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4WS Unmanned Vehicle Lateral Control Using PUS and Gyro Coupled by Kalman Filtering

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Abstract : *The localization of vehicle is an important part of an unmanned vehicle control problem. Pseudolite ultrasonic system(PUS) is the method to find an absolute position with a high accuracy by using ultrasonic sensor. And Gyro is the inertial sensor to measure yaw angle of vehicle. PUS can be able to estimate the position of mobile robot precisely, in which errors are not accumulated. And Gyro is a more faster measure method than PUS. In this paper, we suggest a more accuracy method of calculating PUS which is numerical analysis approach named Newtonian method. And also propose the fusion method to increase the accuracy of estimated angle on moving vehicle by using PUS and Gyro integrated system by Kalman filtering. To control the 4WS unmanned vehicle, the trajectory following algorithm is suggested. And the new concept arbitration of goal controller is suggested. This method considers the desirability function of vehicle state. Finally, the performances of Newtonian method and designed controller were verified from the experimental results with the 4WS vehicle scaled 1/10.*

Key words : *PUS, Gyro, Kalman Filter, 4WS, Unmanned Vehicle*

1. Introduction

Today's vehicle has become more than a means of transportation. And with the advancement of technology, interests in the research of intelligent transportation systems(ITS) have increased. The development of electronic and control technology has replaced many mechanical automobile parts with electronically controlled equipments. And for more convenient and safer driving, supplemental driving equipments, such as electronic stability program(ESP), continuously variable valve timing(CVVT), and electronic throttle system(ETS), have been developed. The increase of vehicles has brought about lack of various transportation facilities, air pollution, and loss due to accidents. To solve these problems, the need for ITS has become more prominent (Bender, 1991; Hedrick et al., 1993).

The objective of the ITS is an efficient and safe transportation system. To incorporate intelligence technology, such as electronic, computer, information, communication, and control technology, into the present transportation system to manage traffic, to provide information, to operate public transportation and cargo vehicles, and to produce vehicles, that is to apply it into the overall field(Schoenian et al., 1996; Ebken et al., 2005).

For an unmanned vehicle to operate, sensing for surroundings information and lateral and longitudinal control technology have to be integrated. US Congress and Korea's Ministry of National Defense have mentioned the possibility of future military unmanned vehicles. Recently unmanned vehicle technology is being contended in the 'DARPA Grand Challenge' which an unmanned car race. In Germany and Europe, real-time communication autonomous robot system and unmanned shuttle buses are being tested and unmanned vehicle research for military use is also actively in process(Fulton et al., 2004).

To safely and conveniently use unmanned vehicles, there are still many problems that need to be overcome. The ultimate objective is to freely arrive at the target point using the most reasonable method. And to achieve this many research and control methods have been proposed(Lovece, 1994). For optimal navigation, measurement and operation techniques are needed to obtain information of the location and what state the moving vehicle is in. Recognition and/or avoidance of moving and/or still obstacles are also very important (Kodaira et al., 1996).

In our study to research the unmanned vehicle's drive, a sample miniature four wheel steering(4WS) vehicle, one tenth of a real vehicle, was assembled to test sensor

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function and lateral and longitudinal control algorithm before testing on a real vehicle. The most important function in an unmanned vehicle is the location estimation function. To improve this function, PUS similar to a GPS was used to locate the vehicle(Kim, 2005). To assess the state of the unmanned vehicle, namely the position and azimuth need to be accurate. The azimuth angle has to be accurate for lateral control. Therefore, the position data obtained from PUS and the rotation data obtained from gyros sensing of the vehicle's azimuth combined with the Kalman filtering enables more accurate azimuth measurements. Lateral control is made up of objective arbitration controller which is a novel control that has tenacity in the changes in road conditions as well as that of the vehicle system parameters. This enhances the control of a vehicle along a given path.

2. Position and azimuth recognition system

2.1. Summary of the pseudolite ultrasonic system(PUS)

The distance measurement using separated ultrasonic transmission and receiving frequency uses the transmission speed and transmission time required between the transmitter and receiver. Time of flight (TOF) is the time needed for the ultrasonic frequency to transmit through air. This can be obtained from the difference between the emitted time from the transmitter t_t and the time it takes for the receiver to intercept the signal t_r.

Global Positioning System(GPS) is a radio navigation system developed in the US. Signal from a satellite is transmitted to a receiver on Earth to measure the coordinates. At least four signals from the satellite have to be received for the receiver to measure the distance using trigonometry.

Using this similar method, ultrasonic positioning can measure the distance with separated transmitter-receiver. The transmitter like the GPS satellite is fixed at a location and transmits signals to the receivers on the surface which are used to measure the distance between the ultrasonic satellites. In GPS, the transmitted time from the satellite and the position information are included in the transmission. However, in the PUS, the signal from the fixed satellite position is transmitted together with the RF signal so the transmitted time between the transmitter and receiver can be synchronized. The PUS in this paper checks the location in means of the receiver installed in the moving vehicle measuring the signal transmitted from the fixed satellite. The transmitter is fixed at a certain location and even though several receivers exist, each receiver does not interfere with the others since each receiver calculates the location independently. This method is more advantageous in locating positions of various moving vehicles installed with a receiver.

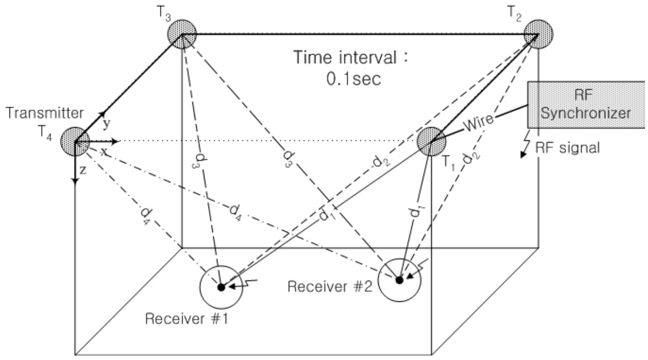


Fig. 1 Configuration of PUS(Pseudolite Ulrasonic System)

The pseudo-satellite system, that is pseudolite system shown in Fig. 1, has four transmitters placed at four different locations which transmit its coordinates and the distance of each transmitter to the receiver whereas the receiver uses this information to calculate its 3D coordinates. If the RF signal generator is placed with one of the pseudolites, the RF synchronization signal is also transmitted to the receiver and so the consistent ultrasonic generating time can be transmitted to the four pseudolites via a wire system to regulate the signals. The ultrasonic transmitter generates the RF signal and the transmission is transmitted in 0.1 sec intervals in order. The reason for the 0.1 sec interval is because when each pseudolite transmits its signal the interference among the signals causes the prior signal to reflect to the receiver resulting in calculation errors. To prevent this, enough time for the ultrasound to diminish is given. Based on the time of the RF signal reception, the TOF of transmitted signal is calculated one by one to obtain the distances between the transmitter and receivers, d1, d2, d3, and d4. Each distance is calculated with a 0.1 sec interval so to measure all four signals a total of 0.4 seconds is required. The position can be measured in 0.1 sampling cycles from each signal.

Generally, GPS sampling cycle is 1Hz while PUS can measure positions at 10Hz. This is due to the fact that the PUS is more accurate at perceiving absolute positions than the GPS. Also the PUS is more accurate in locating robots and/or moving objects indoors than the GPS.

2.2 Location and azimuth angle measurement of PUS

When estimating the coordinates of the receiver with the PUS, in the case of more than two receivers, if the 3D rectangular coordinates of the receiver are converted into spherical coordinates, the direction angle of the vehicle and the reception distance can be calculated. When the coordinates of the receiver located in front of the vehicle are $P_{front} = (x_f, y_f, z_f)$ and the coordinates of the receiver located behind the vehicle are $P_{rear} = (x_r, y_r, z_r)$, the reception distance of the vehicle and azimuth angle are presented as the following Equations (1) and (2), respectively.

$$\rho = \sqrt{(x_f - x_r)^2 + (y_f - y_r)^2 + (z_f - z_r)^2} \quad (1)$$

$$\psi = \tan^{-1}\left(\frac{y_f - y_r}{x_f - x_r}\right) \quad (2)$$

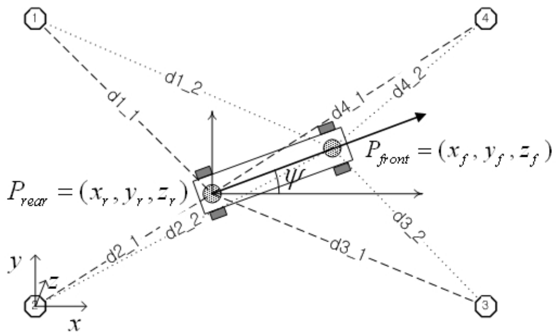


Fig. 2 Measurement of yaw angle

To achieve precise vehicle lateral control, accurate azimuth angles are essential. Fig. 2 shows the method of calculating the azimuth angle in relation to the two receivers. However, the precision of the calculated azimuth angle is greatly influenced by the measurement errors of the receiver coordinates. The further the distance of the receiver, the less the measurement error influences the azimuth angle, so the distance of the sensor needs to be as far away from the vehicle as possible. The vehicle's azimuth angle can be measured from two receivers and the distance between the two receivers can be measured to confirm the azimuth angle. If the distance between the two receivers is calculated to be larger or smaller than the actual value, error occurs in the receiver coordinates which is considered to be the result of noise. This value is considered unreliable and guarantees wrongful information is not processed.

2.3 Measuring azimuth angle using gyro

Gyroscope is a device consisting of a wheel that spins rapidly inside a frame and does not change position when the frame is moved which is used for measuring orientation.

The principle of measurement is when the structure is vibrating in a specific direction due to electrostatic power, the angular velocity is induced and Coriolis force acts perpendicular to the vibrating direction. The Coriolis force causes the vibration to change the power shortage between inertia object and electrode. The rate of velocity can be measured from the induction caused by the change.

The measurement of gyro is as Equation (3) when DC offset, scale factor, and bias are assumed to exist, where φ is angular velocity (deg/sec), V is gyro voltage output, c is conversion factor, sf is scale factor and b is bias (draft), respectively.

$$\varphi = sf \times c \times V + b \quad (3)$$

The present vehicle direction angle can be obtained when the angular velocity from the gyro is integrated as in Equation (4).

$$\theta = \int \dot{\theta} dt + \theta_{init} \quad (4)$$

There are many methods of integration from the numerical analysis approach. We use a trapezoid integral method that can be quickly processed on a low-cost processor with minimum errors. The trapezoid integral method uses two data, that is k data and k-1 data, as in Equation (5), where θ is angle (°deg), φ is angular velocity and Δt is time interval, respectively.

$$\theta(k+1) = \theta(k) + (\varphi(k) + \varphi(k-1)) \times \Delta t / 2 \quad (5)$$

When the measured angle from gyro is integrated with the trapezoid integral method, the changed direction angle of the vehicle from the starting point can be calculated.

2.4 Combining the Kalman filter to the azimuth angle

The Kalman filter combines the probability of the dynamic propagations and the observations of the state space system(Brown et al., 1997). The covariance of the actual state value x and of the estimated state value $\hat{x}$ are minimized so the estimation is unbiased.

The quick sampling cycle characteristics of inertial sensors and the good properties of gyro sensors in limited time area and ultrasonic positioning systems that do not accumulate errors even during long periods can be combined with the Kalman filter for more accurate assumption of the direction angle. The state variable to acquire azimuth using gyro is as follows.

$$x = \begin{bmatrix} \theta \\ \varphi \end{bmatrix} \tag{6}$$

The θ is the vehicle's azimuth angle and φ is the rotation angle velocity obtained from gyro. The state space equation in continuous time is acquired as follows.

$$\dot{x} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} x + Q \tag{7}$$

The sampling cycle of the data is shown as t to discretize the state space equation to get Equations (8) and (9). Here Q is the process noise covariance and Γ is the coefficient of white Gaussian noise w(k).

$$\Phi(k) = \begin{bmatrix} 1 & \Delta t \\ 0 & 1 \end{bmatrix} \tag{8}$$

$$Q(k) = \int_0^{\delta t} \Phi(\tau)\Gamma Q \Gamma^T \Phi(\tau)^T d\tau = \begin{bmatrix} \frac{W}{3}\Delta t^3 & \frac{W}{2}\Delta t^2 \\ \frac{W}{2}\Delta t^2 & W\Delta t \end{bmatrix} \tag{9}$$

The measurement equation is as follows. The azimuth angle data input for the measurement equation is from the ultrasonic positioning system.

$$[\theta] = H(k)x(k) \tag{10}$$

$$H(k) = [1 \quad 0] \tag{11}$$

The above state space equation and the measurement equation repetitively process the flight time and the observation update through the Kalman filter. The error covariance of the gyro and PUS is minimized to obtain optimal azimuth.

3. The design of vehicle lateral controller

3.1 Path algorithm

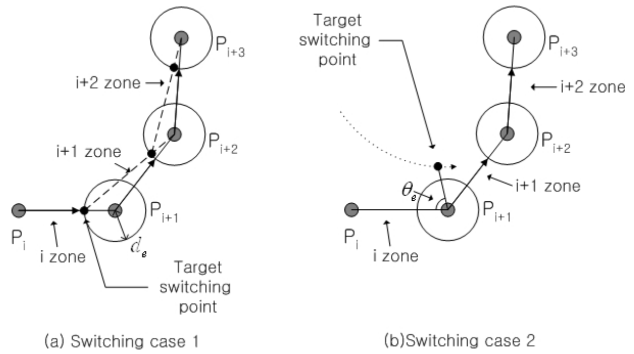


Fig. 3 Switching method of target point

Vehicles use the point to point method to move. This method designates a target point P_i to which the vehicle moves, on arriving at the target point a new target point is selected thereby continuing to move. Designating target points along the desired path enables the vehicles to drive along the desired path according to the target points. The present target point P_i and the next target point P_{i+1} as shown in Fig. 3 are accomplished if any one of the following two conditions are satisfied.

In general driving vehicles, the navigation is within the traffic lanes. Therefore, instead of exactly follow the navigation path, it is more reasonable to navigate within the road width of the desired path. If the target point is continuously changed this way, the vehicle moves onto the next target point stably along the desired path. Setting the target point with the target point exchange method presented in Fig. 3 allows autonomous designation of the target point regardless of the vehicle's initial position.

3.2 Setting control variables

The appropriate input that makes the control variable 0 is confirmed to control the vehicle. Angle error and distance error are given in Equations (12) and (13). Here L_e is the prior target point and θ_e is the vehicle azimuth, respectively.

$$\theta_e = \theta_i - \psi \tag{12}$$

$$L_e = \left| \overline{P_{i-1}P_i} \perp P_c \right| \tag{13}$$

This increases the vehicle modeling error which makes lateral control difficult. Therefore, it is necessary for lateral control to reduce speed according to the curvature of the lane.

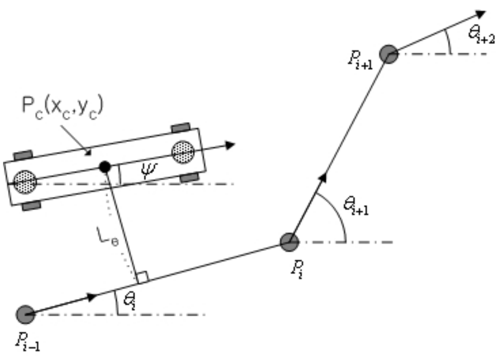


Fig. 4 Definition the control variable

3.3 Design of an objective arbitration based controller

For the vehicle to move right or left, the lateral control has to be applied to some kind of steering device. To make up this control, the error variable needs to be calculated from the observed vehicle state variable. The lateral control input desirability has to be determined for each error variable. The function of the lateral control desirability for each error variable can come in various types. The quality will depend on the experience of the function designer and its performance.

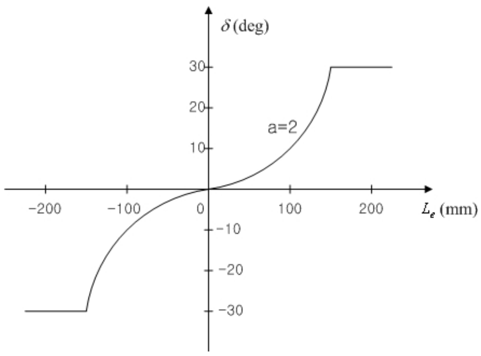


Fig. 5 Desirability function about length error

The defined error variable is defined by two variables, distance error L_e and angle error θ_e depending on these errors, the control input desirability function is established. The desirability function according to the distance error in Fig. 5 is presented in Equations (14) and (15).

$$D_{\delta 1} = \begin{cases} k_1 \left| L_e^{\,a} \right| & L_e \geq 0 \\ -k_1 \left| L_e^{\,a} \right| & L_e < 0 \end{cases} \tag{14}$$

$$k_1 = \delta_{\max} / L_{e\,\max}{}^{a} \tag{15}$$

When the higher the difference of the desirability function according to the distance error, the smaller the distance error becomes so the lateral control steering value has to be small for straight driving. When the distance error is large, the lateral control steering value entry has to be large for faster return along the fixed path.

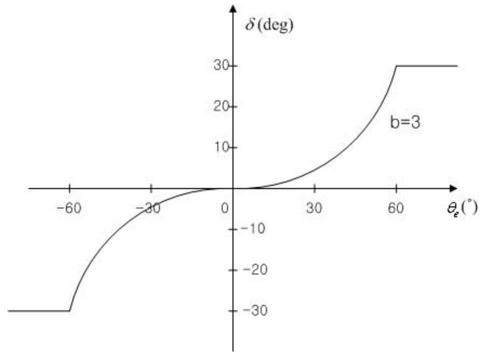


Fig. 6 Desirability function about angle error

$$D_{\delta 2} = \begin{cases} k_2 \left| \theta_e^{\,b} \right| & \theta_e \geq 0 \\ -k_2 \left| \theta_e^{\,b} \right| & \theta_e < 0 \end{cases} \tag{16}$$

$$k_2 = \delta_{\max} / \theta_{e\,\max}{}^{b} \tag{17}$$

The maximum steering input value of the vehicle $\delta_{\max}$ is 30^{o} side to side. Even when the larger value is needed, the steering input value is 30^{o}. The maximum range of the distance error L_e is −150mm∼150mm. Distance errors exceeding this range inputs the maximum steering input value. The maximum range of the angle error θ_e is -60^{o} $\sim 60^{o}$ and the angle errors exceeding this range inputs the maximum steering input value. The difference of the desirability function was determined to be a=2, b=3 which showed the best performance during repeated experiments. The difference can change depending on the desired performance.

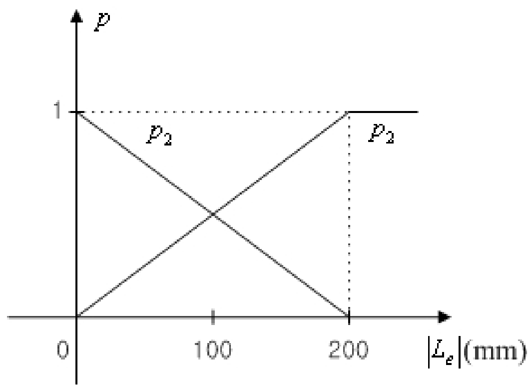


Fig. 7 Arbitration of goal function

Here, Equation (18) is given.

$$\delta_{input} = p_1\delta_1 + p_2\delta_2,$$
$$constraint: p_1 + p_2 = 1. \quad (18)$$

The steering control input converted to a single input changes according to each observation of the vehicle. When the distance error and angle error of the vehicle on the driving path requires input, in the case of the same direction input, the bigger steering angle is entered. In the case of different steering angle direction, the role of the objective arbitration function increases and the steering angle that is most appropriate in that situation is entered. The accuracy of the observation data and the faster the renewal cycle, the performance of the vehicle increases.

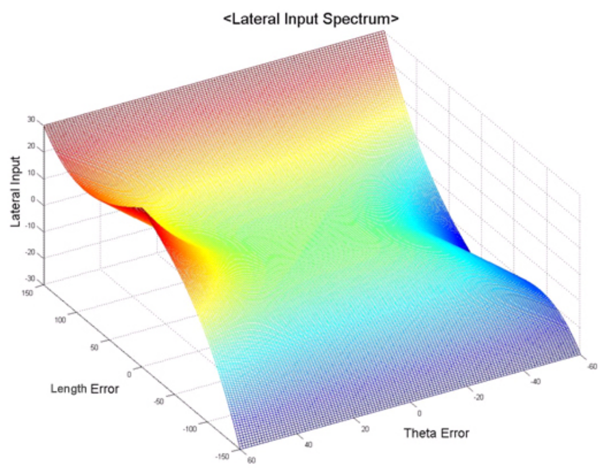


Fig. 8 Control input spectrum of steering angle

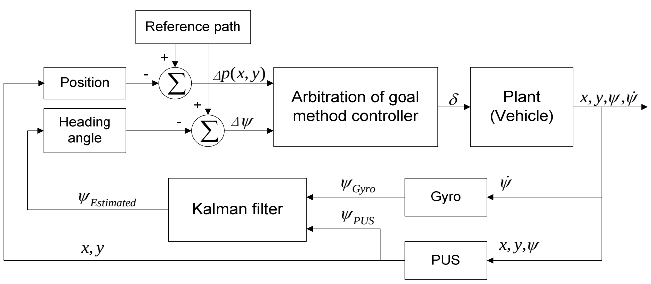


Fig. 9 Block diagram of lateral control system

The block diagram of the control system is presented in Fig. 9. The approved control input of the vehicle plant is steering angle δ. This control input is determined by the spectrum in Fig. 8 and more accurate fit function, objective arbitration function, and set variables are produced. The state variables fed back are position values (x, y), vehicle azimuth ψ and $\dot{\psi}$. The state variables are measured using the gyro sensors and PUS. These data go through the Kalman filter for possible combination to produce a more precise azimuth angle ψ

4. Experiments and performance evaluations

4.1 System organization

The organization of the test vehicle is divided into six modules. The state of the vehicle and its position is monitored in live feed. The position, azimuth angle, speed, steering angle data are communicated via Bluetooth to the microcontroller board (Atmega128 board) which controls the movement of the vehicle and the remote controller where the Kalman filter and objective arbitration controller are encoded. The PUS senses the position information and the gyro IMU400 measures the position and azimuth. The transmitted steering order and speed order from the control computer goes to the microcontroller board and relayed to each yaw angle servo motor and driving DC motor to operate the vehicle.

The structure modules used to operate the vehicle are RC servo motor to steer right and left, the RC servo motor driver, the Atmega128 data transmitter receiver board, the DC motor for forward and backward movement, and the DC motor driver. The RC motor is a product of HITEC which permits PWM signals so the motor rotates in the desired angle. The RC motor driver controls the RC motor with PWM signals and is the SMC PRO product of COMFILE TECHNOLOGY. 5V power supply is required and it produces a total of 8 different PWM signals. Atmega128 data transmitter receiver board is used to communicate between the monitoring computer and data transmitter. Steering input and velocity information is transmitted to each operating module. Then the control computer filters the transmitted PUS data and gyro data through the Kalman filter and produces the steering angle and speed information with an objective arbitration control encoded program to operate the vehicle. The DC motor is the IG32GM motor of DNJ which has rated torque 12kg.cm at 1/5 of the moderating ratio. It operates on 12V and controls the two motors that operate the front wheels and the rear wheels, respectively. The DC motor driver uses a FET device according to the PWM signal to control the operating current which controls the velocity of the DC motor.

The specification of the test vehicle is presented in Table 1.

Table 1 Specification of vehicle

Length(L)	L = 0.7m
Wheelbase(l)	l = 0.66m
Tread(D)	D = 0.19m
Distance from C.G(l_f, l_r, D_l, D_r)	l_f, l_r,= 0.33m D_l, D_r = 0.095m
Weight(M)	M = 5.2kg

Table 2 Specification of gyro sensor

Range: Yaw(°/sec)	±100
Bias: Yaw (°/sec)	< ±1.0
Scale Factor Accuracy(%)	< 1
Non-Linearity(% FS)	< 1
Resolution (°/sec)	< 0.025
Bandwidth (Hz)	> 25
Random Walk (°/$hr^{1/2}$)	> 2.25
Operating Temperature(℃)	-40 to +70
Non-Operating Vibration (g rms)	6
Non-Operating Shock (g)	1000

The gyro sensor is the IMU400 product of Crossbow which provides the three axle gain velocity and the three axle angle velocity. In our experiment, only the lateral gyro sensor data was used. The specifications of the gyro sensor are presented in Table 2. The PUS used to acquire the positioning information of the vehicle is a product of Korea LPS. The distance between the transmitter installed at a designated position and the receiver in the vehicle is calculated using ultrasonic frequency. Generally, four 40kHz ultrasonic bandwidth is used. RF signal is made to synchronize the transmitter and the receiver.

Fig. 10 shows the structure of the test vehicle.

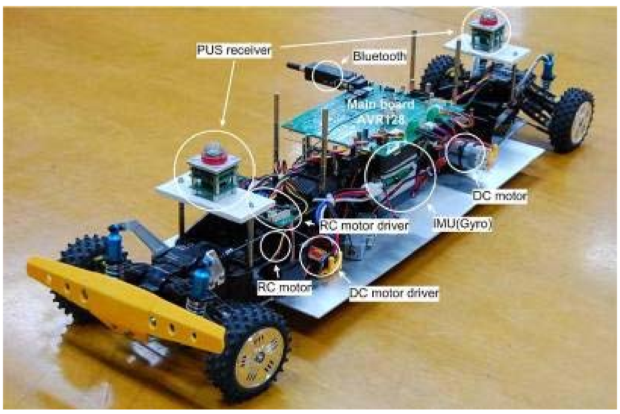


Fig. 10 Configuration of experimental vehicle

4.2 Experiment results

In this paper, the numerical analysis of the Newton-Raphson method was used to more precisely calculate the position of the moving object(Farrell et al., 1998). In the existing simultaneous equation, when the Z coordinates of the stationary transmitter are the same, the position cannot be calculated since the inverse matrix of the simultaneous equation matrix does not exist. Therefore, the Z coordinate of one of the transmitters has to set differently to solve the equation. When using the existing method error can occur in the distance measurement due to noise or spatial distortion in the 3D coordination calculation can occur due to moving object reducing the accuracy of the position measurements. The newly suggested Newton-Raphson method in this study, estimates the elevation value of the Z axis fairly accurate so the position measurement using the Z axis value is reliable.

Fig.11 and 13 represent the test results of circular path at 0.18m/s and at 0.61m/s, respectively. This graph compares the X, Y plane position measurement results calculated with the existing simultaneous equation and that of the Newton-Raphson method. The accuracy of the existing equation is reduced due to noise during measurement and depending on the speed and/or moving direction of the vehicle. Especially, since the inverse matrix is not 0, when coming closer to the position of the transmitter, the precision reduces. In contrast, with the Newton-Raphson method, numerical analysis results show close accuracy to the real position.

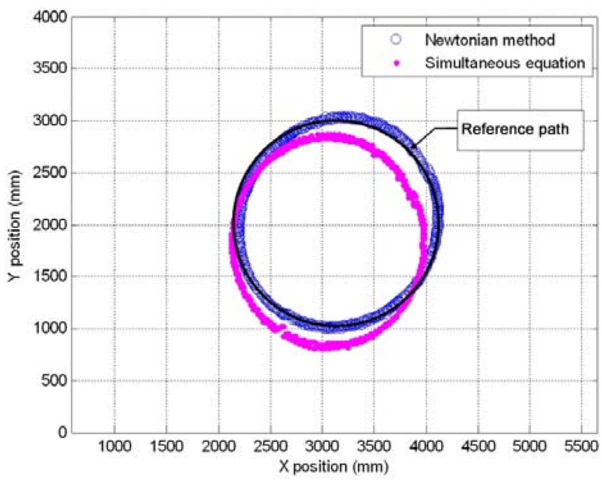
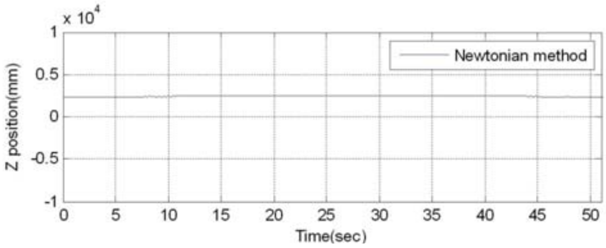
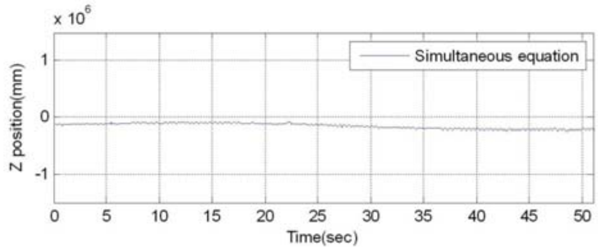


Fig. 11 Experimental results of X,Y estimation at speed 0.18 m/s

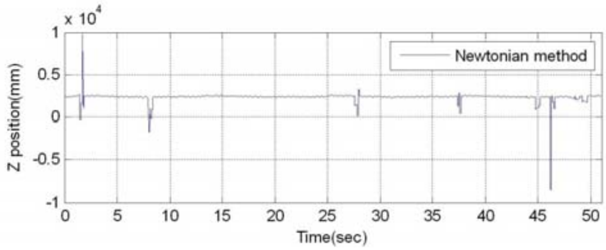


(a) Newtonian method Z position estimation

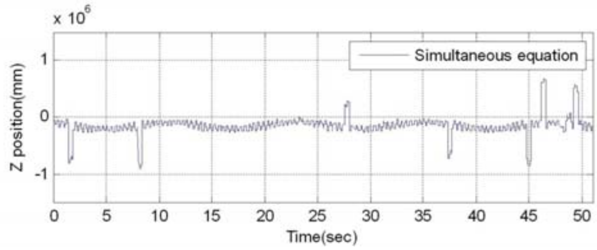


(b) Simultaneous equation Z position estimation

Fig. 12 Experimental results of Z estimation at speed 0.18 m/s



(a) Newtonian method Z position estimation



(b) Simultaneous equation Z position estimation

Fig. 14 Experimental results of Z estimation at speed 0.61 m/s

Fig.12 and 14 are the performance results of Z axis position estimations. In the existing equation, the Z axis position results show unusable errors. However, with the Newton-Raphson method, results are close to the actual height of 2160mm. During movement, the measurement comes to 2500mm which is taller than the actual height. This is due to the fact that sum of the four distance measurements are bigger or smaller than the sum during stationary state. Also, occasionally, the ultrasonic frequency data miscalculates due to the noise, this occurs more frequently when on a highway.

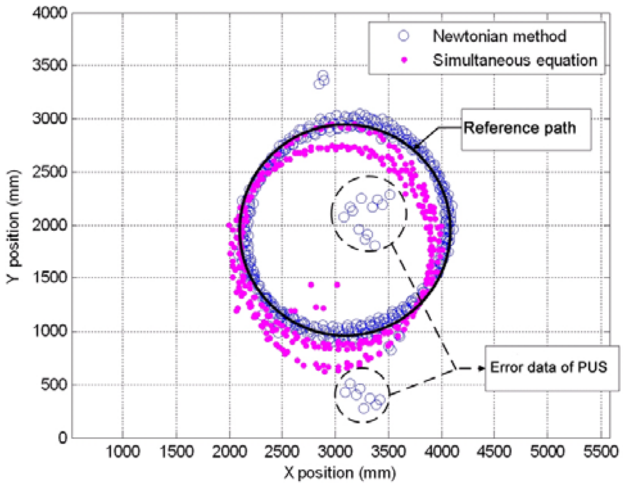


Fig. 13 Experimental results of X,Y estimation at speed 0.61 m/s

4.3 Azimuth angle Kalman filter performance experiment results

Two ultrasonic positioning system receivers are placed and the azimuth is measured from the position of the two receivers. In the case of noise, wrong azimuth can be obtained from the two receivers. Or the distance between the two receivers can be closer than the error making the azimuth error larger. In this experiment, the distance of the installed reception was 60cm longer than the receiver measurement error, which reduced the azimuth error. However, the closer distance between receivers, the noise of the ultrasonic measurement value increases the azimuth error. This leads to incorrect input in the lateral control causing error in steering.

The obtained angular acceleration from gyro is integrated to measure azimuth angle. To measure the azimuth angle using gyro, it is necessary to first set an initial position. In gyro, the data gain cycle is very short and the data is fairly accurate compared to the short section. However, the longer it takes to integrate, the accumulation of bias, drift, and noise causes errors to accumulate as well.

Fig. 15 and 16 show the results of the measured azimuth and that of Kalman filter using the absolute position estimated equation of the PUS and the inertial navigation equation of the gyro attached to the IMU at 0.18m/s and 0.61m/s, respectively. The noise of the gyro and the

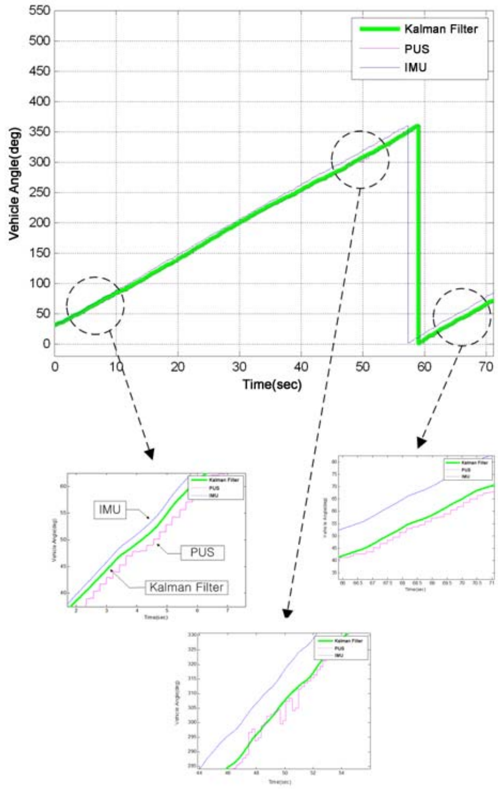


Fig. 15 Results of yaw angle integrated by Kalman filter at speed 0.18 m/s

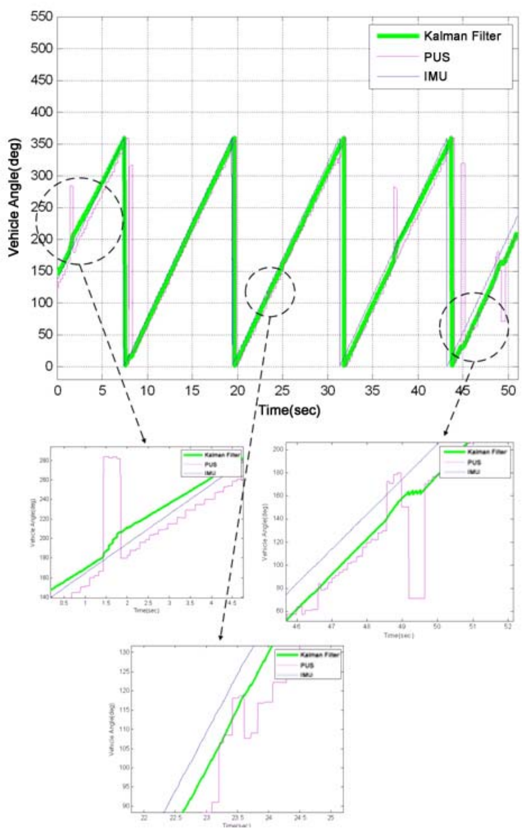


Fig. 16 Results of yaw angle integrated by Kalman filter at speed 0.61 m/s

integration bias caused error accumulation, so the difference between the two increases with time. The azimuth measured with the PUS can be calculated with a larger value due to the noise during measurement. In the PUS, the faster the vehicle, the more likely error will occur. The faster speed results (Fig. 16) shows more frequent errors than the slower results (Fig. 15). The use of Kalman filter reduces these errors for more accurate and precise azimuth.

5. Conclusion

To achieve unmanned vehicle or mobile robots, the main technology requirement is to quickly estimate the present position of the moving object. The position estimation of outdoor vehicles has been mostly based on GPS. Using an ultrasonic frequency similar to GPS, to measure the pseudorange, PUSs are being developed. In our studies, we use an PUS to measure the position and azimuth of a 4WS vehicle. Also, a gyro is used to measure the azimuth angle. More precise azimuth angle measurements were obtain from the PUS and gyro using Kalman filtering.

When calculating the position of the vehicle with the PUS, a new numerical analysis of the Newton-Raphson method and least square method were used to increase the accuracy and precision of the position estimations. Weights were introduced to reduce structure errors. Obtaining stable and accurate position and azimuth information reduces and/or eliminates the errors in navigation. The controller made with the objective arbitration method provided with more precise distance error and angle error feedback resulted in faster and more accurate navigation. Controlling the differences and coefficients of the desirability function used in the objective arbitration method allowed more stable and accurate path navigation. Experiments and results imply that this can be applied to real vehicle and safe unmanned vehicle navigation is possible within a certain speed.

Future complementary studies need to include the installation of an accelerometer, the installation of an encoder on the tires for faster and more accurate positioning. And in the dynamics of the 4WS vehicle, making the navigation more stable is necessary. With the design of a control that considers the variations of the steering angle and position, the navigation will become more stable. Research will continue until these are applied to a real vehicle.

References

[1] Bender, J. G.(1991), "An overview of system studies of automated highway system", IEEE Trans. On Vehicular Technology, Vol.40, No.1.

[2] Brown, R. G. and Hwang, P. Y. C.(1997), Introduction to random signals and applied Kalman filtering, 3rd ed., Wiley, New York.

[3] Ebken, J., Bruch, M., and Lum, J.(2005), "Applying unmanned ground vehicle technologies to unmanned surface vehicles", International Society for Optical Engineering, Vol.5804, No.1, pp.585-596.

[4] Farrell, J. and Barth, M.(1998), The global positioning system & inertial navigation, McGraw-Hill, New York.

[5] Fulton, J. and Pransky, J.(2004), "DARPA Grand Challenge - a pioneering event for autonomous robotic ground vehicles", The Industrial Robot, Vol.31, No.5, pp.414-422.

[6] Hall, C. S., Marsh, J. N., Scott, M. J., Gaffney, P. J., Wickline, S. A., and Lanza, G. M.(2001), "Temperature dependence of ultrasonic enhancement with a site-targeted contrast agent", The Journal of the Acoustical Society of America, Vol.110, No.3, pp.1677-1684.

[7] Hedrick, J. K., McMahon, D. H., and Swaroop, D.(1993), "Vehicle modeling and control for automated highway system", ITS Publication.

[8] Kodaira, M., Ohtomo, T., Tanaka, A., Iwatsuki, M., and Ohuchi, T.(1996), "Obstacle avoidance travel control of robot vehicle using neural network", Systems and Computers in Japan, Vol.27, No.12, pp.102-112.

[9] Kim, S. Y.(2005), "Position estimation and performance evaluation of a mobile robot using ultrasonic pseudo-satellites", Master Thesis, Pusan National University.

[10] Lovece, J.(1994), "Unmanned Vehicle Update: recent activities and trends relating to unmanned systems programs", Unmanned Systems, Vol.12, No.1.

[11] Schoenian, R. J. and Cameron, D. L.(1996), "CVO vehicle-to-roadside communications applications", SAE Transactions, Vol.104, No.2, pp.824-829.

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