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Francesco Fanelli

Development and Testing of Navigation Algorithms for Autonomous Underwater Vehicles

Doctoral Thesis accepted by
University of Florence, Italy

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To my family

Supervisor's Foreword

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

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Journals

Costanzi R., Fanelli F., Meli E., Ridolfi A., Caiti A., Allotta B., *UKF-Based Navigation System for AUVs: Online Experimental Validation*, IEEE Journal of Oceanic Engineering, Vol. PP, Issue 99, pp. 1–9 (2018).

Costanzi R., Fanelli F., Monni N., Ridolfi A., Allotta B., *An Attitude Estimation Algorithm for Mobile Robots Under Unknown Magnetic Disturbances*, IEEE/ASME Transactions on Mechatronics, Vol. 21, pp 1900–1911, Apr. (2016).

Allotta B., Caiti A., Costanzi R., Fanelli F., Fenucci D., Meli E., Ridolfi A., *A new AUV navigation system exploiting unscented Kalman filter*, Journal of Ocean Engineering, Vol. 113, pp. 121–132 (2016).

Allotta B., Costanzi R., Fanelli F., Monni N., Ridolfi A., *Single axis FOG aided attitude estimation algorithm for mobile robots*, Journal of Mechatronics, Vol. 30, pp. 158–173 (2015).

International Conferences

Allotta B., Costanzi R., Fanelli F., Monni N., Paolucci L., Ridolfi A., *Sea currents estimation during AUV navigation using Unscented Kalman Filter*, Proceedings of the 20th IFAC World Congress, Toulouse (FR), pp. 13668–13673, July 9–14 (2017).

Costanzi R., Fanelli F., Ridolfi A., Allotta B., *Simultaneous navigation state and sea current estimation through augmented state Unscented Kalman Filter*, Proceedings of the MTS/IEEE OCEANS'16 Monterey, Monterey (CA, US), Sept. 19–22 (2016).

Allotta B., Costanzi R., Fanelli F., Monni N., Ridolfi A., *Underwater Vehicles Attitude Estimation in presence of Magnetic Disturbances*, Proceedings of the IEEE International Conference on Robotics and Automation, Stockholm (SE), pp. 2612–2617, May 16–21 (2016).

Allotta B., Caiti A., Costanzi R., Fanelli F., Fenucci D., Meli E., Ridolfi A., *Unscented Kalman Filtering for Autonomous Underwater Vehicles*, Proceedings of ECCOMAS MARINE 2015, Rome, June 15–17 (2015).

Allotta B., Caiti A., Chisci L., Costanzi R., Di Corato F., Fanelli F., Fantacci C., Fenucci D., Meli E., Ridolfi A., *A comparison between EKF-based and UKF-based navigation algorithms for AUVs localization*, Proceedings of the MTS/IEEE OCEANS'15 Genova, Genova (IT), May 18–21 (2015).

Book Chapters

Caiti A., Costanzi R., Fenucci D., Allotta B., Fanelli F., Monni N., Ridolfi A., *Marine Robots in Environmental Surveys: Current Developments at ISME—Localisation and Navigation*, Marine Robotics and Applications, pp. 69–86 (2018).

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

To all the people mentioned here goes my sincere gratitude, for they have contributed to shape the person I am and the one that I want to be.

Francesco Fanelli

Contents

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)
$C(\boldsymbol{\nu})$	Centripetal and Coriolis effects matrix
$C_A(\boldsymbol{\nu})$	Added centripetal and Coriolis effects matrix
$C_{D,i}$	*i*-axis drag coefficient (1)
$C_{RB}(\boldsymbol{\nu})$	Rigid body centripetal and Coriolis effects matrix
$D(\boldsymbol{\nu})$	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
$R_B^N(\boldsymbol{\eta}_2)$	Earth-fixed frame to body-fixed frame rotation matrix (1)
R_U^N	Earth-fixed frame to USBL-fixed frame rotation matrix (1)
$T_B^N(\boldsymbol{\eta}_2)$	Angular velocity to $\boldsymbol{\eta}_2$ 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)
$\boldsymbol{\delta}_P^N$	Earth-fixed frame GPS measurement noise (m)
$\boldsymbol{\delta}_U^N$	Earth-fixed frame USBL measurement noise (m)

$\boldsymbol{\delta}_a$	IMU acceleration measurement noise (m/s^2)
$\boldsymbol{\delta}_g$	IMU angular velocity measurement noise (rad/s)
$\boldsymbol{\delta}_m$	Compass magnetic field measurement noise (AU)
$\boldsymbol{\delta}_v$	DVL measurement noise (m/s)
$\boldsymbol{\eta}$	Earth-fixed pose
$\boldsymbol{\eta}_1$	Earth-fixed position (m)
$\boldsymbol{\eta}_2$	Earth-fixed orientation (rad)
$\boldsymbol{\nu}$	Body-fixed velocity
$\boldsymbol{\nu}_1$	Body-fixed linear velocity (m/s)
$\boldsymbol{\nu}_2$	Body-fixed angular velocity (rad/s)
$\boldsymbol{\nu}_{c,h}^N$	North and East current components (m/s)
$\boldsymbol{\nu}_c$	Body-fixed current velocity
$\boldsymbol{\nu}_c^N$	Earth-fixed current velocity
$\boldsymbol{\nu}_r$	Relative velocity
$\boldsymbol{\omega}_{IMU}^B$	IMU gyroscope bias (rad/s)
$\boldsymbol{\omega}_c$	Correction term of the attitude estimation filter (rad/s)
$\boldsymbol{\tau}$	Body-fixed vector of forces and torques
$\boldsymbol{\tau}_1$	Body-fixed force (N)
$\boldsymbol{\tau}_2$	Body-fixed torque (Nm)
δ_d	Depth sensor measurement noise (m)
δ_f	FOG measurement noise (rad/s)
$\{O^B x^B y^B z^B\}$	Body-fixed reference frame
$\{O^N x^N y^N z^N\}$	Earth-fixed reference frame
ω_{FOG}^c	FOG measured angular rate after compensation of Earth's angular rate effect (rad/s)
ω_{FOG}^m	FOG measured angular rate (rad/s)
$\omega_\sigma, \boldsymbol{\omega}_m, \Omega_c$	Weights of the Unscented Transform (1)
ϕ	Roll angle (rad)
ψ	Yaw angle (rad)
ρ	Water density (kg/m^3)
B^B	Body frame buoyancy (N)
$\mathrm{H}_\perp^{N,B}$	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^N	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)

g	Gravitational acceleration (m/s^2)
$g_{\boldsymbol{\eta}}(\boldsymbol{\eta})$	Gravitational and buoyancy effects vector
m^B	Compass measured magnetic field (AU)
m^c	Calibrated magnetic field measurements (T)
$m^c_{\perp}$	Projection of calibrated magnetic field measurements on the plane orthogonal to acceleration (T)
r^B_b	Body frame position of the center of buoyancy (m)
u	Control input vector
v	Measurement noise
v^B_{DVL}	DVL measured velocity (m/s)
w	Process noise
x	State vector
y	Measurement vector
θ	Pitch angle (rad)
d^N_{DS}	Depth sensor measured depth (m)
$diag\{I_x, I_y, I_z\}$	Principal inertia matrix (kgm^2)
m	Mass (kg)
p	Body-fixed x-axis angular velocity (rad/s)
q	Body-fixed y-axis angular velocity (rad/s)
r	Body-fixed z-axis angular velocity (rad/s)
$r_{H,h}$	Magnitude of the horizontal projection of the magnetic field (T)
t	Time (s)
u	Body-fixed x-axis linear velocity (surge motion) (m/s)
v	Body-fixed y-axis linear velocity (sway motion) (m/s)
w	Body-fixed z-axis linear velocity (heave motion) (m/s)
x	Earth-fixed x-axis position (m)
y	Earth-fixed y-axis position (m)
z	Earth-fixed z-axis position (m)

Acronyms

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