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Strategic Innovation Promotion Program（SIP）
Automated driving systems／Field operational test ／Next generation transport

Development of sensing and control technology for Docking of Advanced Rapid Transit system

Report of 2017 year (Summary)

30th,March,2018
JTEKT Corporation
R&D Headquarters

Development of sensing and control technology for docking of ART system

>Sensor fusion technology : Vehicle position, surroundings (pedestrian, bicycle and others)

>Control technology : Integrated control of steering and braking

Target	*Development item*	*Technology*

① Smoothness at getting on/off at station

>Get on and off safely

>Shorten staying time at station

Target gap ; 40mm±20mm

② Robust control in various environments

>The best routing for docking even in severe condition

Approaching speed ; 40km/h

③ Smooth braking and steering control

>Prevention of in-car accident

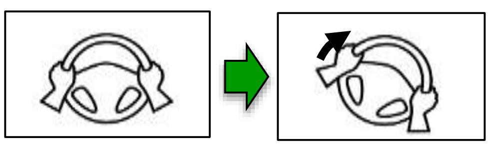
>Passenger comfort

Maximum acceleration ; 1.0m/s^2

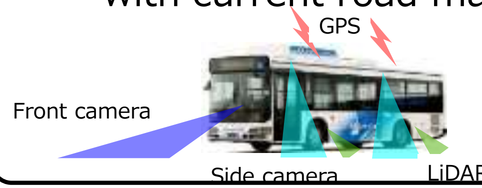
Maximum jerk ; 1.0m/s^3

④ Cooperative docking control with driver

>Maneuvering by driver in case



1) Sensor fusion technology compatible with current road marking

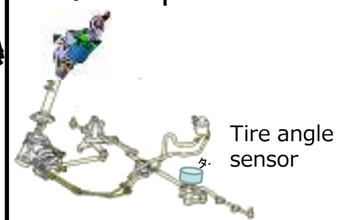


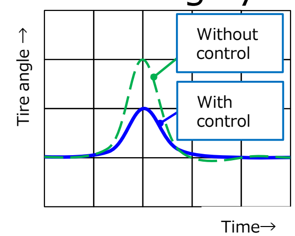
>Robustness in various environments

>Small infrastructure investment

>Fast image processing

2) Improvement of steering system control performance

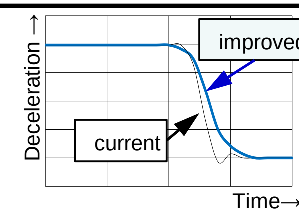




>Advanced steering control reducing dead band or delay caused by mechanical issue

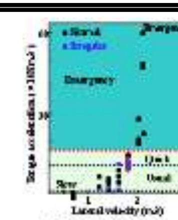
3) Reducing jerk at braking and cornering

>Sophisticated and integrated steering and braking control



4) Harmonizing driver and automated operation

>Precise estimation of driver intention from steering torque or deviation of steering torque



1）Survey on subject about precision docking

・Improvement of system control performance

・steering ・braking

- Improvement of steering system control performance
  - Optimization of control gain
  - Optimization of calculating transverse deviation
  - Steering control which compensate the tire angle response to the steering angle behavior.

Optimization of control gain

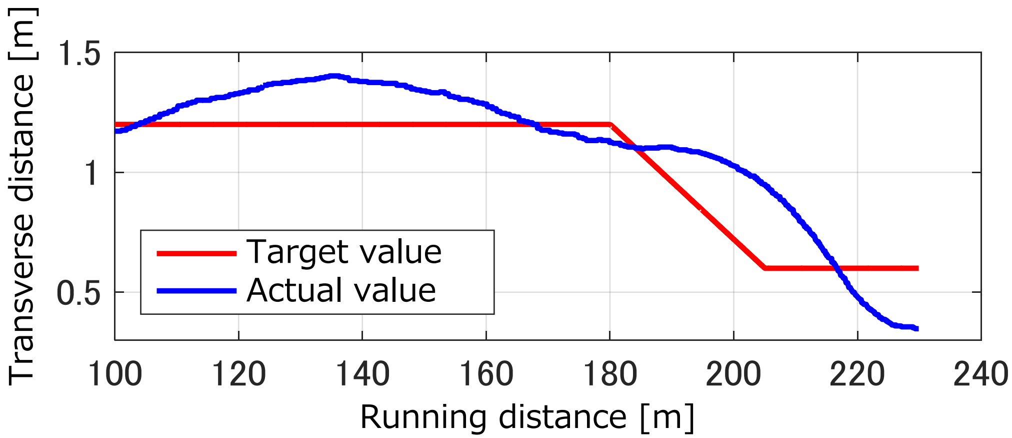
Control gain k2（term of decreasing transverse deviation)

k2 value was Constant → Switch k2 values（straight / docking)

⇒ Optimum vehicle behavior in each situation

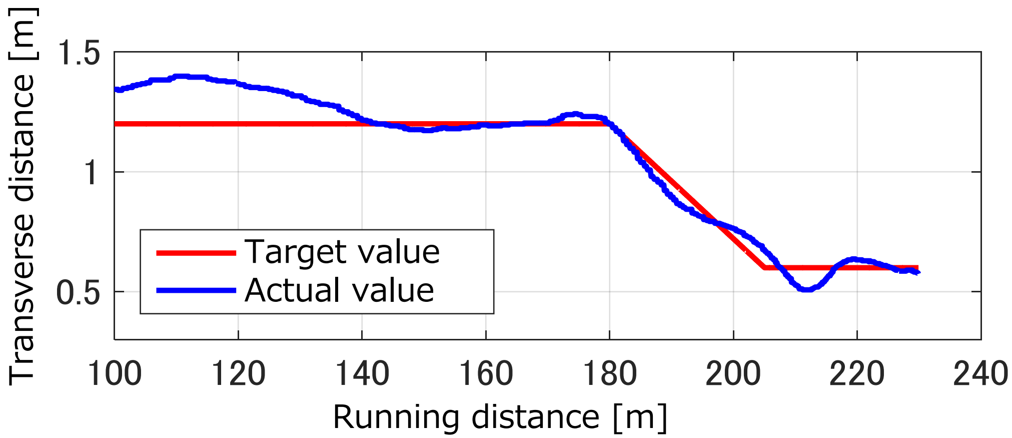
<u>Constant</u>

Optimized gain in straight situation.



<u>Switching (straight / docking)</u>

Optimized gain in each situation.



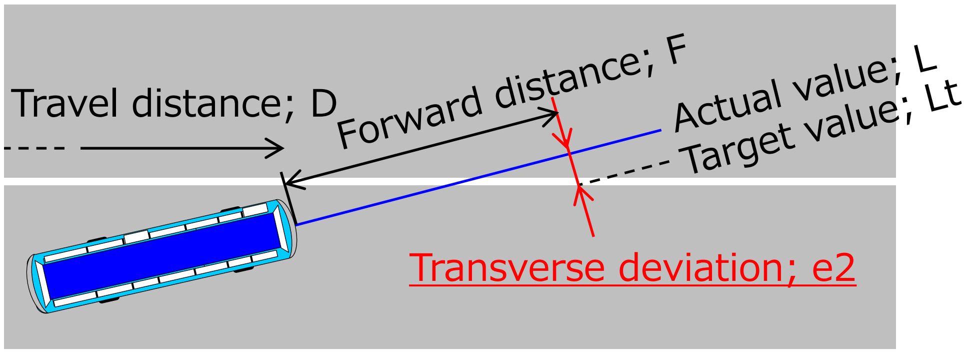
<u>◎Tracking performance is considerably improved.</u>

Optimization of calculating transverse deviation

Transverse deviation

①Change calculating position (vehicle forward) for target value.
(Last year, calculating position for actual value was already changed.)

②Optimize calculating position depending on speed, situation (straight/ docking).



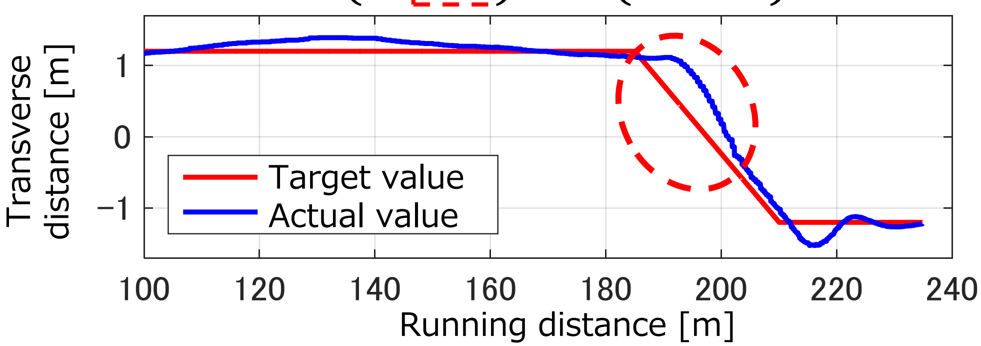
$$e2 = Lt(D + F) - L(D + F)$$

- $e2$: Transverse deviation
- Lt: Target value
- L: Actual value
- D: Travel distance
- F: Distance between calculating position and vehicle front

Effect of changing calculating position (target value)

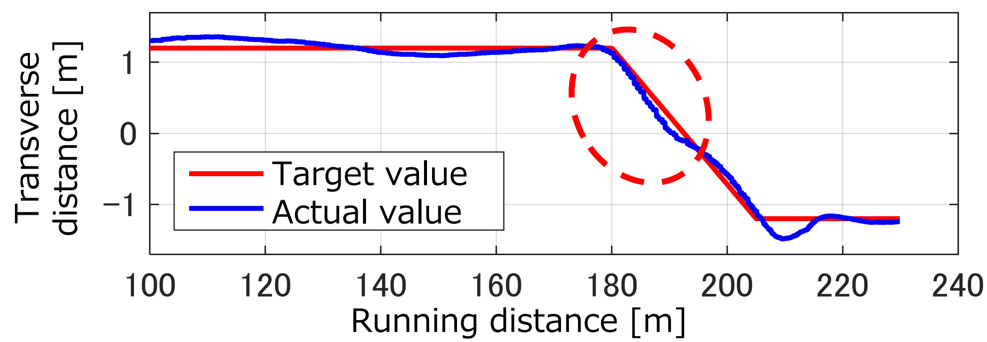
Calculated at vehicle front

$$e2 = Lt(D \;[\;\;]) - L(D + F)$$



Calculated at vehicle forward position (distance F)

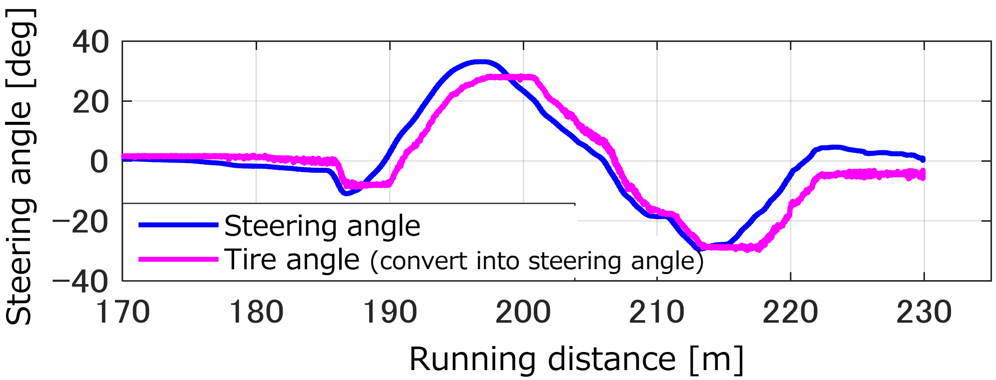
$$e2 = Lt(D + \boldsymbol{F}) - L(D + F)$$



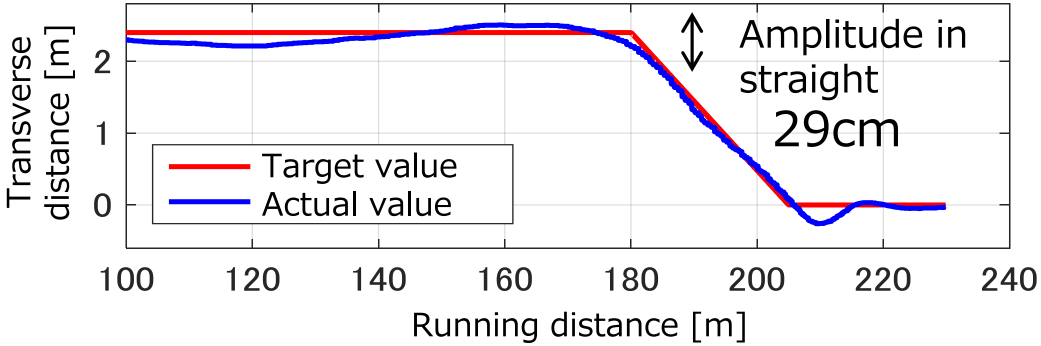
◎ Tracking performance is improved.

Steering control which compensate the tire angle response to the steering angle behavior

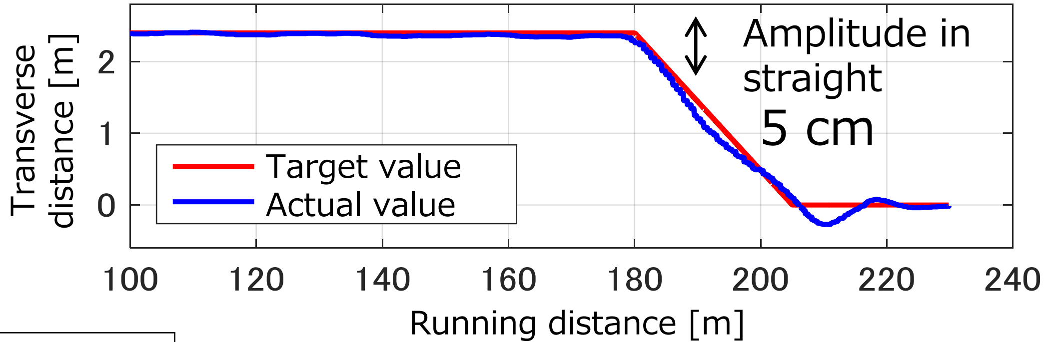
Dead zone between steering angle and tire angle is about 11degrees.
⇒ Correct target steering angle.



Without compensation



With compensation



Results of docking control
(Lateral moving distance is 2.4m.)

	Without compensation (N=15)	With compensation (N=23)
OK（both front and middle door)	**30%**	**73%**
NG（NG at least one of the doors)	**70%**	**27%**

Target range: ±20mm.

◎Improved by compensation

- Improvement of braking system control performance
    - Braking control strategy for stopping to the bus stop with high accuracy.

Stop to the bus stop with high accuracy

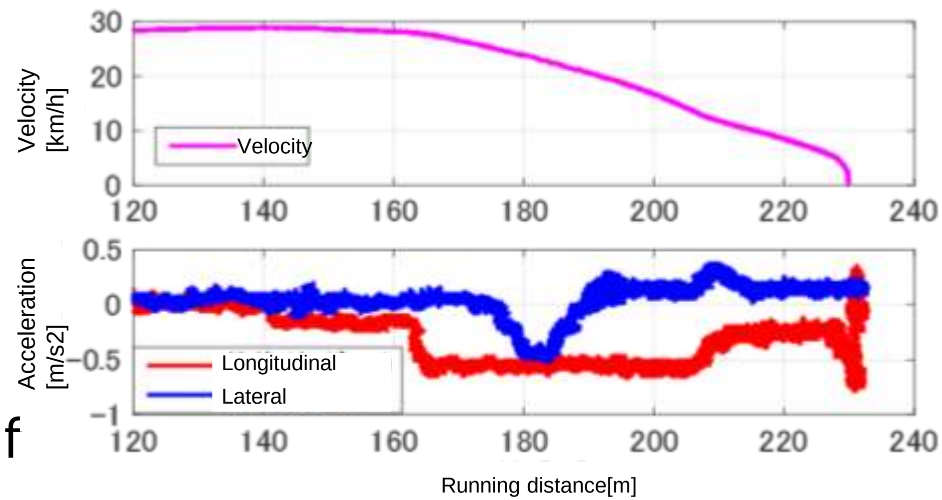
Braking control method

- Calculate target acceleration using assumed stop point. $a = \dfrac{v^2}{2(St - S)}$

※a : target acceleration, v : velocity

S : runnig distance, St : assumed stoppingpoint

- Set different values of assumed stop point in the first half and the latter half of lateral moving



Result

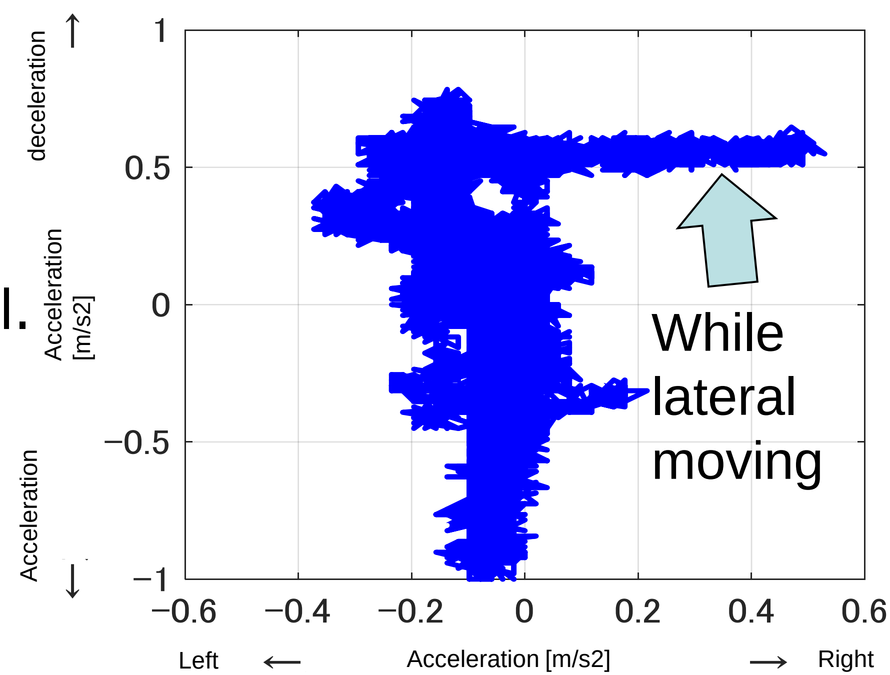
Longitudinal deviation: ±0.2m

※Allowable range: ±0.5m

Next step

Current status: only realize brake control.

⇒ Construct control strategy harmonizing steering and braking for decreasing maximum of acceleration and jerk while turning with deceleration.



Next Step precision docking control

(1) Improve Control performance and robustness
Robust to environment changes
Example: vehicle weight , wind speed and wind direction.

(2) Harmonize steering and braking control for ride comfort
Current status: only realize brake control
⇒ Construct control strategy for decreasing maximum of acceleration and jerk while turning with deceleration
- ・Optimize target of braking control variables
- ・Create limitation function based on acceleration of vehicle

(3) Improve accuracy of control variables
Example : Heading angle derived from front camera is control variable, however, the value is not the same with real value.
⇒ This may affect docking performance.
⇒ Consider the method of compensating achieved data.
Utilize data from other sensing device, for example, GPS, LiDAR···

(4) Improve steering angle behavior and driver’s steering feeling
Current: sometimes generate quick steer when compensating the tire angle response.

2）Investigate issues to minimize infrastructure development

- Detection of line edge
- Detection of curb edge
- Integration of line and curb detection

Tasks in sensing for control technology of precision docking

- In order to realize the accuracy of 40±20mm,
  resolution is insufficient in sensing with GPS or front camera image
- Infrastructure development is necessary
  for sensing with guidance lines or magnetic markers
  Also, it is difficult to avoid with obstacles such as cars parked on the street

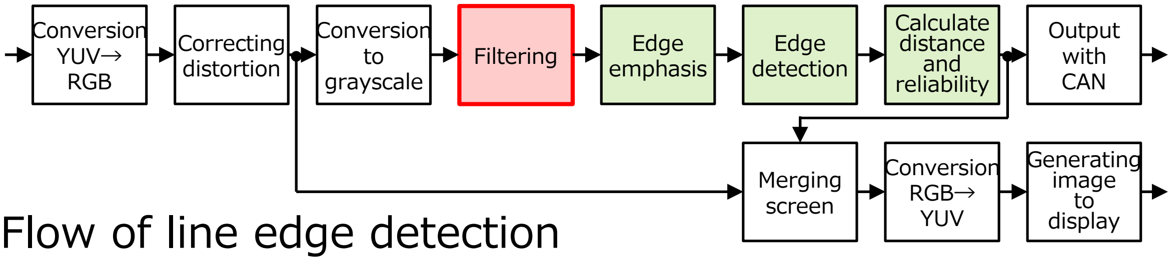
→By using side camera,
boundary and position detection such as line was made high accuracy

→Ultimately, minimize infrastructure and achieve target accuracy
of precision docking by integrating multiple sensing

Cars parked near the bus stop

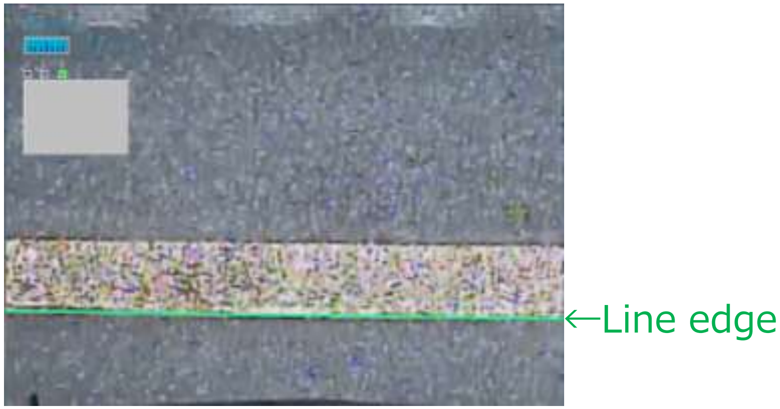
Detection of line edge

Monocular camera on the bus → **Line edge detection**
→However, there is false detection …
Factor:Blur of lines・wetting/drying of the road surface
→**Improvement of detection algorithm** (Filtering)
→Improved tolerance to blur of lines and wetting of the road surface
→**Measurement variation was suppressed to about 10 mm**



Flow of line edge detection

Side camera (Monocular)



The result of detecting the line

The result of detecting the lateral displacement

Actual value of displacement	Detection result by side camera	**Detection error**
732 mm	731 mm	**-1 mm**
740 mm	739 mm	**-1 mm**
760 mm	767 mm	**7 mm**
775 mm	773 mm	**-2 mm**

Detection of curb edge of bus stop

In many cases there is no line
near the bus stop
↓
Detection of curb edge
↓
Identification by monocular camera is difficult
↓
Detection of curb edge by stereo camera

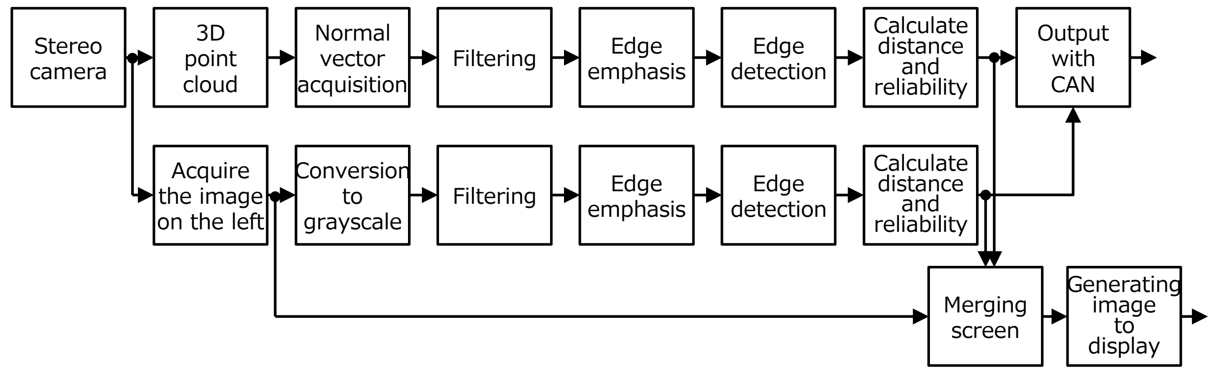
Bus stop
(The front of Toyosu station)

Camera mounting position
(Over the center door)

Side camera（Stereo）

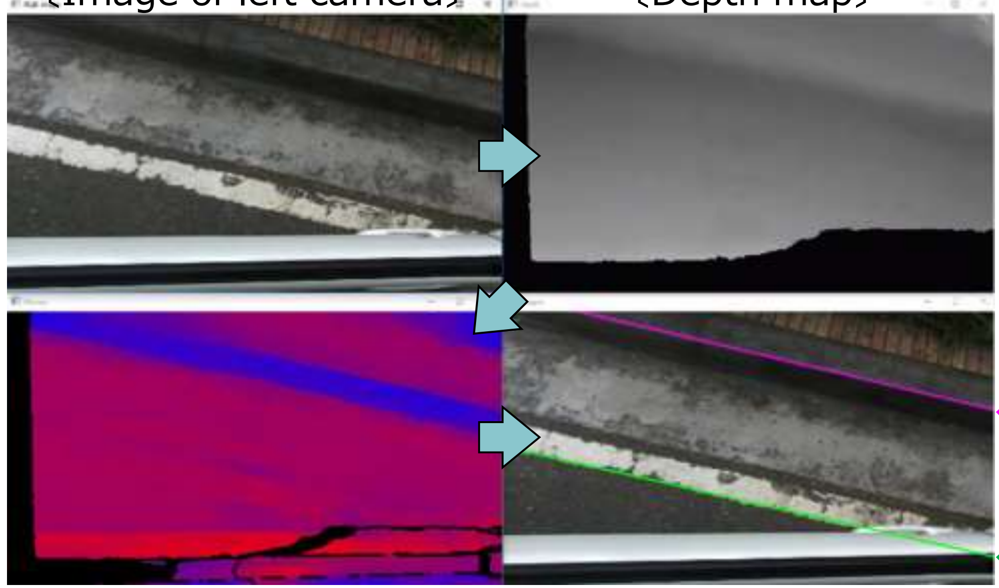
Integration of line and curb detection

Integration of
line and curb detection
↓
Detection tried near bus stop
↓
Both line and curb could be detected



Integrated flow of line and curb detection

〔Image of left camera〕 〔Depth map〕



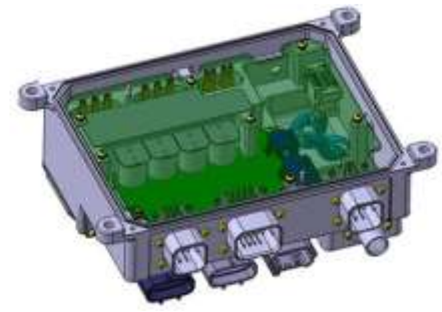
〔Normal vector〕 〔Detection result〕

Detection result of line and curb

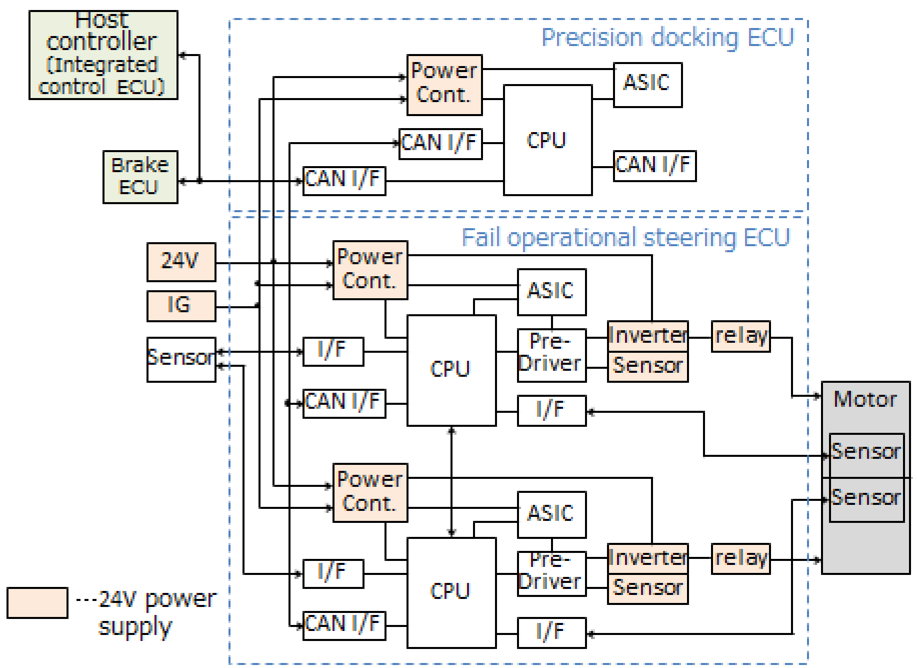
3）Study of ECU configuration considering commonization

ECU configuration

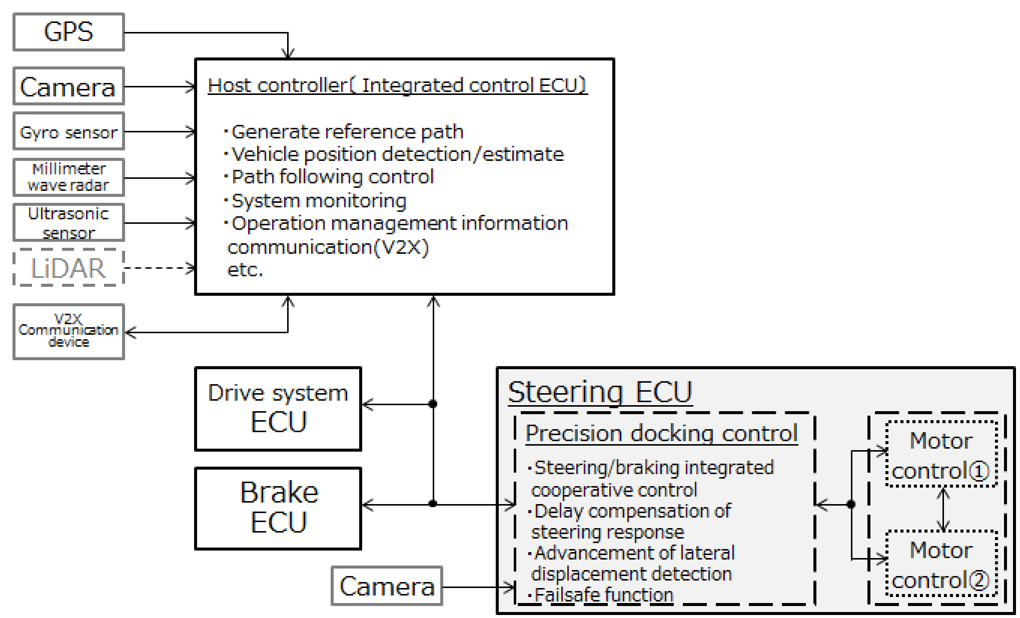
- Fail operational steering ECU in common with passenger car
- Correspond to different power supply voltages
  (Passenger car:12V → Bus:24V)
- Addition of bus specific precision docking control function



Conceptual image of steering ECU



Block diagram of bus steering control system corresponding to automated driving



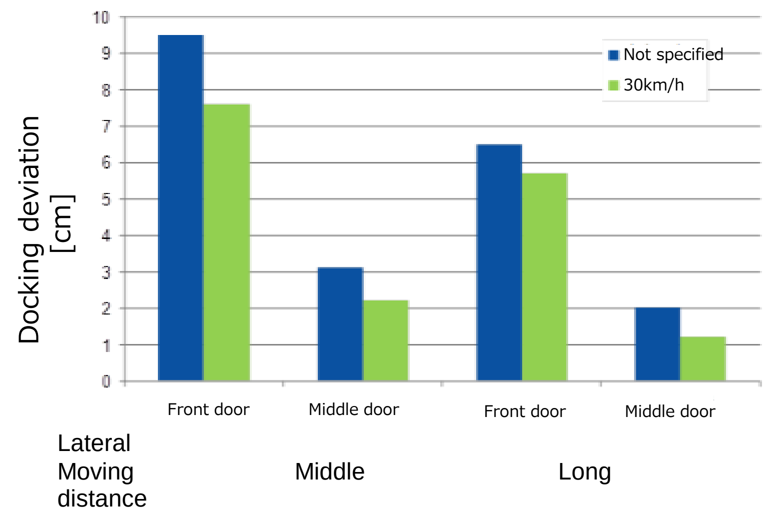
Outline of bus automated driving system configuration

4) Harmonizing driver and automated operation

Vehicle test with fix professional bus driver

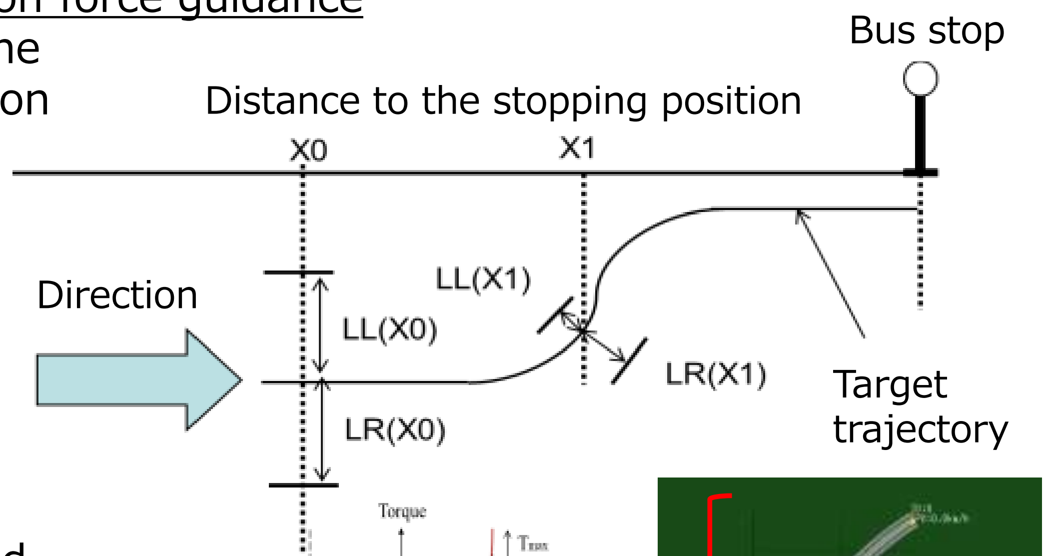
- Object
  Achieve the knowledge
  to consider the ideal precision docking
- Implementation content
  Acquire the data about driving maneuver, trajectory
  Vehicle : Hino Liesse (Property of Advanced Smart Mobility Co., Ltd.)
  Situation : Docking, Turn at intersection, Parking, Public road
  Data : Position(GPS),Curb(LIDAR)
  White line (Camera), Veicle behavior(Gyro Sensor)
  Steering angle, torque, Line of sight
- Analysis example
  the effect of vehicle velocity before docking
  ・velocity : ①30km/h specified ②not specified
  Result : Docking deviation is smaller
  when ①30km/h is specified.
- Next step
  Analyze the acquired data.
  Estimate the bus driver’s driving behavior.
  Decide the ideal target of precision docking.

Test field in Univ. of Tokyo

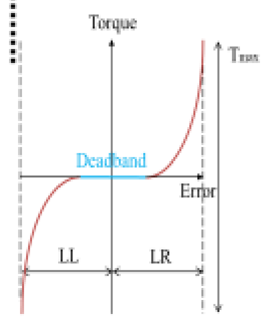


Idea for shared control system in precision docking

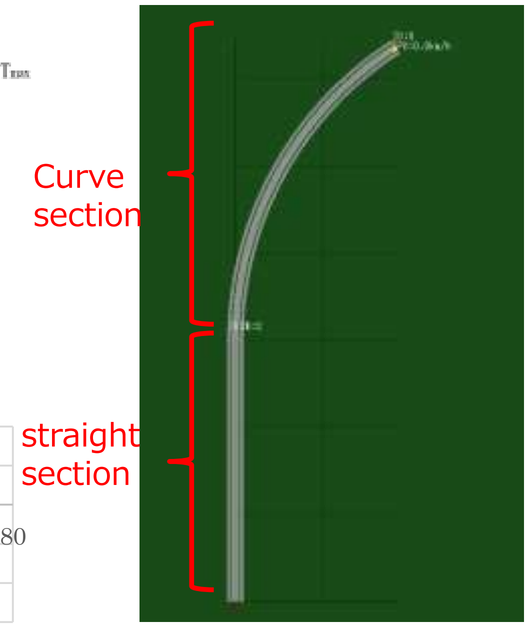
- Precision docking system (LKA type) by reaction force guidance
  1. Regard target trajectory as centerline of lane
  2. Lane width (L) will be assumed depending on the distance to the stopping position (X). When close to the stop (short X), lane width is short (short L)
- Advantage
  High degree of freedom for driver in further position from the bus stop.



- Implementation content
  The reaction force for guidance was estimated when vehicle velocity and turning radius are constant.
- Analysis example
  velocity:40km/h, turning radius : 180m
  ⇒ Vehicle could follow the target trajectory with steer operation intended by driver

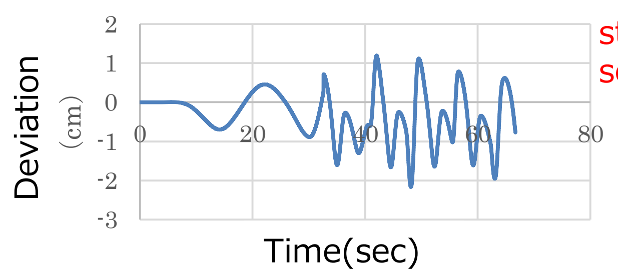


Guidance torque



Trajectory for adjusting reaction force

- Next step
  Adjust the reaction torque for various turning radius
  Apply for docking trajectory
  Evaluate with bus driver



Deviation while driving with manual steer