Error Estimation of INS Ground Alignment Through Observability Analysis

YEON FUH JIANG, Student Member, IEEE
YU PING LIN
National Chiao Tung University
Taiwan

A systematic analysis of the observability of an inertial navigation system (INS) in ground alignment with Bar-Itzhack and Berman's error model is presented. It is shown that the unobservable states are seperately contained in two decoupled subspaces. The constraints on the selection of unobservable states are discussed. An estimation algorithm which is derived fully from the horizontal velocity outputs for computing the misalignment angles is provided. It reveals that the azimuth error can be entirely estimated from the estimates of leveling error and leveling error rate, without using gyro output signals explicitly.

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Authors' addresses: Y. F. Jiang, Institute of Electronics, National Chiao Tung University, Hsinchu, Taiwan, R.O.C.; Y. P. Lin, Institute of Control Engineering, National Chiao Tung University, 1/5 Po-Ai St., Hsinchu, Taiwan, R.O.C.

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I. INTRODUCTION

Initial misalignment is one of the major error sources of inertial navigation systems (INS). For terrestrial navigation, the initial alignment errors will affect the system error not only in the attitude indication but also in the velocity and position information [1–3]. Therfore, prior to normal navigation, alignment process must be performed to determine the orientation of the platform axes with respect to the navigation coordinate frame. One method for obtaining the initial angular orientation is through the use of an external reference by optical means. However, this method is very limited to operational enviroments. Alternatively, for most ground based applications, a self-contained alignment method known as gyrocompassing [2–7] provides another operational approach. As a general rule, gyrocompassing consists of two phases, that is, leveling and azimuth alignment. The basic principle of gyrocompassing consists of feeding signals propotional to the accelerometer outputs or/and velocity error outputs to the appropriate level gyros and azimuth gyro.

The purpose of initial alignment process is to drive the misalignment angles to zero. Unfortunately, this goal can never be achieved in a practical system. This drawback is deduced from the sensor errors which cannot be compensated ideally. From the control theorectical point of view, the basic difficulty associated with the self-alignment technique is that the system is not completely observable [8–10].

The determination of unobservabale states during initial alignment process is very important in consideration of system performance. Generally, the system state variables can be transformed into the observable canonical form. It means that the observable part and unobservable part can be seperated intentionally. However, the choice of observable (unobservable) states is certainly not unique since the number of transformations are innumerable. Early research workers showed that the determination of unobservable states was a part of physical judgments. This interesting problom of selection of the suitable unobservable states motivates us to investigate the observability of INS during ground alignment phase of operation.

We examine the observability of a linearized INS error model of a stationary vehicle. The horizontal velocity outputs of INS are the system measurements. We have found that the unobservable states which are distributed in two decoupled subspaces can be systematically determined. Also, the leveling errors can be estimated from the system measurements and their first derivatives. However, to estimate the azimuth error, the second derivative of system measurement is needed. It is equivalent to state that the estimation of azimuth error can be obtained from the estimates of leveling error and leveling error rate. This phenomenon may facilitate the designing of filters for leveling and azimuth alignment simultaneously, without using gyro outputs explicitly.

II. GROUND ALIGNMENT ERROR MODEL

In order to look into the behavior of an inertial navigator, a proper error model is now derived. It is well known that the description of the INS error propagation using a linearized error model is quite a good approximation. The characteristcs of INSs can be derived from the linear error model.

Many different error models can be found in the literature. For the purpose of our analyses, we adopt the Bar-Itzhack and Berman's [10] derivation of the error model for INS in ground alignment. Assuming the navigation system coordinate frame is the local-level north (N), east (E), and down (D) coordinate system. Since the coupling of the vertical channel with the horizontal channels is very weak, the vertical channel can be ignored. When the initial alignment process is done at a fixed ground base where the geographic position is known precisely, then the gravity error and the position error state can be ruled out. Moreover, the system is nearly stationary and hence the coriolis acceleration can also be ignored. Under these assumptions, the error dynamics including the horizontal velocity errors and the attitude errors can be made considerably simple. In this case, the INS ground alignment error model can be written as [10]

$$\begin{bmatrix} \delta\dot{v}_N \\ \delta\dot{v}_E \\ \dot{\phi}_N \\ \dot{\phi}_E \\ \dot{\phi}_D \end{bmatrix} = \begin{bmatrix} 0 & 2\Omega_D & 0 & g & 0 \\ -2\Omega_D & 0 & -g & 0 & 0 \\ 0 & 0 & 0 & \Omega_D & 0 \\ 0 & 0 & -\Omega_D & 0 & \Omega_N \\ 0 & 0 & 0 & -\Omega_N & 0 \end{bmatrix} \times \begin{bmatrix} \delta v_N \\ \delta v_E \\ \phi_N \\ \phi_E \\ \phi_D \end{bmatrix} + \begin{bmatrix} \delta a_N \\ \delta a_E \\ \delta\omega_N \\ \delta\omega_E \\ \delta\omega_D \end{bmatrix} \tag{1}$$

where δv and ϕ represent the velocity error and attitude error, respectively; δa and $\delta\omega$ represent, respectively, the generalized accelerometer error and the generalized gyro drift rate [11]; g is the local gravity; Ω represents the Earth rate; finally, the subscripts N, E, and D denote the corresponding components in the North-East-Down navigation coordinate system. Note that a form of this error model can be used for gimballed systems as well as strapdown systems [11, 12].

Rewrite (1) in compact notation

$$\dot{\mathbf{x}}' = A'\mathbf{x}' + \mathbf{b} \tag{2}$$

where the variables $\mathbf{x}'$, A', and $\mathbf{b}$ are identified with its counterpart in (1). It is reasonable and practical to assume the generalized accelerometer errors and gyro drift rates as constant in ground alignment phase. Hence, the sensor errors can be modeled as

$$\dot{\mathbf{b}} = \begin{bmatrix} \delta\dot{\mathbf{a}} \\ \delta\dot{\omega} \end{bmatrix} = 0 \tag{3}$$

where $\boldsymbol{\delta}\mathbf{a} = [\delta a_N, \delta a_E]^T$ represents the generalized accelerometer error vector and $\delta\boldsymbol{\omega} = [\delta\omega_N, \delta\omega_E, \delta\omega_D]^T$ represents the generalized gyro drift rate vector.

Combing (2) and (3), yields

$$\begin{bmatrix} \dot{\mathbf{x}}' \\ \dot{\mathbf{b}} \end{bmatrix} = \begin{bmatrix} A' & I \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \mathbf{x}' \\ \mathbf{b} \end{bmatrix} \tag{4}$$

where I is the identity matrix. This linear dynamic error model can also be expressed in compact notation as

$$\dot{\mathbf{x}} = A\mathbf{x} \tag{5}$$

where $\mathbf{x}^T = [\mathbf{x}'^T, \delta\mathbf{a}^T, \delta\omega^T]$ and the definition of A is obvious from (4).

Finally, we consider the outputs of INS horizontal velocity components as the system measurements, namely,

$$\mathbf{z} = [z_1, z_2]^T = [\delta v_N, \delta v_E]^T. \tag{6}$$

Then the relationship between the measurements and the system A' in (2) can be written as

$$\mathbf{z} = C'\mathbf{x}' \tag{7}$$

where

$$C' = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix}. \tag{8}$$

Similarily, the relationship between the measurements and the system A in (5) can be written as

$$\mathbf{z} = C\mathbf{x} \tag{9}$$

where

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}. \tag{10}$$

Now, the observability of the system A' and the system A can be analyzed.

III. OBSERVABILITY EXAMINATION

Consider a linear time-invariant system. If the rank of the observability test matrix is equal to the order of the system, then the system is completely observable. On the contrary, if the system is not completely observable, the number of unobservable states is the difference between the order of the system and the rank of the observability test matrix. In general, the observability test matrix for the system matrix A with measurement matrix C can be expressed as [8]

$$O = \begin{bmatrix} C \\ CA \\ \vdots \\ CA^{n-1} \end{bmatrix} \tag{11}$$

where n is the order of the system. Therefore, the necessary condition for the observable system is that the observability test matrix is full rank.

Now, the observability test matrix for the system A' with measurement matrix C' can be written as

$$Q' = \begin{bmatrix} C' \\ C'A' \\ C'A'^2 \end{bmatrix}. \tag{12}$$

After some explicit calculations by substituting (8) and the definition of A' (see (2)) into (12), it is easily seen that the rank of Q' is 5 which is equal to the order of the system A'. Thus the matrix Q' is full rank. So, the system A' is completely observable. It implies that if the sensor errors are fully compensated, the estimation problem during alignment process can be automatically solved.

For the system A with measurement matrix C, the observability test matrix can be written as

$$Q = \begin{bmatrix} C \\ CA \\ \vdots \\ CA^4 \end{bmatrix}. \tag{13}$$

After some explicit calculations by substituting (10) and the definition of A (see (5)) into (13), it can be found that the rank of Q is 7 which is smaller than the system order 10. Thus the matrix Q is not full rank. So, the system A is not completely observable and the estimation becomes an unsolvable problem with three unobservable states. It is clear that the observability loss in system A is generated by the augmentation from (2)–(5). It implies that the system can be made observable if the dynamics of the sensor errors are ignored. However, this assumption is practically weak. The determination of the unobservable states is now a key problem for estimation in alignment and calibration phase of operation.

Since the system measurements are observable by definition, states δv_N and δv_E are undoubtly observable. For convenience, let's define the following:

$$\mathbf{x}_1 = [\delta v_N, \delta v_E]^T \tag{14}$$

$$\mathbf{x}_2 = [\phi_E, \delta a_N, \delta\omega_N, \delta\omega_D]^T \tag{15}$$

$$\mathbf{x}_3 = [\phi_N, \phi_D, \delta a_E, \delta\omega_E]^T \tag{16}$$

and

$$\mathbf{y}_1 = \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \tag{17}$$

$$\mathbf{y}_2 = \begin{bmatrix} \dot{z}_1 - 2\Omega_D z_2 \\ \ddot{z}_2 + 4\Omega_D^2 z_2 \\ z_1^{(iii)} + 8\Omega_D^3 z_2 \\ z_2^{(iv)} - 16\Omega_D^4 z_2 \end{bmatrix} \tag{18}$$

$$\mathbf{y}_3 = \begin{bmatrix} \dot{z}_2 + 2\Omega_D z_1 \\ \ddot{z}_1 + 4\Omega_D^2 z_1 \\ z_2^{(iii)} - 8\Omega_D^3 z_1 \\ z_1^{(iv)} - 16\Omega_D^4 z_1 \end{bmatrix}. \tag{19}$$

Since the rank of a matrix is invariant under elementary row operations, the observability associated with the matrix Q, (13), is equivalent to the solvability of the following equation

$$\begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \\ \mathbf{y}_3 \end{bmatrix} = \begin{bmatrix} I & 0 & 0 \\ 0 & Q_2 & 0 \\ 0 & 0 & Q_3 \end{bmatrix} \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \mathbf{x}_3 \end{bmatrix} \tag{20}$$

where I is the identity matrix

$$Q_2 = \begin{bmatrix} g & 1 & 0 & 0 \\ -3g\Omega_D & -2\Omega_D & -g & 0 \\ -7g\Omega_D^2 - g\Omega_N^2 & -4\Omega_D^2 & -3g\Omega_D & g\Omega_N \\ 15g\Omega_D^3 + 3g\Omega_N^2\Omega_D & 8\Omega_D^3 & 7g\Omega_D^2 & -3g\Omega_N\Omega_D \end{bmatrix} \tag{21}$$

and

$$Q_3 = \begin{bmatrix} -g & 0 & 1 & 0 \\ -3g\Omega_D & g\Omega_N & 2\Omega_D & g \\ 7g\Omega_D^2 & -3g\Omega_N\Omega_D & -4\Omega_D^2 & -3g\Omega_D \\ 15g\Omega_D^3 + g\Omega_N^2\Omega_D & -7g\Omega_N\Omega_D^2 - g\Omega_N^3 & -8\Omega_D^3 & -7g\Omega_D^2 - g\Omega_N^2 \end{bmatrix}. \tag{22}$$

Equation (20) shows that the observability of the system can be determined by the solvability of three decoupled matrix equations. It is obvious that $\mathbf{x}_1$ is observable. Hence the three unoservable states must reside in $\mathbf{x}_2$ and $\mathbf{x}_3$ which are, respectively, governed by

$$\mathbf{y}_2 = Q_2\mathbf{x}_2 \tag{23}$$

and

$$\mathbf{y}_3 = Q_3\mathbf{x}_3. \tag{24}$$

It is easily found that when the system is not at the Earth pole, $\Omega_N \neq 0$. Notice that the first column of Q_2 is a linear combination of other three columns. So, from (21), the rank of Q_2 is 3 which is one less than the order of Q_2. Therefore, only one unobservable state can be chosen from the components of $\mathbf{x}_2$.

Similarily, because the first column of Q_3 is a linear combination of the third and fourth columns, the second column of Q_3 is equal to the fourth column times Ω_N. From (22), the rank of Q_3 is 2. It is thus obvious that there are two unobservable states contained in $\mathbf{x}_3$. By observation, ϕ_D and $\delta\omega_E/\Omega_N$ have the same effect on the measurement derivatives $\mathbf{y}_3$. Therefore, (24) can be rewritten as

$$\mathbf{y}_3 = \begin{bmatrix} -g & 0 & 1 \\ -3g\Omega_D & g\Omega_N & 2\Omega_D \\ 7g\Omega_D^2 & -3g\Omega_N\Omega_D & -4\Omega_D^2 \\ 15g\Omega_D^3 + g\Omega_N^2\Omega_D & -7g\Omega_N\Omega_D^2 - g\Omega_N^3 & -8\Omega_D^3 \end{bmatrix} \times \begin{bmatrix} \phi_N \\ \phi_D + \dfrac{\delta\omega_E}{\Omega_N} \\ \delta a_E \end{bmatrix} \quad (25)$$

which shows that only one of ϕ_D and $\delta\omega_E$ can be observed at a time. However, they can be chosen as unobservable states simultaneously. Thus ϕ_N and δa_E must be observable.

Note that when the system is located at the Earth pole, $\Omega_N = 0$, both the fourth column of Q_2 and the second column of Q_3 are zero. Then both $\delta\omega_D$ and ϕ_D are definitely unobservable. That is why the INS cannot be self-aligned at the pole. In this case, the rank of Q_2 is reduced to 2 and the rank of Q_3 is unchanged.

IV. ESTIMATION OF MISALIGNMENT ANGLES

The objective of initial alignment is to drive the misalignment angles ϕ_N, ϕ_E, and ϕ_D to zero or as small as possible. It is necessary that these states be all observable. Following the discussions given in Section III, δa_E and $\delta\omega_E$ in $\mathbf{x}_3$ are inevitably unobservable. Then, only one unobservable state can be chosen from the components of $\mathbf{x}_2$. Theorectically, the choice is arbitary except ϕ_E. However, in order to achieve better accuracy, the unobservable state must be selected carefully. Intuitively, from the first two columns of Q_2, it is obvious that ϕ_E and $\delta a_N/g$ are strongly coupled. Besides, if we do not choose δa_N as the unobservable state, more time derivatives of measurements are needed to compute the estimate of ϕ_E. That causes poor estimation which should be avoided in practice. Therefore, the best choice of the unobservable states are δa_N, δa_E, and $\delta\omega_E$ for the system in ground alignment process. In this case, both $\delta\omega_N$ and $\delta\omega_D$ can also be estimated for the purpose of calibration.

Once the unobservable states have been selected, we can engage in designing an estimation algorithm for computing the estimates of misalignment angles. Combing the first equation of (23) and the first two equations of (25), we have

$$\dot{z}_1 - 2\Omega_D z_2 = g\phi_E + \delta a_N \quad (26)$$

$$\dot{z}_2 + 2\Omega_D z_1 = -g\phi_N + \delta a_E \quad (27)$$

$$\ddot{z}_1 + 4\Omega_D^2 z_1 = -3g\Omega_D\phi_N + g\Omega_N\left(\phi_D + \frac{\delta\omega_E}{\Omega_N}\right) + 2\Omega_D\delta a_E. \quad (28)$$

Substituting (6) into the above equations and solving for misalignment angles, yields

$$\phi_N = -\frac{1}{g}(\delta\dot{v}_E + 2\Omega_D\delta v_N - \delta a_E) \quad (29)$$

$$\phi_E = \frac{1}{g}(\delta\dot{v}_N - 2\Omega_D\delta v_E - \delta a_N) \quad (30)$$

$$\phi_D = \frac{1}{g\Omega_N}(\delta\ddot{v}_N - 3\Omega_D\delta\dot{v}_E - 2\Omega_D^2\delta v_N + \Omega_D\delta a_E) - \frac{\delta\omega_E}{\Omega_N}. \quad (31)$$

Since we have chosen δa_E, δa_N, and $\delta\omega_E$ as unobservable states, the best estimates can be obtained by setting these unobservable states to zero, i.e.,

$$\hat{\phi}_N = -\frac{1}{g}(\delta\dot{v}_E + 2\Omega_D\delta v_N) \quad (32)$$

$$\hat{\phi}_E = \frac{1}{g}(\delta\dot{v}_N - 2\Omega_D\delta v_E) \quad (33)$$

$$\hat{\phi}_D = \frac{1}{g\Omega_N}(\delta\ddot{v}_N - 3\Omega_D\delta\dot{v}_E - 2\Omega_D^2\delta v_N). \quad (34)$$

These equations show that the leveling errors, ϕ_N and ϕ_E, can be estimated from the system measurements and their first time derivatives, and that the azimuth error, ϕ_D, can be estimated from the measurements and their time derivatives up to second order.

It is evident, from (32)–(34) and (29)–(31), that the errors in the estimation are

$$\begin{bmatrix} \delta\phi_N \\ \delta\phi_E \\ \delta\phi_D \end{bmatrix} = \begin{bmatrix} \hat{\phi}_N - \phi_N \\ \hat{\phi}_E - \phi_E \\ \hat{\phi}_D - \phi_D \end{bmatrix} = \begin{bmatrix} -\dfrac{\delta a_E}{g} \\ \dfrac{\delta a_N}{g} \\ \dfrac{\delta\omega_E}{\Omega_N} - \dfrac{\delta a_E}{g}\tan L \end{bmatrix} \quad (35)$$

where L is the geographic latitude at the system location. This result is identical with the accuracy that is often shown in the self-alignment schemes [2, 7, 10]. Obviously, this is consistent with physical interpretations. The leveling estimation errors are caused by the accelerometer errors. The azimuth estimation error is caused by the east gyro drift rate and the north leveling error. Both of them are latitude dependent. For example, the leveling estimation error due to 1 mg accelerometer error is 3.4 arc-min. The azimuth estimation error due to 0.015 deg/h east gyro drift rate is 3.4 sec L arc-min; and due to 1 mg east accelerometer error is $-3.4\tan L$ arc-min.

Finally, differentiating (33), yields

$$\dot{\hat{\phi}}_E = \frac{1}{g}(\delta\ddot{v}_N - 2\Omega_D\delta\dot{v}_E). \quad (36)$$

Substituting (32) and (36) into (34), it can be found that

$$\hat{\phi}_D = \frac{1}{\Omega_N}(\dot{\hat{\phi}}_E + \Omega_D\hat{\phi}_N) \quad (37)$$

which shows that the azimuth error can be computed from the estimates of the leveling error about north axis and the leveling error rate about east axis. Note that the estimation of azimuth error does not explicitly depend upon gyro output signals. This phenomenon can be used in an alternate filter design for leveling and azimuth alignment simultaneously.

It is also easy to modify the estimation algorithm for aligning an arbitary wander-azimuth mechanization system.

V. CONCLUSIONS

Based upon the Bar-Itzhack and Berman's INS error model, the observability of INS operating in ground alignment phase is analyzed. It is realized that the unobservable states are induced by the augmentation of sensor errors. In general, there are three unobservable states with one contained in $\mathbf{x}_2 = [\phi_E, \delta a_N, \delta\omega_N, \delta\omega_D]^T$ and two contained in $\mathbf{x}_3 = [\phi_N, \phi_D, \delta a_E, \delta\omega_E]^T$. The selection of unobservable state from $\mathbf{x}_2$ is arbitary. However, the unobservable states in $\mathbf{x}_3$ cannot be arbitarily chosen in that ϕ_D and $\delta\omega_E$ cannot be observed at the same time.

When the system is located at the Earth pole, the number of unobservable states becomes 4 among which ϕ_D and $\delta\omega_D$ are definitely unobservable states.

The determination of the unobservable states is dependent upon mission requirements. For the purpose of alignment, the best choice of unobservable states are δa_N, δa_E, and $\delta\omega_E$. An estimation algorithm has been derived for aligning the INS on ground stationary base. It is shown that the leveling errors can be estimated from the measured velocity outputs and their first time derivatives. While the second time derivative of north-velocity component is needed in estimating the azimuth misalignment angle. Furthermore, the estimated azimuth misalignment has been found proportional to the estimates of the leveling error about the north axis and the leveling error rate about the east axis. This property is useful for designing alternate filter algorithms for leveling and azimuth alignment.

Though this paper focuses on analyzing the local-level north-slaved system, it can be easily extended to cover arbitary wander-azimuth mechanization systems.

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Yeon Fuh Jiang was born in Taiwan, R.O.C., on April 10, 1954. He received the B.S. and the M.S. degree in physics from the University of Chinese Culture and the National Tsing Hua University in 1976 and 1978, respectively. After serving two years in the Chinese Army, he was employed by the Chung Shan Institute of Science and Technology from 1980 to 1987. He has experiences in the design and analysis of inertial navigation systems.

He is currently a doctoral student in the Institute of Electronics, National Chiao Tung University, Taiwan, R.O.C. His research area are inertial technology and control engineering.

Yeon Fuh Jiang is a student member of the IEEE, also a member of Phi Tau Phi.

Yu Ping Lin was born in Kwangsi, China, on Dec. 10, 1929. He received the B.S. degree in mechanical engineering from the Chinese Naval College of Technology in 1953 and the B.S. in electrical engineering from the U.S. Naval Postgraduate School in 1965, and the M.S. degree and electrical engineer degree in electrical engineering from Stanford University, Stanford, CA, in 1972.

He served in the Chinese Navy as a technical officer for eight years, and as jointed faculty member of Chung Cheng College of Science and Technology as professor of system engineering for ten years. He has been a fellow of the Center for Advanced Engineering Studies, M.I.T. in 1975–1976 specializing in inertial navigation. He is currently the Professor and Chairman of the Control Engineering Department, National Chiao Tung University, Hsinchu, Taiwan, R.O.C.