MEMS IMU Based INS/GNSS Integration: Design Strategies and System Performance Evaluation

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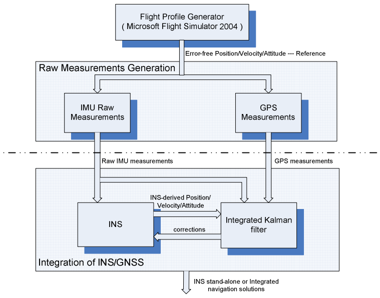
Abstract

This study focuses on the integration design of INS with GNSS based on MEMS IMU sensors. The sophisticated MEMS IMU error models are employed to evaluate the MEMS error impacts on INS performance. Through the use of the MEMS IMU error model, the MEMS IMU raw measurements can be simulated conveniently. Moreover it provides the fundamental model for the inertial sensor error compensation before INS calculation. The Kalman filter based integration configuration is also designed by combining GNSS solutions in this paper. Different experimental scenarios are designed to evaluate the performance of the proposed integration configuration by various simulation tests. The experimental results indicated that the performance of the MEMS based INS is greatly enhanced by integration of GNSS compared with its stand-alone usage and by employing the MEMS IMU error model to compensate the deterministic sensor errors.

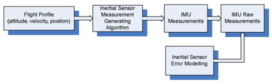
Research Outlines

- MEMS IMU Based INS/GNSS Integration Structure (Simulation)
- INS Digital Integration Algorithm Design
- Integrated Kalman Filter Design
- System Validation and Experimental Results

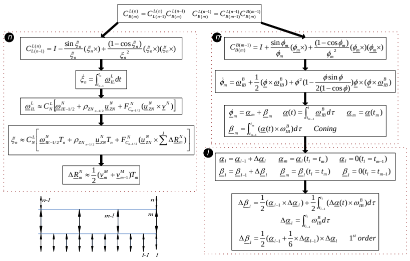
Design Methods



Flight Profile Generator
(Microsoft Flight Simulator 2004)
Error-free Position/Velocity/Attitude — Reference
Raw Measurements Generation
IMU Raw Measurements
GPS Measurements
Raw IMU measurements
GPS measurements
INS-derived Position/ Velocity/Attitude
INS
corrections
Integrated Kalman filter
Integration of INS/GNSS
INS stand-alone or Integrated navigation solutions



Flight Profile (attitude, velocity, position)
Inertial Sensor Measurement Generating Algorithm
IMU Measurements
IMU Raw Measurements
Inertial Sensor Error Modelling



$$C^{L(n)}_{B(m)} = C^{L(n)}_{L(n-1)} C^{L(n-1)}_{B(m)} \qquad C^{L(n-1)}_{B(m)} = C^{L(n-1)}_{B(m-1)} C^{B(m-1)}_{B(m)}$$

n

$$C^{L(n)}_{L(n-1)} = I - \frac{\sin \xi_n}{\xi_n}(\underline{\xi}_n\times) + \frac{(1-\cos\xi_n)}{\xi_n^{\;2}}(\underline{\xi}_n\times)(\underline{\xi}_n\times)$$

$$\dot{\underline{\xi}}_n = \int_{t_{n-1}}^{t_n} \underline{\omega}^L_{IL} dt$$

$$\underline{\omega}^L_{IL} \approx C^L_N \left[\underline{\omega}^N_{IE-1/2} + \rho_{ZN_{n-1/2}} \underline{u}^N_{ZN} + F^N_{C_{n-1/2}}(\underline{u}^N_{ZN} \times \underline{v}^N)\right]$$

$$\underline{\xi}_n \approx C^L_N \left[\underline{\omega}^N_{IE-1/2} T_n + \rho_{ZN_{n-1/2}} \underline{u}^N_{ZN} T_n + F^N_{C_{n-1/2}}(\underline{u}^N_{ZN} \times \sum^j \Delta \underline{R}^N_m)\right]$$

$$\Delta \underline{R}^N_m \approx \frac{1}{2}(\underline{v}^M_m + \underline{v}^M_{m-1}) T_m$$

m

$$C^{B(m-1)}_{B(m)} = I + \frac{\sin\phi_m}{\phi_m}(\underline{\phi}_m\times) + \frac{(1-\cos\phi_m)}{\phi_m^{\;2}}(\underline{\phi}_m\times)(\underline{\phi}_m\times)$$

$$\dot{\underline{\phi}}_m = \underline{\omega}^B_{IB} + \frac{1}{2}(\underline{\phi}\times\underline{\omega}^B_{IB}) + \phi^2\left(1-\frac{\phi\sin\phi}{2(1-\cos\phi)}\right)\underline{\phi}\times(\underline{\phi}\times\underline{\omega}^B_{IB})$$

$$\underline{\phi}_m = \underline{\alpha}_m + \underline{\beta}_m \qquad \underline{\alpha}(t) = \int_{t_{m-1}}^{t} \underline{\omega}^B_{IB} d\tau \qquad \underline{\alpha}_m = \underline{\alpha}(t_m)$$

$$\underline{\beta}_m = \int_{t_{m-1}}^{t_m} (\underline{\alpha}(t)\times\underline{\omega}^B_{IB}) d\tau \qquad Coning$$

l

$$\underline{\alpha}_l = \underline{\alpha}_{l-1} + \Delta\underline{\alpha}_l \qquad \underline{\alpha}_m = \underline{\alpha}_l(t_l = t_m) \qquad \underline{\alpha}_l = 0(t_l = t_{m-1})$$

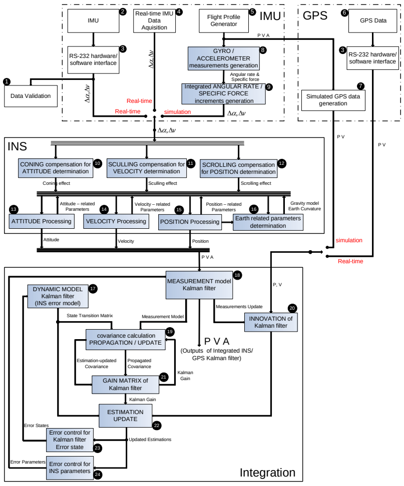
$$\underline{\beta}_l = \underline{\beta}_{l-1} + \Delta\underline{\beta}_l \qquad \underline{\beta}_m = \underline{\beta}_l(t_l = t_m) \qquad \underline{\beta}_l = 0(t_l = t_{m-1})$$

$$\Delta\underline{\beta}_l = \frac{1}{2}(\underline{\alpha}_{l-1}\times\Delta\underline{\alpha}_l) + \frac{1}{2}\int_{t_{l-1}}^{t_l}(\Delta\underline{\alpha}(t)\times\underline{\omega}^B_{IB})d\tau$$

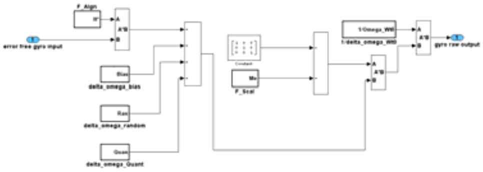
$$\Delta\underline{\alpha}_l = \int_{t_{l-1}}^{t_l} \omega^B_{IB} d\tau$$

$$\Delta\underline{\beta}_l = \frac{1}{2}(\underline{\alpha}_{l-1} + \frac{1}{6}\times\Delta\underline{\alpha}_{l-1})\times\Delta\underline{\alpha}_l \qquad 1^{st}\ order$$

Attitude Determination



IMU
GPS
IMU ②
Real-time IMU Data Aquisition ④
Flight Profile Generator ⑤
GPS Data ⑥
RS-232 hardware/ software interface ③
GYRO / ACCELEROMETER measurements generation ⑧
Angular rate & Specific force
Integrated ANGULAR RATE / SPECIFIC FORCE increments generation ⑨
Data Validation ①
Simulated GPS data generation ⑦
Real-time
simulation
P V A
P V
$\Delta\alpha, \Delta v$
INS
CONING compensation for ATTITUDE determination ⑩
SCULLING compensation for VELOCITY determination ⑪
SCROLLING compensation for POSITION determination ⑫
Coning effect
Sculling effect
Scrolling effect
Attitude – related Parameters
Velocity – related Parameters
Position – related Parameters
Gravity model Earth Curvature
ATTITUDE Processing ⑬
VELOCITY Processing ⑭
POSITION Processing ⑮
Earth related parameters determination ⑯
Attitude
Velocity
Position
Integration
MEASUREMENT model Kalman filter ⑱
DYNAMIC MODEL Kalman filter (INS error model) ⑰
State Transition Matrix
Measurement Model
Measurements Update
P, V
INNOVATION of Kalman filter ⑳
covariance calculation PROPAGATION / UPDATE ⑲
P V A
(Outputs of Integrated INS/ GPS Kalman filter)
Estimation-updated Covariance
Propagated Covariance
Kalman Gain
GAIN MATRIX of Kalman filter ㉑
ESTIMATION UPDATE ㉒
Error States
Updated Estimations
Error control for Kalman filter Error state ㉓
Error Parameters
Error control for INS parameters ㉔



$$\Phi_m = I + \Delta\Phi_{\lambda\lambda_m} + \frac{1}{2}\Delta\Phi_{\lambda\lambda_m}{}^2 \qquad \Delta\Phi_{\lambda\lambda_m} = \int_{t_{m-1}}^{t_m} A(t)dt$$

Kalman Filter Dynamic Model

$$A(t) = \begin{cases} \dot{\underline{\Psi}}^N = -C^N_B \delta\underline{\omega}^B_{IB} - \underline{\omega}^N_{IN} \times \Psi^N \\ \delta\dot{\underline{V}}^N = C^N_B \delta\underline{a}^B_{SF} - \underline{a}^N_{SF} \times \Psi^N + \delta\underline{g}^N_{Mdl} - (2\underline{\omega}^N_{IE} + \underline{\omega}^N_{EN}) \times \delta\underline{V}^N \\ \delta\dot{\underline{R}}^N = \delta\underline{V}^N - \underline{\omega}^N_{EN} \times \delta\underline{R}^N \end{cases}$$

$$\dot{\underline{\Psi}}^N = -C^N_B \delta\underline{\omega}^B_{IB}$$

$$\delta\dot{\underline{V}}^N = C^N_B \delta\underline{a}^B_{SF} - \underline{a}^N_{SF} \times \Psi^N$$

$$\delta\dot{\underline{R}}^N = \delta\underline{V}^N$$

INS Error Equations

$$a_{SF_{Puls}} = \frac{1}{A_{W_{to}}}(I + G_{Scal})(G_{\mathrm{Alg}\,n}\underline{a}_{SF} + \delta\underline{a}_{Bias} + \delta\underline{a}_{Size} + \delta\underline{a}_{niso} + \delta\underline{a}_{Quant} + \delta\underline{a}_{Rand})$$

$$\underline{\omega}_{Puls} = \frac{1}{\Omega_{W_{to}}}(I + F_{Scal})(F_{\mathrm{Alg}\,n}\underline{\omega} + \delta\underline{\omega}_{Bias} + \delta\underline{\omega}_{Quant} + \delta\underline{\omega}_{Rand})$$

MEMS Sensor Error Modelling

$$\Delta\Phi_{\lambda\lambda_m} = \int_{t_{m-1}}^{t_m} A(t)dt = \begin{cases} A(t_{m-1}) \cdot T_m & (1) \\ \frac{1}{2}[A(t_{m-1}) + A(t_m)] \cdot T_m & (2) \end{cases}$$

$$T_m = t_m - t_{m-1}$$

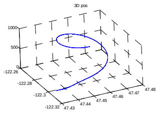
Integration algorithm of INS error equations

System Validation and Experimental Results

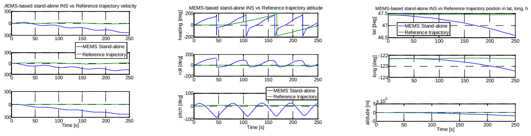
	Accelerometers	
Error Model Parameters	Bias [μg]	Noise [μg/√Hz]
Navigation II	0,1 - 10	1 - 10
Navigation I	10 - 300	50
Tactic	200 - 1000	200 - 600
Commercial(MEMS)	1000 - 10000	800 – 10000
	Gyro	
Error Model Parameters	Bias [deg/h]	Noise [deg/h/√Hz]
Navigation II	0,002 - 0,01	0,002 - 0,005
Navigation I	0,002 - 0,1	0,002 - 0,05
Tactic	1 - 50	0,2 - 0,5
Commercial(MEMS)	50 - 3600	0,5 - 1

Summit Instruments 65210A - Accelerometers	
Bias [μg]	Noise [μg/√Hz]
3×10^5	10^3
Summit Instruments 65210A – Angular Rate Output	
Bias [deg/h]	Noise [deg/√h]
10^4	1.2

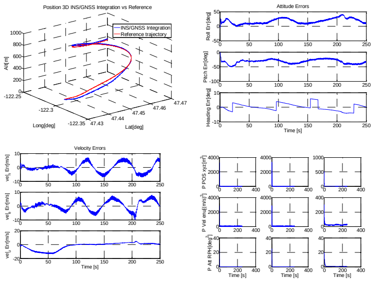
Error Model Parameters



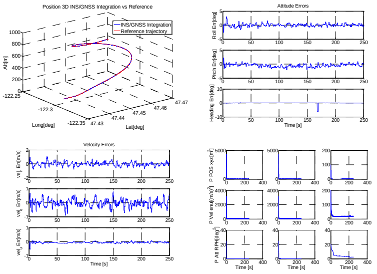
Trajectory



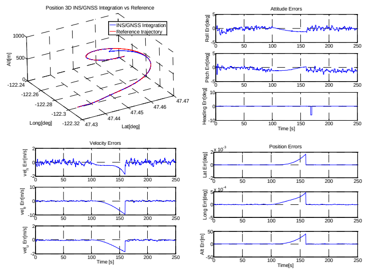
MEMS-based INS Stand-alone Solutions



INS/GNSS Integration Solutions without MEMS Biases Compensation



INS/GNSS Integration Solutions with MEMS Biases Compensation



INS/GNSS Integration 3D-Solution with GNSS 60s Blockage

Conclusion

- MEMS IMU error models are introduced to simulate the various noises in the raw MEMS IMU measurements.
- Proposed models provide the fundamental structure for the compensation of raw IMU deterministic noises.
- Integrated INS/GNSS Kalman filter is designed to deliver the optimally integrated solutions meanwhile compensating the random noises in the raw MEMS measurements.

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