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Doctoral Thesis accepted by University of Florence, Italy
To my family
With an ever increasing interest for what lies below the ocean’s surface, the use of autonomous underwater robots is rapidly becoming a common practice, both within industry and academia. Nonetheless, the demanding accuracy requirements needed to successfully complete autonomous tasks in such a hostile environment call for precise and reliable navigation systems. Addressing the abovementioned issues, this thesis focuses on the study of self-localization techniques for underwater robots. In particular, exploiting only sensors which are commonly mounted on board underwater vehicles (thus not requiring external instrumentation, which comes with relevant cost and deployment time), attitude and position estimation algorithms are derived. The theoretical argumentation, illustrated with clarity and scientific rigor, is paired with a considerable share of validation results composed of simulation results exploiting real navigation data, or field validation tests aimed at assessing the effectiveness of the developed solutions in a real-world scenario. Indeed, field testing constitutes a relevant share of the research activity described in this thesis, giving value and significance to the whole work: the developed navigation algorithms, successfully validated, pave the way for additional research activity, and practical field application in a wide variety of sectors.

Florence, Italy

October 2018

Prof. Benedetto Allotta
Parts of this thesis have been published in the following documents:

**Journals**


**International Conferences**


**Book Chapters**

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For their loyalty, I am grateful to my lifetime friends; times may change, but the trust I have in them will always be the same.

Finally, I would like to thank my family for supporting and loving me during the highs and lows of these years.

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Francesco Fanelli
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Nomenclature

Measurement units for non-uniform quantities are not reported. A 1 in the units field denotes a unitless quantity.

- $A_{f,i}$: Projection of the area of the hull on a plane perpendicular to the $i$-axis (m$^2$)
- $C(\nu)$: Centripetal and Coriolis effects matrix
- $C_A(\nu)$: Added centripetal and Coriolis effects matrix
- $C_{Di}$: $i$-axis drag coefficient (1)
- $C_{RB}(\nu)$: Rigid body centripetal and Coriolis effects matrix
- $D(\nu)$: Hydrodynamic damping effects matrix
- $K$: Body-fixed $x$-axis torque (Nm)
- $M$: Body-fixed $y$-axis torque (Nm)
- $M_A$: Added mass matrix
- $M_{RB}$: Rigid body mass and inertia matrix
- $M_m$: Mass and inertia matrix
- $N$: Body-fixed $z$-axis torque (Nm)
- $P$: State covariance
- $Q$: Process noise covariance
- $R$: Measurement noise covariance
- $R^N_B(\eta_2)$: Earth-fixed frame to body-fixed frame rotation matrix (1)
- $R^N_U$: Earth-fixed frame to USBL-fixed frame rotation matrix (1)
- $T^N_B(\eta_2)$: Angular velocity to $\eta_2$ time derivative transformation matrix (1)
- $V$: Volume (m$^3$)
- $W$: Magnetometer Soft Iron, Scale Factor, and Misalignment effect (1)
- $X$: Body-fixed $x$-axis force (N)
- $Y$: Body-fixed $y$-axis force (N)
- $Z$: Body-fixed $z$-axis force (N)
- $\delta^N_P$: Earth-fixed frame GPS measurement noise (m)
- $\delta^N_U$: Earth-fixed frame USBL measurement noise (m)
\( \delta_a \) IMU acceleration measurement noise \((m/s^2)\)

\( \delta_b \) IMU angular velocity measurement noise \((rad/s)\)

\( \delta_m \) Compass magnetic field measurement noise \((AU)\)

\( \delta_i \) DVL measurement noise \((m/s)\)

\( \eta \) Earth-fixed pose

\( \eta_1 \) Earth-fixed position \((m)\)

\( \eta_2 \) Earth-fixed orientation \((rad)\)

\( \nu \) Body-fixed velocity

\( \nu_1 \) Body-fixed linear velocity \((m/s)\)

\( \nu_2 \) Body-fixed angular velocity \((rad/s)\)

\( \nu_{c,h}^N \) North and East current components \((m/s)\)

\( \nu_c \) Body-fixed current velocity

\( \nu_e^N \) Earth-fixed current velocity

\( \nu_r \) Relative velocity

\( \omega_{IMU}^B \) IMU gyroscope bias \((rad/s)\)

\( \omega_c \) Correction term of the attitude estimation filter \((rad/s)\)

\( \tau \) Body-fixed vector of forces and torques

\( \tau_1 \) Body-fixed force \((N)\)

\( \tau_2 \) Body-fixed torque \((Nm)\)

\( \delta_d \) Depth sensor measurement noise \((m)\)

\( \delta_f \) FOG measurement noise \((rad/s)\)

\( \{O_{Bx,y,z,B}\} \) Body-fixed reference frame

\( \{O_{Nx,y,z,N}\} \) Earth-fixed reference frame

\( \omega_{FOG}^B \) FOG measured angular rate after compensation of Earth’s angular rate effect \((rad/s)\)

\( \omega_{m}^B \) FOG measured angular rate \((rad/s)\)

\( \omega_\sigma, \omega_m, \Omega_c \) Weights of the Unscented Transform \((1)\)

\( \phi \) Roll angle \((rad)\)

\( \psi \) Yaw angle \((rad)\)

\( \rho \) Water density \((kg/m^3)\)

\( B^B \) Body frame buoyancy \((N)\)

\( H^N_{x,B} \) Body frame estimate of Earth’s magnetic field projected on the plane orthogonal to acceleration \((T)\)

\( H^N \) Earth’s magnetic field \((T)\)

\( H_d \) Magnetometer Hard Iron effect \((AU)\)

\( P_{GPS} \) GPS fix

\( P_{GPS}^N \) Earth-fixed frame GPS measured position \((m)\)

\( P_{USBL}^N \) Earth-fixed frame USBL measured position \((m)\)

\( P^U \) Earth-fixed frame USBL position \((m)\)

\( W^B \) Body frame gravitational force \((N)\)

\( a_{IMU}^B \) IMU measured acceleration \((m/s^2)\)

\( a_f \) Filtered accelerometer measurements \((m/s^2)\)

\( b_g \) IMU measured angular velocity \((rad/s)\)
Gravitational acceleration (m/s²)
$g$

Gravitational and buoyancy effects vector
$g_\eta(\eta)$

Compass measured magnetic field (AU)
$m^B$

Calibrated magnetic field measurements (T)
$m^c$

Projection of calibrated magnetic field measurements on the plane orthogonal to acceleration (T)
$m^c_\perp$

Body frame position of the center of buoyancy (m)
$r_b^B$

Control input vector
$u$

Measurement noise
$v$

DVL measured velocity (m/s)
$v_{DVL}^B$

Process noise
$w$

State vector
$x$

Measurement vector
$y$

Pitch angle (rad)
$\theta$

Depth sensor measured depth (m)
$d_{DS}^N$

Principal inertia matrix (kgm²)
$\text{diag}\{I_x, I_y, I_z\}$

Mass (kg)
$m$

Body-fixed x-axis angular velocity (rad/s)
$p$

Body-fixed y-axis angular velocity (rad/s)
$q$

Body-fixed z-axis angular velocity (rad/s)
$r$

Magnitude of the horizontal projection of the magnetic field (T)
$r_{H,h}$

Time (s)
$t$

Body-fixed x-axis linear velocity (surge motion) (m/s)
$u$

Body-fixed y-axis linear velocity (sway motion) (m/s)
$v$

Body-fixed z-axis linear velocity (heave motion) (m/s)
$w$

Earth-fixed x-axis position (m)
$x$

Earth-fixed y-axis position (m)
$y$

Earth-fixed z-axis position (m)
$z$
### Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ADCP</td>
<td>Acoustic Doppler Current Profiler</td>
</tr>
<tr>
<td>AHRS</td>
<td>Attitude and Heading Reference System</td>
</tr>
<tr>
<td>AUV</td>
<td>Autonomous Underwater Vehicle</td>
</tr>
<tr>
<td>DS</td>
<td>Depth Sensor</td>
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<tr>
<td>DVL</td>
<td>Doppler Velocity Log</td>
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<tr>
<td>EKF</td>
<td>Extended Kalman Filter</td>
</tr>
<tr>
<td>FOG</td>
<td>Fiber Optic Gyroscope</td>
</tr>
<tr>
<td>GNC</td>
<td>Guidance, Navigation, and Control</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
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<tr>
<td>IMU</td>
<td>Inertial Measurement Unit</td>
</tr>
<tr>
<td>INS</td>
<td>Inertial Navigation System</td>
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<tr>
<td>KF</td>
<td>Kalman Filter</td>
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<tr>
<td>LBL</td>
<td>Long BaseLine</td>
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<tr>
<td>MEMS</td>
<td>Micro-Electro-Mechanical Systems</td>
</tr>
<tr>
<td>MMSE</td>
<td>Minimum Mean Square Error</td>
</tr>
<tr>
<td>NECF</td>
<td>Nonlinear Explicit Complementary Filter</td>
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<tr>
<td>NED</td>
<td>North, East, and Down</td>
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<tr>
<td>ROV</td>
<td>Remotely Operated Vehicle</td>
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<tr>
<td>RV</td>
<td>Random Variable</td>
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<tr>
<td>SNAME</td>
<td>Society of Naval Architects and Marine Engineers</td>
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<tr>
<td>UKF</td>
<td>Unscented Kalman Filter</td>
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<tr>
<td>USBL</td>
<td>Ultra Short BaseLine</td>
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<tr>
<td>UT</td>
<td>Unscented Transform</td>
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<tr>
<td>UUV</td>
<td>Unmanned Underwater Vehicle</td>
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