Background and History

• TERCOM conceived by *Chance-Vought* in 1958
  – Later and still applied to cruise missiles (e.g. Tomahawk)

• A Kalman filter based system suggested by *Hostetler* in 1976, developed into SITAN by Sandia National Laboratories
  – AFTI/SITAN: F16 terrain navigation 1985
  – HELI/SITAN: helicopter terrain navigation 1990

• TERPROM a fusion of TERCOM (initial mode) and SITAN (track mode) developed by BAE systems during the 80s

• FFI generalisation of SITAN algorithm for bathymetric navigation (developed independently) in 1997 by *Heyerdahl* and *Kloster*
  – Developed into TRIN: AUV terrain navigation with DVL in 2001

• Non-linear Bayesian approach by *Bergman* in 1999 for aircraft terrain navigation (SAAB)
  – Point mass filter (PMF) and particle filters
Why use Terrain Navigation?

- Surface and Air applications: GPS is available
  - Redundant navigation system in critical systems
  - Navigation system integrity
  - Backup navigation system during GPS fall-outs or jamming
Why use Terrain Navigation?

- **Underwater applications:**
  - GPS is not available
  - Deepwater: GPS fix not feasible
  - Shallow water: GPS fix possible
    - Not in covert operations
  - No infrastructure required
    - DGPS-USBL requires a mother ship
    - LBL / UTP requires transponder(s)
Basic Principles

• Lose integration
  – Navigation system data are combined with terrain measurements
  – Correlated with the expected DTM value in a search area
  – A Position solution is produced and passed back to the Navigation System

• Algorithms:
  – TERCOM
  – Point Mass Filter
  – Particle Filters

• Usually batch within ping
  – Batch over time interval possible
  – Recursive possible
Basic Principles

- Tight integration
  - Terrain sensors are integrated along with Nav sensors
  - Correlated with the expected DTM value of current navigation solution
  - Full navigation solution is produced

- Algorithms
  - Kalman filter based
  - TRIN
  - SITAN

- Always recursive in time
  - Batch within ping possible
Underwater Measurement Geometry

- Sensor ensonifies a seafloor area
  - The footprint
- Slant range and angles are computed
  - Ray bending
  - The beam vector
- The beam vector is transformed into a body-fixed earth tangent plane system
  - Relative depth
- Further transformed into a Global Reference System
  - Global depth
Underwater Vertical Reference

- The vehicle measures pressure
- Vertical reference error directly adds to seafloor depth estimate error
  - Correlated between each beam
  - Correlated in time
- Slow-changing bias is ok
  - Tidal wave error
  - Atmospheric pressure error
  - CTD error
- Dynamic pressure error is not ok
  - Waves
Bathymetric sensors

- Multibeam Echosounder (MBE)
  - Across track profile at each ping, a fan of beamvectors
  - EM3000 tested from surface ship and Hugin AUVs
- Doppler Velocity Log (DVL)
  - 4 beamvectors in Janus configuration
  - RDI WHN 300,600,1200 tested on AUVs (Hugin, OEx, Remus)
- Single Beam Echosounder
  - Large footprint
- Interferometric SAS
  - High resolution
- Underwater Laser Camera
  - High accuracy, low range
- 3D Sonar
  - Surface at each ping
Digital Terrain Models

• Algorithm requirements
  – Random access
  – Fast access

• In memory representation
  – Regular grid
  – Bilinear interpolation

• Resolution requirement
  – Terrain navigation accuracy is in the order of DTM resolution
  – For typical AUV operations: at least 10 m

• Accuracy description requirement
  – Ideally a spatial statistical description (grid node depth error)
  – Usually not available in exchanged DTMs
Sensor/DTM measurement model

- We only have a model of true terrain $h(x)$
  - Horizontal node spacing
  - Interpolation
  - Node depth estimates

- Measurements are made towards true terrain

$$h(x)$$

Deterministic

Stochastic
Extended Kalman Filter (EKF) approach (TRIN, SITAN)

- Linearization for EKF requires a gradient map
  - Ok in linear and weekly non-linear topography
- Highly non-linear topography handled by stochastic linearization
  - Best fit surface tangent plane within uncertainty area
  - Automatically detects non suitable terrain
Terrain Contour Matching (TERCOM)

- For each grid point:
  - Calculate mean absolute distance (MAD) between measured and expected profile

Position fix from minimum of the MAD correlation matrix

- No inherent accuracy of fix is available
Point Mass Filter (PMF) from TerrP

- The position error probability density function (pdf) is estimated on a grid
- An initial pdf, depending on INS accuracy, can be used
- Each measurement is blended with current pdf using Bayes’ rule, and a sensor error pdf
- INS drift diffuses the pdf between each ping

Ping 8

\[ \text{NOfs} = -1.38, \text{EOfs} = -4.81, \text{StdDevN} = 7.46, \text{StdDevE} = 5.96, \text{Confidence} = 0.99 \]
Particle Filters (PF) from TerrLab

- Position error pdf represented by free particles
- Initial state is simulated from INS position error distribution
- Measurement: Each particle is weighted using the sensor error pdf
- Resampling
- Dynamic update through simulation on INS drift distribution
Terrain Suitability?

**TRIN, SITAN**
- Clearly defined gradients
- Linear beach
- Parabolic beach
- Fjord
Terrain Suitability?

TERCOM, PMF, PF

- Rough topography
- Not self similar
Tactical Use of Terrain Navigation
Applications

• Cruise missiles
  – Backup system
  – Independent of GPS, cannot be jammed
• Fighter aircrafts
  – Redundant navigation system
  – Terrain following aid for low altitude flying
• AUVs
  – Autonomous missions
  – Covert operations
• Submarines
  – Always covert
  – Transmission of sound is restricted
  – “Man in the loop”
FFI Developed Systems

• Terrain Referenced Integrated Navigation (TRIN)
  – MatLab implementation of FFI’s EKF based algorithm
  – Verified in 2 NATO experiments for different AUVs and a surface vessel

• Terrain Navigation Processor (TerrP)
  – Real-time terrain navigation system (TERCOM, PMF)
  – Primarily designed for HUGIN
  – Verified on playback of real data from HUGIN

• Terrain Navigation Laboratory (TerrLab)
  – MatLab toolkit for terrain navigation algorithm development, simulation and post processing
  – TERCOM, PMF, Particle Filters