Underwater Navigation System Solution using MEMS-Mobile Sensors during the GPS Outage

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Abstract —These position of Unmanned Surface Vehicle (USV) is very important in most navigation applications. The Global Position System (GPS) can be used for navigation system for most applications on the earth's surface, but its signal is not available underwater and indoor areas. Inertial Navigation System (INS) can be used for navigation system in such environments, but it has errors increase over time. This paper presents a method based on the integrated GPS with MEMS (Micro-Electro Mechanical System) INS mobile sensors to enhance the navigation system of USV and provide a continuous navigation solution during GPS outage. In this study, real-time data from GPS, MEMS-INS mobile sensors are fused and integrated by Kalman Filtering (KF); to estimate and correct errors of navigation system when GPS is available. When GPS becomes outage, the MEMS-INS system can provide acceptable navigation system within a not long of time until the GPS system is available. The performance of navigation system based on GPS/MEMS-INS cell phone is tested to a reference path when GPS is available and during its outage on parts of the path.

Index Terms—Global Position System (GPS), Micro-Electro Mechanical System with Inertial Navigation System (MEMS-INS) mobile sensors, Kalman Filtering (KF), experimental test.

I. Introduction

On earth surface, Global position system (GPS) is popular navigation system, that developed by United States Department of Defense (DOD). It can provide acceptable position information anywhere when there is direct line of sight to four or more satellites. However, it suffer from signal outage in urban area and underwater, where signals from satellite can be blocked. [1]. In literature, Inertial Navigation System (INS) is a method of navigation, which determines the status of moving vehicle using motion sensors without depending on external source (satellite). States of the vehicle refer to position, velocity, and orientation of the vehicle. INS is used in aircrafts, ships, guided missiles and UAVs [2]. INS is an autonomous system that comprises of three-axis accelerometers and gyroscopes; placed along the three mutually orthogonal directions that capable of measuring vehicle liner acceleration and angular velocity. Most smart mobiles contain many Micro-Electro Mechanical System (MEMS) sensors such as GPS, accelerometer, gyroscope, compass, and altimeter, humidity and so on. However, one of the disadvantages of these sensors is; their low accuracy [3]. These disadvantages of GPS and MEMS-INS can be reduced by integration procedures. GPS is integrated with INS to provide the continuous navigation solution during GPS outage [4]. In this dissertation, a proposed method is designed for enhanced navigation system of Unmanned Surface Vehicle (USV) based on integrated GPS with MEMS-INS mobile sensors, to continuous navigation solution when GPS is out-age and minimize errors of MEMS-INS system when GPS is available. By this method, the real time measurements from GPS and MEMS-INS- mobile sensors are integrated with Kalman Filter (KF). Kalman Filter is used to estimate and correct errors of the navigation system of USV.

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II. Navigation System Structure

The main part of the navigation system is GPS and MEMS-INS mobile to provide the continuous navigation solution when GPS becomes outage and minimize errors of MEMS-INS system when GPS is available. The navigation system consists of GPS, MEMS-INS subsystems and the Kalman Filter. Kalman Filter is used to estimate the MEMS-INS position errors based on GPS measurements.

A. MEMS-INS System

MEMS-INS mobile sensors consist of three gyroscopes and three accelerometers. The gyroscope sensors are used to determine angular rates (p, q, and r) that use to determine attitude (ϕ, θ, ψ). The accelerometer sensors are used to determine accelerations (a_x, a_y, a_z) that use to determine velocities (U, V, W) in the Vehicle Coordinating System (VCS) [5]. The attitude uses to find the Direction Cosine Matrix (DCM) that is used to convert the vehicle velocities from VCS to Navigation Coordinating System (NCS) [6] and [7]. The Euler angles are used to express the relationship between VCS and

NCS [8]. The relationship between the angular rates (p, q, and r) and Euler angles is given by Eq. (1) below, [9]:

$$\begin{bmatrix}\dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{bmatrix} = \begin{bmatrix}1 & \sin\phi\tan\theta & \cos\phi\tan\theta\\ 0 & \cos\phi & -\sin\phi\\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta\end{bmatrix}\begin{bmatrix}p\\ q\\ r\end{bmatrix} \quad (1)$$

By integration of Eq. (1), we can derive that; the Euler angles uses initial conditions of a known attitude (ϕ, θ, ψ). By a given time, the accelerations of the vehicle along the three body axes are read by the MEMS-INS mobile accelerometers. The initial velocities and angular rates are all available as states. The acceleration due to gravity (g) is supplied as a function of location around the earth [10], and then $\dot{U}$,$\dot{V}$ and $\dot{W}$are given by

$$\begin{aligned}\dot{U} &= a_x + rV - qW + g\sin\theta\\ \dot{V} &= a_y - rU + pW - g\cos\theta\sin\phi\\ \dot{W} &= a_z + qU - pV - g\cos\theta\cos\phi\end{aligned} \quad (2)$$

By integration of Eq. (2), we can derive that the velocities uses initial conditions of a known attitude (U, V, W). At a given time, The Direction Cosine Matrix [10] is given by DCM equal

$$DCM=\begin{bmatrix}\cos\theta\cos\psi & \cos\theta\sin\psi & -\sin\theta\\ \sin\theta\sin\phi\cos\psi - \sin\psi\cos\phi & \sin\psi\sin\theta\sin\phi + \cos\psi\cos\phi & \sin\phi\cos\theta\\ \sin\theta\cos\phi\cos\psi + \sin\psi\sin\phi & \sin\phi\sin\theta\cos\phi - \cos\psi\sin\theta & \cos\phi\cos\theta\end{bmatrix} \quad (3)$$

DCM is used to convert Velocities (U, V, W) on VCS frame to North-East-Up (V_N, V_E, V_U) that fame as follows Eq.(4):

$$\begin{bmatrix}V_N\\ V_E\\ V_U\end{bmatrix}_{INS} = DCM^T\begin{bmatrix}U\\ V\\ W\end{bmatrix}_{INS} \quad (4)$$

Since GPS is used as an updating and correcting the source of MEMS-INS System. It uses a geodetic frame (latitude, longitude, and altitude). Letting ⋋, µ and ɦ denote to the latitude, longitude, and altitude of the vehicle at any instant, respectively. Then the rate of change of latitude, longitude, and altitude ($\dot{⋋}, \dot{µ}, \dot{ɦ}$) is given by Eq. (5) below:

$$\dot{⋋} = \frac{V_N}{R_e}$$

$$\dot{µ} = V\_E/(R\_e\ \cos⋋) \quad (5)$$

$$\dot{ɦ} = V_U$$

By integration Eq. (5), giving the position (⋋, µ, ɦ) in geodetic frame by using the initial condition of a known position at a given time. A block diagram representation of MEMS-INS equations is shown in Fig. 1.

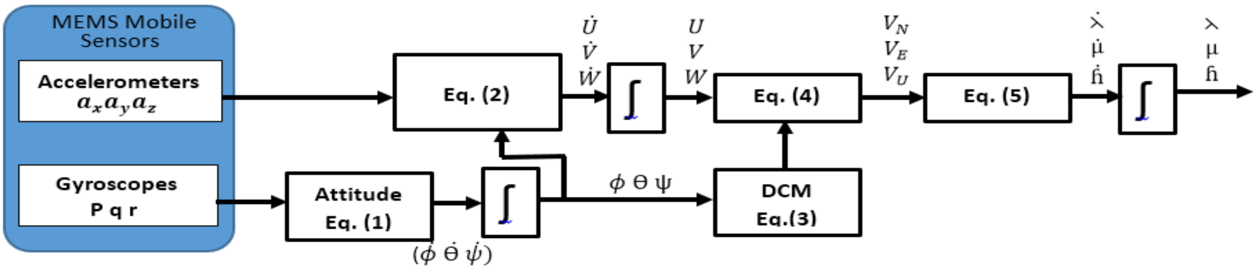

Fig. 1. Block diagram of MEMS-INS equations

B. Kalman Filter

The Kalman filter is an estimation algorithm that operates recursively based on the previous estimates and prior information. It consists of two stages, the prediction stage and the update stage [11].

On the production stage, the state vector ($\hat{x}_k$) and the error covariance matrix (P_k) at the start of the current epoch (k) are predicted based on the values obtained from the previous epoch (k-1) it is given by Eq. (6) below [12]:

$$\hat{x}_k^- = f(k, \hat{x}_{k-1}^+) \quad (6)$$

where $f(k,x)$ is the integral of dynamics matrix [28]. Error covariance matrix (P_k) is given by Eq. (7) below:

$$P_k^- = F_{k-1}P_{k-1}F_{k-1}^T + Q_k \quad (7)$$

where F_k denotes the system dynamics matrix and Q_k is a spectral density matrix. IN the update stage, Kalman gains (K_K) that is given by Eq. (8) below:

$$K_k = P_k^- H_k^T (H_k P_k^- H_k^T + R_k)^{-1} \quad (8)$$

where H_K is an observation matrix and R_k is the noise measurement matrix. The state vector ($\hat{x}_k$) is then updated using the following Eq. (9):

$$\hat{x}_k^+ = \hat{x}_k^- + K_k z_k - h(k, \hat{x}_x^-) \quad (9)$$

where z_k is the measurement vector and $h(k,x)$ is the integral of the observation matrix (H_K). The error covariance matrix is then updated using the following Eq. (10):

$$P_k^+ = P_k^- - K_k H_k P_k^- \quad (10)$$

The prior information such as the transition matrix (ϕ_k), noise covariance matrix (Q_k), observation matrix (H_k), shaping matrix (G_k), and measurement noise matrix (R_k) need to be determined before the start of the experiment. The transition matrix (Φ_k) can be expanded using the Taylor's series expansion. It is given by Eq. (11) below:

$$\Phi_k = exp(F_{k-1}\mathcal{T}_i) \approx I + F\mathcal{T}_i \quad (11)$$

where I is the identity matrix and $\mathcal{T}_i$ is time varying. The noise matrix (Q_K) is given by Eq. (12) below:

$$Q_k = diag(n_{rg}^2 I_3 n_{ra}^2 I_3 0_3 n_{bad}^2 I_3 n_{bdg}^2 I_3)\tau_i \quad (12)$$

where I_3 is a (3 x 3) identity matrix, n_{rg}^2 is the power spectrum density (PSD) of angular rate error, n_{ra}^2 is the PSD of the velocity error, n_{bad}^2 is the PSD of bias instability of accelerometer, and n_{bgd}^2 is the PSD of bias instability of gyroscope. The observation matrix (H_k) is given by Eq. (13) below:

$$H_k = \begin{pmatrix} 0_3\ 0_3\ -I_3 0_3 0_3 \\ 0_3 -I_3\ 0_3\ 0_3 0_3 \end{pmatrix}_k \tag{13}$$

where 0_3 is a (3 x 3) Zero matrix. The shaping matrix (G_k) is given by Eq. (14) below:

$$G_k = \begin{pmatrix} C_b^n & 0_3 \\ 0_3 & C_b^n \\ 0_{9x3} & 0_{9x3} \end{pmatrix} \tag{14}$$

where C_b^n is rotating matrix, to convert errors of the INS frame (b) to the navigation frame (n).

Noise measurement matrix (R_k) is the main square of measurement noise (v_k) . It is given by Eq. (15) below:

$$R_k = E\ (v_k v_k^T) \tag{15}$$

In the state-space model, the error of the state vector and measurement vector are calculated. The dynamic System $(\dot{x}_k)$ of EKF model is given by Eq. (16) below:

$$x_k = f(\hat{x}_k) + G_k w_k \tag{16}$$

where w_k is the process noise of INS and the measurement vector (z_k) of EKF model is given by Eq. (17) below:

$$z_k = h(\hat{x}_k) + v_k \tag{17}$$

III. GPS/MEMS-INS Integrated System

Traditionally, MEMS-INS and GPS can be coupled via different modes, namely; loosely coupled integration and tightly coupled integration [13]-[15]. In the loosely coupled integration, data from the GPS is fed back to aid and improve the MEMS-INS system, but each one of them retains its own individual data processing algorithm throughout the interchange process. While in the tightly coupled integration, the integration is "deeper"; because raw measurements are directly combined system in a suitable filter. In this paper, the loosely coupled GPS/MEMS-INS integration strategy is used to provide a continuous navigation solution when GPS becomes outage and minimize errors of MEMS-INS system when GPS is available.it is shown in Fig. 2.

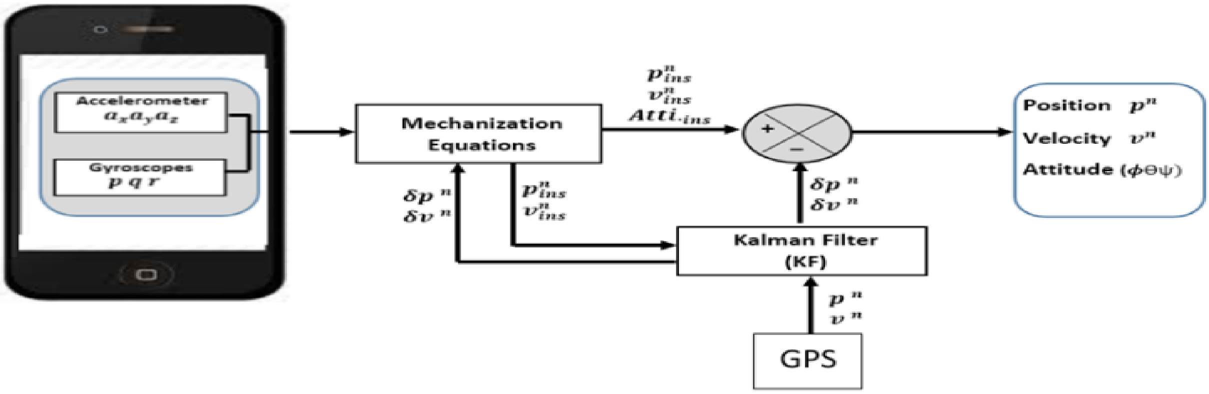

Fig. 2. MEMS/GPS navigation system outages

The main advantage of the loosely coupled strategy; it has small dimensions of the state vectors in the filter, then it take a short time and high speed processing [16]. [17].Another advantage of this approach is the computational simplicity of its implementation.

The disadvantage of loosely coupled integration is that; in general, a GPS receiver needs at least three satellites to compute the navigation solution in height-constrained mode. In urban and indoor areas, GPS signal maybe become weak or unavailable that effect on the accuracy of the loose integration method. Therefore, GPS signal must not be outage for a long time [18], [19], and [20].

IV. Test Efficiency of Navigation System

The purpose of this study was to enhance and provide the continuous navigation system based on integrated MEMS-INS mobile sensors with GPS. To verify the efficiency of the MEMS-INS/GPS navigation system, the real time data measurements from GPS and MEMS-INS mobile sensors (accelerometers and gyroscopes) are taken on 600-m reference trajectory as shown in Fig. 3:

Fig. 3. Reference trajectory

During the evaluation test, when GPS is available without any outages, the Maximum (Max.) errors of MEMS/GPS navigation system are very small, about 0.79 Meters (m) for latitude, 0.63 m for longitude and 0.98 m for position as shown in Table I:

TABLE I: THE MAX. ESTIMATED ERRORS OF LATITUDE, LONGITUDE AND DISTANCE WITHOUT ANY GPS OUTAGES

	Latitude Max. Error (m)	Longitude Max. Error (m)	Distance Max. Error (m)
GPS without any outages	0.79	0.63	0.98

TABLE II: THE RMS ESTIMATED ERRORS OF LATITUDE, LONGITUDE AND DISTANCE DURING GPS OUTAGES

MMES/GPS with several outages			
GPS outage (s)	Latitude Max. Error (m)	Longitude Max. Error (m)	Distance Max. Error (m)
for 8 S from (34s to 42s)	1.67	1.43	2.183
for 24 S from (152s to 166s)	4.93	4.14	5.35
for 50 S from (273s to 323s)	9.21	8.64	10.451
for 33 S from (481s to 524s)	6.34	5.63	6.981
for 17 S from (560s to 577s)	3.73	2.82	4.295

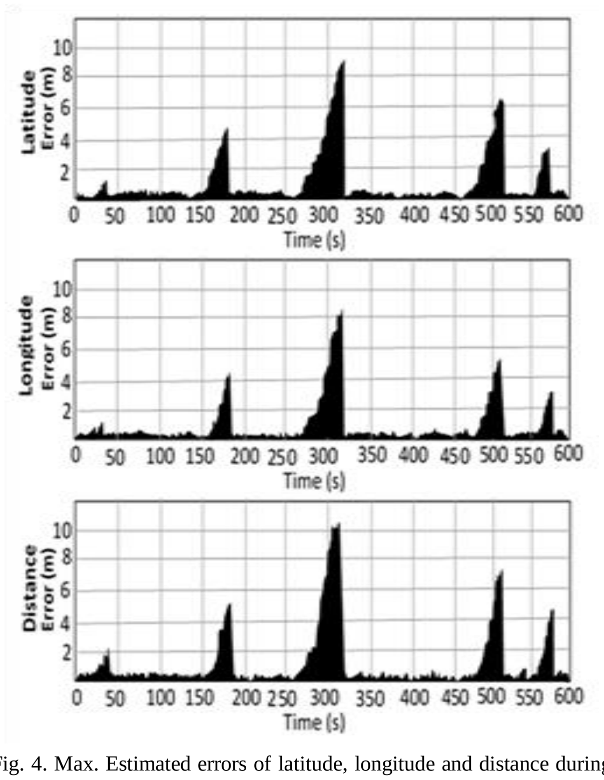

Fig. 4. Max. Estimated errors of latitude, longitude and distance during GPS outages.

To simulate GPS outage, GPS device was switched off for 8, 24, 50, 33 and 17 seconds respectively, on parts of reference trajectory. Fig. 4 shows the Max and Estimated errors of latitude and longitude that provided by Kalman filter during GPS outage.

Estimated errors of latitude and longitude that provided by Kalman filter during GPS outage.

When the GPS signal becomes outage, the error of the MEMS-INS/GPS increases due to MEMS sensor error. During a GPS outage for 50s, the (Max) and Errors are about 9.21 m for latitude, 8.64 m for longitude and 10.451 m for the Position.

Table II also shows the RMS estimated errors during GPS outages for 33s, 24s, 17s and 8s.

Fig. 5. shows the comparison between three trajectories relative to the reference trajectory (orange color):

The first trajectory (blue color) represents MEMS-INS mobile alone without any integration.

The second trajectory (red color) represents MEMS/GPS without any outage. The third trajectory (violet color) represents MEMS/GPS with outages for different times (45s, 3s, 21s, 13s and 8s) on several parts of the path.

V. CONCLUSIONS

In this article, the proposed MEMS-INS/GPS system was successfully implemented the acceptable navigation system and provided the continuous navigation solution during GPS outage. This article provided a mean for real-time implementation of a loosely coupled MEMS-INS/GPS system using low-cost MEMS sensors. It used the KF to correct MEMS errors when GPS is available and provide a continuous navigation solution when GPS is outage for no length of time. Based on this study, a good solution of navigation system can be developed with the integration of MEMS mobile sensors and GPS, which would reduce the cost and the size. This navigation system able to implement several tasks in the civilian and military applications.

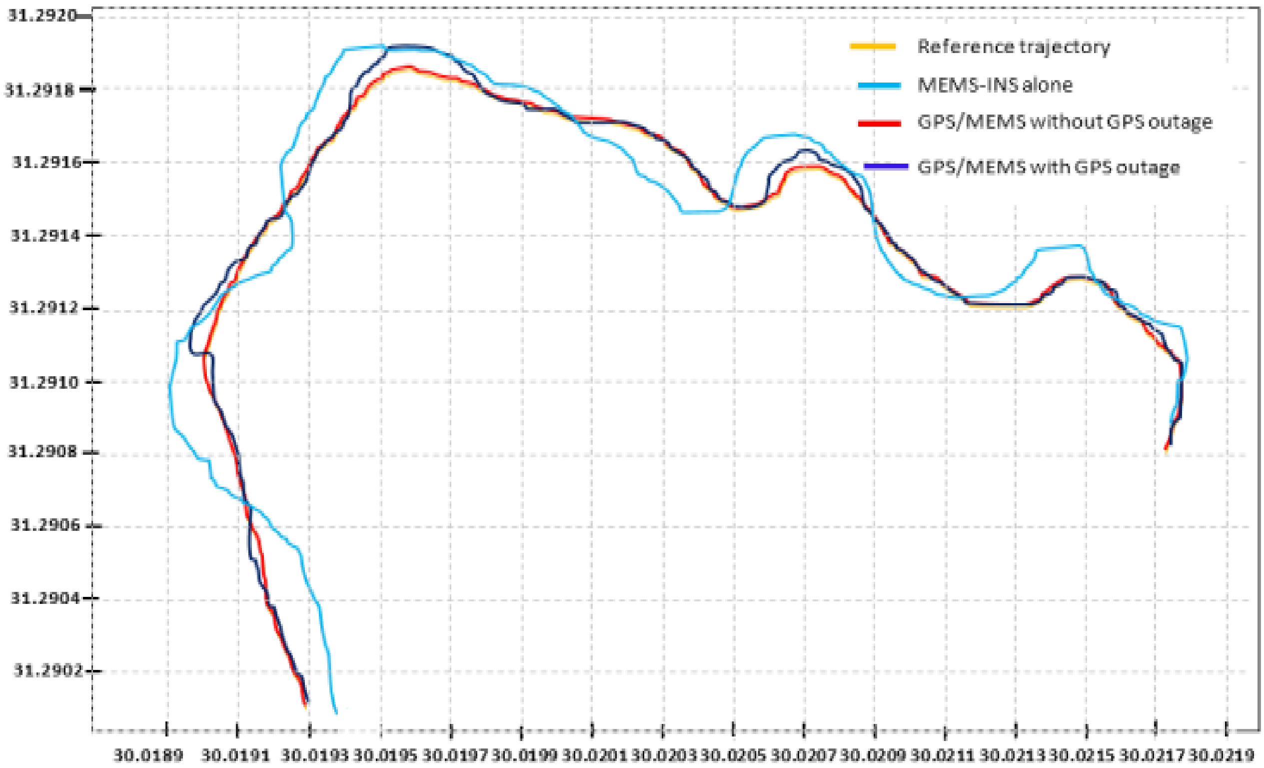

Fig. 5. Comparison of the three trajectories relative to reference trajectory (orange line) with and without GPS outages

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