A Novel, Processing Efficient Failure Detection and Isolation Scheme for Triad-Hexad Configuration of Inertial Sensors

Vinoj VS*, Dr. Radhika VN, Kesavabrahmaji K, Syamala S, A Abdul Shukkoor, Dr. PP Mohanlal
ISRO Inertial Systems Unit, ISRO, Thiruvananthapuram-695013, India

Abstract

This paper discusses a novel fault detection and isolation scheme for a skewed triad-hexad configuration of inertial sensors. This geometry is used for accelerometers in ISRO's next generation inertial navigation system for launch vehicles called mRESINS (Miniaturized REdundant Strapdown Inertial Navigation System). The geometry of accelerometer channels gives better fault tolerance, enhanced redundancy management, reliability and accuracy. The conical array of six accelerometers provides the best possible accuracy and GDOP. A computationally efficient Failure Detection and Isolation (FDI) scheme is designed for the acceleration channels. The FDI scheme design is capable of detecting and isolating upto two sensor failures. The parity equations are formed by comparing each sensor measurements against its best estimates. The FDI logic is designed in such a way that minimum one parity is available for detecting each sensor failure. Since one sensor failure scenario is covered in two sensor failure cases, second one alone is considered for the design. For all possible 15 two sensor failure cases, a geometry matrix is generated which is used to transform the sensor measurements to vehicle body axis and use them to generate the parity equations (60 numbers). Gram Schmidt Orthonormalization procedure is employed to obtain minimum parity equations (15 numbers) required to detect all the possible single or two sensor failure cases from all the parity equations. From the set of 15 parity equations, three independent parity equations are selected and used for accumulated residue processing. The novel algorithm reduces processing load by 40% and reduces memory usage by 80% of FDI processing budget. The algorithm is implemented in flight software and extensive failure simulation tests are completed in various test beds with and without INS hardware. The flight test of the system is also completed.

**Corresponding author: vinoj_syamala@vssc.gov.in*

Keywords

FDI, accelerometer geometry, triad-hexad configuration, redundancy management in INS

I. INTRODUCTION

Inertial navigation systems are critical elements in launch vehicles, spacecrafts, missiles etc. The accuracy of such systems depends heavily on the accuracy of INS. Inertial navigation systems (INS) require minimum three accelerometers and three gyroscopes to generate navigation information: position, velocity and attitude. The use of redundant sensors is employed to avoid single point failures, ensure mission reliability and improved navigation accuracy. Failure detection and isolation (FDI) design is a major method to remove faulty sensors from navigation computation.

REdundant Strap-down Inertial Navigation System (RESINS) is used for measuring attitude and navigation data required for the closed loop guidance and control system in ISRO launch vehicle missions. RESINS have evolved through various configurations and mRESINS is the next generation miniature INS with optimum sensor geometry.

II. TRIAD-HEXAD CONFIGURATION OF ACCELEROMETERS AND MEASUREMENT EQUATION

The conical array of six accelerometers with half cone angle of 54.74^o is used for acceleration measurement which can be visualized as two orthogonal triads. The accelerometer geometry is given in figure1. S1 to S6 indicates six accelerometers each makes an angle of α (α= 54.74^o) with Z axis. The adjacent accelerometers make an angle 60^o in X-Y plain.

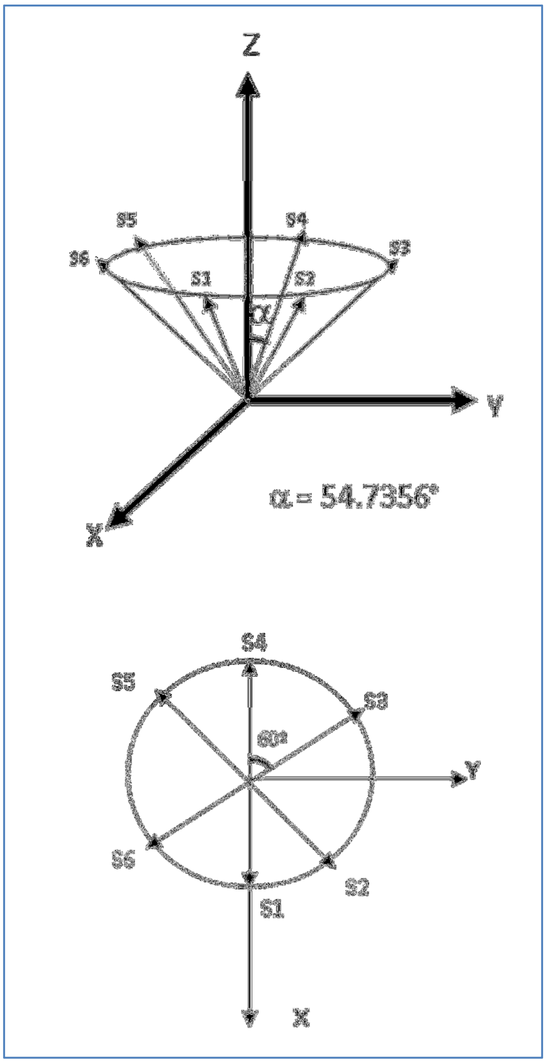

Fig. 1 Accelerometer geometry in inertial sensing unit

The acceleration channel measurement equation is: **M=H.X+e**
Where:

$$M = \begin{bmatrix} S1 \\ S2 \\ S3 \\ S4 \\ S5 \\ S6 \end{bmatrix}$$

M :The measurement vector of all the six accelerometers

H: The geometry matrix relating the sensor measurement to body axis inputs.

$$H = \begin{bmatrix} \sin\alpha & 0 & \cos\alpha \\ \sin\alpha * \cos 60 & \sin\alpha * \sin 60 & \cos\alpha \\ -\sin\alpha * \cos 60 & \sin\alpha * \sin 60 & \cos\alpha \\ -\sin\alpha & 0 & \cos\alpha \\ -\sin\alpha in\alpha co & -\sin\alpha * \sin 60 & \cos\alpha \\ \sin\alpha * \cos 60 & -\sin\alpha * \sin 60 & \cos\alpha \end{bmatrix}$$

Where $\alpha = 54.7356°$

X : Specfic force in body axis : X, Y, Z

$$\underline{x} = \begin{bmatrix} fx^{b} \\ fy^{b} \\ fz^{b} \end{bmatrix}$$

$\underline{e}$: Measurement error vector

$$\underline{e} = \begin{bmatrix} err1 \\ err2 \\ err3 \\ err4 \\ err5 \\ err6 \end{bmatrix}$$

The total error in each of the channels is a combination of systematic errors of the sensors and the measurement uncertainties. The systematic errors are laboratory calibrated and compensated onboard. Since all the sensors used are having good short term stability, the only uncertainty expecting in flight is the measurement uncertainty, which is very small and random in nature and hence can be assumed as zero mean Gaussian noise.

The sensor measurement is converted to engineering unit using scale factor and then compensated for bias and second order non-linearity. All the parity computations are done in the velocity increments domain.

III. STATE ESTIMATION ACCURACY AND FAILURE DETECTABILITY

The contribution of sensor geometry in estimation accuracy of final measurement is given by GDOP. Lowest GDOP offers best estimation accuracy.

$$\underline{M} = H.\underline{X} + \underline{\text{E}}$$

The least square error estimate of the vector X is,

$$\hat{\underline{X}} = (H^T.H)^{-1}.H^T].\underline{M}$$

The state error covariance matrix is :

$$\text{cov}(\hat{\underline{X}}) = E[(\hat{\underline{X}} - E(\hat{\underline{X}})).(\hat{\underline{X}} - E(\hat{\underline{X}}))^T]$$

$$\text{cov}(\hat{\underline{X}}) = \sigma^2 (H^T.H)^{-1}$$

$$GDOP = \sqrt{Trace(H^T.H)^{-1}}$$

The triad-hexad configuration is one of the optimum geometry of six sensors. GDOP of acceleration channels are computed for different failure cases and given in Table1. The best GDOP is obtained when all the sensors are healthy.

TABLE 1: GDOP FOR DIFFERENT SENSOR FAILURE CASES

SI No	Sensor Failure Case	GDOP
1	No sensor failure	1.224745
2	After one sensor failure	1.414214
3	After two alternate sensor failure	1.58114
4	After two diametrically opposite sensor failure	1.65831
5	After two adjacent sensor failure	2.024845

Failure detectability is assessed using S matrix and is defined as:

$S = I - H.[(H^T.H)^{-1}.H]$,

H: Geometry matrix.

The failure detectability of mRESINS acceleration channels is summarized in the table2. As the S matrix diagonal increases, failure detectability increases. With all the six healthy sensors, uniform detectability of 50% is available. With a single sensor failure uniform detectability is available if failed sensors are diametrically opposed, otherwise detectability is minimum. After two sensor failure FDI design cannot identify the failure.

TABLE2: FAILURE DETECTABILITY OF ACCELERATION CHANNELS

SI No	Failure Case	Minimum S matrix diagonal	Remarks
1	No sensor failure	0.5	Uniform detectability available for the single failures
2	After one sensor isolation	0.27778	Detectability is minimum
3	After 2 diametrically opposite sensor isolation	0.25	FDI design cannot identify the failure
4	After 2 adjacent sensor isolation	0.1	
5	After 2 alternate sensor isolation	0.05556	

IV. FAILURE DETECTION AND ISOLATION STRATEGY

Failure detection and isolation philosophy is to detect and isolate failure(s) in the acceleration channel(s) by a set of parity checks. The parity checks utilize only the functional output from the sensors. FDI design is to isolate up to 2 channel failures. If fault detection is done but identification is not possible, mission salvage shall be indicated to enable open loop guidance mode making the system fail-op-fail-op-fail-safe.

FDI is designed with 2 levels of parity checks called hard check (2 second moving sum of residues obtained from compensated velocity increments) and soft check (30 second moving sum). Parity check is done on the sensor data which passes the range check. Range check is a coarse check where the raw sensor data is compared against a higher and lower limit of maximum thrust expected. If the sensor data is more than the upper range or less than the lower range, that sensor will be isolated. Hard parity check is to isolate a faulty sensor quickly and soft parity check is for isolation of slightly degraded sensor for mission accuracy improvement. If a sensor is isolated in higher level checks, that sensor will not be considered for lower level checks. If a sensor is found faulty for a fixed duration, that sensor will be isolated permanently.

A. Parity Equations

All the six sensors are available in a three dimensional space and no three sensors are co-planar, so minimum three sensors are sufficient for estimating the specific force in sensor body axis. With four healthy sensors, failure detection is possible, with five sensors, detection of two failures and isolation of one failure is possible, with six sensors (Configuration of mRESINS), detection of three failures and isolation of two failures possible.

Since one sensor failure scenario is covered in two sensor failure cases, we consider two sensor failure cases only. For all the possible 15 two sensor failure cases, we generate a geometry matrix which is used to transform the sensor measurement to vehicle body axis.

The measurement equation is:

$$M=HX+E,$$

Error compensation makes E~0.

$$M=HX$$

For a sample case of S1, S2 failure the H matrix is:

$$H_{12} = \begin{bmatrix} -0.4082 & 0.7071 & 0.5774 \\ -0.8165 & 0 & 0.5774 \\ -0.4082 & -0.7071 & 0.5774 \\ 0.4082 & -0.7071 & 0.5774 \end{bmatrix}$$

M is the measurement matrix and is available every cycle. Hence an estimate of the specific force in body axis can be computed using least square error estimate.

$$\underline{\hat{X}} = (H^T.H^{-1}).\ H^T.\underline{M}$$

Estimate X using S2,S3,S4,S5: X_{12}

$$\hat{X}_{12} = \begin{bmatrix} 0.3674 & -0.7348 & -0.4899 & 0.8573 \\ 0.7778 & -0.1414 & -0.5657 & -0.0707 \\ 0.8660 & 0.0000 & -0.0000 & 0.8660 \end{bmatrix} . \begin{bmatrix} S3 \\ S4 \\ S5 \\ S6 \end{bmatrix} .$$

If all sensors are healthy estimate of M is :

$$\hat{M} = H_{12}.\hat{X}_{12}$$

$$M - \hat{M} \sim 0$$

$$M - H_{12}.\ \hat{X}_{12} \quad \sim 0$$

$$M - H_{12}.\ L_{12}.M = M.(I - H_{12}.L_{12}) \sim 0,$$

$$\text{Where } L_{12} = (H_{12}^T.H_{12})^{-1}.H_{12}^T$$

$$\begin{bmatrix} S3 \\ S4 \\ S5 \\ S6 \end{bmatrix} . \begin{bmatrix} 0.1000 & -0.2000 & 0.2000 & -0.1000 \\ -0.2000 & 0.4000 & -0.4000 & 0.2000 \\ 0.2000 & -0.4000 & 0.4000 & -0.2000 \\ -0.1000 & 0.2000 & -0.2000 & 0.1000 \end{bmatrix} \sim 0$$

This generates 4 residue equations (4x4 matrix). This 4x4 matrix can be reduced to 4x1 vector (R1) using gram Schmidt Orthonormalization procedure

$$\begin{bmatrix} S3 \\ S4 \\ S5 \\ S6 \end{bmatrix} . \begin{bmatrix} 0.3162 & -0.6325 & 0.6325 & -0.3162 \end{bmatrix} \sim 0$$

R1 =(0.3162..S3-0.6325..S4+0.6325.S5-0.3162.S6)

The same procedure is repeated for all the 2 failure cases generating 15 parity equations as shown below

R1 =k1(0.S1+0.S2+1.S3-2.S4+2.S5-1.S6)
R2 =k2(0.S1+1.S2+0.S3-2.S4+3.S5-2.S6)
R3 =k3(0.S1+1.S2-1.S3+0.S4+1.S5-1.S6)
R4 =k2(0.S1+2.S2-3.S3+2.S4+0.S5-1.S6)
R5 =k1(0.S1+1.S2-2.S3+2.S4-1.S5+0.S6)
R6 =k1(1.S1+0.S2+0.S3-1.S4+2.S5-2.S6)
R7 =k2(2.S1+0.S2-1.S3+0.S4+2.S5-3.S6)
R8 =k3(1.S1+0.S2-1.S3+1.S4+0.S5-1.S6)
R9 =k2(1.S1+0.S2-2.S3+3.S4-2.S5+0.S6)
R10=k1(2.S1-1.S2+0.S3+0.S4+1.S5-2.S6)
R11=k2(3.S1-2.S2+0.S3+1.S4+0.S5-2.S6)
R12=k3(1.S1-1.S2+0.S3+1.S4-1.S5+0.S6)
R13=k1(2.S1-2.S2+1.S3+0.S4+0.S5-1.S6)
R14=k2(2.S1-3.S2+2.S3+0.S4-1.S5+0.S6)
R15=k1(1.S1-2.S2+2.S3-1.S4+0.S5+0.S6)

Where:

k1: 0.316227766016838
K2: 0.235702260395515
k3: 0.500000000000000

B. Basis Parity Residues

All the fifteen parity equations are available in a 3 dimensional space and hence three independent residues are sufficient to compute the other 12 residues. R1, R10, R15 forms the basis parities. The coefficient matrix for computing non-basis parity residues are found by the method of pseudo inverse as follows.

$$H=K.B$$
$$K=H.B^T.(B^T.B)^{-1}$$

Where H: Parity matrix

B: Basis parity matrix

K: coefficient matrix

This leads to the following 12 equations, which derive non-basis residues from basis residues.

$$R2 = p1(4.R1+1.R10-2.R15)$$
$$R3 = p3(1.R1+1.R10-2.R15)$$
$$R4 = p1(-1.R1+2.R10-4.R15)$$
$$R5 = p2(-2.R1+1.R10-2.R15)$$
$$R6 = p2(2.R1+2.R10-1.R15)$$
$$R7 = p1(1.R1+4.R10-2.R15)$$
$$R8 = p3(-1.R1+2.R10-1.R15)$$
$$R9 = p1(-4.R1+2.R10-1.R15)$$
$$R11 = p1(-2.R1+4.R10+1.R15)$$
$$R12 = p3(-2.R1+1.R10+1.R15)$$
$$R13 = p2(-1.R1+2.R10+2.R15)$$
$$R14 = p1(-2.R1+1.R10+4.R15)$$

Where

p1:0.248451997499977

p2:0.333333333333333

p3:0.527046276694730

This method needs only three basis residues to be stored in the computer for accumulated residue computation for hard and soft parity check. This saves more than 80% of the memory and more than 40% of processing time.

If all sensors are healthy, all the 15 residues will be normal. For one sensor failure, 5 residues will be normal. For all the possible 15 combination of two sensor failures a unique single residue will be normal.

The sensor failure signature for all the sensor failure combinations (upto 2 sensor failure) are shown in figure3

C. Threshold Computation of FDI Residue

The maximum possible residue for a set of healthy channels is computed offline and loaded onboard for in-flight threshold check. The factors considered are the 3σ values of

- Sensor Bias error
- Scale factor error
- Misalignment between sensors
- Scale factor Non linearity
- Quantization noise
- Sensor channel phase lag error

SI No	Failed Sensors		R15	R14	R13	R12	R11	R10	R9	R8	R7	R6	R5	R4	R3	R2	R1
1	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	S1		1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
3	S2		1	1	1	1	1	1	0	0	0	0	1	1	1	1	0
4	S3		1	1	1	0	0	0	1	1	1	0	1	1	1	0	1
5	S4		1	0	0	1	1	0	1	1	0	1	1	1	0	1	1
6	S5		0	1	0	1	0	1	1	0	1	1	1	0	1	1	1
7	S6		0	0	1	0	1	1	0	1	1	1	0	1	1	1	1
8	S1	S2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
9	S1	S3	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1
10	S1	S4	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1
11	S1	S5	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1
12	S1	S6	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1
13	S2	S3	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
14	S2	S4	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
15	S2	S5	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
16	S2	S6	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1
17	S3	S4	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
18	S3	S5	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
19	S3	S6	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
19	S4	S5	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1
21	S4	S6	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
22	S5	S6	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Figure3: Sensor failure signature

V. Conclusion

1. Fault detection and isolation scheme is designed for acceleration channels for inertial sensing unit with six accelerometers saving 80% of memory usage and 40% of processing capability usage.
2. The scheme is capable of detecting upto three sensor failures and able to isolate two failures
3. FDI residue thresholds are designed for avoiding quick isolation of faulty sensors with minimum false alarm

4. The flight test of the system is completed

REFERENCES

[1] Duk-Sun Shim and Cheol-Kwan Yang " Optimal Configuration of Redundant Inertial Sensors for Navigation and FDI Performance", Sensors 2010, 10, 6497-6512; doi:10.3390/s100706497, www.mdpi.com/journal/sensors

[2] MARK A STURZA, Litton systems Inc, "Skewed axis inertial sensor geometry for optimal performance", © 1988 American Society for Aeronautics and Astronautics

[3] ROLF ISERMANN, Fault-Diagnosis Applications, Springer, ISBN 978-642-12766-3

[4] KROGMANN U: 'Design considerations for highly reliable hard and soft fault tolerance inertial reference systems' DGON proceedings *Gyro Technology Symposium,* Stuttgart 1990

[5] BORTZ, JE: 'A new mathematical formulation for stapdown inertial navigation', IEEE transactions on Aerospace and Electronics Systems