F2004I046

DEVELOPMENT OF AN EXPERIMENTAL VEHICLE FOR EVALUATING HIGHWAY TRAFFIC COMPOSED OF AUTOMOTIVES WITH AND WITHOUT ADAPTIVE CRUISE CONTROL SYSTEMS

[1]OGUCHI, Takashi*, [2]AKAHANE, Hirokazu, [3]NISHIKAWA, Isao and [3]KUWAHARA, Masao
[1]Tokyo Metropolitan University, Japan, [2]Chiba Institute of Technology, Japan, [3]University of Tokyo, Japan

KEYWORDS - Intelligent Transport Systems, Adaptive Cruise Control, experimental vehicle, extended Kalman smoother, image processing

ABSTRACT - The purpose of this study is to develop an experimental vehicle in which several kinds of sensors and an integrated data recording system are installed, and to develop a software algorithm for obtaining dynamic characteristics of the vehicle and those of other vehicles having relation to the one, such as speeds, accelerations, spacings, longitudinal and lateral positions simultaneously. This paper describes the results of verification of the experimental vehicle and the software algorithm. With this algorithm, state variables of vehicle kinematics are identified with the Kalman smoother technique based on the maximum likelihood estimation. This vehicle is also equipped with video cameras and after an image processing in the laboratory, the movements of vehicles around the experimental vehicle can be observed. Therefore, the experimental vehicle and the software algorithm can provide not only the kinematics of the experimental vehicle but also those of the vehicles around this vehicle. Speed, heading direction, and angular velocity of the experimental vehicle are measured by each sensor and integrated with the GPS measurement. The Kinematic GPS (K-GPS) mode have very high accuracy but is not so stable, less accurate modes such as Differential GPS (D-GPS) or normal GPS modes sometimes take place. The authors propose a state equation of three-dimensional vehicle kinematics of parallel movement and angular movement with thirty state variables, and the extended Kalman smoother algorithm (E-KSA) is adopted. E-KSA can estimate vehicle state variables simultaneously and consider the every data collected in the past and the future even if a variable is not measured at the moment with maximum likelihood estimation. Practical data are applied to the algorithm. The validity of the algorithm is checked. This algorithm can produce very precise state variables of the experimental vehicle's kinematics. The experimental vehicle can also take the digital video image of diagonally front and diagonally behind of the vehicle on the right hand side. A semi-automated image processing technique is developed, and it can manage to identify every surrounding vehicle easily. The system shown here makes great advances in developing driving behaviour models because the dynamics of vehicles can be observed precisely enough. These models lead to the possibility for assessment of control strategy of vehicles with ACC (Adaptive Cruise Control systems) in terms of highway traffic safety and efficiency in the mixed-traffic operating condition.

MAIN SECTION - INTRODUCTION

For the former stage of the fully Automated Highway System (AHS) in the field of Intelligent Transport Systems (ITS), it should become a period of highway traffic composed of mixed automotives with some Advanced Cruise Control (ACC) systems and those without ACC (normal vehicles). In the case of traffic condition on a heavy traffic highway, for example at merging sections, the interactions between vehicles with- and without ACC systems might become critical for traffic operations. Therefore, it is mostly important to evaluate the impact of introducing ACC system to such heavy traffic conditions and to assess the mixed traffic conditions from both viewpoints of traffic safety and traffic efficiency.

One of the most effective methods to assess the mixed traffic conditions is utilizing a microscopic traffic simulation technology. The technology must consist of car-following model, lane-changing model, speed decision model, gradient effect model, etc., and it must contain reproducibility of real world not only in static relationship between cause and effect but also in dynamic response characteristics. But any engineers or researchers do not have enough knowledge about these microscopic models, because there were not good tools to observe or measure the practical drivers' behaviour with enough accuracy. To develop microscopic models, the interaction between each vehicle in the heavy traffic condition should be observed or measured precisely enough with both static and dynamic aspects in the field studies.

The purpose of this study is to develop an experimental vehicle in which several kinds of sensors and an integrated data recording system are installed, and to develop a software algorithm for obtaining dynamic characteristics of the vehicle and those of other vehicles having relation to the one, such as speeds, accelerations, spacings, longitudinal and lateral positions simultaneously.

This paper describes the system of the experimental vehicle and the software algorithm. With this algorithm, state variables of vehicle kinematics are identified with the Kalman smoother technique based on the maximum likelihood estimation. This vehicle is also equipped with video cameras and after an image processing in the laboratory, the movements of vehicles around the experimental vehicle can be observed. Therefore, the experimental vehicle and the software algorithm can provide not only the kinematics of the experimental vehicle but also those of the vehicles around this vehicle.

EXPERIMENTAL VEHICLE AND INSTALLED EQUIPMENTS

The System Outline

The core of the on-board system is utilizing the high-precise time information provided by the Global Positioning System (GPS) for data collection. The synchronizing signals and the time-codes are successively created in the "Synchronized Signal Generator with GPS (SSG-GPS)" with the high-precise time information. Any data are collected at the time synchronized accurately with each frame of the video image (1/30 second). They are incorporated in the personal computer through Ethernet, after they are inputted to the "Driver's Behaviour Data Processing Equipment (DB-DPE)" and are carried out once an integrated processing such as an output conversion in making this time-code to be time unit of data collection. At the same time, the differences of the sampling frequency between measuring instruments are absorbed, such as rearranging as the intervals of each or the multiple of 1/30 second. The general illustration of the on-board system is shown in the Figure 1.

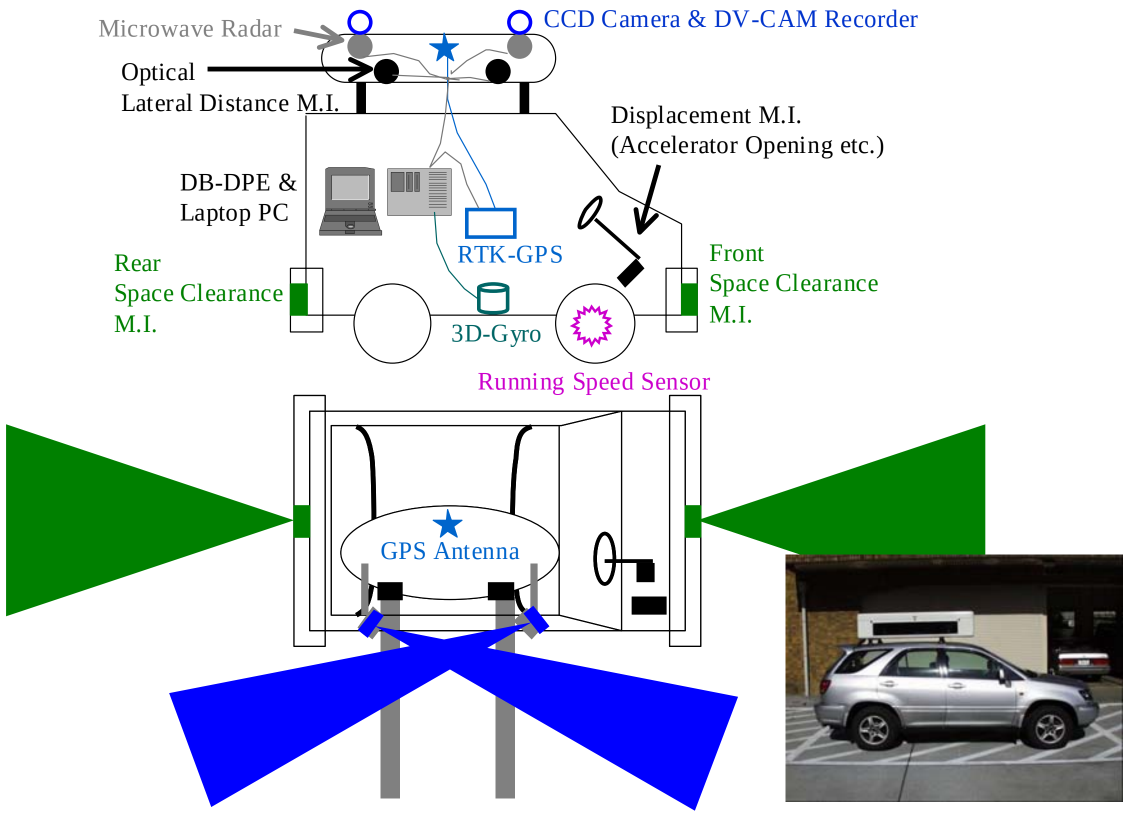

Figure 1. General illustration of the experimental vehicle on-board system

Measuring Instruments for the Experimental Vehicle Itself

Position: RTK-GPS (Real Time Kinematic GPS)

Formerly, targets of object such as kilo-meter-posts (set up by road administrators) were made to be a target of the position discriminant, and an experimenter had pushed the trigger button by the visual observation of the targets. This position and the time passing by the point are most important elements for data analysis. In such data of the position and the time collected by manually, the collation between trigger input time and position information was not only some troublesome feature but also very difficult without no error. This information (the position and the time) is influence largely on the reliability of the whole measurements.

In the on-board system of this experimental vehicle, the positioning data by the GPS is directly used as a subject vehicle position. Since the vehicle position data is most important as a basis of the measurements, the positioning derived by the real-time kinematic GPS (RTK-GPS), which enables with the error of degree of several centimetre, is adopted for the system. The position measurement of RTK-GPS needs another GPS station as the reference station (it is separately installed for any experiment) installed by fixed in the ground, and the correction information data should be transmitted continuously from the reference station by mobile phone. RTK can be achieved by the real-time analysis of the two information of the position (experimental vehicle and reference station).

However, the RTK positioning accuracy depends on the systematic error caused by the arrangements of the satellites and effects of the ionosphere, etc. The selection of the position of reference station is very important for keeping accuracy of positioning good enough because the positioning becomes inaccurate as the distance between the reference station and mobile station (experimental vehicle) is longer. This causes difficulty particularly in the investigation for inter-city expressway. This problem of selection and distance of the reference station was solved by using the 'virtual reference station' service, which became in service since last July in Japan.

Since continuous data exchange between mobile station (experimental vehicle) and the reference station by mobile phone are necessary for the RTK positioning, it is impossible to keep the RTK positioning when the line breaks off. When this break off occurred, for the recovery of RTK positioning, the mobile station must be fixed on the earth for a moment after reconnection to the mobile phone network. This means the test run must be stopped whenever the vehicle enters any tunnels or pass under the overpass. Because of this reason, the authors settled different subsystems to collect "raw data ' for GPS positioning (non-processed data) for each of the mobile station and the reference station simultaneously, and save the data into each of personal computers. And the positioning analysis (so called 'kinematic processing' GPS (K-GPS)) can be done afterward using these two systems of 'raw data' to have the position and the time successively as accurate as RTK. RTK-GPS can be done only when the mobile phone is nected continuously and the satellite condition (such as the number of satellites and elevation angle) is fairly good. However, K-GPS can be done without continuous connection of mobile phone, with satellite condition good enough.

There is the time at which the necessary number for RTK/ K-GPS of satellites cannot be ensured. The same situation also often takes place in the region with many high-rise buildings inside of the metropolis. The system developed here can enables the positioning with the accuracy level of 1 metre (Differential GPS (D-GPS)) or even with the accuracy level of 10 metres (normal GPS). The difference of accuracy of measured position can be taken into consideration in the 'true value estimation' by the data processing with extended Kalman smoother.

Speed Sensor

The speed of the experimental vehicle is calculated successively using the axle rotation pulse information by branching from the information for the antilock brake system (ABS).

Heading Direction and Angular Velocity: 3-Axial Dynamical Angle Sensor

By using three high-precise gyroscopes and three high-precise acceleration sensors, the information of the heading direction and angular velocity for the experimental vehicle is derived by the three-dimensional dynamical angle sensor (3-D DAS). The sensors can measure three dimensional parallel motion acceleration, angular velocity of roll, pitch and azimuth. The sensors can also reproduce the roll angle, pitch angle and azimuth angle by integrating the angular velocity with respect to the time, but the real measured variables are only the angular velocity. The algorithm developed by the authors for the 'true value estimation' data processing can also reproduce the three kinds of angles, and the preciseness of calculation with the algorithm must be better theoretically than those reproduce by the sensor.

Measuring Instrument of Surrounding Vehicles

The authors had also developed former experimental vehicle, the measurement was not possible for the behaviour of the vehicles of the adjacent lane. The newly developed experimental vehicle can measure the relative position of a particular surrounding vehicle in the adjacent lane to the experimental vehicle by combining features of the available measuring instruments (M.I.).

Front and Rear Space Clearance M.I.

Using two systems of the laser radar, which already on a commercial base as an alarm device for the rear end collision prevention of large automobile, the front and rear space clearances of the experimental vehicle are measured. These systems radiate the laser beam from the laser radar head, and also catch the light reflected by the vehicle ahead or behind the experimental vehicle. The measurable range is within around hundred metres.

Optical Lateral Distance M.I.

By the instrument of which the directionality to the front face direction is very high, the measurement of the distance is possible in the range of seven metres at the maximum. Two of the instruments are installed as parallel with each other since the measuring distance to the vehicle running right at the side of experimental vehicle in the adjacent lane seems to be comparatively small.

Microwave Radar

The instrument is the measurable equipment in the relatively wide directionality, of which the distance measurement range is from five metres to about fifty metres. By installing two of the instruments by turning these instruments way of the diagonal front and rear to the adjacent lane, the distance to the obstruction of diagonal front and rear of the experimental vehicle is measured.

When a vehicle over-passing the experimental vehicle comes from diagonal rear direction, the microwave radar installed to the diagonal rear direction can firstly start to measure the relative position from the experimental vehicle. The approaching vehicle comes to right at the side, then the two optical lateral distance measurement instruments can detect the existence of it by turns. After passing the experimental vehicle, the relative position of the passing vehicle is again measured by the microwave radar installed to diagonal front direction. The combination of these sensors enables the almost continuous measurement of a particular vehicle running in the adjacent lane, and the algorithm for the 'true value estimation' can also reproduce the totally full continuous information of absolute position of the subject vehicle.

CCD Camera

The experimental vehicle can also take the digital video image of diagonally front and diagonally behind of the vehicle on the right hand side. Two CCD cameras are installed in the same direction to the microwave radars, and every image taken by those cameras is recorded into a separate DV-CAM recorder, so the experimental vehicle loads two DV-CAM recorders. An image processing software can also measure the relative position from the experimental vehicle to a particular vehicle in the adjacent lane by afterward processing, using the pictures taken by the CCD cameras. Using recorded image, the relative distance from the experimental vehicle can be measured with a semi-automated image processing software.

This image processing software deals every still-image frame in series taken by each DV-CAM recorder and converted into a personal computer as a series of files. The user designates a unique point (for example, license plate) of a subject vehicle existing in the frame as a 'tracking point'. The pattern comparison is carried out in the next frame, and the next 'tracking point' is estimated by the software (and modified by manually also) by taking the highest correlation in the next frame. By repeating this procedure every vehicle each, the 'tracking points' on the screen coordinate system can be obtained for each frame (in the 1/30 second time resolution). Figure 2 shows an example screen image of the software.

DATA PROCESSING

Surrounding Vehicle Behaviour

The image processing software for obtaining relative positions has a function of the coordinate transformation: from the two-dimensional screen coordinate system (in pixels) to the three-dimensional absolute coordinate system (in metres). The principle of the

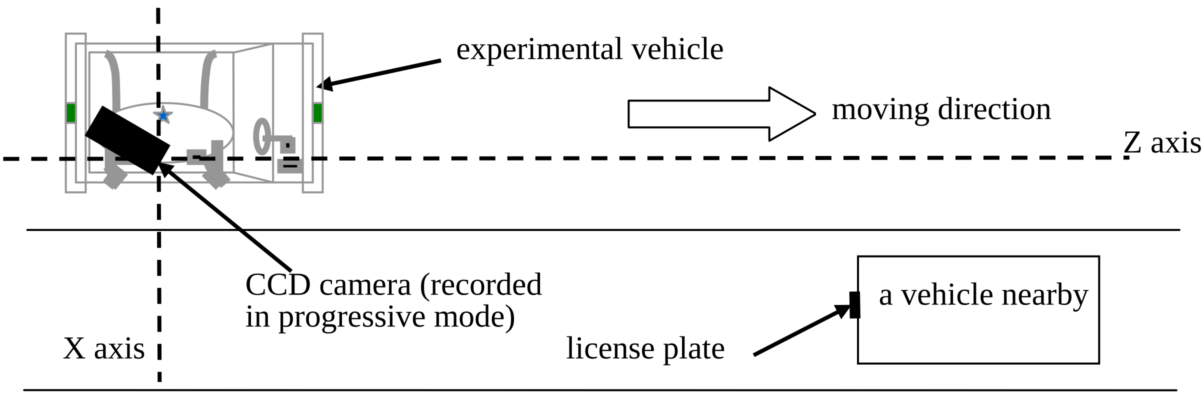

Figure 3. X-Y coordinate in the image processing software

measurements is based on the projection transformation principle. The transformation parameters are estimated with datum points. The user can set two lane marks on the road surface by designating the direction of those marks on the screen coordinate, and the software can calculate the vanishing point of the two parallel lines with the height of the cameras obtained independently. The projection transformation formula is defined as the equation (1) and (2), and physical configuration is shown in Figure 3.

$$\begin{bmatrix} u \\ v \end{bmatrix} = f \begin{bmatrix} x/(-z) \\ y/(-z) \end{bmatrix} \qquad \text{eq. (1)}$$

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \cos(b)\cos(c) & \sin(b)\sin(a)\cos(c)+\cos(a)\sin(c) & -\sin(b)\cos(a)\cos(c)+\sin(a)\sin(c) \\ -\cos(b)\sin(c) & -\sin(b)\sin(a)\sin(c)+\cos(a)\cos(c) & \sin(b)\cos(a)\sin(c)+\sin(a)\cos(c) \\ \sin(b) & -\cos(b)\sin(a) & \cos(b)\cos(a) \end{bmatrix}$$

$$\times \begin{bmatrix} X \\ Y-h \\ Z \end{bmatrix} \qquad \text{eq. (2)}$$

where,

X : horizontal distance [m] of right-hand side direction of the experimental vehicle
Y : vertical distance [m] of the experimental vehilce
Z : horizontal distance [m] ahead of the experimental vehicle
a : yaw angle of the camera
b : pitch angle of the camera
c : rolling angle of the camera
h : hight of the camera [m]
u, v : coordinate of two-dimensional image [pixel]
f : focus length of the lense of the camera [pixel]

Figure 4 shows an example series of pictures taken by two CCD cameras, and a yellow sports car is shown as passing through in the right-hand side lane of the experimental vehicle. In this test run, the experimental vehicle was come from the merging lane from left-hand side (from the shoulder in Japan), and the through traffic on the median lane (right-hand side in Japan) with two-lanes for one direction.

Figure 5 shows an example track of the yellow sports car as the results of procedure carried out by the image processing software to obtain the relative position of the vehicle in the three-dimensional real world coordinate system. The positioning error can be seen in the farther position from the experimental vehicle for both of the cameras. This should be occurred because of the resolution of screen image with pixels. Except for these errors, however, the track of the yellow sports car is reproduced fairly well. And these errors can be eliminated with 'extended Kalman smoother' algorithm. The algorithm is now under implementation, and will be developed as integrated system with the algorithm for the experimental vehicle.

Experimental Vehicle Behaviour

Accidental error and measurement error are included for the data of all collected measuring instruments. The extended Kalman smoother algorithm for correcting all kinds of errors of the frame No.410

frame No.410

frame No.490

Figure 4. Example of series of pictures taken by CCD cameras

state variables of the experimental vehicle is employed. As an advantage of this algorithm, next 3 points are mentioned.

(1) The physical relationship among those variables observed can be taken into consideration. The smoothed variables can satisfy the theoretical relation of physical quantities, for example, the integral of the acceleration with respect to the time is always the speed. The observed variables with errors cannot always meet such relation. It is possible to complement the data by this relation, when there is no observed data at any time intervals.

(2) It is possible that the decision of the current values of variables is made to reflect the correlation with time-related fluctuating values. The algorithm can estimate state variables simultaneously and consider the every data collected in the past and the future even if a variable is not measured at the moment with maximum likelihood estimation.

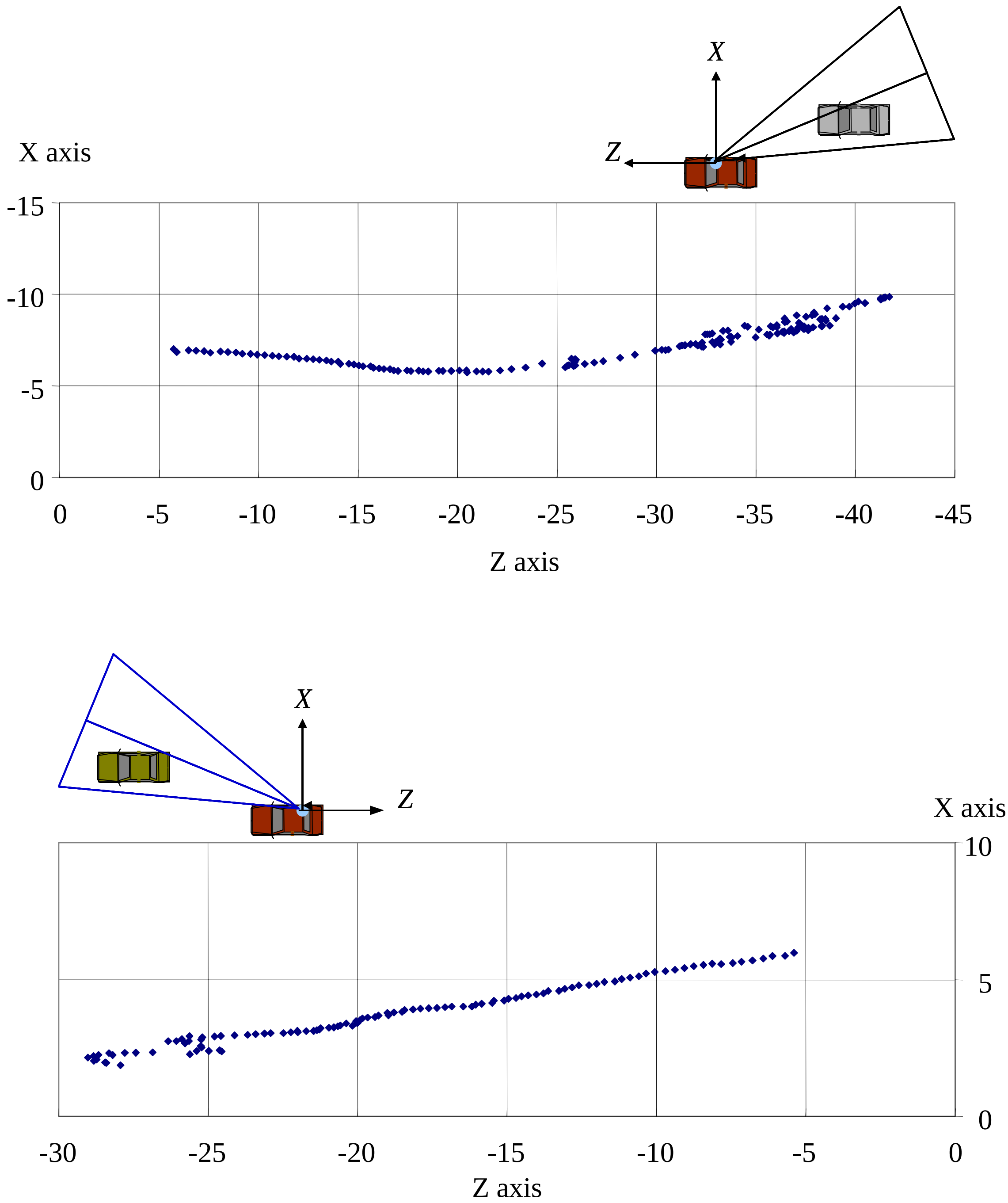

Figure 5. Transformed track of an example vehicle

(3) The reliabilities of the observed variables can be weighted by the estimated error distribution. The specification of the measurement accuracy is different for each sensor. It is possible to reflect this fact for the smoothing treatment.

The authors propose a state equation of three-dimensional vehicle kinematics of parallel movement and angular movement with thirty state variables, and the extended Kalman smoother algorithm (E-KSA), which can handle the nonlinear system model, is adopted. Equation (3) is a linear state equation, and equation (4) is an observation equation with nonliear relationship between state and observed variables.

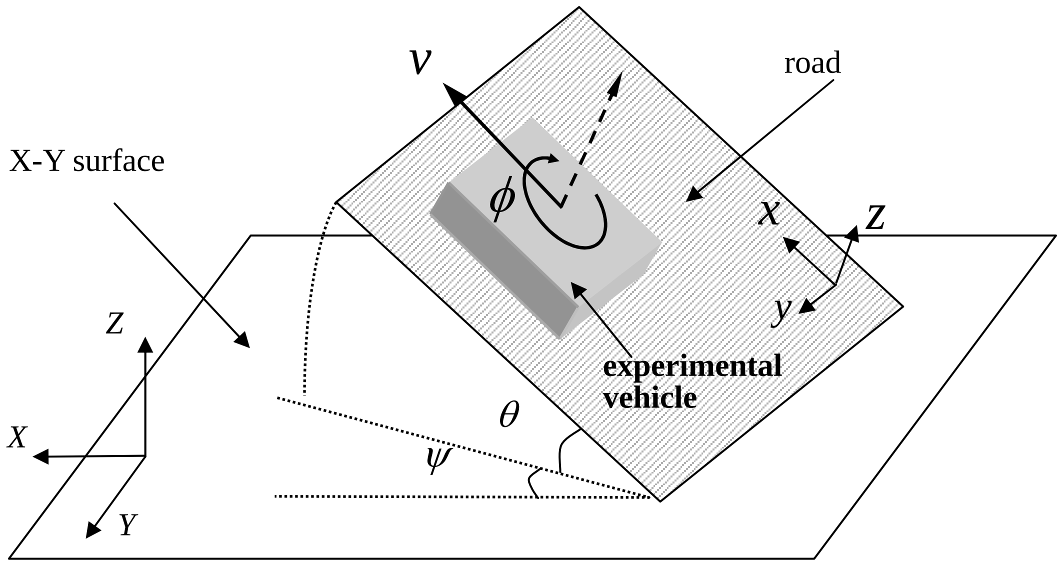

Figure 6. Concept of the experimental vehicle movement

$\vec{x}(t+\Delta)=\mathbf{F}(t)\vec{x}(t)+\vec{w}(t)$ eq. (3)

$\vec{x}^m(t)=\mathbf{H}(\vec{x}(t))\vec{x}(t)+\vec{e}(t)$ eq. (4)

where,

$\vec{x}(t)$: vector of the state variables of the system

$\vec{x}^m(t)$: vector of the observed variables

$\mathbf{F}(t)$: transition matrix

$\mathbf{H}(\vec{x}(t))$: observation vector function matrix

$\vec{w}(t)$, $\vec{e}(t)$: white noise vectors

t: time

Δ: time increment

The number of elements of the observation vector $\vec{x}^m(t)$ is ten, and they are the latitude, longitude and height derived from GPS observation, the directional speed from the axle pulse counter, the accelerations of front-rear direction, the crosswise direction and vertical direction, and the three-dimensional angular velocity of yaw, pitch and rolling. These observed variables are affected by the three-dimensional direction of the experimental vehicle, since the measuring instruments of these variables are fixed on the vehicle.

The absolute coordinate system (*XYZ*) independent from the direction of the experimental vehicle is defined as Figure 6. The number of elements of the state vector $\vec{x}(t)$ is thirty, and they are the component of the position (*X*, *Y* and *Z*), the component of the velocity, the component of the acceleration, the component of the jerk and the component of acceleration bias to the three directions, the component of the vehicular direction (rolling, pitch and yaw), the component of the angular velocity , the component of the angular acceleration, the component of the imperfection of the installation of gyroscope and the component of the angular velocity bias to the three angular direction.

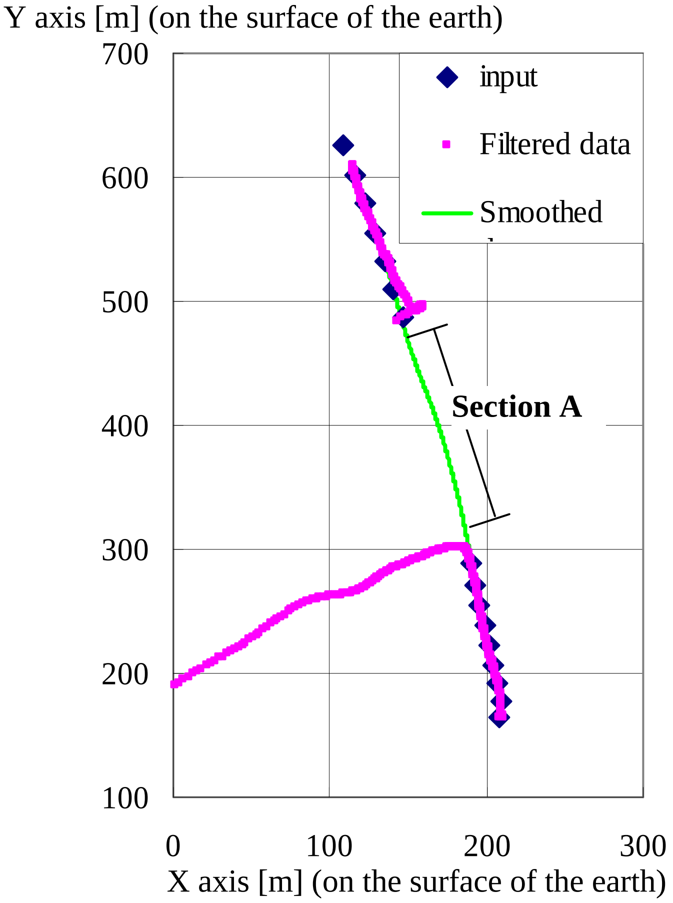

Figure 7. Example of interpolation by the 'Extended Kalman smoother'

Figure 7 shows an example how the extended Kalman smoother algorithm works. The figure shows that lack of observed data as inputs to the algorithm in the 'section A', where an overpass is located. The procedure of the algorithm as a smoother is firstly worked as 'a filter' along with time goes, using the variance-covariance matrix with respect to the former data. The figure also shows the filtered data, and it cannot work well to interpolate the lack of observed data. After the 'filtering', the algorithm begins to work as a 'smoother' for revising the variance-covariance matrix with respect to the whole data in the backward order. The figure shows that the algorithm can produce the adequate interpolated data within the area of lack of observed data.

SUMMARY AND FUTURE STUDY

The experimental vehicle with several measurement instruments and integrated data collection system is developed and the notable feature of the system is high-preciseness of measurement of the vehicle position with high-preciseness of the time measurement using GPS system. The state variables are determined and the true values of those are estimated correctly by applying the extended Kalman smoother algorithm. The behaviour of every surrounding vehicle of the experimental vehicle can be observed and software algorithm with video image can reproduce the relative position of the surrounding vehicle to the experimental vehicle.

The system shown here makes great advances in developing driving behaviour models because the dynamics of vehicles can be observed precisely enough. These models lead to the possibility for assessment of control strategy of vehicles with ACC in terms of highway traffic safety and efficiency in the mixed-traffic operating condition.

ACKNOWLEDGEMENT

The authors are grateful to Mr. Noda, Mr. Mori, Mr. Komiya, and Mr. Ohishi who are (were) the undergraduate and graduate students at Chiba Institute of Technology for making efforts to deal many experimental field works and for coding and debugging of the algorithm developed here.