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The Study of the Position Estimation for an Autonomous Land Vehicle

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Abstract

In this paper, we develop and implement a high integrity GNC(Guidance, Navigation, and Control) system, based on the combined use of the Global Positioning System (GPS) and an Inertial Measurement Unit (IMU), for autonomous land vehicle applications. This paper highlights guidance for the predetermined trajectory and navigation with detection of possible faults during the fusion process in order to enhance the integrity of the navigation loop. The implementation of the GNC system to the autonomous land vehicle presented with fault detection methodology considers high frequency faults from the GPS receiver caused by shadowing and multipath error. The implementation, based on a low-cost, strapdown INS aided by standard GPS technology, is described. The results of the field test in the urban environment are presented and showed effectiveness of the GNC system.

Key words : Guidance, Navigation, IMU, GPS, Error Model

1. Introduction

Recently, autonomous land vehicles and mobile robot have been spotlighted in various industries. In comparison with a general robot that carries out its tasks on a fixed spot, an autonomous land vehicle must be capable of moving autonomously while it performs its job in a given environment. In addition, an autonomous land vehicle should be able to move from one position to another without any constraint. Such systems are necessary to provide knowledge of vehicle position and trajectory and subsequently to control the vehicle along a desired path [1]-[4].

The main idea in studying an autonomous land vehicle begins with very simple matters: "Where am I?" and "How can I get to my goal?" These two questions are defined with navigation and guidance respectively. In other words, navigation and guidance are techniques that make it possible to travel from some reference point to a goal. To achieve such a task, an autonomous land vehicle must identify its exact current position, velocity and attitude.

There are many research about the development of navigation system using several methods. First method is that vehicle has a sensing the magnetic field from magnet which is buried in the center of the road. Second method is that use image processing technique. The vehicle follows the foregoing vehicle using image processing of the size of license plate, or move with image processing the center line. Third method is that use of the landmark. However these navigation systems are dependent of the environment, cost non-effective or burden of calculation..(마침표 하나 삭제) So dependent of environment, the vehicle may lose its position data and drift away from its determined trajectory. This is the main problem to solve when an autonomous land vehicle is operated in outdoor environments. To overcome such a problem, the GPS and/or Inertial Navigation System that is usually applicable in aircraft navigation may be employed [5]-[7].

The inertial navigation system and radio navigation system are used in aeronautical navigation. Although it is capable of collecting data independently, the inertial navigation system, which calculates the position and speed of moving vehicle in inertial navigation coordinates, is mainly used in military and spacecraft applications due to its high cost and error accumulation. Recently, as a result of various research efforts into RLGs (Ring Laser Gyroscopes) and FOGs (Fiber Optic Gyroscopes), the inertial navigation system has been modified in many aspects of performance and applicability. Also, research is being conducted into applications that are combined with radio navigation. The radio navigation system that calculates a moving vehicle's position by using radio waves with installed radio receivers was developed during World-War-II

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and has been widely used for many different purposes. Its merits include cost-effectiveness, ease of installation and usability by multiple individuals. There are several types of radio navigation system, such as Omega, VOR, Loran-C, etc. This radio navigation system still has some weaknesses, among them restrictions on usable area because of the limits of radio power and a lack of precision in terms of geographical environments. To overcome these weak points, satellite applied radio navigation studies were carried out by the US Navy and Air Force. From those studies, a Transit system was constructed with 6 polar orbit satellites and finally the GPS system using 24 satellites was born. The GPS system has a position error of less than 5m or 100m when the SA (Selective Availability) band or public band is used respectively. There are still some difficulties with position errors resulting from multi-path and shadowing problems. Multi-path errors that do not occur in rural areas come from wave delay in urban areas because of satellite wave signal deflection against multiple buildings. Because the GPS identifies position by calculating the distance between an object and the satellite using at least four high frequency signals from satellites, if there are massive structures such as buildings, a position cannot be identified due to such shadowing.

This paper discusses a navigation system constructed with GPS and a low-cost inertial measuring unit. The GPS takes the role of absolute sensor for position measuring. The inertial measuring unit acts as a fault compensator for GPS errors. For each sensor, still tests were carried out. From test data, error-models of sensors were constructed. Finally, traveling test simulation showed successful GPS error compensation in 2-dimensional planar mission profiles.

2. Schematic of the System

Fig.1 shows an overview of the system. Three one-axial gyroscopes calculate angular acceleration rates for axes X, Y and Z. Two bi-axial accelerometers were used for measuring velocity change rates on the X, Y and Z-axis. The accelerometers were placed on the center of the IMU in a perpendicular manner. The gyroscopes were installed at right angles against accelerometers.

Each sensor signal is amplified in regular sequence within a 0-5V level from gyroscopes and supplied to an ADC (Analog-Digital Converter) by a multiplexer. The ADC calculates the position of the moving vehicle by sending a digitized signal toward a DSP chip, integrating the angular rate and a double integration of speed rate. In addition, the DSP chip corrects the position data every second with GPS data transmitted by an RS-232C serial port. The calculated position data are sent to a laptop computer for data logging via an RS-232C serial port.

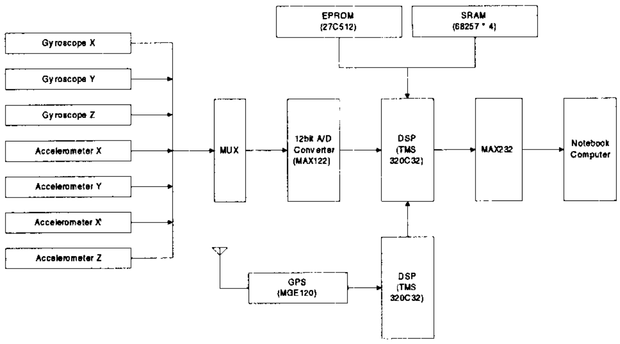

Fig. 1 System Configuration

3. Sensor

3.1 IMU

In aircraft navigation and guidance, an IMU is organized with a gyroscope that measures angular rate and an accelerometer that measures speed. An IMU also can be classified as GINS (Gimbaled Inertial Navigation System) or as SDINS (Strap-Down Inertial Navigation System), depending on whether a gimbal is installed or not. The GINS measuring angular rate has a rotor rotating inside of gimbaled platform which constantly points in the same direction. The speed rate is measured by an accelerometer installed on a platform. In SDINS a gyroscope and an accelerometer are installed on a vehicle directly which has no platform. In early days, GINS were mainly used. However, inertial navigation systems of the SDINS type have been used recently because of cost-effectiveness [3].

Gyroscopes can be classified as RLG (Ring Laser Gyro), FOG (Fiber Optic Gyro) and piezoelectric gyroscope according to the composition material of SDINS. The cost and accuracy are related closely as a trade-off.

The information on the angular acceleration and angular velocity rate of an IMU is dependable in the long term, but integration must be carried on for calculating position data. Thus, error accumulates over time even if the initial error was tiny. Such errors are due to initial attitude error, lineup error of the gyroscope, error of bias and scale factors and integration error.

There are three required Euler angles for getting attitude information for the vehicle. Yaw attitude ψ, pitch attitude θ, and roll attitude ϕ are obtained from integrating the following equations [8].

$$\begin{aligned} \dot{\phi} &= p + q\sin\phi\tan\theta + r\cos\phi\tan\theta \\ \dot{\theta} &= q\cos\theta - r\sin\phi \\ \dot{\psi} &= (q\sin\phi - r\sin\theta)/\cos\theta \end{aligned} \tag{1}$$

where, roll rate p, pitch rate q, and yaw rate r of a vehicle are measured from 3 gyroscopes that are installed on the vehicle.

Accelerometer measure acceleration about each axis of the body frame. So we have velocity with integration of measured acceleration, and position from integration of the velocity.

$$\bar{p} = \int \bar{v}dt = \iint \bar{a}dt \tag{2}$$

where $\bar{p}$ is the position vector, $\bar{v}$ is the velocity vector, a is the acceleration vector.

Autonomous land vehicle frequently has a start and stop motion. Accelerometer measures acceleration due to every external force except the gravitational component. Thus, if one assumes the accelerometer is installed on a vehicle's center of gravity, the measurements of accelerometer shall be same as the following [9].

$$\begin{aligned} a_x &= \frac{F_x}{m} - g_x \\ a_y &= \frac{F_y}{m} - g_y \\ a_z &= \frac{F_z}{m} - g_z \end{aligned} \tag{3}$$

In the above relations, F_x, F_y and F_z are sums of every external force acting on the body frame. m is vehicle mass. g_x, g_y, and g_z are components of gravitational acceleration on each axis as below.

$$\begin{aligned} g_x &= -mg\sin\theta \\ g_y &= mg\cos\theta\sin\phi \\ g_z &= mg\cos\theta\cos\phi \end{aligned} \tag{4}$$

If vehicle has stopped, the accelerometer measures only gravitational force. So we have a calculated attitude as below.

$$\begin{aligned} a_x &= \dot{u} + wq - vr + g\sin\theta \\ a_y &= \dot{v} + ur - wp - g\cos\theta\sin\phi \\ a_x &= \dot{w} + vp - uq \end{aligned} \tag{5}$$

where u, v, w are linear velocity of the X, Y, Z axis of the body frame. Attitude angles ϕ_g, θ_g, ψ_g from gyroscope have a superior property at the high frequency range. So we employ high pass filter for ϕ_g, θ_g, ψ_g as below.

$$\begin{aligned} \phi_m(s) &= \frac{s + k_2}{s^2 + k_2 s + k_1}\dot{\phi}_g(s) \\ \theta_m(s) &= \frac{s + k_2}{s^2 + k_2 s + k_1}\dot{\theta}_g(s) \\ \psi_m(s) &= \frac{s + k_2}{s^2 + k_2 s + k_1}\dot{\psi}_g(s) \end{aligned} \tag{6}$$

where k_1, k_2 are selected from the sensor dynamics.

3.2 GPS

The Navstar/GPS (NAVigation Signal Time and Range/Global Positioning System) is a position determining system using wave signals of satellites that are orbiting 20,183−20,187Km from earth. There are two different types of code: C/A (Coarse/Acquisition) code and P (Precision) code. For public and military applications, C/A code with frequency of 1.023MHz and P code with frequency of 10.23MHz is are used, respectively.

We determine the position of a moving vehicle as follows.

$$s = \begin{bmatrix} s_x \\ s_y \\ s_z \end{bmatrix} \tag{6}$$

The coordinate of the i th satellite whose exact position is known is as follows.

$$S_i = \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} \tag{7}$$

The pseudorange can be calculated from the following relation.

$$r_i = \sqrt{(x_i - s_x)^2 + (y_i - s_y)^2 + (z_i - s_z)^2} + cb \tag{8}$$

where c is the speed of light and b is the clock bias of a receiver. From the calculated pseudorange of satellite, one can get the position of a moving vehicle by triangulation. (폰트가 틀려 수정함)

4. Error Model

The navigation loop is composed of a Kalman filter that estimates the position, velocity and attitude errors of the IMU[10]. The measured data of each inertial sensor was analyzed with null input for an hour. If there are errors in the stationary test, these are due to inaccuracy of the gyroscope and accelerometer, alignment error · of the inertial sensor installation, truncation error in the computation of measured sensor values and error in system modeling approximation. One may separate these errors into two categories by qualitative analysis. The first is a deterministic case that can be easily expressed mathematically with coefficients. These errors are simply compensated for with subtraction. The second is a stochastic case also known as random error. In this kind of case, errors will be handled in a stochastic manner. The reason for such errors may be time−variant and will be treated with a parameter estimation method. The sensor interface board used in the test is shown in Fig.2. We installed an accelerometer in the center of gravity and gyro beside it.

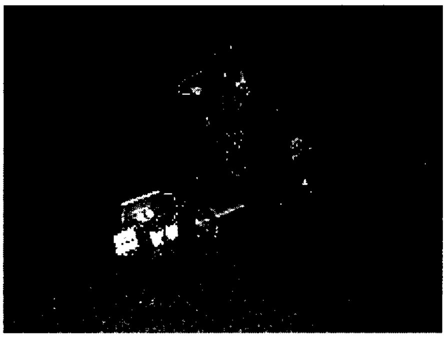

Fig 2. Sensor Interface Board

4.1 Gyroscope

We used three ENV−05DB, which is a gyroscope from Murata Co. as shown in Fig.3. Its measured value of maximum angular rate is +/−80deg/sec and linearity is +/−5% of full scale. The offset drift is maximum 0.2Vp−p, and the bandwidth is 7Hz.

Fig.4 shows the measuring data of the gyroscope in a stationary test. The standard deviation of each axis X, Y and Z are 0.0559deg/sec, 0.0278deg/sec and 0.0129deg/sec.

We make the shaping filter of the gyroscope as follows.

$$e_m(t) = (c_3 t^3 + c_2 t^2 + c_1 t + c_0) w(t) \tag{9}$$

where, $e_m(t)$ is a output of the error model, $w(t)$ is a Gaussian white noise.

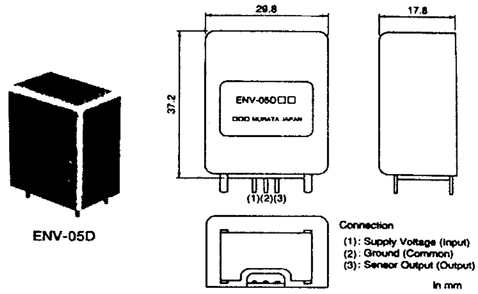

Fig. 3 Gyroscope ENV−05DB

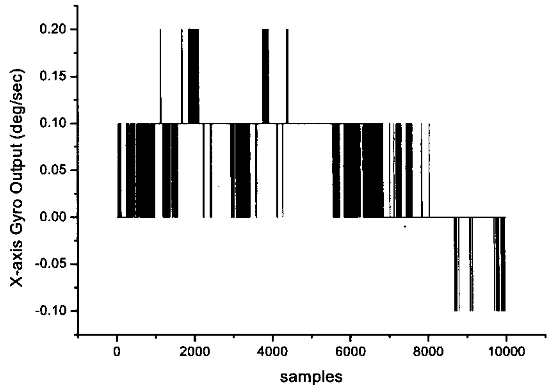

Fig. 4 (a) Stationary Test Result of the Gyroscopes about X−axis

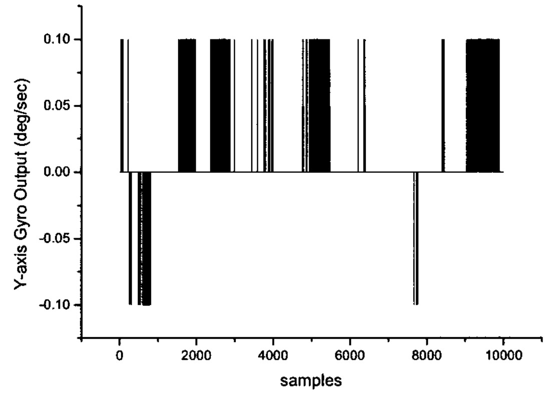

Fig. 4 (b) Stationary Test Result of the Gyroscopes about Y−axis

The coefficients of the X−axis gyroscope model are c_3 =1.77899E−6, c_2 =−0.11971E−3, c_1 =4.92017E−3, c_0 =−2.0295E−3. Fig.5 shows the propensity of average level for the X−axis gyroscope and error model. The dashed line is the output of the gyroscope and dotted line is the output of error model.

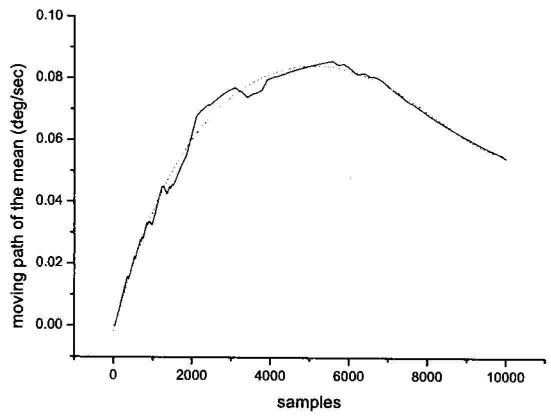

Fig. 5 Moving Path of the means of data and model

4.2 Accelerometer

The accelerometer used in this study was an ADXL202JQC from Analog Device Co. The stationary test data of the ADXL202JQC are shown in Fig.6. Its measured value of maximum linear velocity rate is +/−2g and nonlinearity is +/−0.2% of full scale. The sensitivity is 5mg and the bandwidth is 60Hz.

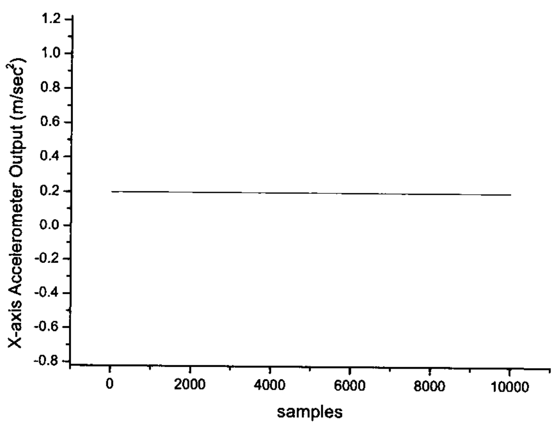

Fig. 6 Stationary Test Result of the Accelerometer about X-axis

The accelerometer error in the stationary test has a bias of 0.2 only. In such a deterministic case, enough error compensation may be achieved by subtraction of corresponding values.

4.3 GPS

The GPS that was used in this study was MGE120 with a GPS engine from Mitac Co. Fig.7 shows the test result. Standard deviations are 0.00026deg and 0.00018deg.

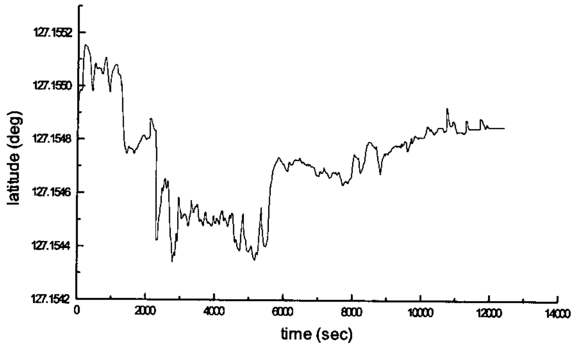

Fig. 7 Latitude Measurement of the GPS at Staionary Test

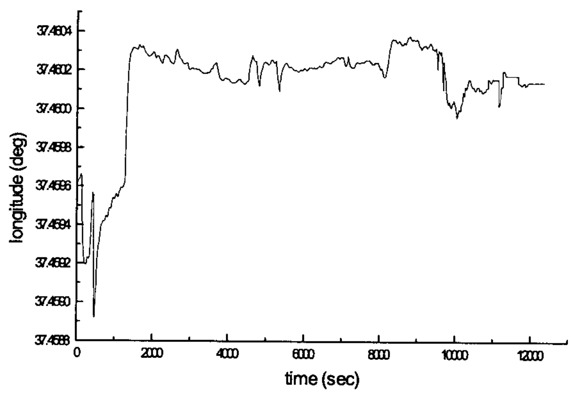

Fig. 8 Longitude Measurement of the GPS at Staionary Test

4.4 Verification of error model

To prove the validity of the error model, a whiteness test was carried out. The remainder value after subtraction from actual measured data to constructed model is white. In the case where the average equals to zero, the constructed model is assumed to be proper [9].

The residual $w(k)$ is shown in the following equation.

$$w_k = e(k) - e_m(k) \qquad (10)$$

where is $e(k)$ sensor data, $e_m(k)$ is output from the error model of the sensor.

5. Navigation Filter

We proposed the navigation filter to reduce the position error. In the horizontal plane, position, measured velocity and azimuth angle of the vehicle are as follow.

$$\dot{x}_i = V\cos\gamma\cos\psi \qquad (11)$$

$$\dot{y}_i = V\cos\gamma\sin\psi \qquad (12)$$

$$V_m = V + \delta V \qquad (13)$$

$$\psi_m = \psi + \delta\psi \quad (14)$$

The velocity components of the vehicle are as below.

$$u_i = (V_m - \delta V)\cos(\psi_m - \delta\psi) \quad (15)$$

$$v_i = (V_m - \delta V)\sin(\psi_m - \delta\psi) \quad (16)$$

We make the matrix form above equations as follow.

$$\begin{bmatrix} \dot{x}_i \\ \dot{y}_i \\ \delta\dot{V} \\ \delta\dot{\psi} \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\cos\psi_m & v_m \\ 0 & 0 & -\sin\psi_m & -u_m \\ 0 & 0 & -k_{\delta v} & 0 \\ 0 & 0 & 0 & -k_{\delta\psi} \end{bmatrix} \begin{bmatrix} x_i \\ y_i \\ \delta V \\ \delta\psi \end{bmatrix} + \begin{bmatrix} \eta_x \\ \eta_y \\ \eta_{\delta V} \\ \eta_{\delta\psi} \end{bmatrix} \quad (17)$$

where, x_i and y_i are position of the inertial frame, η_i are process noise.

We apply the Kalman Filter[10] and have a simulation in the condition as following. The velocity of the vehicle is 16m/sec, and deviation of the velocity is 1m/sec. The deviation of the attitude angle is 2deg. The simulation results are as follows, and similar each other.

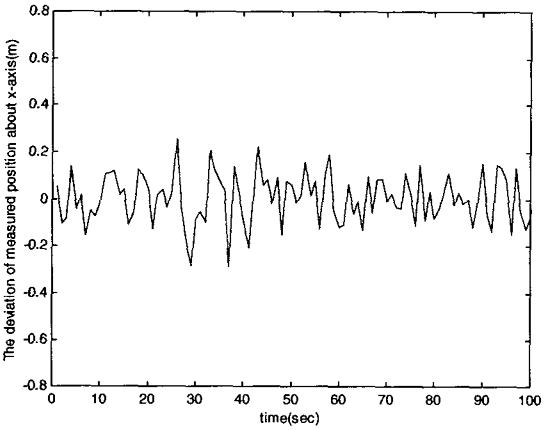

Fig. 9. The deviation of the measured position

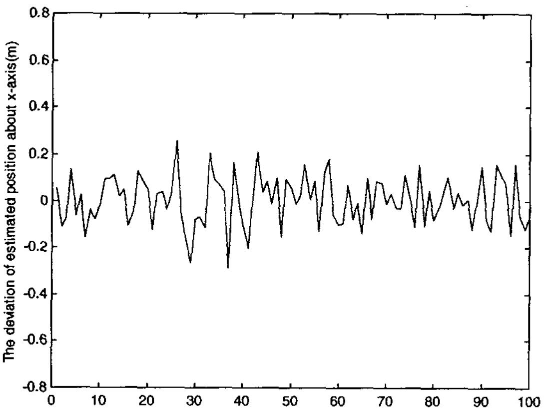

Fig. 10. The deviation of the estimated position

6. Test Result

The simulation tests were carried with an assumption of the moving vehicle as a point mass. The Kalman filter gain was used from a covariance matrix that was taken from the stationary test data of IMU[10]. The moving vehicle was assumed to be moving at a speed of 30KPH on a two-dimensional planar surface. At its start point, the moving vehicle directed the X-axis and its position was (0,0). The mission profile is constructed in the direction of the X-axis for 600 seconds, then in the direction of theY-axis for 600 seconds, next in the direction of the X-axis for 600 seconds and finally in the direction of -the Y-axis to return its starting point. Fig.11 shows the mission profile.

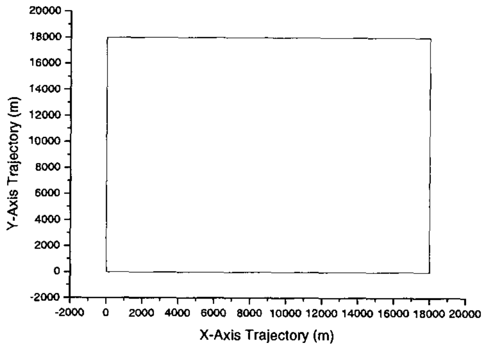

Fig. 11 Mission Profile of the Simulation

Within 1000 to 1400 seconds of the mission profile, shadowing occurred and it was assumed that the GPS could not collect data from satellites. The simulation result is shown in Fig.12. When the GPS cannot receive data from satellites, its engine fixes the last transmitted data as its position. Therefore, it holds the position data at 1000 seconds until the next transmission.

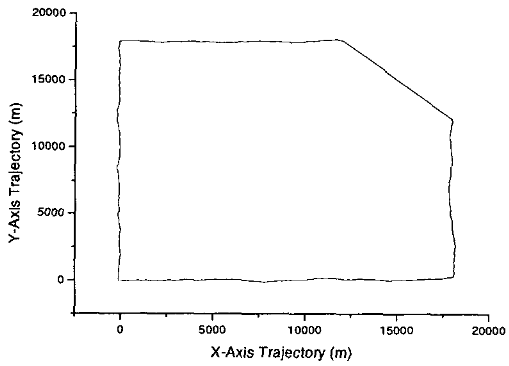

Fig. 12 Trajectory of the Vehicle using GPS Navigation

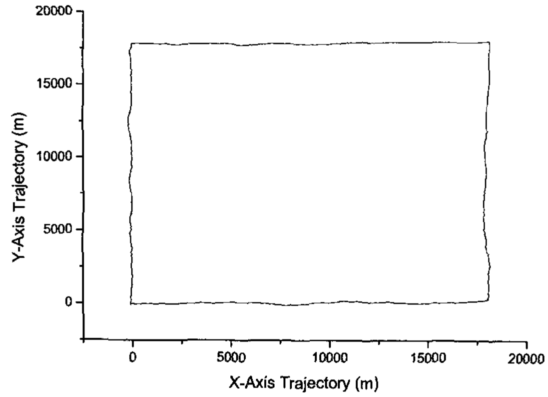

Fig. 13 Trajectory of the Vehicle using IMU and GPS Navigation

Fig.13 shows the result of simulation when an IMU and GPS are combined in an inertial navigation system. From this simulation, the moving trajectory of the vehicle was correctly estimated even if the GPS cannot receive a proper signal from satellites.

We have a road test in the Sungnam City. We start from Sung Nam Polytechnic College through tunnel, downtown and highway to College. Fig. 14 shows the number of visible satellite. When the vehicle entered tunnel, and passed below the bridge, and between the building, GPS cannot received satellite signals.

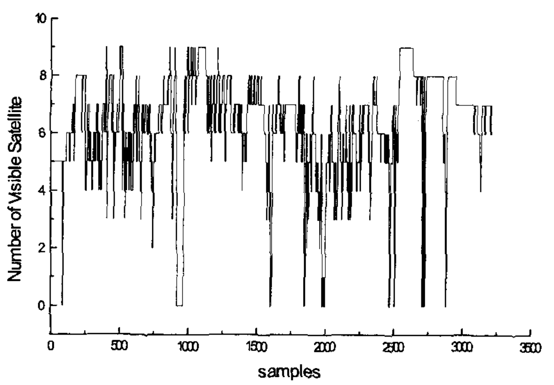

Fig. 14 Number of Visible Satellites

Fig. 15 shows a road test result which IMU compensated the position data when GPS missing the satellite signals. Fig. 16 shows the position data when GPS missing the signals.

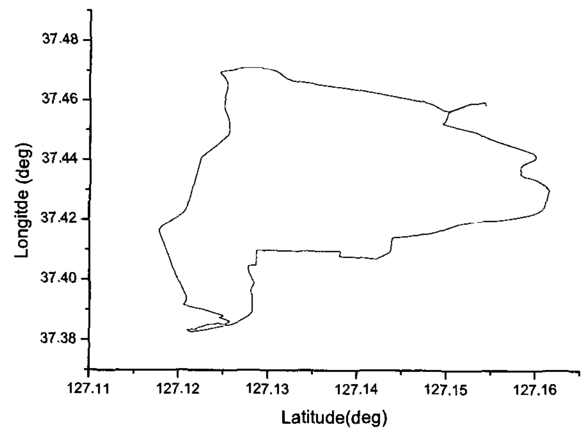

Fig. 15 Road Test Result

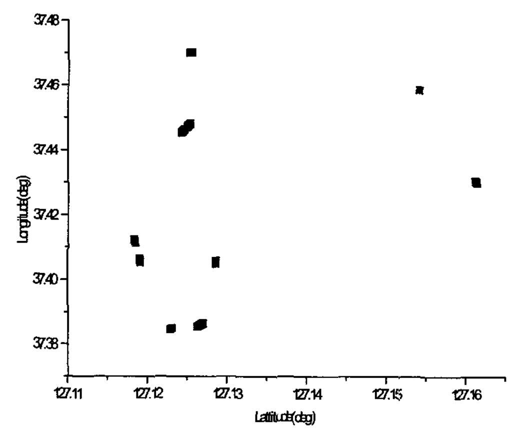

Fig. 16 Position when GPS missing satellite signals

6. Conclusion

This paper discusses an GNC system for autonomous land vehicle combine with IMU and GPS. We collected data from the sensors of a vehicle in a stationary test. An error model was established with sensor error data and its validity proved by using a whiteness inspection approach. For the case of vehicles which cannot receive a proper signal from satellites because of GPS shadowing, we built a Mission Profile to show how the designed navigation system was capable of identifying its proper position. We have a road test in real environment and proved its correctness. To achieve the more accurate position data, we will have a study with DGPS(Differential GPS) and IMU.

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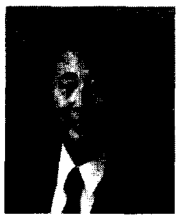

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