a necessary but time consuming process
  – Testing on public roadway (EmX) requires comprehensive fault detection and management system in place
  – Fault testing often requires firmware and software changes
  – All major revisions of software/firmware need re-testing (and revision if necessary) of the fault detection/management system
  – Software interlock mechanism and fault testing protocol safeguards mistakes in the fault testing procedure
Lessons Learned: VAA Deployment Included a Discovery Process

- LTD prototype design/tuning was an iterative discovery & learning process
  - Train ride is different from a bus ride
    - EmX track is not a typical “train” track
    - The smoothness of a “train” ride depends first on the smoothness of the track
    - The softness of a train ride depends on the appropriate speed on any given “curve”
  - Driver is sensitive to automatic steering actions
    - Driver normally coordinates his speed control with his steering action
  - VAA automatic steering characteristics (look-down) is different from driver’s (look-forward)
  - Drivers’ confidence about the system safety affects automated operations

- A comprehensive approach should be used in the future to streamline the design, tuning and deployment process
  - Survey method and maneuver curve design should include early evaluation of how experienced bus operators drive
  - Softness and tightness should be designed and tradeoff with respect to track layout, measurement noises, operational speed, as well as controller robustness
  - All controllers and safety managements should be designed and tuned under the same framework
Lessons Learned: 3 VAA Suspensions: Trouble-shooting Examples

- **Emergency button HMI issue (4/25/2013)**
  - A driver reported 2 “failures” of the VAA system: system provided warning and then turned off during docking maneuvers
  - Reason found: driver’s left knee touched the emergency button and slightly depressed the micro switches inside without engaged the switched lock (VAA correctly reported faults)
  - Solution: added a protective plate to the emergency button

- **Power Issues (7/2013)**
  - VAA system detected intermittent faults during VAA operations; system provided warnings and maintained degraded-mode control
  - Reasons found (VAA correctly reported faults):
    - Problems before July (first alternator failure – cannot charge + bad battery) were due to intermittent low voltage to the sensors
    - Problems after mid-July (second alternator failure – diode failure) were most due to power glitch to sensors
    - Problems in late July were due to power glitch to sensors that was generated by the video system power circuit failure
  - Solution: identify the source and reconnected VAA to a more stable power source

- **Survey error issue (10/24/2014)**
  - A driver reported that the middle tire of the articulated bus possibly touched the curb when approaching westbound Walnut Station
  - Reasons found: discrepancies between surveyed curb location and true locations + warp in the articulation joint due to blown radius rod bushings (bus was always close to the curb at that specific location)
  - Solution: “move” trajectory 5cm away from that curb using existing software function
Lessons Learned: Summary

• Successful deployment of a new system (product) depends on
  – Needs, resource/money, technology/team, and customer

• Deployment addresses all phases in the life cycle of a product
  – Management, planning & design, product development (system, hardware, software, integration, testing), operation & maintenance, and decommissioning

• Key deployment lessons learned from VAA
  – Risk management is important (VAA risks: contracts, safety, team, liability, availability)
  – Planning & design needs to (iteratively, adaptively) identify and address the weak(est) links (safety, performance, cost, resources, operations)
  – Product development demands addressing all issues (specifically, worst case scenarios) encountered in real world (extremely detail oriented process)
  – Supports and cooperation from customers (LTD management, operation, maintenance) is critical to the deploying the system to the real world environment
  – Key elements for VAA: Caltrans & LTD supports, strong technical team (& competent suppliers)

• VAA key technical tasks:
  – Design and documentation (requirements - system & interface, plans - integration, test, operation, software architecture, integration and test reports, driver training); steering actuator (mechanical, electrical, embedded processor, algorithm); embedded magnetometer sensors (sensors, processor, signal processing, enclosures); control computer (OS, CAN, communication, software architecture); HMI (device, watchdog, processor); bus sensors (integration, interface); algorithms (estimation, controls, transitions, warning); safety (redundancy, fault detections, fault controls, management, ...); vehicle integration (installation, grounding, shielding, calibration); testing (component, subsystem, system, operation), track (design, installation, verification); operation (design, support, driver training, revenue service, maintenance, data analysis)