Introduction to Inertial Navigation and Pointing Control

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Outline

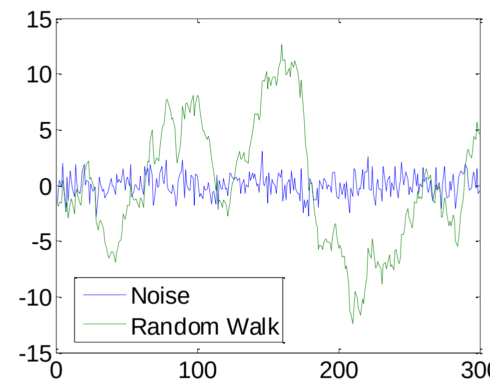
- Inertial Navigation System (INS)
- INS/GPS Integration
- Pointing Control System

Navigation System

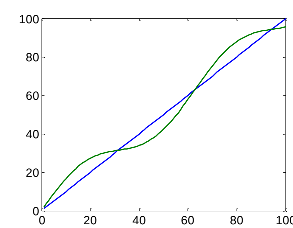
- Navigation: estimate the position, velocity, and orientation of a platform
- Inertial Navigation: use inertial sensors for navigation
  - Based on inertial principles (acceleration and angular velocity)
  - Measurements are always in the inertial frame
- Most common inertial sensors
  - Accelerometers
  - Gyros
- Applications
  - Manned and unmanned aircrafts, spacecrafts, ships, submarines, and land vehicles
  - Short-term motion compensation: EO/IR (stable attitude), SAR (precise velocity)
  - Precise pointing: laser designator/director, ground-based RADAR, telescope
  - Relative positioning: aerial refueling, aircraft carrier landing

Common Sensor Error Terms

- Use weight scale as an example to explain <u>common</u> sensor error terms
  - Weight = Spring Constant * Distance Deflection
  - Ex: 100 lb = 100 * 1 cm   200 lb = 100 * 2 cm
- **Bias Error** – An added constant, independent of input
  - Weight = Spring Constant * Distance Deflection + Bias
  - Ex: 102 lb = 100 * 1 cm + 2   202 lb = 100 * 2 cm + 2
- **Scale Factor Error** – proportional to input
  - Sprint constant is the scale factor in our example
  - Ex: 103 lb = 101 * 1 cm + 2   204 lb = 101 * 2 cm + 2
- **Noise** – fast changing random effect
  - Zero-mean random variable, certain probability distribution
  - **Random Walk**: phenomena when integrating noise over time

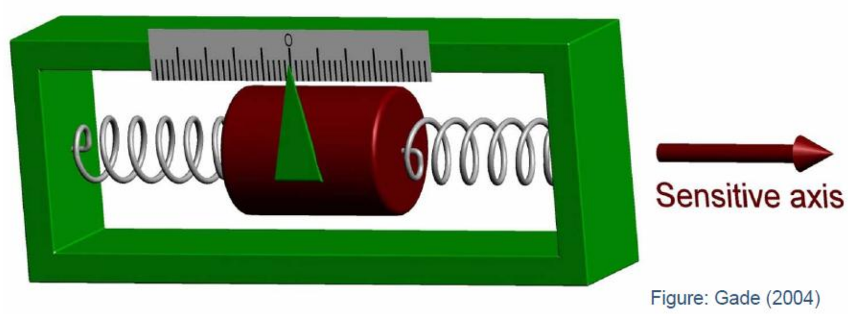


- **Linearity Error** – input-output nonlinearity
  - Ideally, input-output plot is a straight line



- **Misalignment** – Difference between actual sensing axis and perceived sensing axis

Accelerometers



- Measure specific force
  - Specific force = acceleration - gravity
- Error sources: bias, scale factor, misalignment, linearity, random walk
- Bias is typically the dominant error source
  - Navigation grade accelerometers have accuracy of 50 micro-g
  - Simple 1-D model with a constant unknown bias term (No other aiding)

$$a_{meas} = a_{true} + b_a$$

- Velocity can be obtained by integrating the acceleration

$$v_{est} = v_0 + \int_0^t a_{meas} = v_{true} + \delta v_0 + b_a t$$

- Position can be obtain by integrating the velocity

$$p_{est} = p_0 + \int_0^t v_{est} = p_{true} + \delta p_0 + \delta v_0 t + \frac{1}{2} b_a t^2$$

Unbounded Drift Error

Accelerometer Technology Application

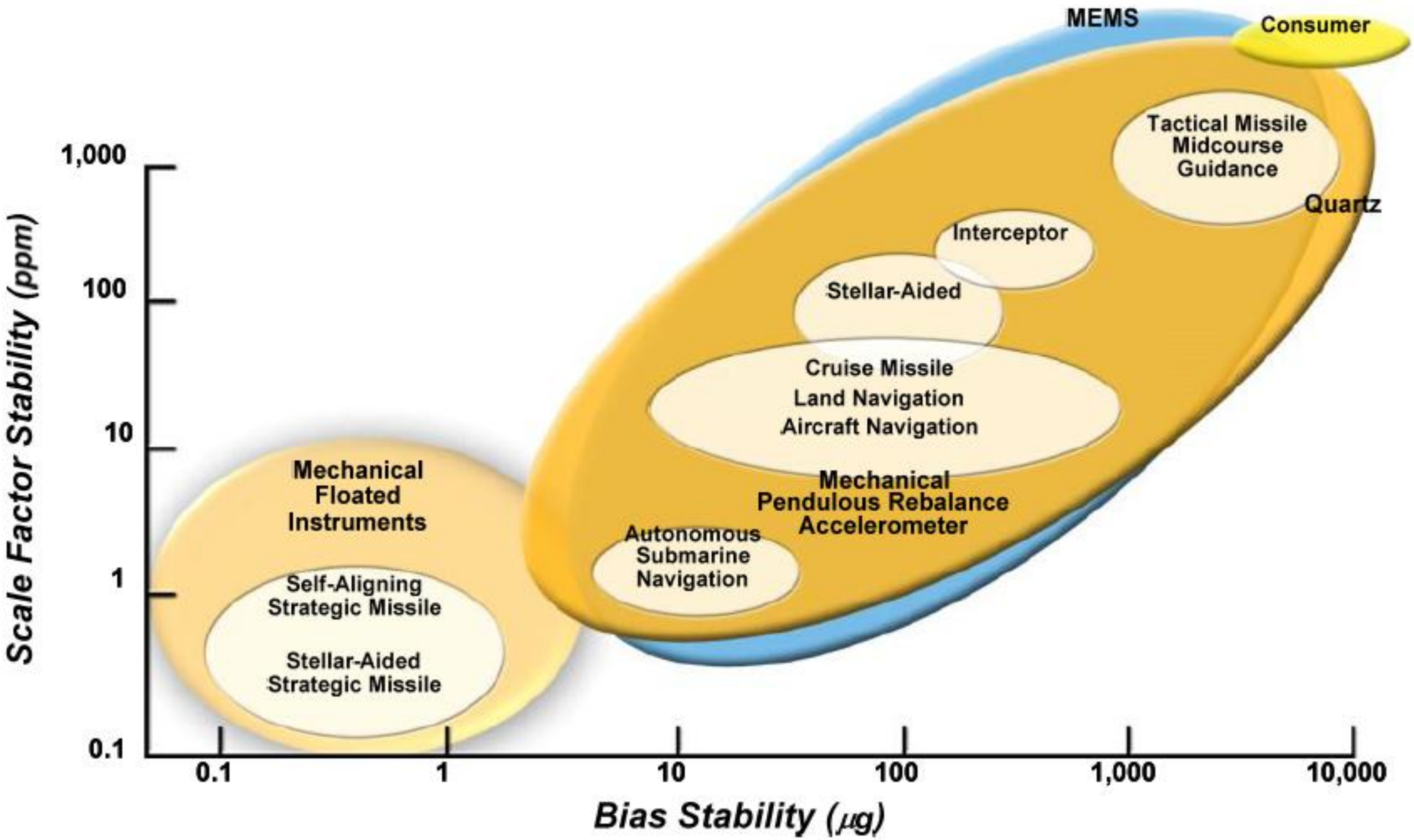


Figure: Schmidt (2011)

Gryos

- Measure angular velocity

Figure: Caplex (2000)

Mechanical Gyros
Maintain angular momentum

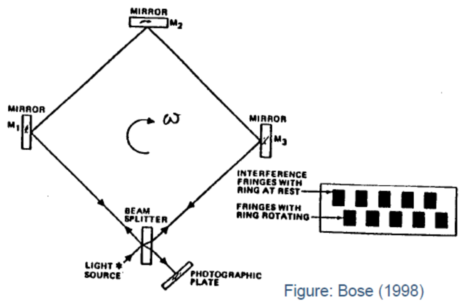
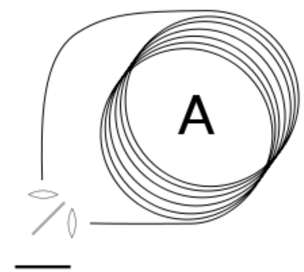


Figure: Bose (1998)



Ring Laser or Fiber Optic Gyros
Sagnac Effect: Light Interference Pattern

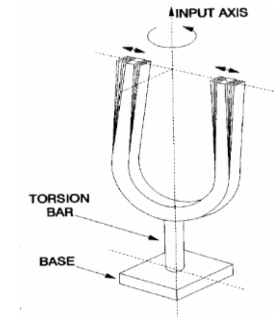


Figure: Titterton & W

MEMS Gyros
Coriolis Effect

- Error sources: bias, scale factor, misalignment, linearity, random walk
- Bias is typically the dominant error source
  - Navigation grade gyros have accuracy of 0.01 °/hr
  - Simple 1-D model with a constant unknown bias term (No other aiding)

$$\omega_{meas} = \omega_{true} + b_g$$

- Attitude (Orientation) can be obtained by integrating the angular velocity

$$\theta_{est} = \theta_0 + \int_0^t \omega_{meas} = \theta_{true} + \delta\theta_0 + b_g t$$

← Unbounded Drift Error

Gyro Technology Application

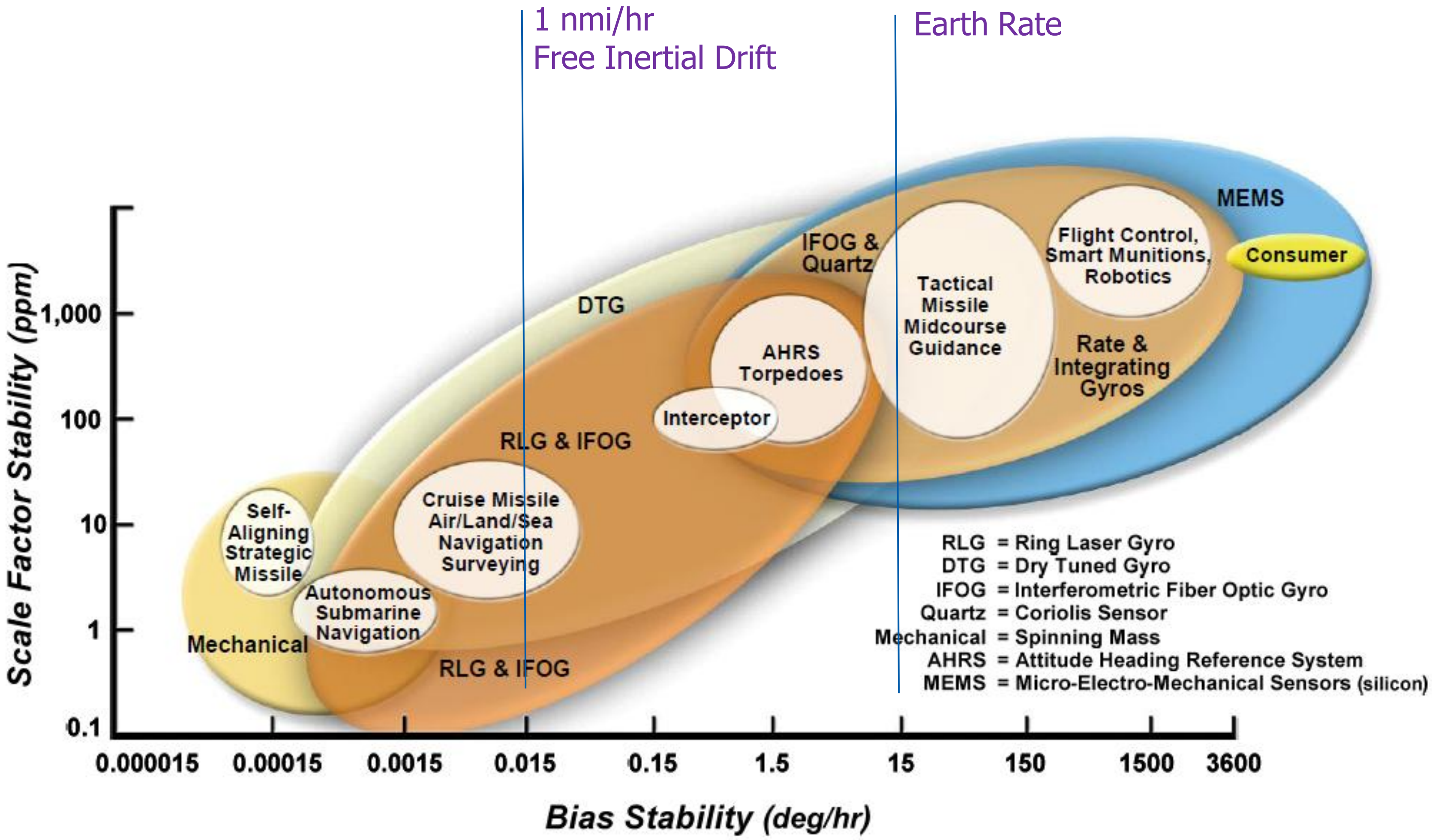


Figure: Schmidt (2011)

Inertial Measurement Unit (IMU)

- Typically an IMU has 3 accelerometers and 3 gyros (x, y, z)

- Strapdown IMU
  - All inertial sensors are rigidly attached to the platform (no mechanical movement)
  - Almost all IMUs on the market today are strapdown systems
  - Example:

    Honeywell HG1700 AG58 (Tactical Grade)
    - Gyros accuracy: 1 deg/hr
    - Accelerometers accuracy: 1 mg

- Gimballed IMU
  - Gyros and accelerometers are isolated from movement by means of gimbals
  - Big, heavy, and very expensive to make and maintain
  - Only used when the highest possible accuracy is required
  - Example:

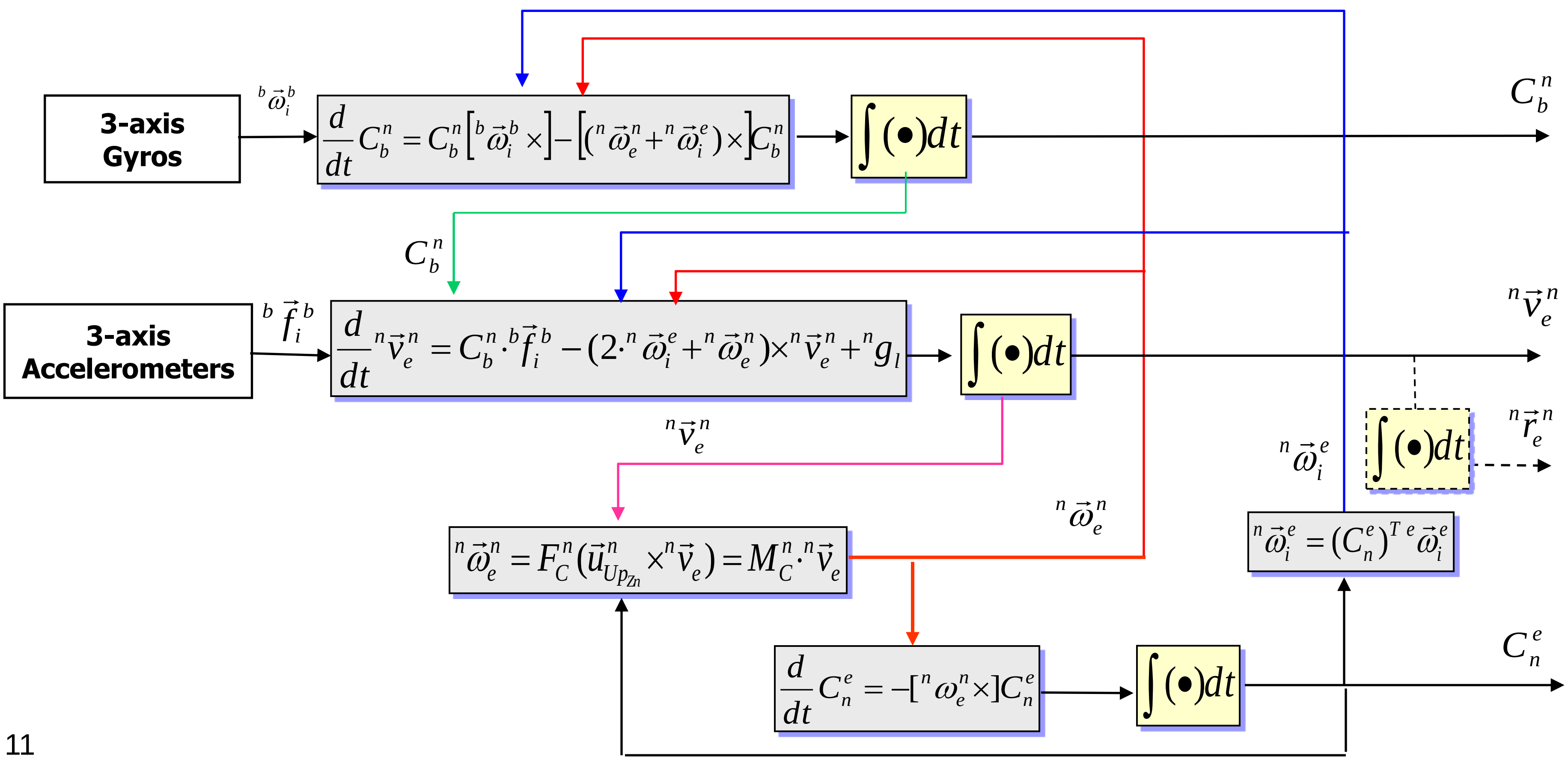
    SPIRE System

IMU Performance and Application

				Inertial Sensor Performance Across Applications				
				Strategic Grade/High Performance	Navigation Grade/Medium Performance	Inertial AHRS Grade	Tactical Grade	Flight Control
		Performance			< 1.0 nmph CEP			
					< 1.0 mil pointing	2 - 5 mil heading		
GYRO		**Bias**	deg/hr	0.001 - 0.005	0.003 - 0.01	0.05 - 3.0	5 - 50	100
		Scale Factor	ppm	1 - 10	10 - 30	100 - 500	500 - 1500	2000
		Angle Random Walk	deg/√Hz	0.00001 - 0.0005	0.001 - 0.002	0.005 - 0.05	0.1 - 0.5	1.0
Accel		**Bias**	μg	0.1 - 10	20 - 50	100 - 500	500 - 1,000	1,500
		Scale Factor	ppm	0.1 - 10	40 - 150	300 - 900	1,000 - 3,000	5000
		Angle Random Walk	μg/√Hz	2 - 5	5 - 20	25 - 40	50 - 75	100
			Applications	Stabilization	Inertial Navigation	Attitude & Heading Reference	Missile Midcourse guidance	Rate monitoring
				Pointing & Slewing	Air	Gimbal Stabilization		Munitions guidance
				Orbit Correction	Land	Sensor Pointing		
					Marine	SAR Velocity Ref		
				Strategic Plaform Navigation	Pointing			

Inertial Navigation System (INS)

- An <u>INS</u> consists of a IMU and a system processor
- The system processor computes the solution (position, velocity, attitude)
  - Due to errors in gyros and accelerometers, the solution has unbounded drift error
- Strap-down INS integration equations



INS Aidings

- Inertial sensors can accurately capture high-frequency dynamics
- To limit drift error in the integrated solution, an INS requires aiding

Aiding System	Measurement
GPS	Pseudo range, delta pseudo range
Star tracker	Attitude orientation
Receive signal strength	Attitude orientation
Image Correlation (EO/IR)	Attitude orientation
Multi-antenna GPS	Attitude orientation
Barometer	Altitude
Magnetometer / Compass	Heading
Doppler radar	velocity
Underwater pressure sensor	Depth
Underwater transponder	Range from known position

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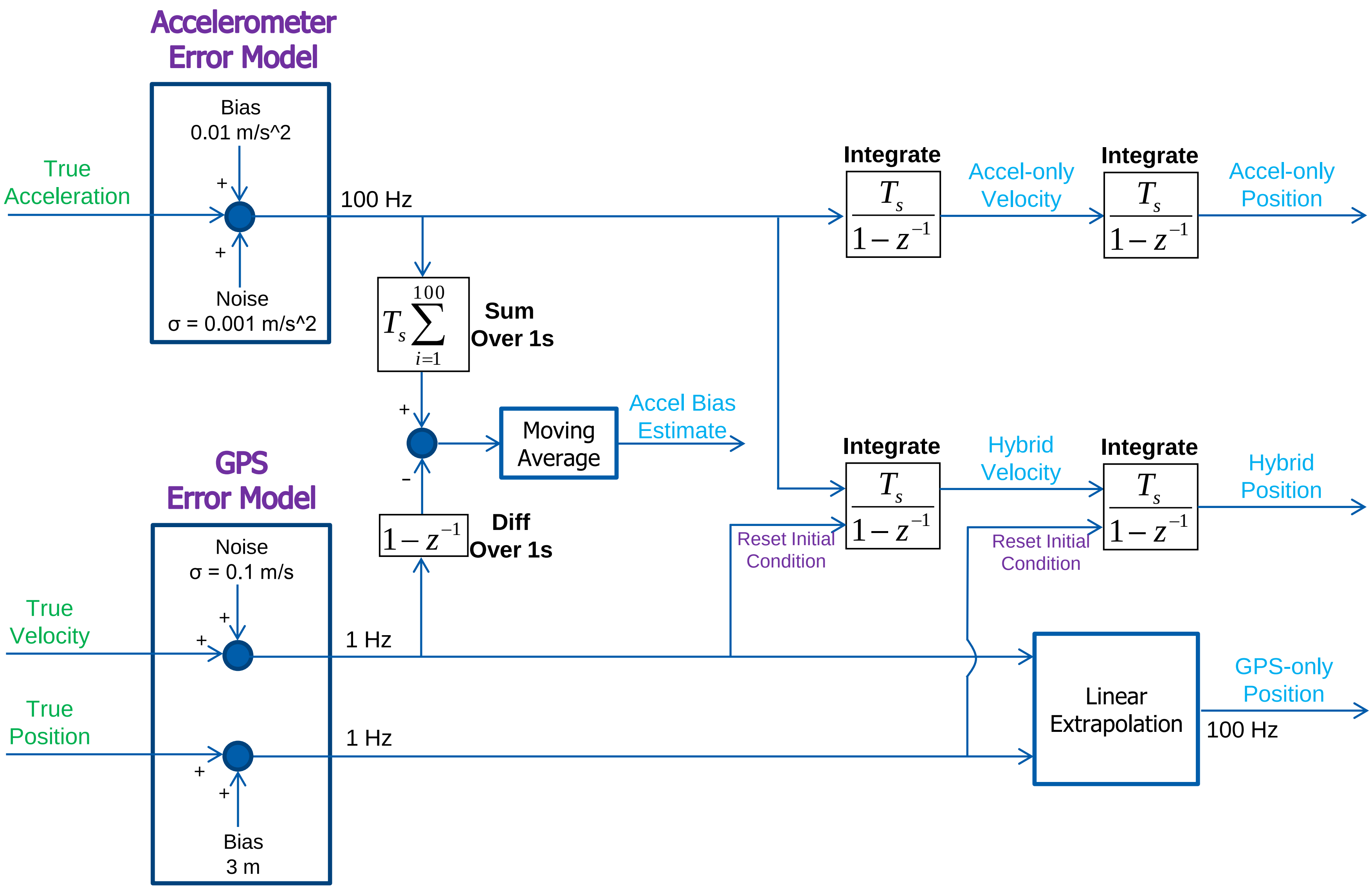
One Dimensional Example (Part 1)

-- A car with one accelerometer driving on a perfectly straight road

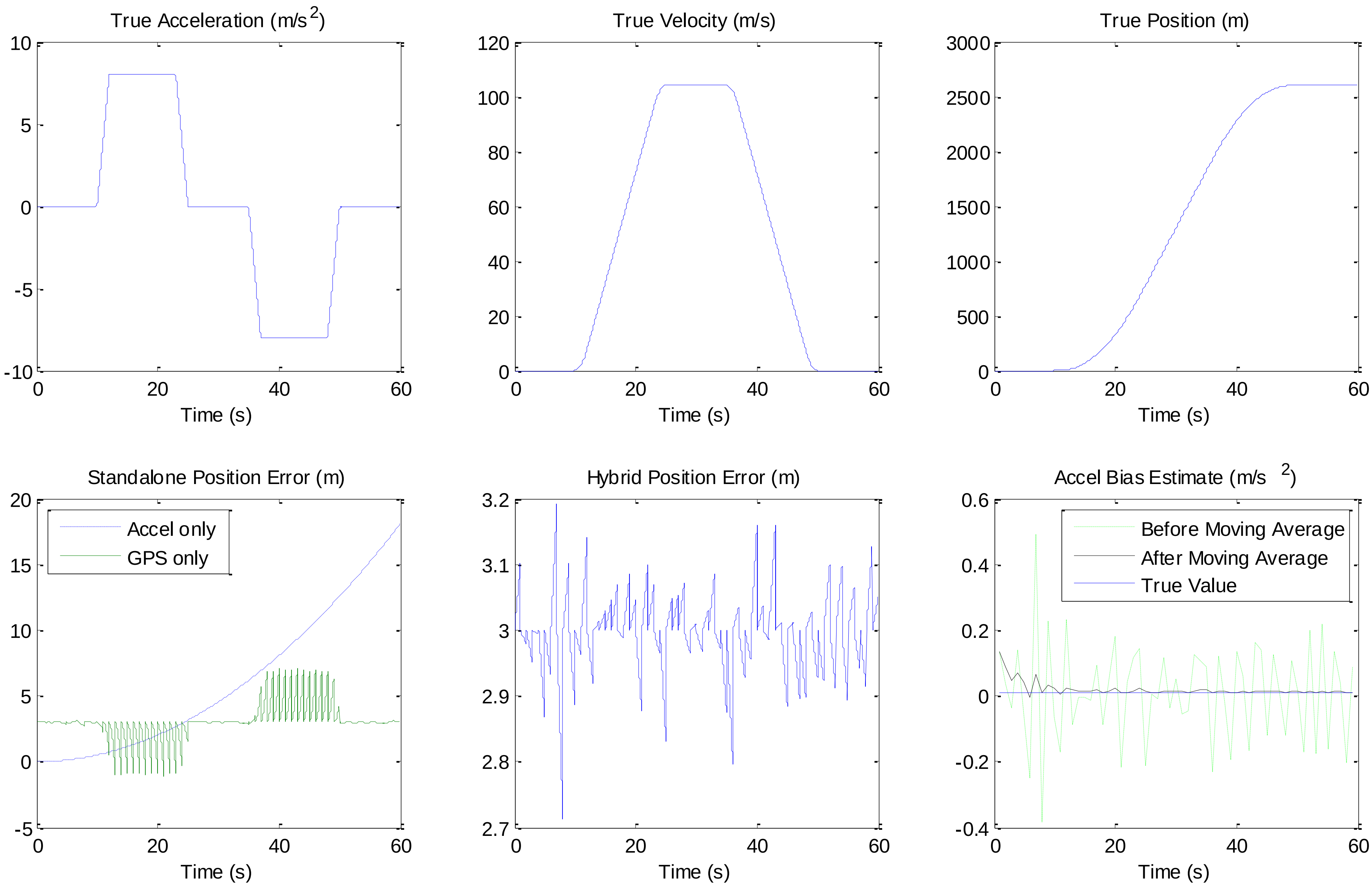
-- GPS aiding, naïve open loop design



One Dimensional Example (Part 2)

-- A car with one accelerometer driving on a perfectly straight road

-- GPS aiding, naïve open loop design using two 1st order filters

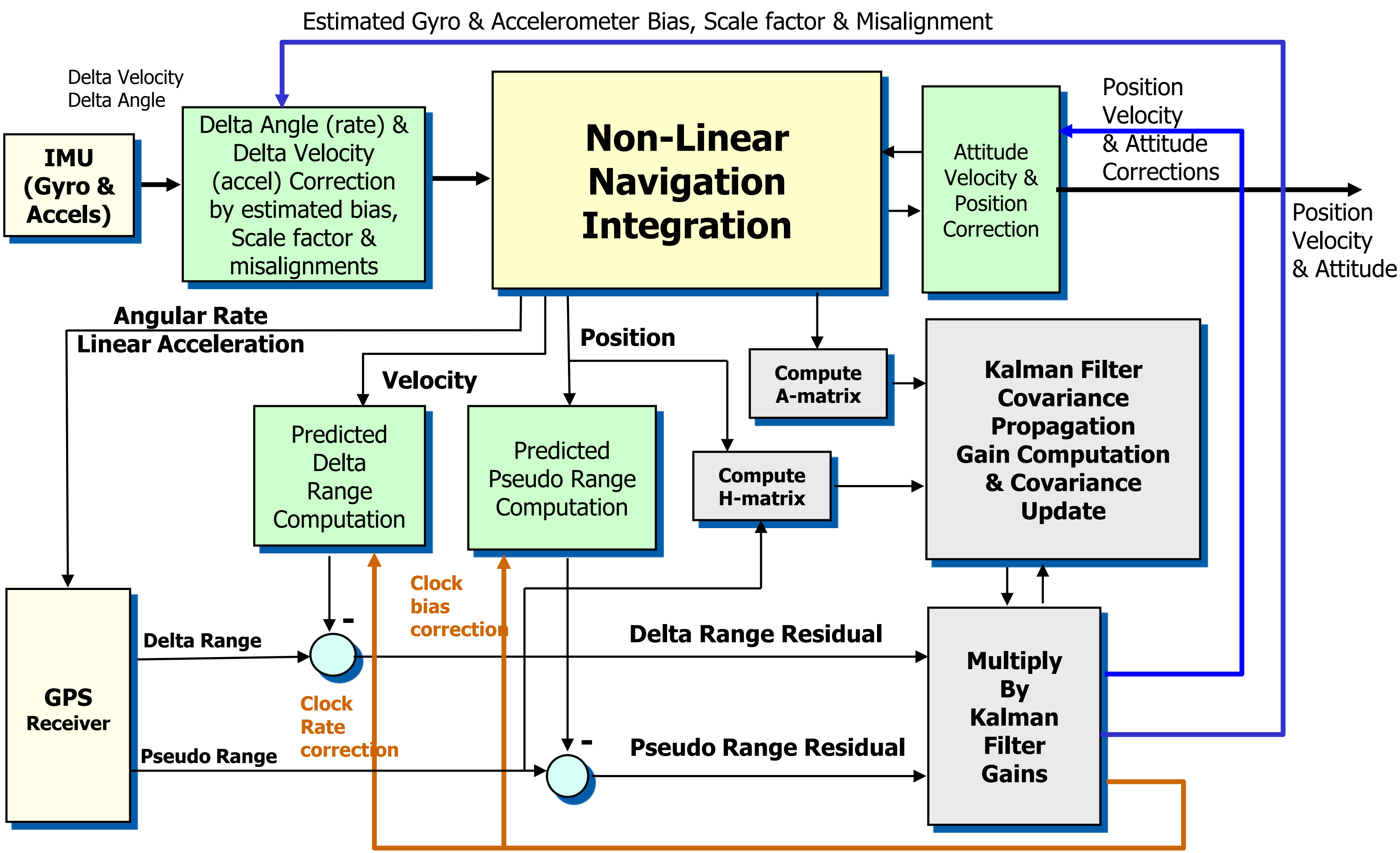


Approach of INS/GPS Integration

- Navigation solution is computed via:
  - Attitude determination by 3-axis attitude propagation using
    - Body to Inertial frame rate / delta angles measured by Gyros
    - Inertial to Navigation frame delta angles derived from
      - Velocity of the vehicle
      - Earth rotation rate
  - Velocity and Position Determination
    - Position is integration of velocity
    - Velocity is integration of acceleration / delta velocity measured by Accelerometers

- Navigation solution is corrected by the Kalman Filter integrated with the GPS receiver (aiding), resulting in a “tightly coupled” GPS/INS implementation, which computes:
  - Attitude, Position, and Velocity corrections
  - Gyro Bias, Scale Factor, and Misalignment estimates
  - Accelerometer Bias, Scale Factor, and Misalignment estimates
  - GPS receiver clock Bias and Drift estimates

Tightly-Coupled INS/GPS Architecture



INS/GPS Kalman Filter: States

$$\vec{X} = \begin{bmatrix} \vec{\theta}_n^{\hat{n}} \\ \delta^n \vec{v}_e \\ \delta^n \vec{r} \\ \delta \vec{x}_{gyro} \\ \delta \vec{x}_{acc} \\ \delta \vec{x}_{gpsr} \end{bmatrix}$$

$\vec{\theta}_n^{\hat{n}}$ attitude error, navigation frame (3×1)

$\delta^n \vec{v}$ velocity error : $[\delta v_N, \delta v_E, \delta v_D]^T$, navigation frm. (3×1)

$\delta^n \vec{r}$ position error : navigation frm. (3×1)

$\delta \vec{x}_{gyro}{}^T = [{}^b\vec{b}_g, \vec{S}_g, \vec{\theta}_{\mathrm{m}_g}, \vec{\beta}_g]$

- ${}^b\vec{b}_g$: gyro bias, body frame (3x1),
- $\vec{S}_g$: gyro scaled factors, (3×1),
- $\vec{\theta}_{\mathrm{m}_g}$: gyro rotational misalignment, (3×1)
- $\vec{\beta}_g$: gyro non-orthogonality misalignment, (3×1)

$\delta \vec{x}_{acc}{}^T = [{}^b\vec{b}_a, \vec{S}_a, \vec{\beta}_a]$

- ${}^b\vec{b}_a$: accelerometer bias, body frame, (3x1)
- $\vec{S}_a$: accel. scaled factors, (3x1)
- $\vec{\beta}_a$: accel. non-orthogonality misalignment, (3×1)

$\delta \vec{x}_{gpsr}{}^T = [\delta t_r, \delta \dot{t}_r]$

- δt_r : GPS receiver clock bias, (1x1)
- $\delta \dot{t}_r$: GPS receiver clock drift, (1x1)

Total # states $= 32$

INS/GPS System Initialization

- Initialization: estimate the initial values
  - The nonlinear navigation integration equation needs some initial values
  - The Kalman filter requires good initial values for solution convergence
- Position, velocity, and GPS receiver clock bias are initialized using GPS
- Attitude initialization

Method	Value	Limitation
Accelerometer	Roll, Pitch	Stationary or steady motion
Gyro compassing	Heading	Stationary and high-quality gyros
Magnetometer / Compass	Heading	Magnetic interference
Star tracker	Roll, Pitch, Yaw	Visibility to stars
Multi-antenna GPS	Roll, Pitch, Yaw	Baseline distance and convergence time

- All other parameters (bias, scale factor, etc) can be initialized to 0

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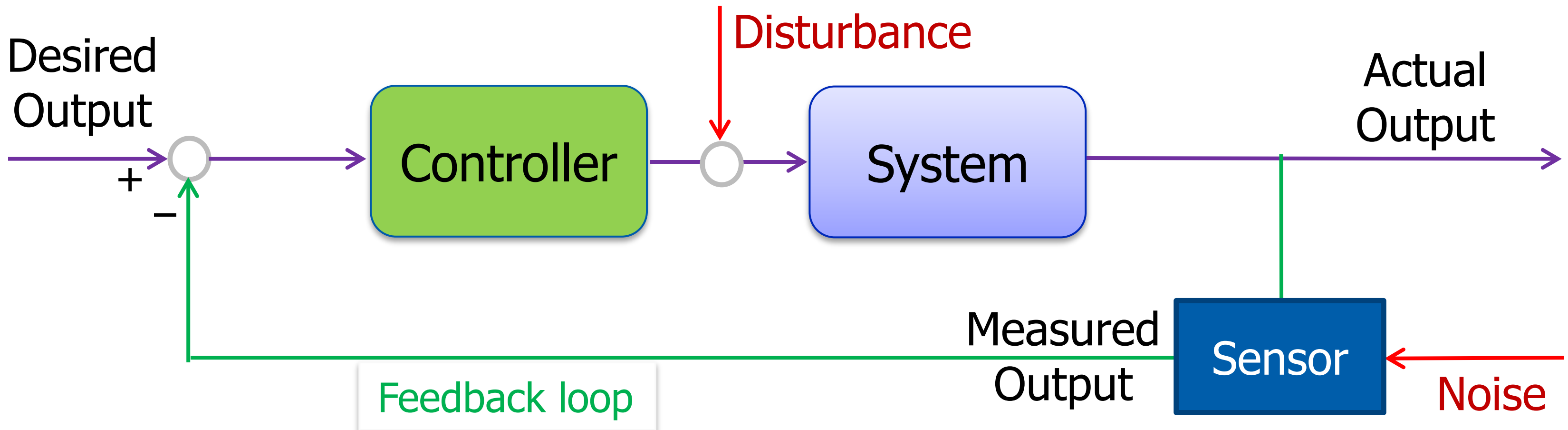
Feedback Control



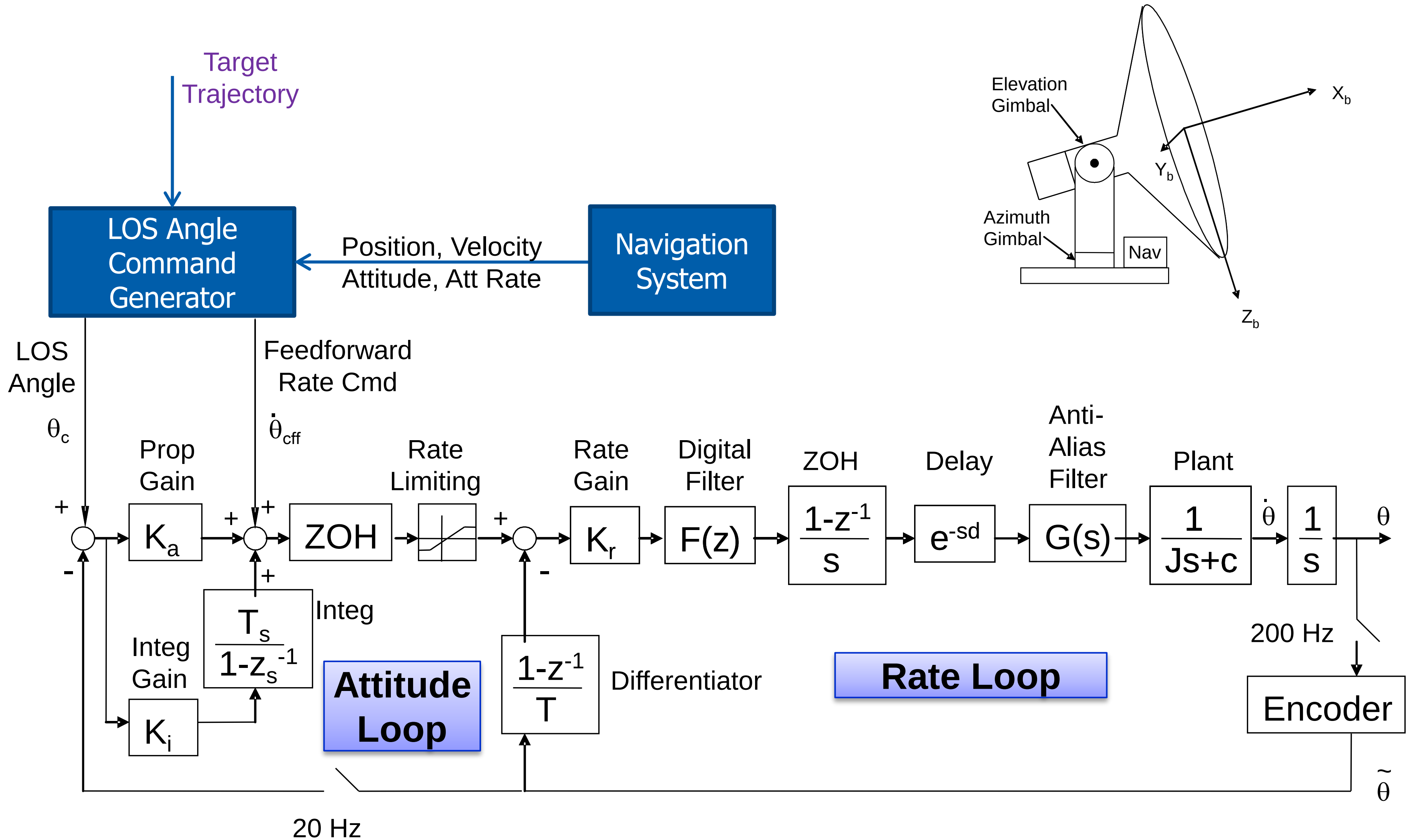
- Example
  - Consumer: temperature control (oven, A/C), cruise control, hard disk arm control
  - Defense: missile guidance, flight control, attitude control, pointing control

- Why do we need feedback?
  - To deal with **Uncertainty**
    - Approximate model of the system dynamics
    - Unknown disturbance and noise

Control Methods

- **Classic Control**
  - Deal with single-input single-output (SISO) system
  - Based on transfer function (zeros/poles) or impulse response model
  - PID control, Lead-Lag compensator
    - PID is by far the most widely known and used control technique in practice
  - For many multi-input multi-output (MIMO) systems in practice, can decouple to multiple SISO systems
- **Moderm Control**
  - Based on state-space model that naturally includes MIMO case
  - Linear Quadratic Regulator (LQR)
  - LQG, H_∞ and robust control
- **Nonlinear Control**
  - Bang-Bang Control (on/off)
  - Lyapunov function, Pontryagin's minimum principle
- **Others**
  - Adaptive Control, Model Predictive Control
  - Distributed Control, Cooperative Control, Hybrid Control
  - ...

Gimbals Pointing Control

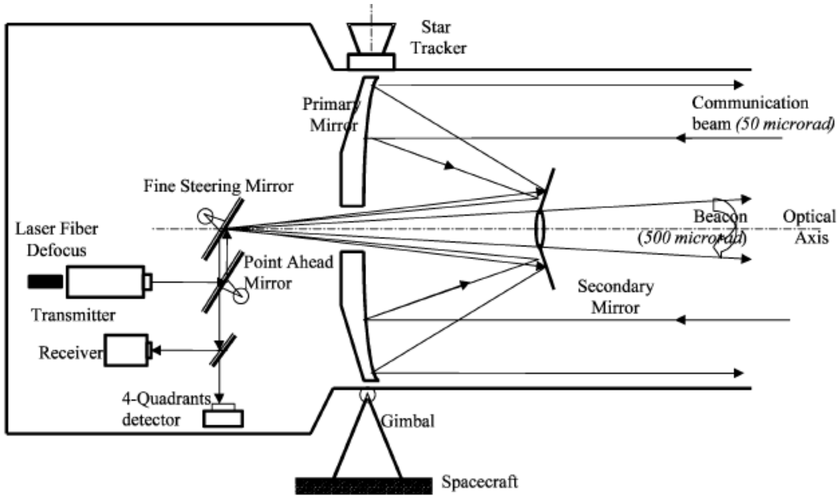


Laser Pointing

- Laser pointing requires very accurate pointing (< 0.005°)
  - Laser has a much narrower beam width than RF
  - Ex: Inter-satellite communication, directed energy weapon

- Coarse Pointing - Gimbals
  - Use conventional electrical motors
  - Sufficient for acquisition and tracking
  - Control bandwidth: 5 – 50 Hz

- Fine Pointing - Mirrors
  - Use piezoelectric or ultrasonic motor
  - Use 4-quadrants detector to provide feedback
  - Very high resolution (arc-sec)
  - Can achieve control bandwidth > 1000 Hz

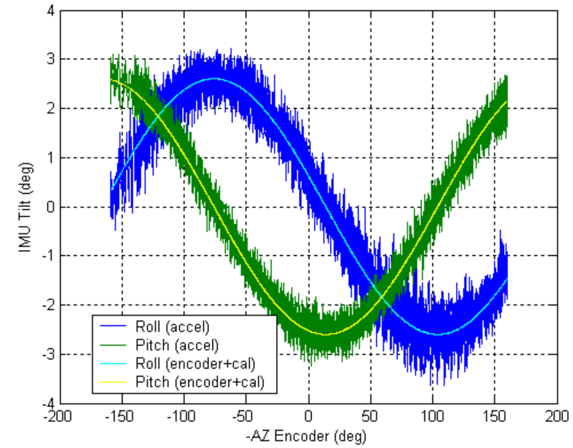


Guelman 2004

Model Fidelity

- Mechanical misalignment
  - Design online / offline calibration methods to estimate the misalignment and lever arm between the navigation system and payload pointing system
  - Ex 1: Use received signal strength in communication pointing
  - Ex 2: Use image correlation in camera (EO/IR) pointing
  - Ex 3: Install low quality IMU on the payload pointing system (Transfer Align, Velocity Matching)

Example →

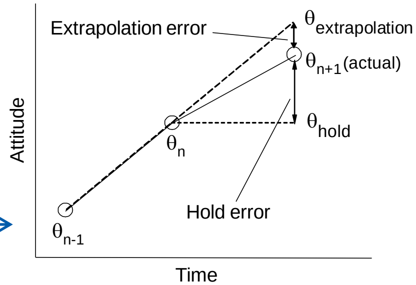


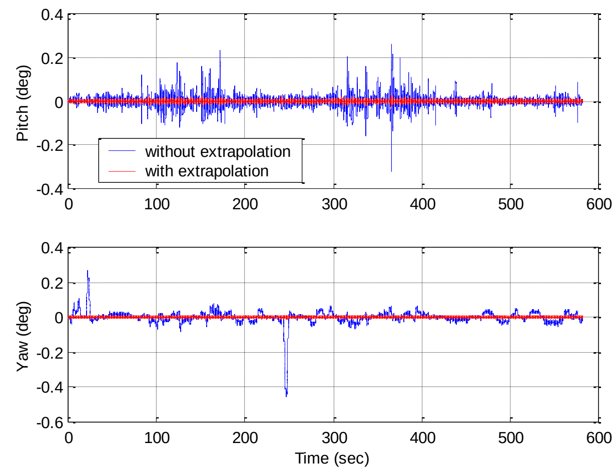
Encoder outputs on the Gimbals match IMU outputs after misalignment calibration

- Better model of unknown disturbance
  - Ex 1: Periodic vibration
  - Ex 2: Reaction wheel in spacecraft
  - Ex 2: Time-correlated (Non-white)

- Compensate delay by extrapolation
  - Accurate data time tag
  - Linear or quadratic extrapolation

Example →





Conclusion

- This brief presentation covers some basic principles in the inertial navigation system and the pointing control system.

Thank you for your interest

- Further references
  - Inertial Navigation
    - D. Titterton and J. Weston, *Strapdown Inertial Navigation Technology*
    - J. Farrell, *Aided Navigation*
  - Automatic Control
    - D.G. Luenberger, *Introduction to Dynamic Systems*
    - Anderson and Moore, *Linear Optimal Control*
    - S. Sastry, *Nonlinear systems: Analysis, Stability, and Control*