Progress in Marine Science and Technology 6

Technology and Science for the Ships of the Future

Proceedings of NAV 2022: 20th International Conference on Ship & Maritime Research

Edited by
Enrico Rizzuto and Valerio Ruggiero

IOS Press

The oceans are a key resource for transportation, energy and material extraction, and food production, representing one of the most important environments on the planet. Technological developments enabling us to exploit marine resources in a sustainable way are therefore of the greatest importance.

This book presents the proceedings of the NAV 2022 conference, held in Genoa and La Spezia, Italy, from 15 to 17 June 2022. The conference is held every 3 years, attracting specialists in marine technology from all over the world. NAV 2022 was the 20th edition of the conference, and covered a full spectrum of maritime technology themes, all related to the exploitation of sea resources. The book contains 87 scientific papers, covering subjects ranging from comfort on board; to conceptual and practical ship design; deep sea mining and marine robotics; protection of the environment; renewable marine energy; design and engineering of offshore vessels; digitalization and cyber security; unmanned vehicles; yacht and pleasure craft design, and inland-waterway vessels.

Providing a comprehensive coverage of the latest scientific and technical maritime issues, the book will be of interest to all those involved in this vital global industry.

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Preface

On behalf of the Scientific Committee, I am glad to introduce the proceedings of NAV 2022.

They contain contributions by Italian and European Universities and Research Centres, as well as from Industries and the Italian Navy, covering the most updated subjects in the field of naval, commercial and pleasure crafts.

The papers have been presented in a three-day conference organised by ATENA and held in Genova and La Spezia on 15 to 17 June 2022. After a delay of one year due to the COVID Pandemic it was an excellent return to the tradition of NAV conferences, reaching this year the 20th edition. As known, these events have been organised itinerantly in Italy since as far back as 1980.

The contributions have been selected and reviewed by experts in the relevant fields and are now collected here for your convenience.

Please enjoy the reading!

Enrico Rizzuto
Chairman of the Scientific Committee of NAV 2022

Contents

Preface v
Enrico Rizzuto

About the Conference vii

A Combined CFD-FEM Approach to Evaluate Acoustic Performances of an Integrated Scrubber-Silencer for Marine Applications 1
Giada Kyaw Oo D'Amore, Francesco Mauro, Mitja Morgut, Giovanni Rognoni and Marco Biot

Wind-Assisted Ship Propulsion Feasibility Study 9
Veronica Vigna and Massimo Figari

A Numerical Method to Fit the Need of a Straightforward Characterization of Viscoelastic Materials for Marine Applications 18
Giovanni Rognoni, Giada Kyaw Oo D'Amore, Emanuele Brocco and Marco Biot

Industry 4.0 in Shipbuilding. Application in Autonomous Ships 26
Rodrigo Perez Fernandez

ARGOS: A Solution to Increase Security and Safety of Ships 34
Franco Gottifredi, Marco Cappella, Krzysztof Marcinek, Alina Anton and Barbara Amerio

Dynamic Instability of Ships in Stern-Quartering Seas Within the SGISC 42
Christian Lena and Matteo Bonci

Intact Stability Assessment of RO-RO Pax Vessel in the Framework of Second Generation Intact Stability Criteria with a Specific Focus on the Operational Profile 52
Nicola Petacco, Valerio Ruggiero and Paola Gualeni

A Systematic Ferry Series 60
Marcello Costanzo, Andrea Mancini and Luca Mauro

Fully-Recyclable Epoxy Fibres Reinforced Composites (FRCs) for Maritime Field: Chemical Recycling and Re-Use Routes 70
Lorena Saitta, Eugenio Pergolizzi, Claudio Tosto, Claudia Sergi and Gianluca Cicala

Study of the Corrosion Behaviour of Welded Systems for Marine Industry Applications 78
Alfredo Rondinella, Francesco Andreatta, Lorenzo Dorbolò, Ruben Offoiach, Giovanni Capurso, Gianluca Buffa, Davide Campanella and Lorenzo Fedrizzi

Naval Fleet Integrated Logistic Design Optimization: The Italian Navy Experience in Enhancing Feedback from the Field 86
Alessandro Peisino and Simone Tesconi

Deep Neural Network (DNN) Method to Predict the Displacement Behavior of Neutral Axis for Ships in Vertical Bending 95
Alessandro La Ferlita, Emanuel Di Nardo, Massimo Macera, Thomas Lindemann, Angelo Ciaramella and Patrick Kaeding

Innovative and Sustainable Materials for Naval Applications Through National Cooperative Research: The Experience of the THALASSA Project 104
Simone Panfiglio, Guido Di Bella, Edoardo Proverbio, Lugi Calabrese, Annamaria Visco, Gianluca Cicala, Fabrizio Sarasini and Gianluca Buffa

Numerical Modelling of the Hydrodynamic Response of a Fixed Dual-Chamber Oscillating Water Column Wave Energy Converter Through the Meshless DualSPHysics Method 112
Gael Anastas, João Alfredo Santos and Conceição Juana E.M. Fortes

A Roadmap Towards the Autonomous Ship: The Marin R&D Project 120
Luca Sebastiani, Andrea Pecoraro, Francesco Pettinato, Daniel Luceri, Alessandro Largo, Paolo Corvaglia, Paola Rametta, Fabrizio Benvenuto, Sergio De Giuseppe and Marco Spedicato

SKIN: The Use of External Surface in Yacht Design 130
Maria Carola Morozzo Della Rocca and Giulia Zappia

Ammonia as an Alternative Fuel for Large Passenger Ships: Benefits and Challenges 138
Filippo Scamardella, Giorgio Zamboni, Edward Canepa, Paola Gualeni and Angelo Macocco

Hydrodynamic Assessment of Double-Ended Ferry for Operation in Venice 146
Enrico Della Valentina, Victor Ferrari, Andrea Bortolato and Antonio Ferrari

BESS-Based Hybrid Propulsion: An Application to a Front Line Naval Vessel Preliminary Design 154
Daniele Belvisi, Raphael Zaccone, Massimo Figari, Sergio Simone and Bruno Spanghero

A Zero-Emission Ferry for Inland Waterways 162
Luca Maloberti, Raphael Zaccone, Paola Gualeni and Paolo Mazzucchelli

Experimental Investigation on a Lightweight Ship Balcony Overhang with Bimetallic Welded Joints 170
Giulia Palomba, Pasqualino Corigliano, Vincenzo Crupi, Gabriella Epasto and Eugenio Guglielmino

CFD Prediction of the Asymmetrical Shaft Unbalance During Ship Maneuvers 178
Diego Villa and Stefano Gaggero

On the Structural Response of Bio-Based Adhesives for Wooden Hulls 188
Serena Bertagna, Pasqualino Corigliano, Vincenzo Crupi and Alberto Marinò

A Digital Twin Approach to the Diagnostic Analysis of a Marine Diesel Engine 198
Marco Altosole, Flavio Balsamo, Maria Acanfora, Luigia Mocerino, Ugo Campora and Francesco Perra

Sensitivity Analysis of a Marine Gasoline Engine: From Power to Emissions 207
Luigia Mocerino, Vincenzo Piscopo and Antonio Scamardella

Cyber Resilience of Automated and Autonomous Ships 215
Enrico Carrara

Regulatory Measures to Tackle Climate Changes 223
Giovanna Carosi

A Swappable Battery to Reduce Emissions of Ships 231
Paolo Scialla, Matteo Roiaz, Ryan Kostos, Shaun White, Dimitris Kontosfyris and Jan-Erik Räsänen

Environmental Protection: Underwater Noise and Noise in Port 239
Elisa Fassola

Noise and Vibration: Comparison Between Prediction and Measurements on Yachts 246
Elisa Fassola and Lorenzo Kustermann

Experimental Analysis of Cavitation Erosion on Blade Root of Controllable Pitch Propeller 254
Afaq Ahmed Abbasi, Michele Viviani, Daniele Bertetta, Marina Delucchi, Rico Ricotti and Giorgio Tani

Classifying the Innovation: The Certification of New Designs for Power Generation, Conversion and Energy Storage Focusing on the Reduction of Ships Emissions 263
Matteo Roiaz, Paolo Scialla, Fabrizio Cadenaro, Marco Nardo and Gabriele Sancin

Free Surface Hydrodynamics of Submarine Masts Configurations 271
Giuliano Vernengo, Stefano Gaggero, Diego Villa, Giorgio Mazzarello and Paola Gualeni

Numerical Approaches for Submarine Hydrodynamic Design and Performance Analysis 279
Stefano Gaggero, Benedetto Piaggio, Giuliano Vernengo, Diego Villa, Michele Viviani and Paola Gualeni

Remote Passive Acoustic Barrier with Maritime Unmanned Systems: Preliminary Tests During REPMUS-21 287
Lorenzo Bazzarello, Daniele Terracciano, Vincenzo Manzari, Matteo Bresciani, Francesco Cannarsa, Alessandra Tesei, Riccardo Costanzi, Andrea Caiti and Mirko Stifani

Surfing Green, Saving Money 295
Elisabetta Piana

On the Development of a Ship Simulation Model for Maneuvering Tasks in Waves 305
Maria Acanfora, Marco Altosole, Ernesto Fasano and Davide Lauria

Hybrid System Virtualisation for Predicting Performance and Eliminating Risks and Uncertainties 314
Amodio Palma, Stefan Goranov, Markus Wenig and Maciej Bendyk

Weather Routing Model for Ship Motions Reduction and Fuel Saving 323
Silvia Pennino and Antonio Scamardella

The Evolution of Large Pleasure Vessel Towards a Green Future 331
Gianmarco Vergassola, Dario Boote and Federico Tocchi

Systems Engineering and Ship Design: A Synergy for Getting the Right Design and the Design Right 340
Mattia Bottero and Paola Gualeni

An Innovative Cruise-Ship Onshore Power Supply Facility in the Port of Marseille 348
Alessandro Boveri and Franco Porcellacchia

A Multipurpose Simulation Framework for Ship Design and Operational Assessment 364
Luca Isgro, Luca Fengone and Davide Tozzi

Assessment of Shipboard Sound Insulation in the Low Frequency Range Through a Laboratory Experimental Methodology Based on a Modal Approach 374
Mirko Bassetti, Federico Gaggero, Andrea Prato, Alessandro Schiavi, Tatiana Pais, Paolo Silvestri and Enrico Lembo

Airborne Sound Propagation Induced by a Cruise Ship Through Simulation and Correlation with Real Measurements 382
Mirko Bassetti, Maurizio Morelli, Attilio Binotti, Enrico Lembo and Andrea Iuliano

Application of Transfer Path Analysis Technique to Cruise Ships 397
Mirko Bassetti, Riccardo Tonna, Tatiana Pais, Paolo Silvestri, Enrico Lembo and Andrea Iuliano

Shock Characterization of Fiberglass Composite Laminates: Numerical and Experimental Comparison 408
Francesco Mannacio, Fabrizio Di Marzo, Marco Gaiotti, Massimo Guzzo, Cesare Mario Rizzo and Marco Venturini

Technical Feasibility Study of an Ammonia-Fuelled Mega-Yacht Powered by PEM Fuel Cells 416
Roberta Russo, Maria Acanfora, Tommaso Coppola and Luca Micoli

Visual Languages Effectiveness in the Context of Communications for Safety and On-Board Orientation 424
Maria Linda Falcidieno, Maria Elisabetta Ruggiero, Ruggero Torti and Nicoletta Sorrentino

Experiments for the Definition of Communication Models: The Visual Identity of Navigation Companies in Relation to On-Board Services 432
Maria Linda Falcidieno, Maria Elisabetta Ruggiero, Massimo Malagugini, Ruggero Torti and Nicoletta Sorrentino

Road to Maritime Sector Decarbonization 440
Maurizio Archetti and Barbara Bosio

Environmentally Friendly Composites and Surface Treatments for Metal-to-Composite Hybrid Joints for Marine Application 448
Fabrizio Sarasini, Jacopo Tirillò, Vincenzo Fiore, Antonino Valenza, Lorena Saitta, Claudio Tosto, Gianluca Cicala, Francesca Felline, Antonio Gerardi, Carlo Ighina and Simone Panfiglio

"One digit" Estimation of Navigation Area Parameters for a Monohull Fast Ferry 456
Oleksandr Kanifolskyi and Valerio Ruggiero

A Smart Mockup for an Innovative Interior Yacht Design Approach 464
Mario Ivan Zignego, Paolo Andrea Gemelli and Alessandro Bertirotti

Proposal of a Coastal Ferry Using Last Hybrid Technology for Green Transportation in Touristic Areas 470
Matteo Zangrandi, Valerio Ruggiero and Gian Piero Repetti

Alternative Assessment of Passenger Ship Safety – Early Results from the EU Project FLARE 478
Alessandro Maccari, Spyros Hirdaris, Antoine Breuillard, Fabien Conti and Dracos Vassalos

Fluid Structure Interaction in Marine Applications Using Open-Source Tools 486
Claudio G. Caccia, Giovanni Bailardi, Joel Guerrero and Davide Marini

The Study of an Innovative Propulsion Plant for a High-Speed Catamaran Ferry for Decarbonisation in the Marine Industry 494
Alessandro Taylor, Kurt Mizzi, Selmar Spijker, Michele Martelli and Kurt Gutteridge

Near Future Submarine: Development of a Combined Air Independent and Lithium Battery Propulsion System (AI-LiB Propulsion System) 503
Decio Trinca

SHIP URN: UNIGE Activities in the Context of LIFE-PIAQUO Project 512
Stefano Gaggero, Tomaso Gaggero, Giorgio Tani, Diego Villa, Enrico Rizzuto and Michele Viviani

Surface Unmanned Multipurpose Research Marine Vehicle: SUNMARE Project 522
Maicol Laurenza, Gianluca Pepe, Federica Mezzani, Alec Malito, Massimo De Lauro, Salvatore Mauro, Antonio Culla and Antonio Carcaterra

A Numerical Investigation of the Effect of Spatial and Temporal Resolution Together with Turbulence Modelling on the Hydrodynamic Forces of a Cavitating Foil 530
Mariana Zammit Munro, Simon Mizzi, Claire De Marco Muscat Fenech, Giorgio Tani and Yigit Demirel

A DIS-Based Air Cavity Concept for Planing Hull 538
Fabio De Luca, Simone Mancini, Claudio Pensa, Riccardo Pigazzini and Vincenzo Sorrentino

A Methodology for the Hull Forms Design of a Passenger Catamaran for the Venice Lagoon 546
Luca Braidotti, Serena Bertagna, Mattia Zanin, Donato Padolecchia, Alberto Marinò and Vittorio Bucci

Fast Estimation of the Time-to-Flood on Simple Geometries 555
Luca Braidotti, Jasna Prpić-Oršić, Samuele Utzeri, Vittorio Bucci and Alberto Marinò

Life Cycle Assessment in the Naval Sector: Between Certification and New Materials 564
Barbara Busetto, Alessandro Bordignon, Anna Bortoluzzi, Stefano Milanesi, Andrea Paduano and Andrea Mio

Numerical and Physical Modeling of Ship Impacts on Fenders 572
A. Gomes, L. Pinheiro, J. Simão, C. Costa, C.E.J. Fortes and J.A. Santos

Safety System for Ships in Harbours 580
Liliana Pinheiro, Andreia Gomes, Conceição Fortes and João A. Santos

Decarbonization and Efficiency: The Potential of Digital Fleet Management 588
Michela Schenone

The Inside Story of COVID-19 Pandemic on the Diamond Princess as the *prime mover* of Present and Future Ship Design 597
Gennaro Arma and Angela Denise Peri

How COVID-19 Has Been Affecting the Overall Cruise Ship Design Paradigm 610
Massimo Musio-Sale, Angela Denise Peri and Valerio Ruggiero

Innovative Solutions for the Integration of Medical Facilities on *dual-use* Naval Ships 622
Nicola Norcia, Serena Bertagna, Luca Braidotti, Vittorio Bucci and Alberto Marino

Strategies for Ship Decarbonisation: Technical Measure for Reducing Energy Efficiency Existing Ship Index 632
Valentina Bortuzzo, Massimo De Domenico and Vittorio Bucci

Rapid Prototyping for Enhanced Dynamic Positioning Systems 641
Silvia Donnarumma, Camilla Fruzzetti, Michele Martelli, Roberto Chiti, Andrea Pecoraro and Luca Sebastiani

New Generation Mine CounterMeasures Vessels (NG-MCMV) 650
Domenico Guadalupi, Francesco Maiorana and Massimo Guzzo

SDO-SuRS Deployable Assets Program 658
Christian Perrone

Drag Based Shape Optimization of Submarines and AUVs Using CFD Analysis 668
Gianpaolo Damiano Bono and Gianni Buttaro

On the Application of a Vortex Lattice Method to Lifting Bodies Close to a Free Surface 676
Raffaele Solari, Patrizia Bagnerini and Giuliano Vernengo

Investigations on Ultimate Strength for a Container Vessel Under Combined Loads 684
Thomas Lindemann, Patrick Kaeding, Alexander Willsch, Alessandro La Ferlita and Dario Boote

The REShiP Project: Renewable Energy for Ship Propulsion 692
Alessandro Bernardini, Irene Lavagnini, Chiara Dall'Armi, Davide Pivetta, Rodolfo Taccani, Fabrizio Cadenaro, Matteo Roiaz, Maurizio Crucil, Tancredi Chinese, Stefano Malabotti and Michela Zanelli

Energy-Saving Devices: A Retrofit Stern Flap Solution on the "De La Penne" Destroyer Class (Numerical Analysis and Experimental Tests) 702
Mario De Biase, Vincenzo Basile and Simone Mancini

Italian Navy Green Fleet – Energy Saving Measures: A Solution to Increase Overall Efficiency of a Military Ship of "Bergamini" FREMM Class 710
Antonio Bignone and Gianluca Benetello

Definition and Development of "Modularity and Operational Flexibility" with Pros and Cons of the Concepts in the Italian Navy PPA Experience 717
Antonio Petrucci

Optimal Conceptual Design Using NSGA-II Algorithm for Galápagos Interisland Service Small Craft Including Flaps 725
José R. Marín-López, Janeth L. Meléndez, Rubén J. Paredes and Esteban L. Castro-Feliciano

Fracture Mechanics Properties of Al/Steel Structural Transition Joints for Shipbuilding 734
Pasqualino Corigliano, Vincenzo Crupi and Pingsha Dong

Data Driven Digital Twins for the Maritime Domain 744
Alexandros Troupiotis-Kapeliaris, Nicolas Zygouras, Manolis Kaliorakis, Spiros Mouzakitis, Giannis Tsapelas, Alexander Artikis, Eva Chondrodima, Yannis Theodoridis and Dimitris Zissis

Numerical Estimation of Pre-Swirl Stator Efficiency 752
Andro Bakica and Nikola Vladimir

Subject Index 761

Author Index 765

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Surface Unmanned Multipurpose Research Marine Vehicle: SUNMARE Project

Maicol Laurenza[a,1], Gianluca Pepe[a], Federica Mezzani[a], Alec Malito[b], Massimo De Lauro[b], Salvatore Mauro[b], Antonio Culla[a] and Antonio Carcaterra[a]
[a] *University of Rome, Sapienza, Dept. of Mechanical and Aerospace Engineering, Rome, Italy*
[b] *Institute of Marine Engineering, CNR-INM, Rome, Italy*

Abstract. This paper presents the preliminary activities undertaken for the research project SUNMARE (Surface UNmanned multipurpose research MARine vEhicle), which aims at the development of an innovative autonomous platform for marine, oceanographic, lacustrine, and submerged/semi-submerged cultural heritage monitoring/measurements. SUNMARE is a modular ship comprising of a mother unmanned ship and a smaller autonomous vehicle. Through an innovative fully autonomous launch and recovery system (LARS), the Unmanned surface vehicle (USV) can detach and reconnect to the mother ship. The architecture of the LARS and the on-purposely designed control algorithms are here presented together with statistical recovery success analysis concerning the autonomous dynamic connection of the vehicles, so to assess the reliability of the system.

Keywords. Unmanned surface vehicle (USV), Launch and recovery system, Optimal control

1. Introduction and SUNMARE project

Recent improvements in sensor technology, combined with increasing interest in oceanographic measurements, are increasingly pushing the development of autonomous marine vehicles. Public and private research institutions are making considerable efforts in financing intelligent marine vehicles able to autonomously perform a wide range of operations and to collect a large quantity of as much as possible heterogeneous data [1-3]. SUNMARE-Surface UNmanned multipurpose research MARine vEhicle projects, funded by Regione Lazio (see Acknowledgments), stands in this scenario.

The aim of SUNMARE project is the development of a multipurpose autonomous research vessel and it presents an entire series of innovative features. From structural point of view, the hull is meant to be transportable, modular, and customizable. Moreover, it adapts to different missions, is resilient so to stand different and adverse sea conditions, and is eco-sustainable, made up of recyclable materials and equipped with a green propulsion system. Nevertheless, the core of the project and the aspect ensuring the reliability of the overall system is the control architecture, consisting of a complex network of algorithms with a dual sphere of application: on one hand, overall autonomous guidance must be performed [4], and it includes decision making processes, obstacle avoidance [5], safe guidance in surrounded environment conditions, such as harbour manoeuvres [6]. On the other hand, control algorithms are adapted for specific oceanographic measurement purposes. In this specific context stands the case here

[1] Maicol Laurenza, University of Rome Sapienza, Dept. of Mechanical and Aerospace Engineering, Rome, Italy; E-mail: maicol.laurenza@uniroma1.it.

reported of an autonomous mother ship that releases through a launch and recovery system a second smaller autonomous vehicle for survey operations. Such a sophisticated control logic not only provides advantages in terms of safe manoeuvrability, course stability and attitude at low speeds, but also with respect to the achieved level of autonomy, bringing SUNMARE project up to level four according to the MASS (Maritime Autonomous Surface Ship) classification [7].

As intuitive, one of the most critical situations is the recovery of the smaller vessel. Conventional LARS rely on ramps/slipways, crane, intermediate device, and catapults [8] and not by chance human intervention is necessary in most cases [9] to prevent and manage the so-called corner cases. The ambition of SUNMARE is to realise a fully automated LARS, able to retrieve AUV as well as USV. To ensure the recovery, not only the mother ship presents a catamaran-like hull to better host the smaller vessel, as shown in Figure 1, but also the mechanism is structurally designed to pursue high reliability even in adverse sea conditions, a breakthrough in marine technology.

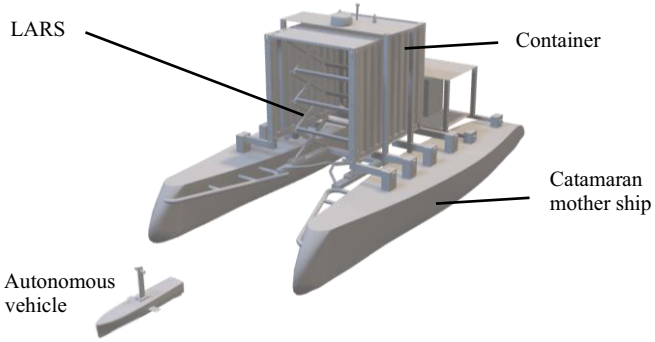

Figure 1. Preliminary design of SUNMARE system

The objective of this work is the assessment of the reliability of the LARS system through statistical analysis and simulations. For this reason, this work initially presents the design of the fully automated LARS; then the strategy and the control algorithms are presented and eventually the results of the simulations are used to demonstrate the robustness of the overall system.

2. Launch and recovery system design

LARS has the only purpose of a safe hooking of the USV. The design responds to the intrinsic requirements of the mission and accordingly, it consists of three main parts (Figure 2):

- *Scissor mechanism*: entrusted with the correct positioning of the fork to perform the launch and recovery of the drone.
- *Fork*: whose purpose is the hooking of the USV through the fin.
- *Fin*: component grabbed by the fork. It houses all the communication tools and sensors.

The *Scissor mechanism* is the part actively absorbing the vertical displacements of the USV. The shape, composed of n groups of scissor arms according to the shape of the mother ship and of the vehicle to recover, is justified by several reasons:

- the parallel kinematics of its geometry is extremely robust

- when closed, it has a compact structure guaranteeing enough space for the recovered vessel within the container
- the gear ratio allows amplification of the speed of the mechanism in adjusting its configuration, consequently able to quickly recover the USV.

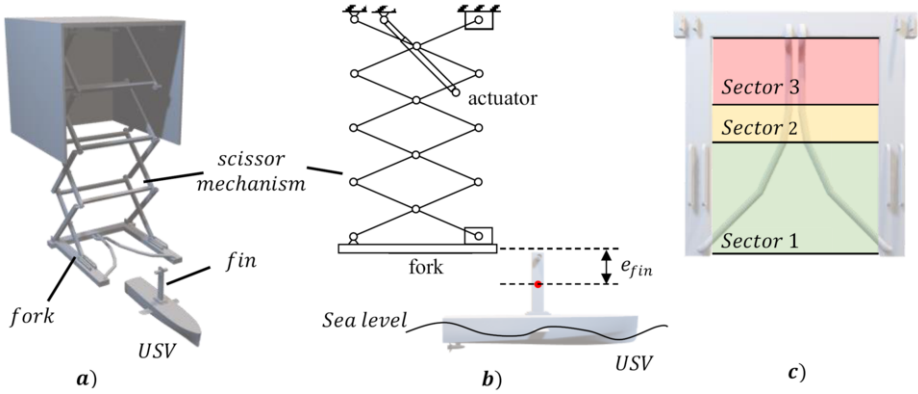

Figure 2. a) 3D view of the LARS; b) scissor mechanism and target identification of the recovery phase; c) structure of the fork and its functionality.

The fork is the element that, during the recovery phase, has the purpose of hooking the drone, passively absorbing roll, and transversal trajectory motions. The shape of the fork, shown in Figure 2, is designed to contain and lead the approaching of the USV, even in case of drifts form the desired alignment because of disturbances that cannot be managed by the control and the sensing systems. The fork can be divided into three sectors. *Sector 1* is the largest portion of the fork since, in this area, the first "encounter" with the fin takes place. The fork can accommodate the drone between the rods inviting it to continue towards *Sector 2* and *3*. The inclination of the rod is designed for the fin to enter the fork even in case of impacts. Despite the fork narrows, it is still possible for the drone to escape from the hook. When in *Sector 2*, the drone has no chance to escape, and the probability of successful recovery is 100%. Eventually, simply by assuring the slipping condition between the rods and the fin with an appropriate inclination of *Sector 3*, a stable equilibrium position is achieved.

3. Launch and recovery strategy

The launch phase starts when the mother ship extends the LARS system until the USV touches the water and flows away from the catamaran. As intuitive, this manoeuvre is less critical with respect to the more challenging recovery one since it demands collaboration between the two independent vehicles. Prior the recovery, both vehicles must be in appropriate relative state, implying effective communication and vehicle positioning need to be guaranteed. The recovery process starts when the USV communicates, via wireless communication, the end of its mission to the mother ship and is not completed until the USV is retrieved and secured on board of the mother ship. This operation is mainly divided in three phases: vehicles alignment along a common direction; mutual approach between the two vehicles and retrieval of the USV with the fork.

The alignment trajectory, common to both vehicles, is defined according to the direction of the wind and the current to the advantage of energy savings and better manoeuvrability (Figure 3).

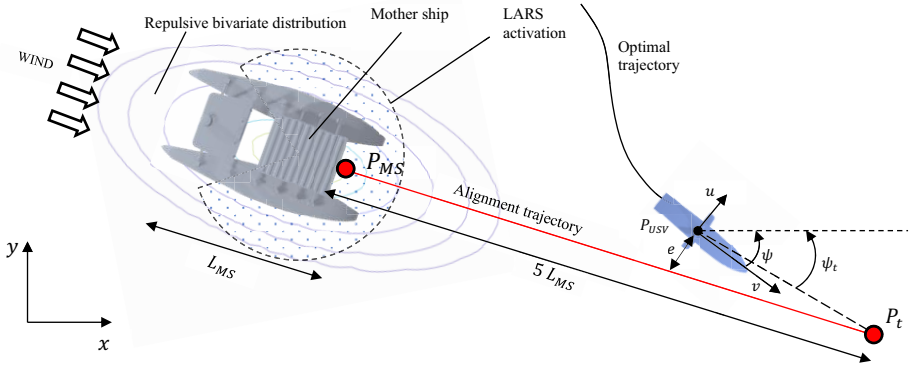

Figure 3. Recovery manoeuvre: alignment phase, LOS guidance law and obstacle avoidance

The mother ship aligns to the trajectory with a cruise speed lower than the USV, and then, a target point P_t is defined along the trajectory at a distance of 5 times the length of the mother ship L_{MS}. When the USV approaches the mother ship, an optimal trajectory is generated, allowing to reach the target point with a desired speed and minimal energy cost. Then, a Model Predictive Control (MPC) strategy [10] is used to follow the optimal trajectory. Once the USV is near P_t, a non-linear feedback control intervenes. The USV switches from following the optimal trajectory to following the alignment trajectory. At this point, the USV reduces its speed so that a relative velocity of 0.5 knots is reached between the USV itself and the mother ship. Eventually, when the USV is within the catamaran, the LARS engages, and the recovery occurs, additionally supported by high accuracy localization sensors. The success of the recovery phase is based on the correct estimation of the state of the system and the consequent selection of the most suitable control logic algorithm according to the relative position between the USV and the mother ship. In the following section the main control algorithms are described.

3.1. Control algorithms

The first step is the generation to the optimal trajectory that must be followed by the USV to reach the same trajectory of the mother ship, aligning with it. The goal of the optimal trajectory generation is the minimization of objective function subject to constraints and model dynamics. The algorithm looks for the so-called open-loop solutions, in which the control $\boldsymbol{u}$ is dependent on the time $\boldsymbol{u}(t)$. The objective function consists of two terms: J_b regards the boundary conditions, the integral term J_t the entire trajectory, both functions of the state $\boldsymbol{x}$, the control $\boldsymbol{u}$, and time.

$$min \quad J_b\big(t_0, t_F, \boldsymbol{x}(t_0), \boldsymbol{x}(t_F)\big) + \int_{t_0}^{t_F} J_t\big(\tau, \boldsymbol{x}(\tau), \boldsymbol{u}(\tau)\big)\, d\tau \tag{1}$$

The solution is achieved by reducing the problem in equation (1) to simple parametric optimization problem [11]. Once the initial guess is defined, the optimal trajectory is found by accounting also for the dynamics of the two vehicles. Soft constraints are considered for actuation, anti-collision and constraints. The optimal solution can be found in few seconds with a PC I7 10th generation.

To guarantee the USV follows the optimal trajectory just found, MPC is applied. It is an optimal control strategy that computes control inputs by minimizing a given objective function J over a finite prediction horizon h:

$$J(x_k, u_k, u_{k+1}, u_{k+2}, \dots) = \sum_{i=0}^{h} \|x_{k+i}\|_Q^2 + \|u_{k+i}\|_R^2 \tag{2}$$

with $Q = Q^T > 0$, $R = R^T > 0$ tuning parameters. The predictive optimal control problem is solved at each sample time over the entire range $[t; t + T_h]$, updating the control solution which represents future control function $u(t)$ over a control horizon T_c typically chosen as $T_c \leq T_h$. With the MPC it is possible to treat linear dynamic systems and linear constraints with quadratic objective functions. In this case, the dynamic model is a simple 2-dimensional linear model [12] shown in Figure 3. The control action is determined only by one thruster, with its magnitude and orientation.

Since MPC is based on a linear model, it is not suitable when a certain level of reactiveness is required. Thus, in any circumstance in which a quick and a precise response is needed, such as when the USV is sensibly close to the mother ship, a feedback control algorithm, such as FLOP-Feedback Local Optimality Control [13], is a more appropriate choice. Indeed, it intervenes when the USV approaches the target point P_t and is capable of minimizing a generic non-quadratic objective function J in the state $\boldsymbol{x}$ and quadratic in the control $\boldsymbol{u}$ with affine dynamic constraints $\dot{\boldsymbol{x}} = \boldsymbol{\phi}(\boldsymbol{x}) + \boldsymbol{B}\boldsymbol{u}$.

$$J = \int_0^T \frac{1}{2}\, \boldsymbol{u}^T \boldsymbol{R}\boldsymbol{u} + \boldsymbol{g}(\boldsymbol{x})dt \quad \text{s.t.} \quad \dot{\boldsymbol{x}} = \boldsymbol{\phi}(\boldsymbol{x}) + \boldsymbol{B}\boldsymbol{u} \tag{3}$$

The function $g(\boldsymbol{x})$ plays a key role in the process of tuning the control logic and can be used to include specific potential functions. For example, to ensure the USV does not collide with the mother ship, it is possible to use a confined repulsive potential function centred on the coordinates of the obstacle, i.e., the mother ship. Defining the state of the USV as $\boldsymbol{x} = [u, v, r, x_{USV}, y_{USV}, \psi]$, where u, v are longitudinal and lateral velocities, r is the angular velocity along the z axis, and x_{USV}, y_{USV}, ψ are the position and orientation of the USV, the function $g(\boldsymbol{x})$ is expressed as:

$$g(\boldsymbol{x}) = w_v(v_t - u)^2 + g_o(x_{MS}, y_{MS}) + w_e e^2(\boldsymbol{x}) + w_\psi(\psi_t(\boldsymbol{x}) - \psi)^2 \tag{4}$$

where w_e, w_ψ, w_v are tuning parameters. The first term in equation (4) leads the USV to keep a target longitudinal velocity v_t; the second is a repulsive bivariate distribution function, centred at the position of the mother ship to avoid collisions between the two vehicles. The last two terms are both related to the guidance law, called *Line-of-Sight* [14], to drive the USV to the target P_t. It consists of making the vehicle converge to the desired point by adjusting the heading direction of the vehicle. Defining the alignment trajectory as the line which joins the mother ship point $P_{MS} = (x_{MS}, y_{MS})$ and the target

point $P_t = (x_t, y_t)$, see Figure 3, it is easy to determine the target orientation ψ_t and cross-tracking error e as:

$$\begin{cases} \psi_t = \operatorname{atan}\left(\frac{x_t - x_{USV}}{y_t - y_{USV}}\right) \\ e = (y_{USV} - y_t)\cos\left(\operatorname{atan}\left(\frac{y_t - y_{MS}}{x_t - x_{MS}}\right)\right) - (x_{USV} - x_t)\sin\left(\operatorname{atan}\left(\frac{y_t - y_{MS}}{x_t - x_{MS}}\right)\right) \end{cases} \quad (5)$$

Converging to the desired path means that the cross-tracking error must tend to zero, and the heading must converge to the heading target. By an appropriate regulation of the function $g(\boldsymbol{x})$ and of the tuning matrix $\boldsymbol{R}$, together with the planar nonlinear dynamic model of the USV vessel, the explicit control law which guarantees local minimization can be obtained via the variational solution [13, 15]. In this configuration, a high accuracy and precision system with positioning antennas, based on UWB technology [16], is used to track the fin. This allows to accurately update the rendezvous point, which is subject to drift and changes of course, related to the mother ship's ability to follow the reference trajectory. UWB is a radio communication technology that uses frequencies form 3.6 GHz up to 10 GHz; it provides fast communication in a range of almost 500m, but one of the main applications of this technology is in positioning systems. Indeed, it is possible to measure the relative distances between two antennas through the Time-of-Flight of the signal. This kind of equipment can reach up to centimetre level precision [17]. The positioning measure allows to determine the relative height of the fin with respect to the fork (Figure 2). Concerning the retrieval and extraction of the USV, the scissor mechanism is controlled by a classical PID algorithm, whose target is the vertical distance between the fork and the midpoint of the fin e_{fin} (see Figure 2). This choice is driven by the need of accounting for external disturbances, since the midpoint allows a certain safety range while the USV changes its altitude.

4. Numerical results and conclusions

This section discusses the results of the numerical simulation performed to analyse the reliability of the control algorithm through the successful alignment of the vehicles first and the probability of successful recovery of the USV soon after. The simulated situation considers the mother ship following a straight trajectory, whose direction is defined by $\psi_{MS} = 180°$, at constant speed of 0.5 knots. At the initial instant, the USV is located at a distance larger than 40 m from the mother ship with direction $\psi_{USV} = 0$. Figure 4 shows the results of the alignment phase on the left-hand side. It is possible to distinguish on one hand the red reference trajectory of the mother ship and on the other hand (i) the dashed reference trajectory, (ii) the black real trajectory, and (iii) the USV measurement estimate.

On the right-hand side of Figure 4, the probability of recovery success is shown. A statistical investigation of the recovery manoeuvre, in multibody environment, has been carried out for different sea and wind conditions, together with the scissor mechanism.

The multibody analysis consists of two steps: (i) in the first, both vehicles are controlled by FLOP control logic to perform the approach manoeuvre, allowing errors due to misalignment to be compensated for; (ii) in the second, pitch, roll, and heave dynamics for both vehicles are also considered to test the hooking phase.

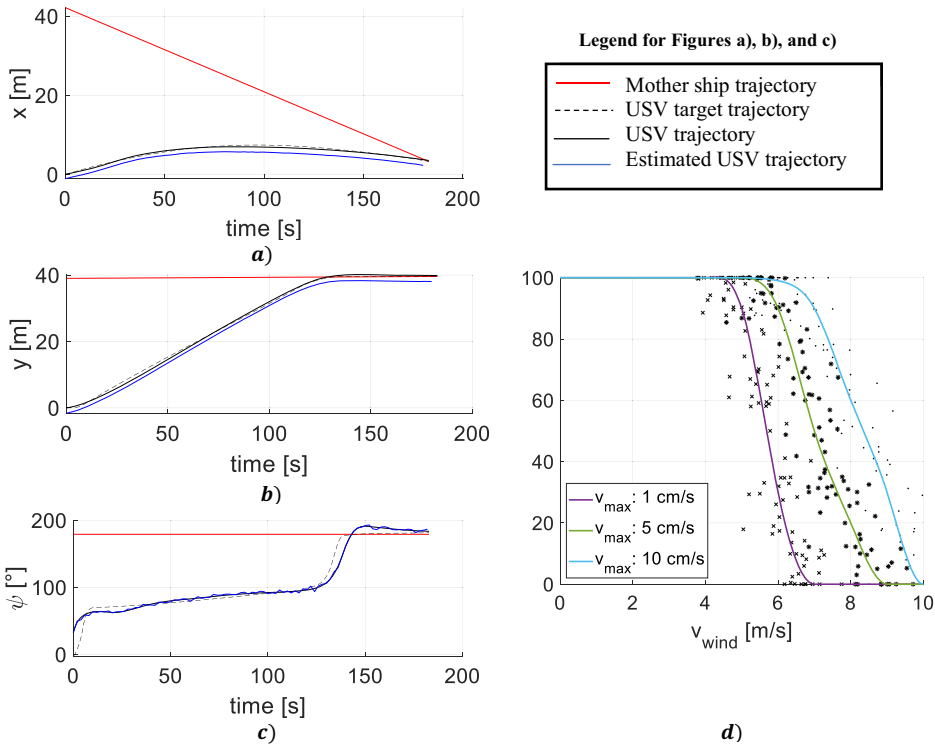

Figure 4. Trajectories performed by the USV and mother ship during the alignment phase: **a**) along x axis, **b**) y axis and **c**) yaw angle ψ; **d**) Success probability of the recovery phase of the USV.

The success of the manoeuvre depends on two main factors: (i) the capability of the mothership to successfully track its reference trajectory and consequently update the USV in the event of drift or changing course; (ii) the ability of the USV to appropriately reach the variable rendezvous point P_t in any sea conditions.

The probability is calculated by setting different maximum speeds of the scissor's actuator. Once all the dynamic characteristics have been established, it is possible to study the probability of hooking as a function of environmental disturbances. In the carried out prototypical simulation a guaranteed ability to success has been found until a wind speed of 5 m/s, which corresponds to a sea level 3 of Beaufort scale. After this threshold, the rate of success lowers down to zero for sea level 5. These results confirm the reliability and the robustness of the LARS thanks to the on-purposely designed control architecture and the mechatronic arm design.

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