Outdoor Localization for Quad-rotor using Kalman filter and Path planning *

Chen-Hu†
Department of Electronic Engineering, Pusan National University, Jangjeon-2-dong, Geumjeong-gu, Busan 609-735, South Korea‡

Yo-Seop Hwang
Department of Electronic Engineering, Pusan National University, Jangjeon-2-dong, Geumjeong-gu, Busan 609-735, South Korea

Wang Zhitao
Department of Electronic Engineering, Pusan National University, Jangjeon-2-dong, Geumjeong-gu, Busan 609-735, South Korea

Jang-Myung Lee
Department of Electronic Engineering, Pusan National University, Jangjeon-2-dong, Geumjeong-gu, Busan 609-735, South Korea
E-mail: chenhu@pusan.ac.kr, mmx001@pusan.ac.kr, jmlee@pusan.ac.kr,zhitao7379@pusan.ac.kr
www.pusan.ac.kr

Abstract

This paper proposes a new technique that produces the improved local information using low-cost GPS/INS system combined by Kalman filter and Path Planning when a Quad-rotor flies. Throughout the research, the low cost GPS is combined with INS by using the Kalman filter in order to improve local information. However, this system has certain disadvantages as follows. The level of estimation accuracy could get worse when the quad-rotor flies through the air by forming a curve. Also, the level of precision for the position information is influenced by the performance of GPS. In order to deal with such disadvantages, the algorithm based on the path planning can be adopted. When the quad-rotor flies outdoor, it is possible to predict that its moving path is short, since all the short moving paths of the quad-rotor can be assumed to be straight. The path planning is used to make such a short moving path and determine the closest local information of the GPS/INS system. Through the foregoing process, an improved kind of local information can be obtained when the quad-rotor flies. Also, the performance of the proposed system can be verified based on the outdoor experiments.

Keywords: Path Planning, Cell Divided Algorithm, Kalman filter, Quad-rotor, GPS, INS

1. Introduction

Recently, the level of interest regarding the unmanned aerial vehicle (UAV), which can effectively carry out various monitoring tasks for disasters, life-saving situations, environmental conditions, traffic congestion and military reconnaissance, has been increased [1]. The low-cost and small-sized quad-rotor can be regarded as a rotary-blade-type UAV which flies by using four rotor s. Since it has various advantages including such functions as vertical takeoff and landing, hovering and omnidirectional movements, the quad-rotor has been widely used in real life for such tasks as serving meals, delivering various objects and supporting various outdoor activities including jogging. Also, researches have been actively carried out in regard to the field. In order to carry out various tasks, the quad-rotor needs to have an autonomous navigation function which is possible only when it can precisely recognize its position. As the quad-rotor carries out its tasks mainly outside, it is necessary to use a precise kind of navigation technology for the estimation of outdoor positions. For such a technology, the recently – executed researches [2][3] have focused on the process of precisely estimating positions based on the combination of the inertial navigation system (INS) and GPS. The INS system is composed of such sensors as the acceleration sensor, the gyro-sensor and the geomagnetic sensor which can be used to estimate both absolute and relative positions simultaneously [4]. It can provide precise information regarding positions within a short time. However, due to the disturbance caused by the property errors of the sensors and the external environment, it is possible to see an accumulation of errors when it is used for a long time. GPS has such a shortcoming as the possibility for having a great position error within a short time. Also, it would be hard to use GPS in the radio-shadow area where the GPS signals can be disconnected [5]. However, it provides a stable kind of information for absolute positions in a long time, since it keeps correcting the position information by continuously receiving signals from the satellite in real time without having any accumulation of errors. In order to establish the GPS/INS fusion position estimation system with the advantages mentioned above, GPS and INS are combined by using the Kalman filter, the extended Kalman filter and the Particle filter, while the properties of each other are compensated through such a process.

This paper is concerned with the process of designing, implementing and experimentally validating the combination of the GPS/INS-fusion position estimation system where the Kalman filter and the path planning algorithm are properly adopted. The Kalman filter is suitable for estimating the states of linear systems with a small amount of computations. However, this Kalman filter is not enough by itself to overcome the linear errors occurring during the flight of the quad-rotor since it has a low level of accuracy for the state estimation regarding the nonlinear path. Even though the precise GPS/INS fusion system can be implemented by using the Kalman filter, its accuracy is also limited by the accuracy of each sensor. To overcome the sensor capabilities as well as the filtering limits, the path planning information has been utilized for the localization with the direction information captured by the geomagnetic sensor in the INS system. In other words, the estimated path has been mapped onto the nearest path provided by the path planning to improve the localization accuracy overall.

The paper consists of the following sections. In Section II, the configuration of the system is introduced. In Section III, the GPS/INS fusion algorithm is described. After that, in Section IV, the Path planning algorithm is discussed. Then, in Section V the performance of the position estimation process, which is suggested in this paper, is verified through an experiment. Lastly, a conclusion is given.

2. System Configuration

In this paper, the configuration of the proposed system is given as shown in Figure 1. The micro-controller unit (MCU), which was used to control the system, is ATMEGA 2560 made by Atmel. Also, MPU-6050, which is a combined form of a tri-axis gyro-sensor and a tri-axis acceleration sensor, HMC-5883, which is a tri-axis geomagnetic sensor, and BMP-085, which is a pressure sensor, were used, while MTK-3329, which is a GPS sensor, was applied for the recognition of positions. In order to generate the thrust of the quad-

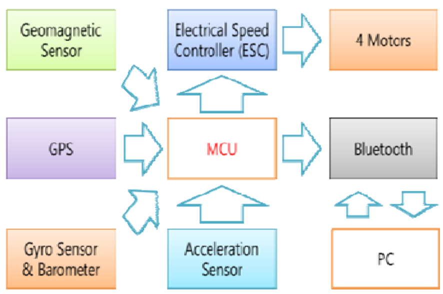

Fig. 1. System Block Diagram

rotor, the electrical speed controller (ESC) and the brushless motor from RoHS were used.

The propellers of the quad-rotor were designed to offset the rotating force of one another and generate a thrust in order to prevent the body from rotating, while RN-42 Bluetooth from RoHS was used to command the robot to move and return. Figure 2 shows the hardware configuration of the system. The GPS receiver was designed to be located on the upper part of the quad-rotor in order to receive the data as accurately as

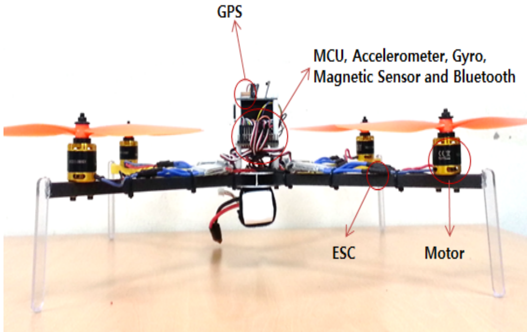

Fig. 2. Total Quad-rotor Configuration

possible, while MCU and IMU sensors were arranged below.

3. GPS/INS Fusion

Since INS consecutively provides information regarding the velocity of the body and the change of positions by integrating the acceleration data twice, its dynamic feature could be good, but it is possible to have an accumulation of errors as time goes by. Also, while GPS provides the position information of the body outside, it could create severe errors based on the geographical features. In order to compensate the disadvantages of GPS and INS by combining the data given by each system, the Kalman filter (KF) and the Extended Kalman filter (EKF) can be used. The Kalman filter can be applied to the linear system, while the Extended Kalman filter can be applied to the nonlinear system. The position and state of the quad-rotor in a straight path contains some linear factors. Therefore, in the research, GPS and INS can be combined by using the Kalman filter.

The GPS/INS-fusion algorithm used in this paper is shown in Figure 3.

By using the angular velocity ($\tilde{\omega}_{ib}^{b}$) obtained from the gyro-sensor, the position expressed in quaternions ($\hat{q}$) can be updated

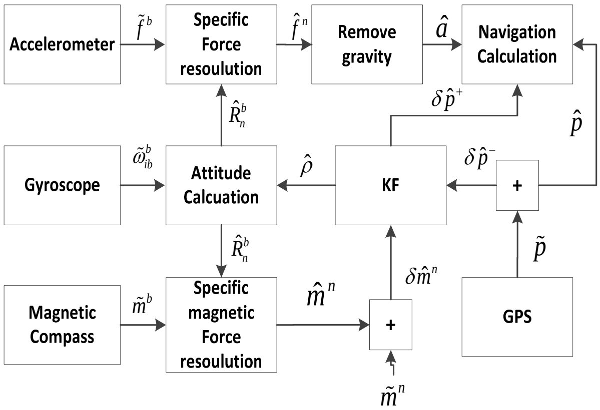

Fig. 3. Fusion algorithm of GPS and INS

$$\hat{q} = \frac{1}{2} q \times (\tilde{\omega}_{ib}^{b} - \hat{b}_{gyro}) \qquad (1)$$

As shown in Equation (1), the position expressed in

$$\hat{R}_{n}^{b} = \begin{bmatrix} \hat{q}_1^2 + \hat{q}_2^2 - \hat{q}_3^2 - \hat{q}_4^2 & 2(\hat{q}_2^2\hat{q}_3^2 - \hat{q}_1^2\hat{q}_4^2) & 2(\hat{q}_1^2\hat{q}_3^2 + \hat{q}_2^2\hat{q}_4^2) \\ 2(\hat{q}_2^2\hat{q}_3^2 + \hat{q}_1^2\hat{q}_4^2) & \hat{q}_1^2 - \hat{q}_1^2 + \hat{q}_1^2 - \hat{q}_1^2 & 2(\hat{q}_3^2\hat{q}_4^2 - \hat{q}_1^2\hat{q}_2^2) \\ 2(\hat{q}_2^2\hat{q}_4^2 + \hat{q}_1^2\hat{q}_3^2) & 2(\hat{q}_1^2\hat{q}_2^2 + \hat{q}_3^2\hat{q}_4^2) & \hat{q}_1^2 - \hat{q}_2^2 - \hat{q}_3^2 + \hat{q}_4^2 \end{bmatrix} \qquad (2)$$

quaternions can be used to calculate the transformation matrix which transforms the structural coordinates to the navigation coordinates.

The difference between the position ($\hat{p}$) which is obtained by integrating the acceleration ($\hat{a}$) of the navigation coordinates twice and the position ($\tilde{p}$) which is obtained through the reception of GPS can be calculated as shown in the following equation.

$$\delta\hat{p}^{-} \equiv \tilde{p} - \hat{p} \qquad (3)$$

By using the transformation matrix, the measured value ($\tilde{m}^{b}$) of the geomagnetic sensor can be transformed to the value of ($\hat{m}^{n} = \hat{R}_{n}^{b}\tilde{m}^{b}$) in order to measure the value of the magnetic value of the earth. The difference between the actual magnetic value of the earth (m^{n}) and the calculated magnetic value of the earth can be defined as $\delta\hat{m}^{n} \equiv \tilde{m}^{n} - \hat{m}^{n}$. By using $\delta\hat{p}^{-}$ and $\delta\hat{m}^{n}$ as the measured values of KF, the following state space equation can be designed to estimate the position error ($\hat{\rho}$) and the location error ($\delta\hat{p}^{+}$). Based on the calculated error, the position and the location can be updated in order to obtain corrected values.

$$\delta \mathbf{x}_k = f_k(\delta \mathbf{x}_{k-1}) + \omega_k,\ \delta \mathbf{y}_k = h_k(\delta \mathbf{x}_k) + v_k \tag{4}$$

The estimated value of k can be given as $\hat{k}$, while the measured value can be defined as $\tilde{k}$. f_k is the state propagation function and h_k is the measurement equation, while ω_k is the system error and v_k is the measurement error. δy_k is the measured value. KF can be considered to have 15 states with such random variables as the 3-dimensional location errors (δp), the velocity errors (δv), the position errors (ρ) and the bias errors given by the acceleration sensor (δb_{acc}) and the gyro-sensor (δb_{gyro}).

$$qx = \begin{bmatrix} \delta p^T & \delta v^T & \rho^T & \delta b_{acc}^T & \delta b_{gyro}^T \end{bmatrix} \tag{5}$$

Here, the equation of $\delta k \equiv k - \hat{k}$ can be given, while the factors of each random variable can be defined as follows.

$$\begin{aligned} p &\equiv \begin{bmatrix} x & y & z \end{bmatrix}^T \\ v &\equiv \begin{bmatrix} v_x & v_y & v_z \end{bmatrix}^T \\ \rho &\equiv \begin{bmatrix} \varepsilon_N & rl & \varepsilon_D \end{bmatrix}^T \end{aligned} \tag{6}$$

Here, ε_N is a tilt error, while ε_D is a heading error.

4. Path Planning Algorithm

The path planning process is carried out by using the cell divide algorithm and the geomagnetic information. The cell divide algorithm is one of the methods used to plan the path of a moving object, which could also be used to divide free space into various cells where such a path can be easily planned in order to plan the entire moving path. By making a graph which connects the neighboring cells based on the divided ones, an optimal path can be traced. In such a case, it is possible to divide the process into the approximate-cell division and the complete-cell division based on the way of dividing cells. In case of the complete-cell division, the divided cells need to become the original free space when they are united [6][7]. Unlike any robot moving on the ground, the flying quad-rotor is not subject to any limitation regarding an obstacle. Therefore, in this paper, the complete-cell division was used.

The order for the determination of positions through the cell divide algorithm proposed in this paper is shown in Figure 4.

A 10m straight route from the current position obtained from the GPS sensor is planned in advance,

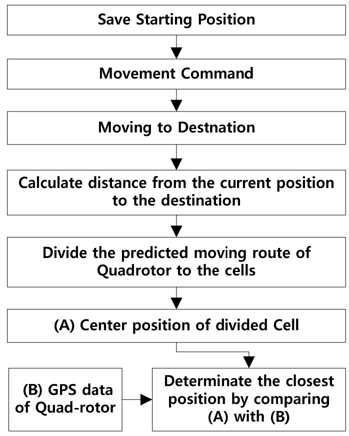

Fig. 4. Block diagram of cell divide algorithm

while the planned route is transformed into approximate longitude and latitude values through an equation before being divided into cells [8]. When the quad-rotor flies along a curve, the route is subject to the rotational transformation process based on the directional values given by the geomagnetic sensor. As a result, it is possible to carry out the path planning process even when the quad-rotor moves along a curve. The center coordinates of the divided cells can be compared with

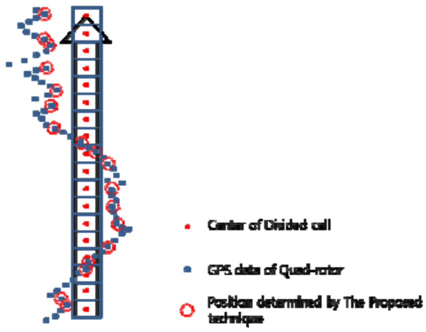

Fig. 5. Position determined by cell divide algorithm

the GPS/INS-fusion position information in order to choose the position information which is the closest to the actual position. Figure 5 shows how the closest position is selected.

5. Experiment

In this paper, the low-cost GPS position information having a relatively great error and the INS position information having an accumulation of errors were combined by using the Kalman filter in order to estimate the outdoor positions of the quad-rotor.

However, since the performance of the Kalman filter tends to be poor in terms of the estimation on a curve which shows a high level of nonlinearity and the GPS/INS-fusion system is greatly influenced by the performance of GPS, the system, which can be used to improve the performance of the position estimation process by applying the path planning algorithm, is proposed to compensate such a problem. In order to evaluate the performance of the proposed system, we carried out an experiment for the position estimation

Fig. 6. The experimental environment

process by flying the quad-rotor over 150m in the playground of our school. The position information of the moving quad-rotor was received in real time by using the Bluetooth communication technology.

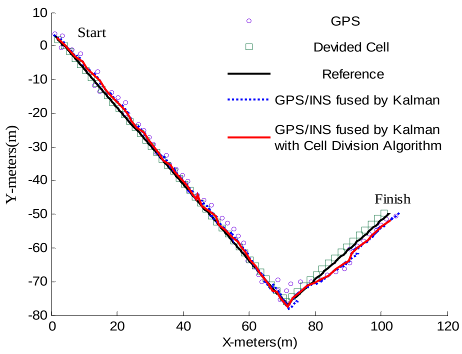

Fig. 7. The experimental result

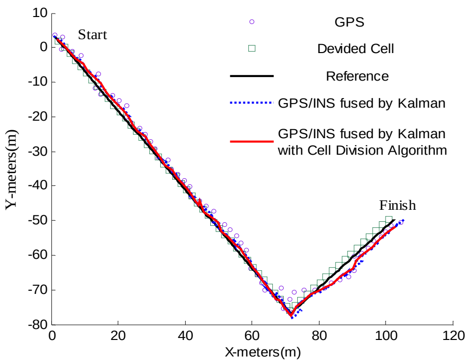

Fig. 8. Partial magnification image of the experimental result

Fig. 7 compares the performance of the position estimation process carried out by the proposed system with the performance of the process carried out by the GPS-INS-fusion system using the Kalman filter.

Table 1. The caption should be placed before the table.

Sort	Average Local Error(m)
GPS	2.8955
GPS/INS	1.8953
Path planning+GPS/INS system	1.612

As shown in Fig. 7 and 8, it is possible to see that the level of precision for the estimation of positions is improved more as the information which is close to the actual positions is chosen out of the position information given by the GPS/INS-fusion system which is combined by using the Kalman filter based on the path planning algorithm. Table 1 show the resulting average position errors.

6. Conclusion

In conclusion, the experimental results reveal that the proposed system, using the Kalman filter and Path planning, is more accurate than a single low cost GPS or GPS/INS system fused by Kalman filter. The results also suggest that when tracking location outdoors, the proposed system is a good alternative to DGPS and RTK-GPS. This is because the proposed system is more cost efficient and similarly as accurate as the other localization systems. After this research, it will be configured that position estimation system which is capable of estimating the mobile robot's position as it travels an outdoor curved path.

Acknowledgements

This research was supported by the MOTIE (Ministry of Trade, Industry & Energy), Korea, under the Industry Convergence Liaison Robotics Creative Graduates Education Program supervised by the KIAT (N0001126).

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