Advanced Ultra-Short Baseline Inertial Navigation Systems

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Thesis Steering Committee Report

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Motivation

- Geological Surveys
- Habitat Mapping
- Underwater demining
- Oil rigs maintenance
- Inspection of estuaries and harbors
- Pipelines underwater inspection
Motivation (continued)

Fish tracking

Intervention missions

Harvesting energy

“The worldwide amounts of methane bound in gas hydrates is conservatively estimated to total twice the amount of carbon to be found in ALL known fossil fuels on Earth”. Gas (Methane) Hydrates -- A New Frontier, USGS fact sheet.

Clathrate hydrate
How to “navigate”?

Inertial Navigation Systems

Linear
- Position (x, y, z)
- Velocity
- Acceleration

Angular
- Attitude (yaw, pitch, roll)
- Velocity

Mission control systems
Control and guidance systems
Mission data geo-referencing
Underwater Acoustic Positioning Systems

Long Base Line (LBL)
- Transponders deployment
- In situ calibration required
- Several Km’s base line
- High complexity

Short Base Line (SBL)
- Hull mounted receivers
- 20~50 m base line
- Hull bending induced degradation

Ultra Short Base Line (USBL)
- Small and compact array
- <50 cm base line
- Reduced complexity
USBL – Ultra-Short Base Line

Distance between receivers much shorter than the distances between the USBL array and the transponder

Inverted USBL configuration

Autonomous vehicles
Discard surface vessel dependent configurations
USBL – Ultra-Short Base Line

Very low update rates (typically inferior to 1Hz)

Poor accuracy (multipath, underwater acoustic waves velocity estimate)

Transponders position \textit{a priori} calibrated

Accuracy degradation as USBL – Transponder distance increases


ddWhen coupled to attitude and heading reference systems (AHRS), USBL positioning devices can provide vehicles position in Earth coordinate framedd
General overview of contributions

- EKF-based INS stochastic approach
- Theoretical contributions in GAS observers design
- Experimental system design and experimental validation
Tightly vs. loosely coupling

GPS

- GPS orbiting satellites
- Atmospheric errors
- Loosely-coupled position fix from pseudo-ranges
- Tightly-coupled pseudo-ranges directly observed

INS

USBL

- Compute range and direction
- Loosely-coupled

Ultra tightly-coupled

Ultra tightly-coupled
**QUESTION**
Given a dynamic system with process and observation noise, what is the possible attainable performance by ANY unbiased estimator we can come up with?
Inertial Navigation Systems

Non-trivial Integration

Rigid body position and attitude kinematics and dynamics

\[
\begin{align*}
\dot{p} &= v \\
\dot{v} &= a_{\text{total}} \\
\dot{\mathcal{R}} &= \mathcal{R}(\omega) \times
\end{align*}
\]

Excellent short-term accuracy

Uncompensated rate gyro and accelerometer errors (biases + noise)

Accuracy degradation over time with unbounded position and attitude errors

skew-symmetric matrix with angular velocity
Inertial Navigation Systems errors

- Bias is a function of **temperature and time** (need for online compensation).
- Misalignment and non-orthogonal setups distort the directionality of the inertial readings.
- Position errors due to bias and noise grow **quadratically** with time.
- Inertial navigation is very important in **aiding sensors outage** (GPS, LBL/USBL) or even during aiding sensors sampling (1 Hz for GPS, < 1Hz for acoustic positioning)

- **10 minute run**
- **Calibrated bias**
- **AWGN**
- **Good sensors**
  - Accel -1 μg
  - Gyros - 3.6°/hr
Aided Inertial Navigation

External aiding devices
- USBL
- Magnetometer

Observations

Inertial Sensors
- Accelerometers
- Rate Gyros
  (Bias update)

INS
(Error correction routines)

EKF
(Prior Estimates
  (Position, Velocity, Attitude)
Control inputs

Enhanced Posterior Outputs

Vehicle dynamics

Estimated Bias and INS errors

EKF implements INS error model
USBL filtering techniques

**Tightly Coupled EKF**
- Underwater Environment
- Signal Acquisition
  - Round Trip Time (RTT)
  - Time Difference Of Arrival
- Computation
  - Transponder Range
  - Transponder Direction

**Loosely Coupled EKF**
- Computation
  - Transponder Position in Body coordinate frame

**Planar-Wave Approximation**

\[ \delta(i,k) = t_i - t_k = -\frac{1}{v_p} d'(p_i - p_k) \]
Stochastic approach results

Exhaustive Monte-Carlo simulations

Tightly-coupled

Vehicle dynamics

All techniques tested in exhaustive Monte-Carlo simulation runs!

Tightly-coupled revealed enhanced performance in error estimation compared to loosely-coupled

Tightly-coupled strategy is able to operate closer to the theoretical performance bound PCR

Vehicle dynamics offers significant information for performance improvement while being robust to modeling uncertainties
EKF-based INS stochastic approach

Theoretical contributions in GAS observers design

USBL

Experimental system design and experimental validation
USBL/DVL nonlinear system

Original nonlinear system dynamics

\[ \begin{align*}
\dot{r}(t) &= -S(\omega(t)) r(t) - v_c(t) - v_r(t), \\
\dot{v}_c(t) &= -S(\omega(t)) v_c(t), \\
\rho_i(t) &= \|b_i - r(t)\|, \quad i = 1, \ldots, n_r.
\end{align*} \]

Transponder position in vehicle frame

\[ r(t) = R^T(t)(s - p(t)) \]
State transformation/augmentation

\[
\begin{bmatrix}
    x_1(t) \\
    x_2(t)
\end{bmatrix} :=
\begin{bmatrix}
    \mathcal{R}(t) & 0 \\
    0 & \mathcal{R}(t)
\end{bmatrix}
\begin{bmatrix}
    r(t) \\
    v_c(t)
\end{bmatrix}
\]

Lyapunov state transformation (preserves observability properties)

\[
\begin{aligned}
    \dot{x}_1(t) &= -x_2(t) - u(t), \\
    \dot{x}_2(t) &= 0, \\
    \rho_i(t) &= \|b_i - \mathcal{R}^T(t)x_1(t)\|, \quad i = 1, \ldots, n_r,
\end{aligned}
\]

LTI dynamics with nonlinear time-varying outputs

Include range dynamics identifying nonlinear term

\[
\begin{aligned}
    x_3(t) &:= \rho_1(t), \ldots, \ldots, \quad x_{n_r+2}(t) := \rho_{n_r}(t), \\
    x_{n_r+3}(t) &:= x_1^T(t)x_2(t), \quad x_{n_r+4}(t) := \|x_2(t)\|^2,
\end{aligned}
\]

\[
\dot{\rho}_i(t) = \frac{1}{\rho_i(t)} \left[(b_i^T S(\omega(t))\mathcal{R}^T(t) - u^T(t))x_1(t) + b_i^T\mathcal{R}^T(t)x_2(t) - x_1^T(t)x_2(t) + b_i^T\mathcal{R}^T(t)u(t)\right].
\]

Augmented artificial yet available outputs for improved observability
Nonlinear observer design summary

Derivation of a **LTV system that fully captures the dynamics of the nonlinear system.**

1. **Original nonlinear system**
   - Lyapunov state transf.
   - Preserves observability properties

2. **State augmentation**
   - LTI dynamics with nonlinear time-varying outputs
   - Augmented LTV system with augmented outputs
   - Observability analysis
   - 2 observability theorems: 1 for LTV system + 1 for the coupling between the LTV and the nonlinear system

3. **Revert Lyapunov state transf.**
   - State observer with GAS error dynamics
   - LTV system in original state space with GAS error dynamics
   - Apply LTV Kalman Filter
   - + 1 theorem for uniform complete observability (UCO)

Preserves observability properties
Monte-Carlo evaluation

- Numerical simulated data inspired in realistic sensor suit with realistic noise
- Performance assessment resorting to Monte-Carlo simulations (20 runs)
- Comparison to Bayesian Cramér-Rao Bound (BCRB)

- Low cost IMU
- Silicon Sensing CRS03 triaxial rate gyro
- LinkQuest NavQuest 600 Micro DVL

Typical lawn-mower trajectory used for terrain survey
Steady state performance analysis

High-grade IMU
iXSea OCTANS AHRS
with Fiber Optic Gyros (FOG)
> 100k EUR

Low-grade IMU
MicroStrain 3DM-GX3-25 AHRS
with MEMS gyros
~10k EUR
EKF-based INS stochastic approach

Theoretical contributions in GAS observers design

USBL

Experimental system design and experimental validation
Commercial Available Solutions

Prohibitive high cost of current INS solutions
- Downgraded IMU accelerometer and rg outputs (exports regulations)

Commercial USBL systems provide only post-processed data
- Range, bearing, and elevation
- No access to raw time delay and propagation data
- Also high cost

Design our own USBL/INS navigation system
- Affordable cost (approx 10 times less)
- Valuable knowledge inherent to the assembly and design of such a system
- Versatility: USBL acoustics + inertial
- Open-prototype research platform
- Exploit configurable receiving geometries
- Access to raw acoustic and IMU data
USBL/INS Open Prototype System

- IMU
  - Rate gyro
  - Accelerometers
- Magnetometer
- AD Converter
  - 24 bit 12-Channel
  - 100 Hz
- XAS3 Microcontroller
- RS-232
- AD Converter
  - 16 bit 4-Channel
  - 250 KHz
- DSP Core
- DMA
- SD Card data logging
- Ethernet
- 4 Hydrophone array
- Underwater Transducer
- Transducer Impedance Matching
- Class D Power amplifier
- PWM Generator
- TCP/IP
- Console Laptop

7/18/11
Underwater acoustic signaling

Sinusoidal pulses
- Poor performance
- Classical approach

Spread-spectrum pulses
- Improved performance
- Better Signal-to-Noise-Ratio (SNR)
- Robustness to ambient and jamming noise
- Better multi-path resolution
- Improved detection jitter
- Multiusers with DSSS modulated signals
Acoustic signal generation

CONTRIBUTIONS IN ACOUSTIC SIGNAL GENERATION WITH APPLICATION TO UNDERWATER RANGING SYSTEMS

- Output voltage feedback based pulse shaping filters
- Explicit input voltage limitations on the transducer
- DLQR with preview information (feed forward gain) of signals to be transmitted
- Experimentally validated
Sea trials

Sesimbra, Portugal, 2010

7/18/11
Concluding remarks

USBL/INS EKF based design
- Tightly-coupled revealed improved performance when compared to loosely-coupled in Monte-Carlo realistic simulations.
- Operates closer to the theoretical performance lower bounds.
- Vehicle dynamics aids the INS with significant information while maintaining robustness to model uncertainties.

GAS position and velocity observers design
- Based directly on the nonlinear range and RDOA nonlinear readings from an USBL.
- Derivation of a LTV system that fully captures the dynamics of the nonlinear system.
- GAS filter error dynamics.
- Performance assessment with Bayesian Cramér-Rao bounds and Comparison to classical strategies.

Integrated USBL/INS prototype system design
- Design of novel pulse-shaping filters for underwater signal transmission, based on output voltage feedback DLQRs with preview information of the signal to be transmitted.
- Complete design and integration of a prototype USBL/INS system to be used for research purposes.
- Experimentally validated.
- Planned sea trials to validate even further the developed system. Implementation of outlier rejection techniques.
Roadmap

USBL-based attitude filtering solution for two vehicles working in tandem formation

Acoustic outlier rejection schemes

Extensive sea trials and further validation of the USBL/INS prototype

EKF-based INS stochastic approach

Theoretical contributions in GAS observers design

Experimental system design and experimental validation
Thesis structure

Outline

Chapter 2

State-of-the-art

Chapter 3

USBL/INS aided inertial navigation

Chapter 4

Advanced topics

Chapter 5

USBL sensor-based position and velocity observers design

Chapter 6

Acoustic signal generation

Chapter 7

Experimental validation

Chapter 8

Directions of future research

Novel tightly-coupled vs. traditional loosely-coupled

Vehicle dynamics aiding

USBL sensor-based attitude estimation for vehicles working in tandem formation

Pulse-shaping filter experimental results

USBL/INS prototype system design

Preliminary sea trials

7.3
Publications

**Journal papers**
+ 2 papers submitted to JOE and TCST are under review.

**10 conference papers as first author**
IEEE Fusion ‘06
IFAC MCMC ‘06 and ‘09
IFAC CAMS ‘07
IFAC WC ‘08 and ’11
IEEE ICRA ’10
IEEE ELMAR ‘11
IEEE CDC ’10
IEEE ICMA ‘11

**Best Student Paper Award**
Posterior Cramér-Rao bounds analysis for INS/USBL navigation systems. 8th IFAC Conference MCMC’09, São Paulo, Brazil, September 2009.

+ 2 conference papers (collaborated)
APCA CONTROLO ‘10
IEEE OCEANS ‘11
Thank you.