Study of Utilizing Multiple IMUs for Inertial Navigation Systems Without GPS Aid

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***Abstract*— Due to their small sizes and lightweights micro electro mechanical systems inertial measurement units (MEMS-IMUs) have become popular in inertial navigation systems (INSs). When the data taken from MEMS-IMUs are fused with the data coming from GPS signal, INS systems most likely to obtain a precise result, however, in GPS-denied environments the results may be misleading. This article studies the error profile of an inertial navigation system in a GPS-denied environment utilizing multiple IMUs. Using NaveGo simulation framework, tracking performance of a inertial navigation system employing single IMU is compared with a triple IMU inertial navigation system. The simulation results reveal that utilizing extra IMUs in a GPS denied environment improves the error profile where up to 82%, 85%, and 83% reductions in latitude, longitude and altitude error figures respectively.**

***Index Terms*-- INS, MEMS-IMU, GPS**

I. INTRODUCTION

In recent years there have been important developments in Micro Electro Mechanical Systems (MEMS) technology. Due to their small sizes and lightweights, MEMS sensors have found a great place in inertial navigation systems (INSs) [1]. One of the most important parts in an INS is inertial measurement units (IMUs) where MEMS gyroscopes and MEMS accelerometers are used to measure rotational motion and change in velocity. When the data taken from MEMS-IMUs are fused with the data coming from GPS signal, the result is most likely to be precise. However, when there is no GPS signal, or the error rate of the GPS signal is high, the result may be inaccurate.

GPS signals are not available all the time as signal blockages occur in some regions due to jamming, hostile weather conditions or environmental factors. In literature, such regions are called GPS-denied regions or GPS denied environments. As navigation without GPS data is commonly encountered in many applications such as military operations or indoor navigation, navigation in GPS-denied regions has become an important topic for researchers to work on. In literature, there exist different methods such as simultaneous localization and mapping (SLAM), visual odometry (VO), or using different filters and algorithms [3]-[15] to improve the accuracy of the navigation in GPS denied environment. In such methods external cameras and image processing algorithms are needed for navigation. Alternatively, utilizing redundant inertial sensors in an inertial measurement unit is used to improve the IMU performance in GPS-denied regions [17]-[19]. One another method is employing multiple inertial measurement units in an INS without GPS aid [19], [21]. In this work the performance of different kind of IMUs will be examined when there is no GPS aid by using NaveGo, a simulation framework for low-cost integrated navigation system [2]. Further, a method will be suggested to reduce the error profile in such situations utilizing multiple IMUs in a strapdown inertial navigation system (SINS). Unique side of this study in comparison with the similar researches conducted earlier is that data coming from different IMUs having different error profiles are used for the navigation in GPS-denied region. For example in [19] and [20] same type of inertial measurement units, MPU9150, are used for the multiple IMUs in a navigation system. However in this study, different type of real IMU profiles are used. Although there are different types of data fusion algorithms for multiple inertial measurement [18], in this study, without dealing with the performances of these algorithms, only the positive effect of using multiple IMUs having different characteristics on the error profile of the navigation system in a GPS-denied environment will be examined. The simulation results reveal that utilizing extra IMUs in a GPS denied environment improves the error profile where up to 82%, 85%, and 83% reductions in Latitude, Longitude and Altitude error figures respectively.

The remainder of this paper organized as follows. Section II reviews the simulation method utilized in this work and Section III presents the simulation results of the proposed multiple-IMU inertial navigation system. Finally, concluding remarks are commented in Section IV.

II. SIMULATION METHOD

A. *Simulation Steps*

In this section, the details of the INS simulation algorithm is reviewed. The ultimate purpose of an INS system is to determine an accurate trajectory utilizing the outputs of the

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IMU sensors. In the INS simulation, the trajectory is estimated based on true input data which is given as,

$$T = [e, p, v^n, a^n, t_s] \tag{1}$$

where $\boldsymbol{e}$ is the true attitude vector, $\boldsymbol{p}$ is the true position vector, $\boldsymbol{v^n}$ and $\boldsymbol{a^n}$ are true velocity and true acceleration vectors expressed in north east down (NED) coordinate system respectively. Finally, $\boldsymbol{t_s}$ is the simulation time vector.

True input data is used as an input for SINS whose characteristic is created in accordance with the error profile of the IMUs in Table I. Then, output taken from SINS is fused with the GPS data and passed through the Kalman Filter. The integration of SINS, GPS and Kalman Filter is shown in Fig. 1 where, $\boldsymbol{v^n}$ and $\boldsymbol{p^n}$ represent the velocity and position vectors coming from SINS, $\boldsymbol{v_G^n}$ and $\boldsymbol{p_G^n}$ represent the velocity and position data coming from GPS, $\boldsymbol{x}$ represents the state vector, $\boldsymbol{x_{(-)}}$ represents the state vector belonging the previous time period and $\boldsymbol{\delta_y}$ and $\boldsymbol{\delta_x}$ are used for the feedback loop. For further details regarding the algorithm the reader is referred to [2].

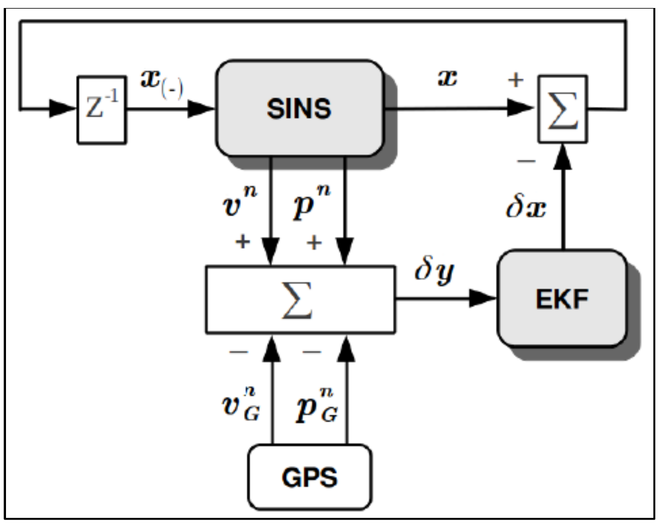

Fig. 1. Diagram of SINS, GPS, and EKF integration [2].

Since SINS with multiple IMUs is used in this study, arithmetic mean of the three different outputs taken from the Kalman Filter is taken as an output of the multiple-IMU SINS.

The simulation that is conducted in this study can be divided into two steps:

- Generating the error profile of an INS employing only one IMU with no GPS aid, for three different IMUs.
- Generating the error profile of an INS employing multiple IMUs without GPS aid.

These two steps are shown on the same graphs in Section III in order to ease the comparison.

B. Reference Trajectory Selection

Although it is possible to define different reference trajectory scenarios, the predefined trajectory reference in NaveGo simulation framework shown in Fig. 2 is adopted in this study as it is sufficient for the purpose of this study.

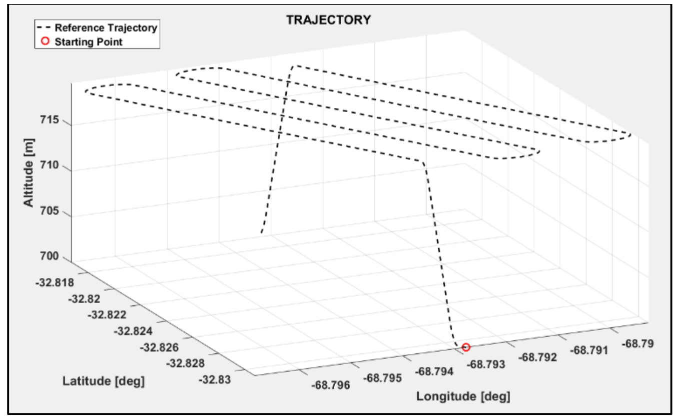

Fig. 2. Trajectory used in this study

Since the latitude, longitude and altitude values all change in the mentioned reference trajectory, it is possible to compare the performances of the single and multiple IMU inertial navigation systems in terms of latitude, longitude and altitude error profiles by using the trajectory in Fig. 2.

C. IMU Selection

IMU selection is one of the most crucial parts of this work. There are two important points regarding IMU selection.

First, the error profiles of the IMUs are supposed to be similar to each other. Because, if the profiles are far away from each other, for example, one of the IMUs provide a highly errored data when the other two provide more precise data then the worst IMU's data corrupt the data coming from the other two IMUs. On the other hand, if the error profiles of the IMUs are close to each other then they can operate in accordance with each other. At one point of navigation if one of the IMUs generates inaccurate outputs then it is most likely for the other IMUs to remedy the trajectory estimation. Therefore, the first criterion of selecting the IMUs is that their error profiles must be similar to each other.

Secondly, the error profiles of the IMUs to be simulated should be formed with the help of the real IMUs. The error specifications of the real IMUs can be obtained from their data sheets. By doing so, the simulation is assumed to be more realistic. Therefore, error specifications of three different IMUs from Analog Devices are used in this work. The model number of these inertial measurement units are namely ADIS16485, ADIS16488 and ADIS16448, which are referred as IMU1, IMU2 and IMU3 in this study respectively.

The profiles of the IMUs mentioned above are shown on Table 1, where ARW is angle random walk noise, VRW is velocity random walk noise, $\boldsymbol{b_g}$ stands for a static bias noise for gyroscopes, $\boldsymbol{b_f}$ is a static bias noise for the accelerometers, $\boldsymbol{\Sigma_{g\delta b}}$ and $\boldsymbol{\Sigma_{f\delta b}}$ are the dynamic bias noises for gyroscopes and accelerometers respectively. Finally frequency express the working frequency of the inertial measurement units.

TABLE 1. IMU Profiles

	ADIS16485	ADIS16488	ADIS16448	
ARW	0.3	0.3	0.66	deg/√h
VRW	0.023	0.029	0.11	m/s/√h
b_g **(1σ)**	0.2	0.2	0.5	deg/s
b_f **(1σ)**	3	16	20	mg
$\Sigma_{g\delta b}$	1.7E-3	1.8E-3	4E-3	deg/s
$\Sigma_{f\delta b}$	0.032	0.1	0.25	mg
Frequency	128	128	128	Hz

III. SIMULATION RESULTS

In order to decrease the effect of GPS on the INS the error factor and the period of the GPS signal is increased. Hence, not only will INS rarely benefit from the GPS signal due to the low frequency of the GPS which is about 0.07 Hz, but it also will be misdirected by GPS signal due to the increased error profile of GPS.

Original frequency of GPS in the simulation when there is a GPS aid is 50 Hz. It means that at each 20 ms INS benefit from the GPS signal. On the other hand, when the frequency is decreased to 0.07 Hz for the simulation of the GPS-denied region, at approximately each 15.000 ms INS will be assisted by GPS data. In addition, the standard deviation constant of the position data coming from the GPS signal is also increased approximately 20 times for the simulation of GPS-denied environment. Therefore, the errored GPS data become more probable to misguide the INS.

When the effect of the GPS signal on INS is decreased by the method explained above, the error profiles from Fig. 3, Fig. 4 and Fig. 5 are obtained for latitude, longitude and altitude errors respectively. As mentioned in Section I, the simulation results for different situations is shown on the same graph for the sake of easy comparison.

IMU1, IMU2 and IMU3 stands for ADIS16485, ADIS16488 and ADIS16448 respectively. Therefore, on the legends of the following graphs IMU1 stands for INS aided with IMU1 data, IMU2 stands for INS aided with IMU2 data and IMU3 stands for INS aided with IMU3 data. On the other hand, IMU1+IMU2+IMU3 stands for INS aided with Multiple IMUs.

MEMS-IMUs can be affected by many different environmental factors. Hence, the simulations depending on only one IMU may result in a highly errored outcome. On the other hand, using multiple IMUs may be helpful to fix the error profile due to the fact that if one of the IMUs gives a wrong data at one point, it is probable that the others give a correct data at the same point. It is possible to see this positive effect of multiple-IMU system in the followings graphs.

For example, in Fig. 3, the latitude error of the system with IMU3 gives a highly errored outcome which is approximately 550 meters at 300th seconds. However, at that point since the data coming from the other IMUs are relatively correct, INS aided with multiple IMUs -that is shown in red- results in a more acceptable error profile which is approximately 100 meters. It means that multiple IMU system configuration provide us with a reduction of about 82%.

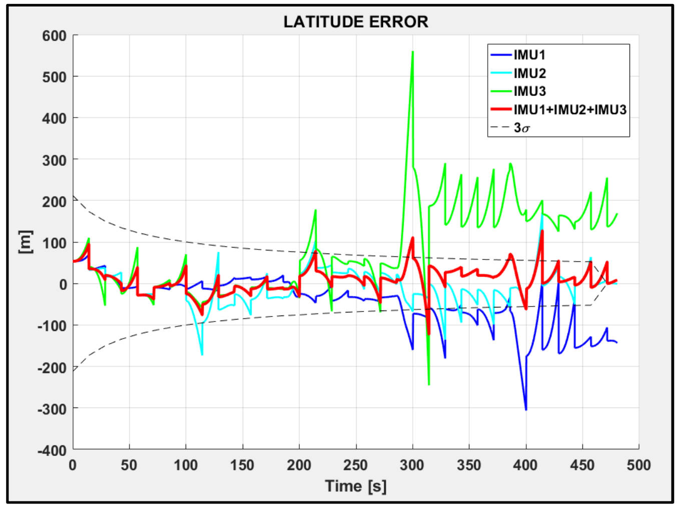

Fig. 3. Latitude Errors of the INSs without GPS aid

In Fig. 4, the longitude error of the INS with IMU1 fails at 410th seconds with a highly errored data of approximately 270 meters. However, at that point thanks to the correct data coming from the other IMUs, multiple IMU system results in a much better error profile which is approximately 80 meters. It means that INS with multiple IMUs provide us with an error reduction of about 85%.

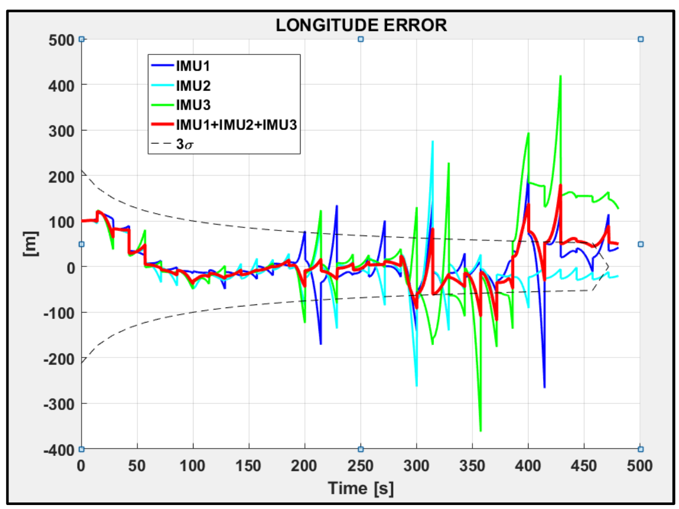

Fig. 4. Longitude Errors of the INSs without GPS aid

The altitude error of the INS with IMU3 results in an errored data of about 230 meters around 370th seconds as seen in Fig. 5. On the other hand, with the help of the other IMUs, INS aided with multiple IMUs - that is shown in red – results in a much better error profile which is approximately 40 meters. It means that INS with multiple IMUs provide us with nearly 83% decrease in error.

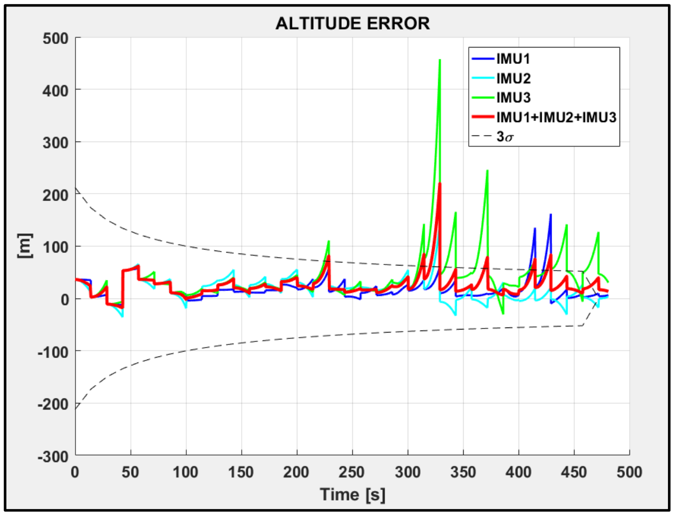

Fig. 5. Altitude Errors of the INSs without GPS aid

IV. CONCLUSIONS AND PERSPECTIVES

In this work, a method is suggested to fix the error profile of an INS system in a GPS-denied environment using NaveGo simulation framework. The suggested method is utilizing multiple IMUs in an INS which is not aided by a GPS signal.

Proposed method is demonstrated by comparing the error profile of an *INS with a single IMU* and an *INS with a cluster of three IMUs*. According to the simulation results, the system aided by multiple IMUs results in a better error profile in comparison with the INS which utilizes only one IMU.

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