

Form 1-Y
Application Form for Research Project (RP) for
Young Academic Staff in FY2027

THEME AND RESEARCH TITLE
Theme (to be related to the maritime field)
Building Resilience in Maritime Transportation
Research Title
Resilient Design and Monitoring of Virtual MOO ring Buoys for Modern Ports Using Digital Twins and Machine Learning
Short Title / Acronym
MOONLINE
Key Words (5)
Virtual mooring; Digital Twin; Finite element modelling; IoT monitoring; Physics-Informed Neural Networks

APPLICANT AND CONTRACTOR	
Applicant	Contractor (Representative of the member institution)
Name: Francesc Turon Position: Assistant Professor Date of birth: 31/01/1992 Member University: Facultat de Nàutica de Barcelona (FNB-UPC) Phone: 650360041 E-mail: francesc.turon@upc.edu	Name: [TO BE COMPLETED – Rector/Dean representative] Phone: [TO BE COMPLETED] E-mail: [TO BE COMPLETED] Signature: _____ Date and place: Barcelona, [DATE]

BACKGROUND (~600 words)
Climate change is reshaping the global ocean environment at an accelerating pace. Rising sea surface temperatures, increasing atmospheric moisture, and shifting storm track patterns are driving a measurable intensification of extreme marine weather events worldwide. The Intergovernmental Panel on Climate Change (IPCC) has consistently reported increases in the frequency and severity of coastal hazards, including storm surges, extreme wave conditions, and compound precipitation-flooding events, across all ocean basins. These trends pose a growing threat to coastal infrastructure, maritime operations, and the communities that depend on them, demanding a fundamental reassessment of how port systems are designed, monitored, and managed. The Mediterranean basin is one of the regions most exposed to these changes. Studies consistently show that the Mediterranean is warming approximately 20% faster than the global average (MedECC, Inform MAR1), with sea surface temperatures rising and storm systems intensifying as a result. Cold-drop atmospheric systems (DANA), fuelled by warmer seas and higher atmospheric moisture content, are producing increasingly frequent and severe storm events across the basin. The vulnerability of Mediterranean port infrastructure to these extremes is already well documented: mooring systems, navigational aids, and harbour operations across the region have been repeatedly disrupted by conditions that exceed the design assumptions under which existing infrastructure was built. Traditional mooring buoys are among the most vulnerable systems, since under extreme conditions they can be displaced uncontrollably outside their designated signalling range. Furthermore, as they are

anchored to the seabed by a chain that drags and sweeps across the bottom during storms, they can completely destroy sensitive marine habitats. As an alternative, **virtual mooring** is gaining traction as a more resilient solution. Its configuration, based on a two-body system, a submerged buoy placed mid-water and connected to the seabed anchor keeps the chain permanently tensioned and lifted off the bottom, while a surface buoy provides the navigational function, which significantly reduces the **swinging circle radius** compared to conventional designs. In addition, since **no part of the chain ever contacts the seabed**, this approach offers a major environmental advantage in areas where high ecological value ecosystems are found.

The current regulatory framework for mooring buoy design, including IALA G1066 Ed.2, is based on simplified analytical formulations that were not originally developed to capture the **complex dynamics of two-body configurations**. More advanced finite element and hydrodynamic models have been developed for offshore mooring systems but have not been extended to virtual mooring buoys in port environments. At the same time, a set of complementary technologies offers promising but largely unexplored approaches for this application: IMU-based (Inertial Measurement Unit) monitoring can provide high-precision kinematic data from floating bodies in operational conditions; Physics-Informed Neural Networks (PINNs) allow model calibration by embedding physical laws directly into data-driven learning; and Digital Twin frameworks enable real-time prediction and decision support by continuously updating a virtual model with live real-world data. The integration of these three methodologies into a unified framework for virtual mooring systems represents a clear gap in the current state of the art.

The Port of Barcelona, already active in climate adaptation strategies, sits at the centre of the exposed Catalan coastline, where wave storm statistics confirm that the frequency and severity of extreme wave conditions are increasing. It also hosts a highly sensitive seabed ecosystem, including *Posidonia oceanica* of significant ecological value, making it an ideal real-world testbed for developing and validating the proposed methodologies under genuine operational conditions. This project directly addresses the identified technical gaps, driven by the documented and growing vulnerability and the urgent need for smarter, more resilient port navigational systems. The relevance of this work is further evidenced by the letter of support from the Port of Barcelona and the letter of interest from IALA, both attached to this proposal.

RESEARCH OBJECTIVES (~250 words)

The aim of **MOONLINE** project is to develop an integrate **numerical, experimental, and digital framework for the resilient design, real-time monitoring**, and predictive management of virtual mooring buoy systems in modern port environments. To pursuit this main objective the following specific research objectives are defined:

O1. To develop and validate a finite element numerical model for two-body virtual mooring systems: This model will be capable of simulating dynamic buoy position and mooring structural response under extreme environmental metocean conditions, including scenarios consistent with climate change projections.

O2. To establish a reliable monitoring system on a two-body virtual mooring buoy: The objective is to acquire and process high-quality kinematic data from an instrumented buoy using an IMU sensor suite over representative long periods of time under a wide range of weather conditions.

O3. To calibrate and refine the finite element numerical model: The acquired experimental data from the monitoring system together with concurrent meteorological records will be used to feed a Physics-Informed Neural Network (PINN).

O4. To implement a Digital Twin of the two-body virtual buoy on the OSI4IOT platform: To integrate the calibrated numerical model with real-time meteorological inputs to provide live visualization of position and structural health state of the buoy, while also enabling rapid parametric design assessments under alternative mooring configurations and projected environmental scenarios.

O5. To formulate technical recommendations for the development of IALA Guideline: To gather in a technical report specifying the engineering requirements of virtual mooring systems under changing environmental conditions.

METHODOLOGY AND DESCRIPTION OF WORK (~1,000 words)

The project is structured into four work packages (WP): three technical WPs and one dedicated to dissemination. The technical WPs are sequential but overlapping, ensuring continuous feedback between modelling, experimentation, and digital integration.

WP1 – Finite Element Numerical Model (Months 1–9)

This WP establishes the computational core of the project. A finite element (FE) numerical model will be developed specifically for two-body virtual mooring systems, consisting of a submerged body, whose purpose is to pre-tension the catenary chain and stabilise the system, and a surface buoy used as a navigational aid. The model will accept as input a complete metocean state: wave spectrum (height, period, direction), current velocity profile, and wind speed and direction. The mooring system geometry and material properties (chain length, diameter, weight per unit length, stiffness) will also be configurable as input parameters. The model outputs will include the dynamic position of the buoy in all six degrees of freedom, catenary tension distribution along the mooring lines, and swinging circle radius under the applied conditions. Advanced hydrodynamic coupling between the two bodies will be accounted for through potential flow theory combined with Morison-type drag formulations. Environmental scenarios will include both present-day operational conditions and projected future extreme events consistent with climate change projections. The model will be implemented using FE and hydrodynamic codes and validated against published benchmark cases prior to experimental calibration.

WP2 – Experimental Monitoring Campaign (Months 3–12)

This WP focuses on the acquisition of high-quality kinematic data from a real buoy system operating in Port of Barcelona, in direct coordination with the port authority. An IMU will be deployed on the buoy, recording rotations in all three axes (roll, pitch, yaw), linear accelerations, compass heading, and GPS position at high sampling frequency over a campaign of nine months. This multi-month duration is deliberately designed to capture a diverse range of meteorological and sea state conditions (from calm operating days to storm events) ensuring the representativeness of the dataset for model calibration and validation. Raw IMU data will be processed together with GPS observations to produce precise estimates of the buoy's kinematic state (position, velocity, orientation) with high temporal resolution and reduced measurement noise. Concurrent meteorological and oceanographic records, wave buoy data from public meteorological service, port anemometric stations, surface current meters, will be compiled in coordination with Port of Barcelona to provide the environmental inputs to the numerical model.

WP3 – Digital Twin Development (Months 7–13)

This WP integrates the outputs of WP1 and WP2 into a unified predictive Digital Twin framework, developed in two phases. In the first phase, the experimental kinematic data from WP2 and the corresponding meteorological records will be used to train a Physics-Informed Neural Network (PINN). The trained PINN will be used to calibrate and refine the numerical model from WP1, correcting modelling assumptions and improving predictive accuracy. In the second phase, the calibrated numerical model will be deployed as the engine of a Digital Twin built on the open-source OSI4IOT platform. This Digital Twin will ingest real-time meteorological inputs automatically retrieved from operational data services providing continuous live visualization of: buoy dynamic position, catenary tension distribution, estimated swinging circle radius, and safety margin indicators using the corrected numerical model. A key feature is its virtual design testing capability: port operators and engineers will be able to modify mooring configuration parameters (chain geometry, length, material) within the platform and immediately evaluate the predicted performance of alternative designs under both current and projected future climate scenarios, enabling informed decision-making without physical trials.

WP4 – Dissemination (Months 1–13)

Dissemination activities run throughout the project. The coordinator will present an *interim report at the Annual General Assembly 27**. A technical report consolidating the project findings will be submitted to IALA as a contribution to the development of Guideline G1066 Edition 3, specifically addressing the engineering requirements and design tools for virtual mooring systems. A *progress report** will be submitted to the IAMU Secretariat by March 2028, and a *final research report** by May 2028. The research team will also prepare a manuscript for submission to a peer-reviewed journal by the end of the project period (eg: Ocean Engineering or Applied Ocean Research).

*mandatory

EXPECTED IMPACT AND DELIVERABLES (~400 words)

This project is expected to generate significant and lasting impacts across scientific, technical, regulatory, and institutional dimensions.

Scientific and methodological impact: The project will produce a validated finite element model specifically developed for two-body virtual mooring buoy systems in port environments, filling a critical gap in the existing literature. The application of enriched Kalman filtering to buoy kinematic monitoring and the use of PINNs for physics-consistent model calibration represent methodological advances in marine structural dynamics. These contributions will be shared with the international scientific community through a manuscript submitted to a peer-reviewed journal (target: Ocean Engineering, ISSN 0029-8018, or Applied Ocean Research, ISSN 0141-1187).

Operational and industry impact: The Digital Twin developed on the OSI4IOT platform will provide Port of Barcelona with a practical, real-time decision-support tool for the management and maintenance of their virtual mooring buoy systems. The virtual design testing capability will enable port engineers to evaluate mooring configuration alternatives, including those optimised for projected future metocean conditions, without costly physical trials, directly contributing to improved operational safety and cost efficiency.

Regulatory and international impact: In close collaboration with IALA, the technical findings will be synthesised into structured recommendations for Edition 3 of IALA Guideline G1066, addressing the engineering requirements of virtual mooring systems under changing environmental conditions. This positions the project to have a direct and tangible influence on international standards for aids to navigation, with implications for port operators, maritime authorities, and navigational aid manufacturers worldwide.

Contribution to IAMU objectives: The project directly addresses IAMU Theme 3: Building Resilience in Maritime Transportation, by generating tools and knowledge that enhance the safety, reliability, and adaptability of port infrastructure under increasingly challenging environmental conditions, as exemplified by the documented and accelerating vulnerability of the western Mediterranean coast. It contributes to IAMU's core mission of advancing maritime research with global relevance and real-world applicability.

Deliverables summary:

- (1) Validated finite element numerical model for two-body virtual mooring systems.
- (2) High-quality experimental kinematic dataset from Port of Barcelona buoy monitoring campaign.
- (3) PINN-calibrated numerical model and associated training methodology.
- (4) Operational Digital Twin deployed on OSI4IOT with real-time visualisation and virtual design testing.
- (5) Technical recommendations report for IALA G1066 Edition 3.
- (6) Interim report presentation at AGA27 (October 2027, Philippines).
- (7) Progress report (March 2028) and Final research report (May 2028).
- (8) Peer-reviewed journal manuscript submitted the end of 2028.

COORDINATOR

Coordinator Information

Name: **Aquí Fermin Otero o Francesc Turon?**
Position: Lecturer (Professor Lector)
Member University: Facultat de Nàutica de Barcelona (FNB-UPC)
E-mail: [TO BE COMPLETED]

Short CV (max. 200 words):

RESEARCH PARTNERS

No formal research partners from other IAMU member universities are included in this proposal.

Project collaborators (same institution, FNB-UPC):

- Fermin Otero
- Rafael Pacheco

Note: The Port of Barcelona participates as an external institutional collaborator, providing access to the instrumented buoy, operational meteorological data, and validation support throughout the project. IALA has expressed interest in the project outcomes and is expected to provide a letter of support.

ATTACHMENTS

The following documents are attached to this application:

1. List of academic achievements by the coordinator in the field related to the proposed research.
2. Research schedule – Gantt Chart (May 2027 – May 2028), including task distribution and milestones.
3. Budget – Form 2-Y.
4. Letter of interest and collaboration from Port de Barcelona [TODO]
5. Letter of interest from IALA [TODO]

*Note: If submitting all application-related files in PDF format, please also provide the MS Word / Excel files for administrative processing.
No signature is required on those MS Word / Excel files.*