International Journal of Engineering Research and Technology.
ISSN 0974-3154 Volume 11, Number 9 (2018), pp. 1471-1483

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A Practical Position/Velocity Estimation for Multicopter Guidance and Control

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ABSTRACT:

In this work, a practical algorithm to estimate the position and velocity which can be used for feedback control of multicopter UAV, is proposed. For the purpose of practical applicability to multicopter, a straight forward algorithm which can be constructed with MEMS AHRS, low-cost GPS, and pressure sensor is considered. The data obtained from flight experiment with the proposed algorithm are analyzed.

Keywords – Estimator, GPS/INS, Low-cost, Multicopter, UAV

I. INTRODUCTION

Recently more and more multicopter UAVs are adopted to various applications. To perform safe and satisfactory missions an efficient flight controller should be designed. Usually the flight controller for multicopter should be run fast up to 500 Hz for good performance. However, GPS signals are usually received at low speed in the range of 10~25 Hz, which is not fast enough for feedback of position and velocity data. Furthermore, since a small multicopter won't allow expensive sensors, measurement devices such as cheap MEMS sensor and GPS receiver are often used for multicopters. However, if Inertial Navigation System(INS) is constructed with MEMS sensors it easily accumulates the error. Thus an estimation scheme such as the Extended Kalman Filter needs to be adopted for reliable and fast navigation data of position and velocity [2]. Although the Extended Kalman Filter gives good estimation data one must know the sensor noise information very well and best tuning is needed, which is not an easy work. Even in that case the performance of EKF often depends on the quality of GPS.

This paper discusses a practical estimation algorithm which can be applied to guidance and control of multicopter with low price AHRS and GPS. An intuitive and fast estimation algorithm is proposed and the performance and limit are analyzed through some flight data of multicopter.

II. GPS/INS ALGORITHM

In general, there are two types of GPS/INS structure: Loosely Coupled(LC) and Tightly Coupled (TC). In this work simple LC method is adopted as in Fig 1[4] because the LC method is simple to implement and does not require direct processing of GPS measurements. In fact, since the estimation algorithm must be operated in the cheap embedded environment (for example, ARM Cortex-m4) the algorithm with few operations is advantageous, which is another reason selecting the LC method.

The basic algorithm structure is shown in Fig 2. The difference from the existing LC method is that Attitude and Heading Reference System (AHRS) is used instead of INS, and an air pressure altimeter is added and the Extended Kalman Filter is not used. Since lots of competent AHRS are commercially available nowadays, it will be more convenient to construct INS with AHRS.

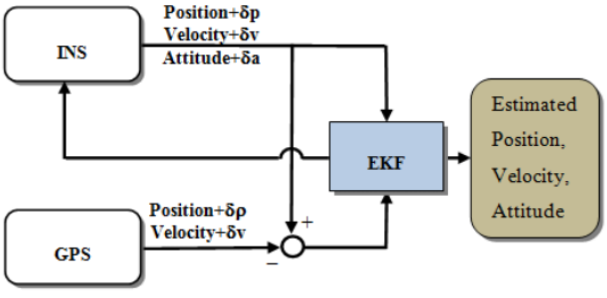

Figure 1. Loosely Coupled Method

III. PROPOSED ALGORITHM

III.I Map Projection

Since GPS receivers generally provide geodetic coordinates (latitude, longitude, height) based on WGS84 datum, a map projection is needed to represent the position of a spherical object on a 2D map. Map projection should be chosen considering the uses and characteristics because the transformation without loss cannot be performed by Gauss's Theorema Egregium. Since a UAV is operated in a given area with a reference point of the map, it would be appropriate to choose a projection method that gives accurate distance and azimuth between the two points. Reflecting these characteristics, Azimuthal Equidistant Projection was adopted in this work.

The projection can be obtained through the following calculation [6].

$$\mathrm{x} = rk\sin(\lambda - \lambda_0)\cos(\varphi)\,, \qquad k = \frac{c}{\sin c} \tag{1}$$

$$\mathrm{y} = rk[\cos\varphi_0 \sin\varphi - \sin\varphi_0 \cos\varphi \cos(\lambda - \lambda_0)] \tag{2}$$

Table 1. Parameter information

Parameter	Mean
r	Earth radius
φ_0, λ_0	Latitude and longitude of the reference point (the origin)
φ, λ	Latitude and longitude of another point
c	great circle distance

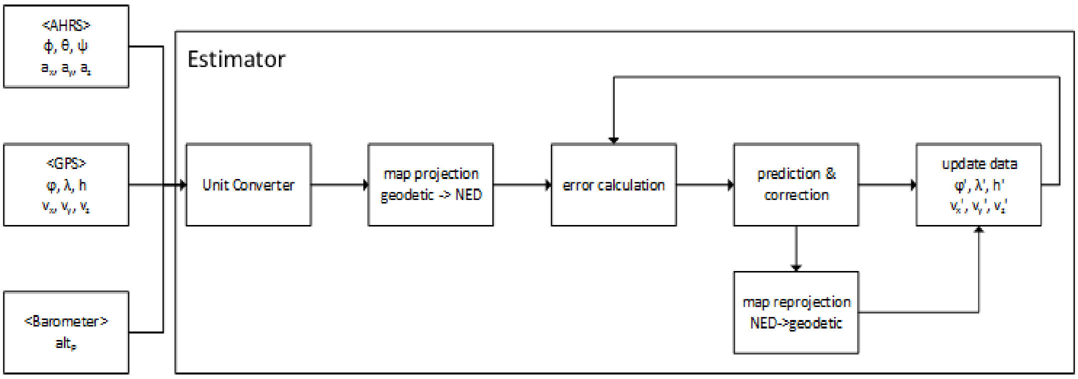

Fig 1. A Position and Velocity Estimation Algorithm with GPS/AHRS/Barometer

In the case of reprojection, the following calculation is performed using the inverse function.

$$c = \sqrt{\left(\frac{x}{r}\right)^2 + \left(\frac{y}{r}\right)^2} \tag{3}$$

$$\varphi = sin^{-1}\left(\cos c \sin\varphi_0 + \frac{y \sin c \cos\varphi_0}{c}\right) \tag{4}$$

$$= \begin{cases} \lambda_0 + tan^{-1}\left(\dfrac{x \sin c}{c\cos\varphi_0 \cos c - y \sin\varphi_0 \sin c}\right), \varphi_0 \neq \pm 90° \\ \lambda_0 + tan^{-1}\left(-\dfrac{x}{y}\right), \quad \varphi_0 = 90° \\ \lambda_0 + tan^{-1}\left(\dfrac{x}{y}\right), \quad \varphi_0 = -90° \end{cases} \tag{5}$$

Selecting a local frame with the origin on the reference point and assuming it to be an NED inertial coordinate system, the coordinates obtained from the above equations (1) and (2) can be expressed on the x-y plane of Fig. 3[7].

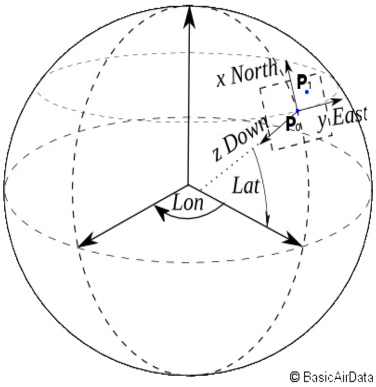

Figure 2. Local frame(NED)

If the two points on the NED coordinate system are P_0 (φ_0, λ_0) and P_1 (φ_1, λ_1), x-axis is northward and y-axis is eastward. On the other hand, the reason for not using the altitude value from coordinate calculation is that the ellipsoid height and the above mean sea level obtained from the GPS receiver is based on WGS84 which will cause 20~30m error in Korea[8]. Therefore, the correction should be performed using the data of the barometric altimeter and the acceleration sensor.

III.II Error Calculation

In the error calculation step, the difference between the estimated result and the measured value from various sensors is calculated. Since the estimated value can be given faster than the measured value, it operates in such a manner that error calculation is repeated every time the value of each sensor is updated. Also, the sensor data are given with different periods, the calculation of the error is performed independently for each corresponding sensor. The overall flowchart of the algorithm is shown in Fig 4. In Fig.4, the processes between the 'initialize process' block and the 'prediction & correction' block correspond to the error calculation part. In order to calculate the error, the reference value must be set first. As shown in the flowchart, 'initialize process' determines the GPS position and the reference altitude of the barometric altimeter. The GPS altitude is less accurate but has the advantage of small drift on reference point over time. The barometric altimeter has the disadvantage of increasing the bias over time and being affected by atmospheric changes such as wind, but it has the advantage of high resolution and fast response to altitude change. By utilizing the advantages of each of these sensors, more accurate altitude measurements can be obtained. The following equations (6) to (10) show the process of calculating altitude error. $\hat{z}_p$ denotes the estimated altitude and $\mathrm{z_{ref}}$ denotes the reference altitude in the NED coordinate system and is equal to the initial GPS altitude. $\mathrm{p_z}$ is the GPS altitude, $\mathrm{W_{p_z}}$ is the GPS weight, dt is the computation time interval, and $\varepsilon_{\mathrm{p_z}}$ is the altitude correction value.

$$\Delta \acute{h}_{br} = o_{br|i-1} - h_{br} - \hat{z}_p \tag{6}$$

$$\Delta \mathrm{p_z} = z_{ref} - p_z - \hat{z}_p \tag{7}$$

$$\varepsilon_{\mathrm{p_z}} = \Delta p_z W_{p_z} dt \tag{8}$$

$$\mathrm{o_{br|i}} = o_{br|i-1} + \varepsilon_{p_z} \tag{9}$$

$$\Delta \mathrm{h_{br}} = \Delta \acute{h}_{br} + \varepsilon_{p_z} \tag{10}$$

Figure 3. Flowchart for Position and Velocity Estimation Algorithm with GPS/AHRS/Barometer

The symbol '$\frown$' denotes an estimated value, the subscript i denotes an update time point of the barometric pressure altimeter, j denotes an update time point of the GPS data, and k denotes an update time point of the estimator. Now that we have covered the vertical error, the next step is to calculate the horizontal error which can be calculated as follows by modifying the algorithm in [9].

$$\underline{p}_{\mathrm{n}} = \begin{bmatrix} p_{n,x} \\ p_{n,y} \\ p_{n,z} \end{bmatrix}, \underline{v}_{\mathrm{n}} = \begin{bmatrix} v_{n,x} \\ v_{n,y} \\ v_{n,z} \end{bmatrix} \tag{11}$$

$$\Delta \mathrm{p}_{\mathrm{n|k}} = \underline{p}_{\mathrm{n|j}} - \underline{\hat{p}}_{\mathrm{n|k-1}} \tag{12}$$

$$\Delta \mathrm{v}_{\mathrm{n|k}} = \underline{v}_{\mathrm{n|j}} - \underline{\hat{v}}_{\mathrm{n|k-1}} \tag{13}$$

The process of calculating $\underline{\hat{p}}_{\mathrm{n}}, \underline{\hat{v}}_{n}$ which is position and velocity, is covered in the next section.

III.III Prediction and Correction

The final step is to estimate and compensate for position and velocity. For this purpose, the accelerometer output is obtained from the AHRS of the strapdown system, so the coordinate system conversion to the NED frame is required. Let $\underline{f}_{\mathrm{b}}$ be the specific force measured in the accelerometer, $\underline{a}_{n}$, the acceleration in the NED frame, and $\underline{b}$, the accelerometer bias, then it can be expressed as equation (14).

$$\begin{gathered} \underline{f_b} = \begin{bmatrix} f_{b,x} \\ f_{b,y} \\ f_{b,z} \end{bmatrix} \\ \underline{\hat{f_b}} = \underline{f_b} - \underline{b_b} \\ \underline{\hat{f_b}} = \underline{f_b} - \underline{b_b} \end{gathered} \tag{14}$$

$\underline{b}_{\mathrm{n}}$ defined in Eq. (14) is estimated using position error and velocity error as follows.

$$\begin{aligned} \mathrm{e}_{\mathrm{n,x|k+1}} &= -\Delta p_{n,x|k} W^2_{p_{xy}|j} - \Delta \mathrm{v}_{\mathrm{n,x|k}} \mathrm{W}_{\mathrm{v}_{xy|j}} \\ \mathrm{e}_{\mathrm{n,y|k+1}} &= -\Delta p_{n,y|k} W^2_{p_{xy}|j} - \Delta \mathrm{v}_{\mathrm{n,y|k}} \mathrm{W}_{\mathrm{v}_{xy|j}} \\ \mathrm{e}_{\mathrm{n,z|k+1}} &= -\Delta p_{n,z|k} W^2_{p_{z}|j} - \Delta \mathrm{v}_{\mathrm{n,z|k}} \mathrm{W}_{\mathrm{v}_{z|j}} \\ \acute{e}_{\mathrm{n,z|k+1}} &= \underline{e}_{\mathrm{n,z|k+1}} - \Delta h_{br} K^2_{br} \end{aligned} \tag{15}$$

$$\underline{b}_{\mathrm{b|k+1}} = \underline{b}_{\mathrm{b|k}} + R_{n|j}^{b}\begin{bmatrix} e_{n,x|k+1} \\ e_{n,y|k+1} \\ e_{n,z|k+1} \end{bmatrix}\mathrm{K_{acc}}dt + R_{n|k}^{b}\begin{bmatrix} 0 \\ 0 \\ \acute{e}_{n,z|k+1} \end{bmatrix}K_{acc}dt \tag{16}$$

The weight parameters that reflect the position error and the velocity error correction are calculated by the gain value and the position accuracy of the GPS receiver. The position accuracy is a positive value, and it means that the closer to 0, the more accurate the values of the position and the speed are. The formula to determine the weight parameter is given as below.

$$\begin{aligned} \mathrm{W_{xy}} &= \frac{\min(\sigma_{xy})}{gps\ Haccuracy},\ \min(\sigma_{xy}) = 2 \\ \mathrm{W_{z}} &= \frac{\min(\sigma_{xy})}{gps\ Vaccuracy},\ \min(\sigma_{z}) = 2 \end{aligned} \tag{17}$$

Haccuracy means horizontal accuracy and *Vaccuracy* means vertical accuracy. These values range from 0~30 within a meaningful range, with minimum value is limited to 2, which is 6% in percentage. The better the position accuracy, the more the reflection portion is. Also, since the size of the value change according to the update speed and the calculation period of the GPS receiver, the gain can be adjusted.

$$\begin{aligned} \mathrm{W}_{\mathrm{p_{xy}}} &= \mathrm{K}_{\mathrm{p_{xy}}}\mathrm{W_{xy}} \\ \mathrm{W}_{v_{\mathrm{xy}}} &= \mathrm{K}_{v_{\mathrm{xy}}}\mathrm{W_{xy}} \\ \mathrm{W}_{\mathrm{p}_z} &= \mathrm{K}_{\mathrm{p}_z}\mathrm{W}_z \\ \mathrm{W}_{v_z} &= \mathrm{K}_{v_z}\mathrm{W}_z \end{aligned} \tag{18}$$

The above parameters are set by the trial and error method and the final values are given as follows.

$$\begin{aligned} \mathrm{e_{n,x|k+1}} &= -\Delta p_{n,x|k} - 2\Delta \mathrm{v_{n,x|k}} \\ \mathrm{e_{n,y|k+1}} &= -\Delta p_{n,y|k} - 2\Delta \mathrm{v_{n,y|k}} \\ \mathrm{e_{n,z|k+1}} &= -0.000025\Delta p_{n,z|k} - 0.001\Delta \mathrm{v_{n,z|k}} \end{aligned} \tag{19}$$

Newton’s second law of motion is used to predict the position and velocity of the UAV[10]. Assuming that the thrust and mass are constant during the calculated period, the current step velocity and position values of the UAV can be predicted by using previous step position, velocity, and acceleration values as in the equation (20). Superscript ‘′’denotes a temporary value during calculation.

$$\begin{aligned} \underline{\acute{p}}_{n|k+1} &= \underline{\hat{p}}_{n|k} + \underline{\hat{v}}_{n|k}dt + \frac{1}{2}\underline{\hat{a}}_{n|k}dt^2 \\ \underline{\acute{v}}_{n|k+1} &= \underline{\hat{v}}_{n|k} + \underline{\hat{a}}_{n|k}dt \end{aligned} \tag{20}$$

However, since the estimated values in Eq. (20) cannot be regarded as true velocity and position, correction is necessary. Therefore, it is necessary to calculate the difference between the position and the velocity measured by the GPS receiver according to the weight parameter and reflect it to the estimated value, this value can be obtained by Eq (21). As the estimated value gets closer to the position and velocity of the GPS that is newly updated, the estimation error such as $\Delta p_{x|k}$ approaches zero.

$$\underline{\hat{p}}_{n|k+1} = \underline{\acute{p}}_{n|k+1} + \begin{bmatrix} \Delta p_{x|k} & 0 & 0 \\ 0 & \Delta p_{y|k} & 0 \\ 0 & 0 & \Delta p_{z|k} \end{bmatrix} \begin{bmatrix} W_{p_{xy|j}} \\ W_{p_{xy|j}} \\ W_{p_{z|j}} \end{bmatrix} \mathrm{dt}$$

$$\underline{\hat{v}}_{n|k+1} = \underline{\acute{v}}_{n|k+1} + \begin{bmatrix} \Delta p_{x|k} & 0 & 0 \\ 0 & \Delta p_{y|k} & 0 \\ 0 & 0 & \Delta p_{z|k} \end{bmatrix} \begin{bmatrix} W_{p_{xy|j}}^{2} \\ W_{p_{xy|j}}^{2} \\ W_{p_{z|j}}^{2} \end{bmatrix} \mathrm{dt} \qquad (21)$$

$$+ \begin{bmatrix} \Delta v_{x|k} & 0 & 0 \\ 0 & \Delta v_{y|k} & 0 \\ 0 & 0 & \Delta v_{z|k} \end{bmatrix} \begin{bmatrix} W_{v_{xy|j}} \\ W_{v_{xy|j}} \\ W_{v_{z|j}} \end{bmatrix} dt$$

When the calculation up to (21) is completed, the output value is confirmed through the validation and reprojection of the values as shown in Fig.4.

IV. EXPERIMENT CONFIGURATION

In this section, the validity is verified using the data obtained from the experiment. The UAV used for the experiment is a quad X-type multicoper with dimensions of 960(L)×960(W)×450(H)mm and 6.25 kg (including battery).

Figure 4. The airframe used in the experiment

The AHRS used in the configuration of the above flight control system is MTi-3[11], which is a low-price AHRS of Xsens and priced at about $250. For the performance comparison, Septentrio's AsteRx-m GPS (high-price) was used for a reference [12], Ublox's M8N GPS (low-price) was used in the estimation [13]. Data were collected at a frequency of 100 Hz using an FDR(Flight Data Recorder). The following is a comparison table of the GPS receiver used in the experiment.

Table 2. Specifications of GPS receiver commercial products

Parameter	Ublox M8N Technical data	AsteRx-m Technical data
Position accuracy	2.5m(h) / 5m(v)	1.2m(h) / 1.9m(v)
Velocity accuracy	0.05m/s	0.01m/s(h), 0.015m/s(v)
Data rate	10Hz	20Hz
Price	100$	1500$

V. FLIGHT EXPERIMENT DATA AND ANALYSIS

In order to verify the data validity and characteristics of the estimator, data on the ground movements were first analyzed in axis-wise. As can be seen in Fig. 6, the horizontal position data show good agreement between GPS measured data and estimated data. Fig. 7 shows good estimate for the altitude data while GPS raw data are more biased. Next an automatic flight data were gathered. Fig. 8 shows the horizontal trajectory and Figs. 9~11 show north and east axis-wise position data, where one can notice that the measured and estimated data are in good agreement and the estimated data with low-price GPS is comparable to high-price GPS data. While the slow GPS (Ublox) gives the data at 10 Hz, the estimated data can be generated at the rate as needed (even up to 500 Hz), which is very favorable for fast multicopter control.

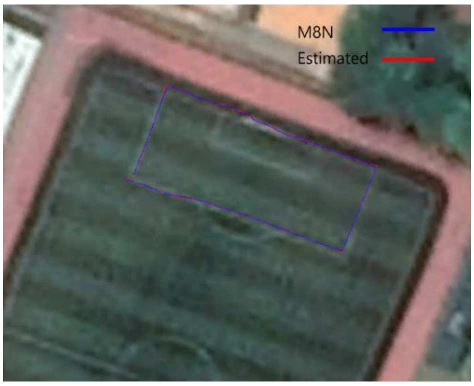

Figure 5. Ground movement data (Horizontal)

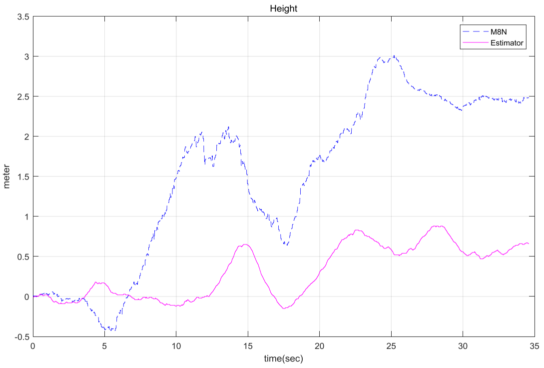

Figure 6. Altitude data for ground movement

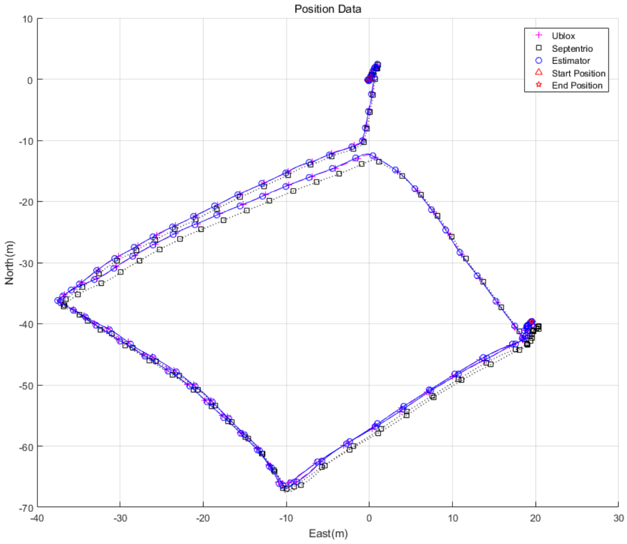

Figure 7. Flight data from automatic maneuver (Horizontal)

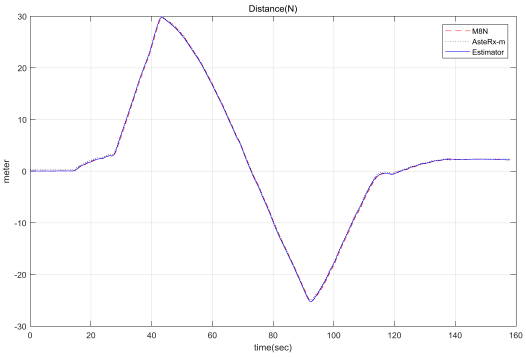

Figure 8. North position

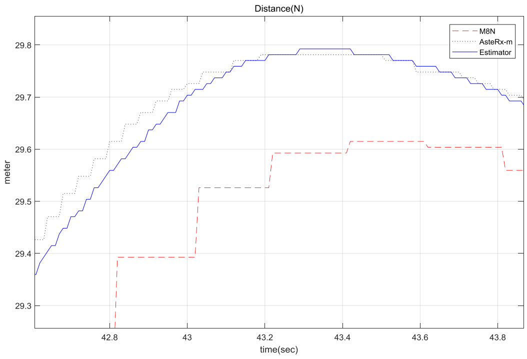

Figure 9. North position (Zoomed)

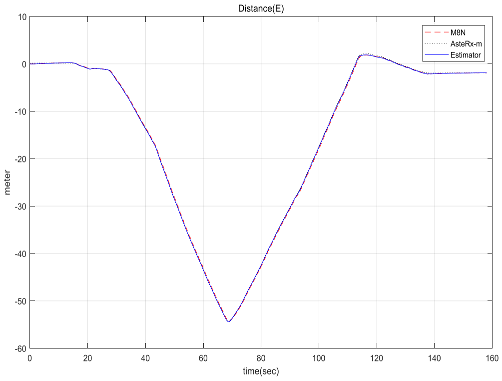

Figure 10. East position

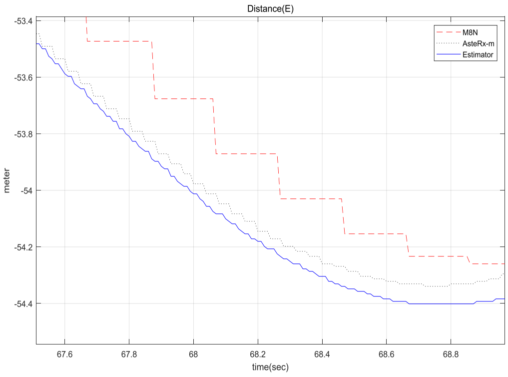

Figure 11. East position(Zoomed)

The altitude data also shows comparable data to high-precision GPS data (Fig. 13). In Figs. 14~17 are plotted horizontal velocities which also show good agreement between the measured and estimated data. Zoomed plots show that the estimated data are comparable to the high-precision GPS data and fast enough for feedback control. The vertical velocity shows rather consistency (Figs. 18 & 19)

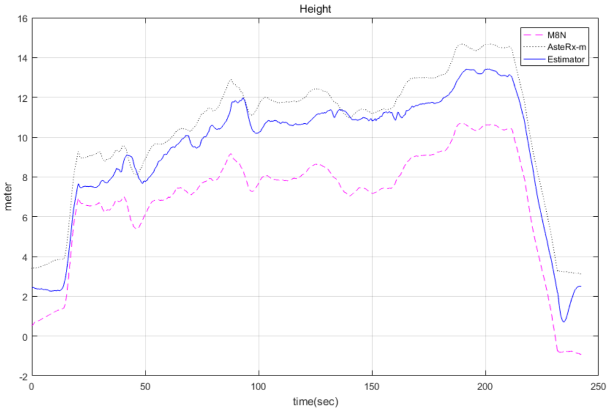

Figure 12. Altitude

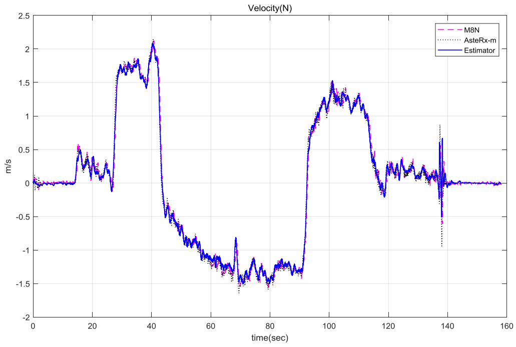

Figure 13. North axis velocity

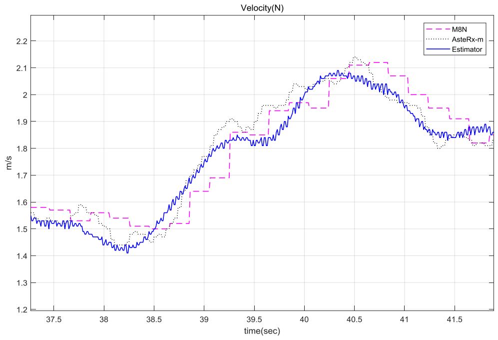

Figure 14. North axis velocity(Zoomed)

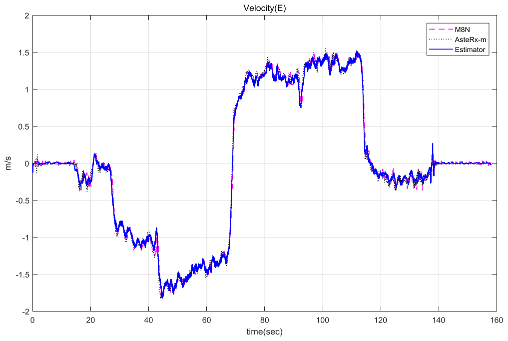

Figure 15. East axis velocity

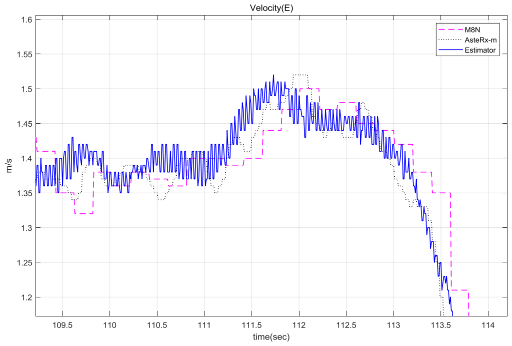

Figure 16. East axis velocity(Zoomed)

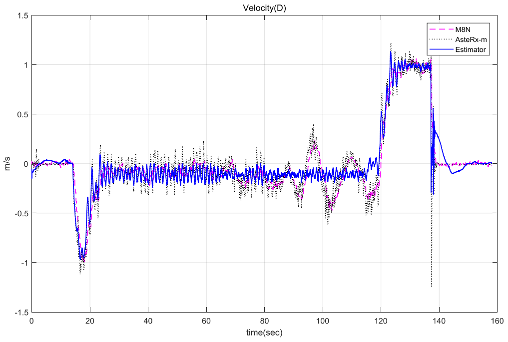

Figure 17. Vertical velocity

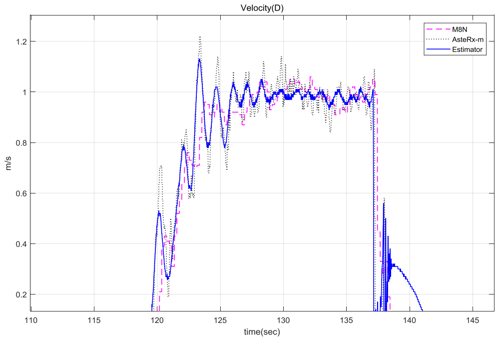

Figure 18. Vertical velocity(Zoomed)

VI. CONCLUSION

In this work, a practical algorithm for estimating the position and velocity which are used for feedback control of multicopter, is proposed. For the purpose of practical applicability to multicopter, a straight forward algorithm which can be constructed with MEMS AHRS, low-cost GPS, and pressure sensor is considered. The data obtained from flight experiment with the proposed algorithm shows that the estimated position and velocity are in good agreement with the measured data by high precision GPS. Furthermore, the estimation algorithm can generate the data as frequent as needed in fast multicopter control.

Acknowledgments

This work was supported by Korea Institute of Planning and Evaluation for Technology in Food, Agriculture and Forestry (IPET) through Advanced Production Technology Development Program, funded by Ministry of Agriculture, Food and Rural Affairs(MAFRA)(grant number : 315014-3)

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