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EMPOWERING THE BLUE ECONOMY THROUGH INNOVATION AND TECHNOLOGY

ABOUT US

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OPENING

SCIENCE & SOCIETY

This is the sixth issue of the journal "INESC TEC Ciência e Sociedade", which was created with the aim of reaching a broader audience than the specialized scientific community capable of reading the scientific articles that we publish regularly, an audience that includes managers, politicians and technicians from entities involved in activities in the areas addressed, as well as, in general, all those interested in scientific topics. We intend, above all, to contribute to a society that is more informed and receptive and aware of what is being done in Portugal.

This number six is entirely dedicated to the economy of the sea, commonly known as the blue economy, which assumes the utmost importance at a time of great attention devoted to climate change.

Once again, the authors are researchers from INESC TEC and external personalities that we invited to ensure a more comprehensive view of the subject.

The structure of this edition is different from previous issues, something necessary to address the wide range of topics covered, with the multidisciplinary vision with which we want to approach the main theme – enabling the blue economy through innovation and technology. Thus, the articles were divided into five major themes: feeling the sea, research and innovation infrastructure, fighting ocean pollution, sea resources, and technology for the sea.

The magazine is distributed online, in PDF format, as well as on a platform that we have been improving, which allows more user-friendly access from mobile terminals. The full PDF version, obviously in a format close to analogue, offers a quality that we have not yet been able to achieve in article-by-article access, and that is why a new platform in being developed.

It only remains for me to thank all those who contributed, highlighting the work carried out by the Editorial Board and the Communication Service of INESC TEC, and, in particular, the team of editors for the subject of this issue and all the authors.

We sincerely hope that the result is to your liking.

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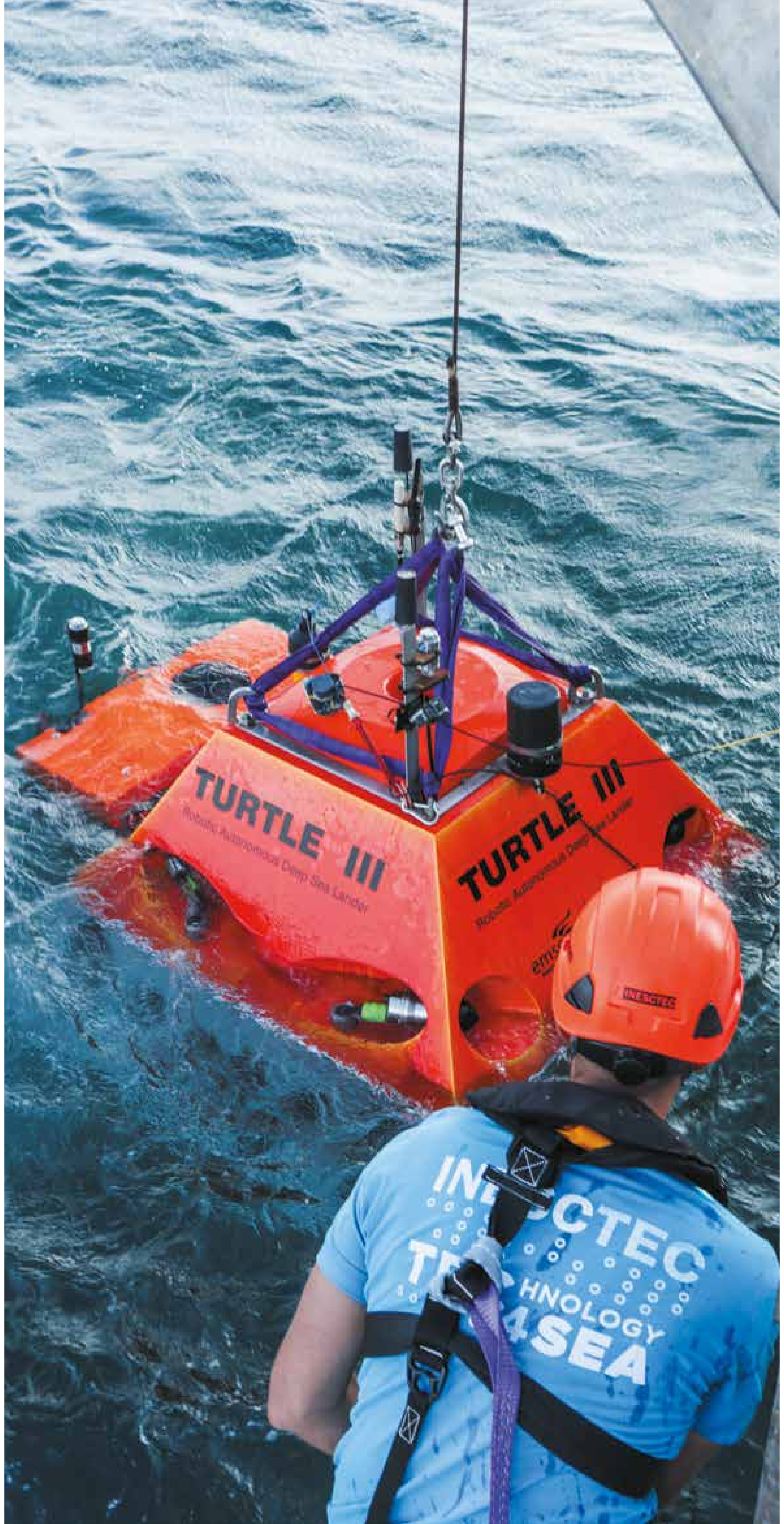
EDITORIAL



EMPOWERING THE BLUE ECONOMY THROUGH **INNOVATION AND TECHNOLOGY**

The importance of our Oceans is widely acknowledged; not only in terms of economic activities but also in supporting life on our planet. Quantifying and valuing all activities associated with or supported by the ocean is quite complex. Some estimates indicate that the gross direct valuation of global marine production is at $2.5 trillion per year, and the global assets associated with the Ocean at $24 trillion.

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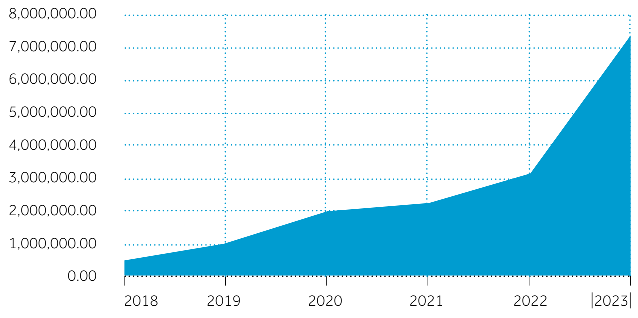
SEA ACTIVITIES HIGHLIGHTS

# National Projects	**59**
# Intern. Projects	**45**
Budget execution	**16,4 m EUR**
EU patent applications	**13**
Non-EU patent applications	**36**
Other protection mechanisms	**5**

EXECUTION OF BLUE ECONOMY PROJECTS AT INESC TEC
(last 6 years)



In our perspective, the following two vectors play a fundamental role in the Blue Economy:

• industries whose main activities depend directly and/or indirectly on the ocean – such as maritime transport, fishing, offshore energy, marine biotechnology, etc., as well as those that complement those value chains, providing services and materials to the formers;

• the natural assets and the ecosystem services that the ocean provides, like fish, algae, shipping routes, CO2 absorption, natural landscapes, etc.

These vectors are intrinsically interconnected, as many aspects of the ecosystem services have strong implications for the performance and growth of sectors belonging to the Blue Economy.

In terms of future performance, we can predict several driving forces that influence the corresponding economic sectors associated with the Blue Economy, with three of them playing a significant role:

A . world population growth;
B. the predominant lifestyle in developed countries serving as role model for underdeveloped countries;
C. geopolitics changes and a multipolar word.

A. WORLD POPULATION

World population growth pushes for several other demands. The continuous growth of the world's population and the increasing intensity of the impact of human activities have exposed the finite capacity of the ocean to "accommodate and mitigate" the damage caused. On the other hand, the importance of the ocean health in valuing the associated industrial activities, has also been uncovered. The continuous migration towards the coastline, with unprecedent coastal developments, creates an extra pressure on coastal ecosystems, influencing the growth of ocean industries.

The limit of ocean resources:
Food supply: even before 2030 at least another 1 billion people will need to be fed, considerably increasing the demand for food. Relying on current methods will not be a solution as Ocean's health is increasingly affected by the cumulative sources of pollution on land, namely contamination by agricultural fertilisers and micro-plastics that are constantly transported by rivers. To environmentally balance this expected increase in protein demand, marine based sources shall increase more significantly than land-based ones. This production shift towards the Ocean harsh environment will demand for new and increasingly intelligent autonomous systems and sensors.

Energy demand: the increase in the world's population will certainly push for increased energy consumption, as well as other blue economy sectors: maritime cargo and passenger traffic; shipbuilding; offshore platforms and maritime infrastructures; among others. Additionally, if the increase in the demand for goods and energy leads to an increase in the demand for mineral products - considering that no alternative materials to those currently used are found -, or if the capacity for extraction on land is exhausted, extraction in the sea floor is being considered as the next alternative.

While the energy transition initially had a negative impact on the marine equipment manufacturing industries and on the industrialisation of autonomous systems (due to the downturn in offshore oil and gas exploration), it is an essential element to advance the implementation of oceanic renewable energies, as well as to the development of algae biofuels based on multi-trophic aquaculture. Offshore renewable energy (wind, solar, waves and tides) will likely continue to grow, reducing production and operating costs, becoming more resilient to oil price fluctuations, and strongly contributing to an increase in the energy market.

Figure 2 **Photo credits: Alfredo Martins**

B. PREDOMINANT LIFESTYLE

An important constraint for the Blue Economy is the impact of human activity on the Ocean, where pollution begins to threaten the habitats of marine life, fish stocks, molluscs, etc. - which, combined with climate changes and overfishing, limits the capacity of the ocean to recover from the low stocks of living resources. The international community has been taking measures to protect stocks of the main species with relevant commercial value. Consequently, the numbers of authorised wild fish caught is likely to remain stable until 2030, pushing for a significant expansion of aquaculture, especially marine aquaculture, to supply the increasing demand for marine-sourced proteins. This increase will bring new challenges, mainly due to the necessary mitigation of the environmental impact of aquaculture and the intense search for available sites with suitable conditions to accommodate the new investments. Furthermore, climate change and the gradual change in the acidity of the ocean, combined with the greater frequency and severity of climate and oceanic events, will limit the quality and location for marine living resources. Long-, short-term and mission-oriented solutions to collect data, monitor, support the development/improvement of models and prediction of a multitude of oceanic events shall be developed and shall play a crucial role in the future.

C. GEOPOLITICS CHANGES AND SOVEREIGNTY

The geopolitical developments towards this multipolar world, creating international tensions and conflicts is another major driving force. Sovereignty will increasingly be imposed to protect the territory, and the resources, and to ensure that value chains are not affected, either by accidents (man-made or nature) or by illegal or irregular actions. In the case of Portugal, national sovereignty in the maritime environment will move to another level with the (expected) extension of the continental shelf. New technologies and new systems,

Figure 3 Photo credits: Carlos Almeida

cheaper, autonomous, and potentially disposable (or easily reproduced within national installations) will be fundamental for the exercise of sovereignty in a new robotic, electronic, and digitalised world.

INESC TEC'S CONTRIBUTION TO THE BLUE ECONOMY

The extensive importance of the Oceans was perceived by INESC TEC several years ago, when the institution embraced different challenges, implying different areas of knowledge and targeting different sectors of activity.

Since then, the activity has been growing and plays a significant role in the institution's activity and overall budget. The following figure presents the last half a dozen years of execution of R&D projects for different Blue Economy sectors, demonstrating INESC TEC R&D+I commitment to Blue Economy.

In addition to the more traditional sectors such as fishing, aquaculture, ports, and maritime transport, INESC TEC has been strongly contributing to increase the knowledge and developing competencies in emerging sectors such as:

- ocean renewable energies;
- technologies for ocean biotechnology;
- marine robotics;
- sustainable use of ocean natural resources (living and non-living);
- environmental monitoring and ecosystem protection;
- deep-sea R&D and education.

These emerging sectors have an enormous potential; and although they may take time to gain relevance in the global economic framework, they must be addressed immediately. INESC TEC's contribution is based on a holistic approach that tries to address different social challenges through the combination of development vectors and their interaction with i) different industries, ii) the ecosystem services, and iii) climate changes. Said challenges, which we aim to address through our R&D competencies, are dominated by five social forces, and can transform and stimulate ocean industries - which, associated with the universal urgency to preserve the health of the oceans, are the driving force behind

Figure 4 Photo credits: Carlos Almeida

our R&D&I. These societal forces, with the same level of urgency, will have a different kind of impact, at different periods. Nonetheless, preserving the value of ecosystem services has, by nature, a more structural effect.

The main social forces are:

1. Contribute to preserve the value of the ecosystem services (challenge - Protect the environment and territory, maintaining territorial integrity, and preserve the value chains of the various ocean industries. Contribute unequivocally to the "Health of the Oceans");

2. Address the increased demand for proteins (challenge - External pressures on ocean industries that contribute to protein production will pose two related sub challenges: a) how to keep the per capita consumption of fish in the world at values that are accessible to the general population; and b) how to increase the value produced by the fisheries and aquaculture industries).

3 Contribute to change the profile of energy vectors extracted from the ocean (challenge - Consolidate world's capacity to: a) produce energy from renewable sources; b) develop technologies and strengthen the supply chains to produce energy from renewable sources [wind, solar, waves and tides].

4. Contribute with solutions to increase our knowledge on the ocean, from its interaction with the atmosphere to the deep sea (challenge - Develop a wide and thorough understanding of the ocean and its phenomena to the point they can be mapped in digital solutions; b) develop technological solutions that help to identify, assess/monitor living and non-living resources important for improving human health conditions and support a sustainable progress);

5. Change the Maritime transport profile (challenge - How ports accommodate: a) the profile change of goods; b) the reconfiguration of maritime transport; c) the transformation process of energy vectors in the maritime transport)

Since 2018, INESC TEC has been involved in more than 100 development projects for the blue economy sectors, accounting for more than €16M. Along this journey, made side by side with national and international industrial partners, associations, academic institutions, and other R&D centres, more than 45 patent applications have been submitted, demonstrating the institution drive towards the scientific, economic, and social impact.

CHAPTER 1

SENSING THE OCEANS

Photo credits: Alfredo Martins

The sustainable economic growth is compatible with a robust public health system, evenly distributed leisure activities among the population, the minimisation of severe natural events like tsunamis, and the monitoring and anticipation of climate change impacts. Achieving these objectives depends on to real-time monitoring and data collection capacities, with highly reliable forecasts models to support decision-making in various areas.

FOUR-MONTHS OF CONTINUOUS OPERATION **EMSO-ERIC IBERIAN MARGIN NODE**

EMSO-ERIC is a distributed infrastructure of deep marine observatories that aims to promote long-term observation of marine environmental processes, including the interactions between the geosphere, biosphere, and hydrosphere - preferably in real time.

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Figure 1 Photo credits: Hugo Ferreira

The Atlantic dimension of Portugal led to the prioritisation of the European Multidisciplinary Seafloor and Water Column Observatory – Portugal (EMSO-PT) in the national scientific infrastructures' roadmap. EMSO-PT is a research consortium that brings together 15 research institutions, aiming at implementing a network of multidisciplinary underwater observatories located along the Atlantic coast, laboratories, and data processing support infrastructures. The goal of EMSO-PT is to generate continuous scientific data on marine environmental processes related to the interaction between the geosphere, biosphere, and hydrosphere and to develop new sensors and platforms which will extend ocean monitoring national capabilities soon. Monitored parameters include biotic and abiotic variables of the ocean floor and water column, namely temperature, salinity, turbidity, acoustics, currents, dissolved oxygen, and carbon dioxide. EMSO-PT is part of a larger European scale effort and corresponds to the Portuguese counterpart of the European Multidisciplinary Seafloor and Water Column Observatory – European Research Infrastructure Consortiums (EMSO-ERIC). The EMSO-ERIC channels and at the "we are Atlantic" digital platform (Silveira et al, 2022) also focus on disseminating data that enable the integration and dissemination of data acquired by all partners of EMSO-ERIC, and by the research community at large. A combination between fixed observatories and autonomous vehicles is also foreseen to extend regular Eulerian observations to major water masses that interact with the different Portuguese Atlantic territories (Carapuço et al., 2022). In this work, we present four-months of continuous operation of EMSO-ERIC Iberian Margin node carried out within the scope of the EMSO-PT initiative.

SCOPE AND ROLE OF EMSO-ERIC

EMSO-ERIC is a distributed infrastructure of deep marine observatories that aims to promote long-term observation of marine environmental processes, including the interactions between the geosphere, biosphere, and hydrosphere - preferably in real time. This infrastructure is organised as an ERIC, constituted on September 29, 2016, with headquarters in Rome (Italy), and bringing together seven member states: Italy, Spain, France, Norway, Romany, Greece, and Portugal.

This infrastructure itself is designed as a distributed set of ocean observation resources located in key places for the study of marine processes, in the Arctic, Atlantic, Mediterranean and Black Sea. EMSO-ERIC aims to be the deep marine component of COPERNICUS and coordinates its activity with similar initiatives in Japan (DONET - Dense Oceanfloor Network System for Earthquakes and Tsunamis) and Canada (Ocean Networks Canada's).

SEAFLOOR AND WATER-COLUMN OBSERVATION IN THEPORTUGUESE MARGIN

Portuguese teams have participated in early EMSO-ERIC initiatives, but with a small role, namely through the incorporation of seismic sensors and biological collectors, in cooperation with Italy (in Iberia) and France (in Azores). The EMSO-PT aims at developing new instrumentation for seafloor and water column sampling, deploying observatories on the seafloor, installing capacities for laboratory analysis and disseminating relevant datasets for ocean monitoring. This integrated approach has the advantage of fostering cooperation between marine engineering research

ADCP

WATER COLUMN PROFILER

EGIM

Figure 1. Recovery of the deployed moorings in the EMSO-ERIC Iberian Margin node. (Photo credits: IPMA)

groups and the oceanographic community, whilst ensuring long term sustainability - both from the technological and the scientific point of view.

The first deploy of a deep seafloor station close to SW Iberia (3207m depth, at 36.3646°N, 9.4814°W) was done between August 2007 and August 2008, under the NEAREST - NEAR shore sourcES of Tsunami project: Towards an early warning system. A GEOSTAR - GEophysical and Oceanographic STation for Abyssal Research platform (Favali et al., 2006) was equipped with a bottom pressure sensor, an accelerometer CMG-5T and a broad-band Guralp seismometer CMG-40T, aiming at acquiring data for Tsunami Early Warning purposes. A second mission took place on November 10, 2009, close to the same location. A near real-time communication system was successfully tested, with the automatic issuing of periodic messages containing a summary of the data acquired by the GEOSTAR observatory from the sea floor to the land station via satellite link. Nevertheless, the buoy mooring remained a vulnerable part of the communication chain (Miranda et al., 2015).

After 2021, the EGIM - EMSO Generic Instrument Module (Lantéri et al., 2017) was taken as the basis for the re-occupation of the Iberian Margin node, ensuring a wider range of sensors and parameters. EGIM payload includes sensors to measure conductivity and temperature (SeaBird SBE37), dissolved oxygen (optical DO - Aanderaa 4381dw), absolute pressure (RBRquartz3 BPR), turbidity (WETLabs ECO FNLTU), passive acoustics (OceanSonics icListen HF SC60) and acoustics doppler current profiler (ADCP) (Teledyne RDI 300 kHz Workhorse Monitor direct-reading).

DEPLOYMENT AND OPERATION

The oceanographic campaign "EMSO-PT leg 2" took place between May 31 and June, 1, 2022. The main goal was the installation of three moorings SW of Cape São Vicente (36.8455°N, 8.9271°W), western Gulf of Cadiz: the EGIM, a vertical wave-powered water column profiler (Wirewalker), and a subsurface ADCP. A short documentary about the EMSO-PT oceanographic campaign is available on IPMA's YouTube channel. The EGIM was installed in a subsurface mooring, suspended 200 m deep, approximately 15 m from the bottom. It was configured with a low-resolution acquisition rate, dependent on the sensor. The conductivity, temperature, turbidity, and dissolved oxygen sensors collect one (1) sample every 15 minutes. The absolute pressure sensor was set to observe at a higher frequency, recording twenty (20) consecutive 1 Hz samples every 2 minutes. The hydrophone (passive acoustics), records one (1) 1-minute audio file every 5 minutes at a rate of 128 kS/s. The EGIM ADCP was set to observe 3 m bins with 120 samples per hour. The Wirewalker was programmed to provide high resolution (2 Hz) and high temporal density (5-6 profiles/hour) vertical profiles of temperature, salinity, Chla, turbidity and dissolved oxygen from the near surface to 150 m depth, complemented by an upward facing ADCP, installed at 150 m depth (Rautenbach et al., 2023).

The three moorings were recovered on October 6, 2022 (Figure 1). Data collected were made freely available through the Centre of Marine Sciences (CCMAR) – ERDDAP: Easier accesses to scientific data (https://erddap.ccmar.ualg.pt/erddap/index.html).

The four-months of continuous operation of EMSO-ERIC Iberian Margin node generated the data displayed in figure 2.

CONCLUSIONS AND FUTURE WORK

The four-month of continuous operation of the Iberian Margin node of EMSO-ERIC is an important step towards a continuous operation on the long term. A second EGIM is being acquired by IPMA (and a vertical water column profiler). In the near future, there will always be an equipment on the seafloor while the redundant instrument will be serviced onshore. It also focus on complementing the existing sensors, to allow the monitoring of carbon intake in the ocean. The described operation was fundamental to test the conditions in which the EMSO-PT ocean observation network will be established in the future for long-term monitoring. The number of resources involved in systematic and continued ocean observation demands such assessment, to evaluate local environmental conditions, catch instrument failures and define optimum sensor configuration and layout.

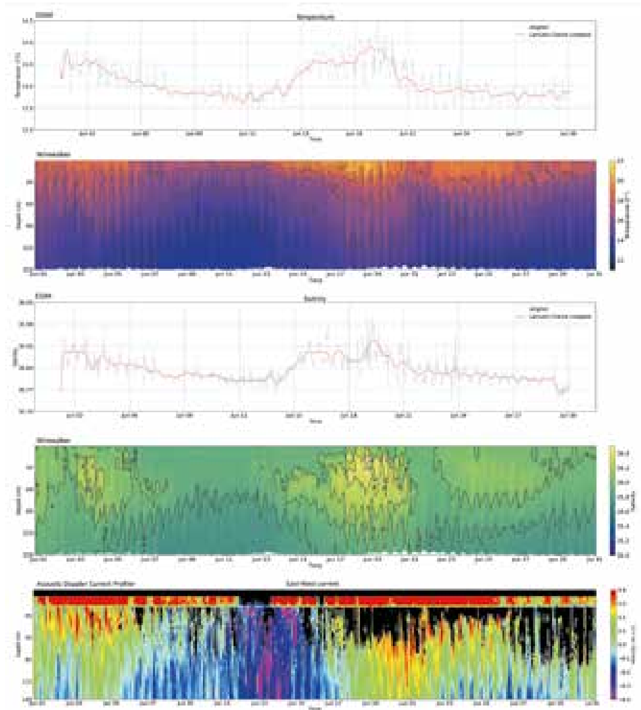

Figure 2. Temperature, salinity, and velocity data from the four-month operation collected at Iberian Margin node of EMSO-ERIC. (Photo credits: IPMA)

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SAILING TO RESEARCH EARTH'S CLIMATE

The atmosphere is able to conduct electric current due to the presence of ions between the surface and the ionosphere. Where do these ions come from? They are the result of the interaction of ionising radiation with the atoms and molecules present in the atmosphere. This radiation has two main sources: the Earth's surface, through natural radioactivity, and space, through cosmic radiation.

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Figure 1 Photo credits: Mauricio Camilo

In stormy weather situations, with thunder and lightning, we become aware (generally, and rightfully so, with a certain degree of fear) of the presence of electricity in the atmosphere. However, and although we don't always realise it, we are constantly surrounded by an intense electric field, even when the weather is good.

Simply put, we can perceive the Earth system as a pair of charged parallel plates. The upper plate is the ionosphere, the upper layer of the atmosphere (starting at 80km altitude), where solar radiation is powerful enough to ionise atoms and molecules (by removing some of their electrons). Hence, the ionosphere is a good electrical conductor, since it is made up of moving electrons and ions. The lower plate is the Earth itself, which is also conductive. The atmospheric electric field stems from the charge difference between the two plates - corresponding to approximately 250.000 volts.

What keeps these "plates" charged? Thunderstorms and electrical discharges, some of the most intense phenomena in the Earth's atmosphere. Inside a thunderstorm cloud, there are strong upward and downward air currents, and the up/down movement of water and ice particles causes the top of the cloud to hold a significant positive charge, while the lower part of the cloud gets a considerable negative charge. The transfer of charge from the cloud to the ionosphere above, and to the Earth's surface below, charges the plates and creates the Earth's atmospheric electric field.

Since the atmosphere is not a perfect insulator, this electric field generates an electric current that flows between the atmosphere and the Earth's surface in areas remote from thunderstorms, constituting Earth's global electrical circuit. At any given moment, there are close to 1000 active thunderstorms on planet Earth that keep the planet's electric field, even in places far from the thunderstorm areas and in fair weather conditions.

The existence of a continuous electric field in the atmosphere, even in the absence of thunderstorms and electrical discharges, and its global nature, was demonstrated through campaigns measuring the atmospheric electric field aboard the Carnegie vessel. The data obtained on board Carnegie, between 1915 and 1929, showed that the electric field exhibited a diurnal variation, reaching highest values at 19:00 UTC (Coordinated Universal Time, corresponding to the Lisbon time zone). Regardless of the location – the Atlantic Ocean, the Pacific Ocean, or the Indian Ocean – those measurements showed that the maximum value of the electric field always occurred at 19:00, Lisbon time. This meant that the electric field depended on the absolute time on Earth, rather than the local time at the measuring location. Given that the measurements made on board the Carnegie vessel were the ones that allowed us to know that the atmospheric electric field varies systematically throughout the day, regardless of the location, this diurnal variation became known as the "Carnegie curve" (HARRISON, 2013; 2020). This curve is, to this day, used as a reference for the diurnal variation of the global atmospheric electric field. Why? Because there hasn't been any further systematic measurements of the electric field over the ocean at different points around the globe since the epic scientific expeditions of the Carnegie vessel, during the early 20th century. Why not measure the atmospheric electric field on land? The atmospheric electric field exists throughout the planet, and it can be measured anywhere. However, the electric field depends not only on the generators (thunderstorms) that maintain the potential difference between the ionosphere and the surface, but also on the atmospheric conductivity, which varies locally due to several factors - making it difficult to observe in land the planetary component of the electric field.

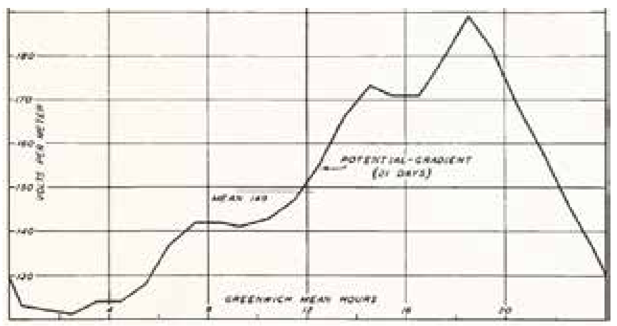

Figure 2 The Carnegie ship under full sail (source: Carnegie Institution of Washington) and example of data collected on board (source: TORRESON, 1946)

to the presence of ions between the surface and the ionosphere. Where do these ions come from? They are the result of the interaction of ionising radiation with the atoms and molecules present in the atmosphere. This radiation has two main sources: the Earth's surface, through natural radioactivity, and space, through cosmic radiation. The radioactive elements that exist on the earth's surface since the formation of the planet cause any soil or rock to emit ionising radiation, resulting from the radioactive decay of these elements; moreover, radon is released into the atmosphere and being a gas it can move in the lower part of the atmosphere (~2 km). This effect of environmental radioactivity occurs primarily over continents and not over the ocean. Ionising radiation reaching Earth from space, beyond the solar system, is the main source of ionisation over the oceans and at high altitudes. While the formation of ions is due to radiation coming from either the earth's surface or space,the removal of ions from the atmosphere is mainly due to aerosols (solid or liquid particles suspended in the air). The concentration of ions depends heavily on the amount and size of aerosols, as ions tend to bind to aerosols, reducing the number of ions or changing their size. Variations in ion concentration cause variations in the electrical resistance of the atmosphere and, consequently, in the atmospheric electric field at a given location.

Therefore, there are many natural and anthropogenic processes that influence the atmospheric electric field, e.g., the amount of radon gas emitted from the earth's surface, sandstorms and snowstorms, volcanic eruptions, or urban pollution. In this sense, ground-based observations of the electric field reflect a wide variety of local contributions. In contrast, observations of the electric field made over the ocean, covering several locations and periods, allow to evaluate the Earth's global atmospheric electrical circuit, which is why the Carnegie curve is still used as a reference of the global electrical circuit - although it is known that the current conditions are different from those existing at the beginning of the 20th century, for a particularly important reason: the climate! Global climate change is expected to influence significantly the global electrical circuit. The increase in the global Earth temperature increases the energy in the atmosphere and the intensity of storms, amplifying the global electrical circuit. Moreover, changes in the number of atmospheric aerosols, due to the intensification of sandstorms and atmospheric pollution, also influence the global electric field. It is particularly difficult to distinguish causes and effects in a complex and interconnected system such as the Earth system; in the case of the global electrical circuit, not only changes in climate alter the global electrical circuit, but changes in the atmospheric electric field have the potential to influence climate - for instance, by influencing aerosol production and cloud formation. Hence, it is of utmost scientific importance for climate and climate change studies to measure the atmospheric electric field in the ocean over time, and in various locations. Obtaining

Figure 3 The sagres under full sail (Photo credits: Mauricio Camilo)

data on the current state of the Earth's atmospheric electric field is crucial since existing measurements date back to the early 20th and the Carnegie expeditions

The opportunity to address this gap appeared with the Portuguese programme commemorating the 500th anniversary of the first circumnavigation of the Earth, carried out between 1519 and 1522 by the Portuguese explorer Fernão de Magalhães,. The celebrations included, among other events, a circumnavigation trip of the Portuguese navy vessel NRP Sagres - which, besides the usual naval, diplomatic, and training missions, would also serve, for the first time, as a platform for scientific projects on board. This raised the opportunity to measure the atmospheric electric field at sea for the first time in the 21st century - 100 years after the Carnegie expedition -leading to the establishment of the SAIL - Space-Atmosphere-Ocean Interactions in the marine boundary Layer project, in partnership with the Portuguese navy.

A curious fact is the reason for the 100-year interval between the first measurements of the global electric circuit aboard the Carnegie, and the modern measurements aboard the Sagres. Given the scientific relevance of the global electrical circuit, in particular its importance in terms of climate change, it is somewhat surprising that the scientific community still uses data from the beginning of the last century, and that a programme of systematic monitoring of the atmospheric electric field has not been implemented. This issue haunted the early stages of development of the SAIL project. Was it because of the lack of a ship? One of the main objectives of the Carnegie campaigns was the measurement of the Earth's magnetic field; hence, the Carnegie was a wooden vessel specifically designed with non-magnetic materials to minimise potential interferences in the measurements of the geomagnetic field. Sagres, on the other hand, is an iron-hulled vessel, equipped with a diesel engine and sails. Perhaps even more concerning: Sagres features the usual instrumentation found on a modern ship in terms of radars, navigation systems, and communications... would it be possible to measure the electric field under these conditions, which are so different - in terms of radiation spectrum - compared to those of the Carnegie? When posing the question to several international experts in the atmospheric electric field, the answer was surprisingly unanimous and encouraging... despite the differences pointed out between Sagres and the Carnegie, it would be worth measuring the electric field on board! Hence, the planning activities of the SAIL project continued with

Figure 4 INESC TEC's instruments on board Sagres (Photo credits: Mauricio Camilo, Carlos Almeida e Guilherme Amaral)

increased spirit and much enthusiasm and support from the international scientific community. However, the doubt persisted... why only 100 years later? Especially since there aren't significant "technical" barriers?

The reasons are, after all, much more prosaic than the ship's structure or electronic interference. One of the current difficulties is the time available to execute a scientific project, which is usually three to four years at most. During this period, one is supposed to plan the experiments, perform them, and publish the results. And part of this period is used to raise funding to support the continuity of the work after the end of the project - which is often not achieved, making it impossible to perform long-term measurements. It seems difficult to justify allocating taxpayers' money to something that has already been measured, and it is much more appealing to ask for funding for something new, rather than a work of continuity. The painstaking work of acquiring data over time is less likely to be funded and to attract recognition. In comparison, the Carnegie was built in 1909 and carried out six scientific expeditions between 1909 and 1921. After the ship's equipment was renovated, it went on a seventh and final expedition between 1928 and 1929, meticulously acquiring data over a period of more than 20 years. Data from the last expedition were only published in 1946 (TORRESON, 1946) and are still in use today.

Another reason is the increasing scientific specialisation and compartmentalisation of knowledge into different domains. While it is true that multi/inter/transdisciplinarity are highly valued today, they are also increasingly difficult because of the ultra-specialisation of scientific practice in progressively narrow and specific areas. Since the atmospheric electric field is such a comprehensive phenomenon in terms of the physical processes involved, from space beyond the solar system to the surface of the earth, and directly related to scientific areas as diverse as the ionosphere, composition of the atmosphere, aerosols, environmental radioactivity, climate, etc., it becomes difficult to gather all the scientific competencies necessary to address the topic in an integrated way. In Carnegie 's time, the distinction between different scientific themes was much more subtle and often one person was proficient in several areas, allowing one to approach a subject like the atmospheric electric field in a more holistic way. The specialisation is not only translated into the scientific knowledge itself, but also into the infrastructure used. Since the electric field is a phenomenon traditionally more connected to the atmosphere than to the sea, resorting to vessels for atmospheric studies is not... obvious. Particularly given how difficult - and expensive - it is to use ships for oceanographic studies - let alone atmospheric and less conventional studies. Despite not being an insurmountable obstacle, it does not facilitate the implementation of a monitoring programme for the marine boundary layer (the part of the atmosphere influenced by the ocean), despite its clear importance, as the majority of the Earth's atmosphere is, in fact, maritime.

Finally, the main reason why there were no new measurements of the atmospheric electric field at sea until 2020, in addition to the reasons already pointed out, is that such endeavour requires an extraordinary collaborative effort. The idea for the SAIL project came up in 2019, and the circumnavigation trip would start in January 2020, so the entire project had to be planned and implemented in less than a year. The existence of a tight and unavoidable deadline led to exceptional human and institutional efforts to carry out what seemed like an impossible mission. In record time, an integrated monitoring system was installed on board Sagres, together with the development of a specific software to collect all the data. An extraordinarily committed team from INESC TEC Centre for Robotics and Autonomous Systems (CRAS) worked day and night to ensure that on January 5, 2020, Sagres set off from Lisbon to measure the atmospheric electric field (and atmospheric visibility, and environmental radioactivity, and solar radiation, and ion concentration). This was only possible thanks to the unusually close and unrivalled collaboration of the Portuguese Navy, which put Sagres at the service of science, by fully supporting the project. In addition to hosting the scientific instrumentation, Sagres also welcomed INESC TEC researchers, who participated in several stages of the circumnavigation trip - just as Carnegie had a scientific team on board. The entire Sagres crew supported the project, integrating the researchers into the ship's affairs, sharing navy traditions (for example, when crossing the equator), and doing everything in their power to ensure the success of the scientific mission.

Sagres' trip, initially planned to last 371 days, came to an unexpected end, as did Carnegie's last expedition. In November 1929 an explosion during Carnegie's fuel supply in Apia (Samoa) sank the ship and killed its iconic captain, James Ault (PAUL, 1932). Sagres' fate was less tragic, but also abrupt and unexpected. Due to the COVID-19 epidemic, the ship was forced to stop the circumnavigation trip, and in March 2020, the vessel sailed from South Africa to Lisbon, instead of sailing to the Indian Ocean - having arrived in Lisbon in early May 2020. Despite the setback caused by the pandemic, the on-board monitoring system has remained operational to this day, collecting about 10 GB of data per day, for over more than three years - an amount and quality of data unthinkable in Carnegie's times! And the expectation is that - as in the case of Carnegie - Sagres' scientific legacy, which is now beginning to take its first steps (BARBOSA et al, 2022; 2023), will endure for a long time.

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CHAPTER 2

Photo credits: Hugo Ferreira

RESEARCH AND INNOVATION INFRASTRUCTURES

The development of complementary and properly equipped infrastructures, capable of supporting the various stages of development, the testing and validation of new solutions and ocean engineering technologies is the only way to address future challenges. The energy and environmental transition, pushed by the expansion into offshore environments, are two domains already demanding for new solutions that will only be achievable with the support of these infrastructures.

A MARITIME TECHNOLOGY AND BLUE INNOVATION ECOSYSTEM IN THE NORTHERN REGION OF THE COUNTRY

The quality of innovation is tested and demonstrated in the pre-commercial phase. Technological innovation in the maritime sector requires properly equipped testing and experimentation zones to meet the needs of companies, R&D centres, and/or anyone seeking to test new technologies for/in the ocean. The Northern region, between Porto, Matosinhos, and Viana do Castelo, concentrates a set of testing and trial infrastructures with the potential to attract tech experts who can benefit from the natural assets — marine and wind conditions — mobilising the existing knowledge potential in various areas e.g., polymers, materials, robotics, computer science, and marine biology.

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Figure 1 Photo credits: Alfredo Martins

THE SEA AND THE NEW WAVE OF DEEP INNOVATION

The new European Innovation Agenda[1] sets an ambitious goal for the European Union: to lead the new wave of deep innovation, capable of presenting transformative solutions to address the challenges of digital transformation, decarbonisation, and circularity of the economy in favour of a more sustainable development model. To achieve this, it is necessary to combine scientific knowledge, technological development, and business capacity. Access to innovation infrastructures, the existence of testing and experimentation conditions, the ability to support and accelerate new startups, attract investment and endeavours are crucial conditions that need to be wisely combined to achieve the best possible results and address the different challenges posed by the demand for goods and services in the international market - in a sustainable manner.

The Sea is a strategic domain for Europe, and innovation in the maritime sector is a fundamental vector for achieving the goal of the New European Innovation Agenda. This path of innovation in the maritime sector has inspired strategies for smart specialisation at the national level (ENEI) and regional level (EREI).

In Portugal, the National Strategy for Smart Specialisation (ENEI)[2] features the Sea within a broad domain referred to as "Great Natural Resources - Sea, Forest, and Space" and highlights the potential of "Transformative Activities" related to "New Technologies for Ocean Exploration", including blue biotechnology, and "Smart Navigation and Logistics."

This article refers to the main dynamics and technological and innovation capabilities in the maritime sector, both established and under development in the Northern region of the country; it also focuses on their development potential, and how they can contribute to establishing the North Atlantic region as an international reference in the field of oceanic technologies.

THE SEA, A DOMAIN FOR THE SMART SPECIALISATION AND DEVELOPMENT IN THE NORTHERN REGION

The Northern region of Portugal has long been committed to the maritime sector, based on a vision established in 2007 with the Agenda for the Sea, developed by the Northern Region Coordination and Development Commission) (CCDR-N)[3]. This strategic framework involved the collaboration of various agents in the scientific, technological, and business domains, with a particular focus on the University of Porto, the Polytechnic Institute of Porto, the Catholic University (School of Biotechnology), as well as several interface centres like the Institute for Systems and Computer Engineering, Technology and Science (INESC TEC), the Interdisciplinary Centre of Marine and Environmental Research (CIIMAR), the Institute of Science and

Innovation in Mechanical and Industrial Engineering (INEGI), and Douro, Leixões and Viana do Castelo Port Administration (APDL).

The establishment of Oceano XXI (2009) - an associative entity managing the Sea Cluster (which later took on the current name, Fórum Oceano – Cluster of the Portuguese Sea, headquartered at UPTEC Mar, in Leça da Palmeira) - brought together a range of R&D entities and strengthened the connection between said entities and the business community.

The Cluster favoured the actions of various R&D organisations, higher education institutions, companies, business associations, and local authorities, creating positive contexts for the emergence and development of projects and the establishment of technological infrastructures in the maritime sector, with the support of European funds. The The Northern Regional Program 2007/2013 financed several introductory projects, such as the Leixões Cruise Terminal (the current CIIMAR headquarters), UPTEC Mar, and the Marine Centre in Viana do Castelo, among others. These investments continued within the scope of the period 2014/2020, thanks to the support of various R&D projects - and, more recently, with the creation of the Blue Hub in Leixões, and the Digital Innovation Hub for the blue economy, funded under the Recovery and Resilience Plan (PRR).

These projects and infrastructures, developed along an axis comprising Porto, Matosinhos, and Viana do Castelo, with a focus on areas such as marine renewable energies, blue biotechnology, robotics, materials, and digitalisation, showcase a significant potential for collaboration among themselves, and with other platforms and institutions operating in the region and the country: CEIIA, the University of Minho, the Polytechnic Institute of Viana do Castelo, and COLAB B2E, among others. In this sense, the North Atlantic territory is relevant in the wave of innovation in the maritime sector.

The Regional Smart Specialisation Strategy (EREI Norte 21-27)[4] comprehends the domain of specialisation referred to as "Marine Resources and Economy," which includes actions aimed at valuing the region's specific resources - particularly in the areas of marine renewable energies and marine biotechnologies -, leveraging natural assets, existing knowledge, technological capacity, and a solid business foundation.

Regarding marine renewable energies, these strategies cover the development of technologies for the installation and maintenance of offshore wind turbines, anchoring structures, mooring systems, grid connection, and wave energy harnessing. In the field of marine biotechnology, these strategies involve the development of technologies for the sustainable production of marine bioactive compounds for pharmaceutical, nutraceutical, and cosmetic industries, as well as to produce biofuels. Knowledge of marine organisms' diversity, their biochemical processes, and marine ecosystems is essential for these purposes.

The blue economy strategy pursued in the Northern region is also aligned with various national strategic frameworks, such as the Thematic Agenda for Marine Research and Innovation[5] and the National Ocean Strategy (2021-30)[6]. In terms of the Thematic Agenda for Marine Research and Innovation, it focuses on "systems for the production of marine renewable energies suitable for the characteristics of the Portuguese coastline", which should be tested to assess and monitor prototype performance. Regarding the National Ocean Strategy, the plan established for the Northern region aligns with Strategic Objectives OE2 "Promote a circular and sustainable blue economy," OE3 "Decarbonise the economy and promote renewable energies and energy self-sufficiency," and OE7 "Stimulate scientific knowledge, technological development, and blue innovation."

THE ATLANTIC NORTH OF PORTUGAL, A POTENTIALLY ATTRACTIVE LOCATION FOR OCEAN TESTING AND TRIALS

The quality of innovation is tested and demonstrated in the pre-commercial phase. Technological innovation in the maritime sector requires properly equipped testing and experimentation zones to meet the needs of companies, R&D centres, and/or anyone seeking to test new technologies for/in the ocean. The Northern region, between Porto, Matosinhos, and Viana do Castelo, concentrates a set of testing and trial infrastructures with the potential to attract tech experts who can benefit from the natural assets — marine and wind conditions — mobilising the existing knowledge potential in various areas e.g., polymers, materials, robotics, computer science, and marine biology. It also benefits from the existing industrial sector, especially in terms of metalworking, composite materials manufacturing, cable manufacturing, and naval industry, as well as the provision of services and logistics made available by the region's port infrastructures.

Noteworthy infrastructures include the testing and experimentation facilities at the University of Porto (wave tank at the Faculty of Engineering), the Porto School of Engineering (testing tank for underwater robotics), INESC TEC (TEC4SEA)[7], a modular platform for research, testing, and validation of technologies to support sustainable blue economy and human resources training), CIIMAR, as well as the Aguçadoura Companhia da Energia Oceânica SA, Leixões Blue Hub (under development), and the Technological Free Zone in Viana do Castelo (close to kick-off).

Figure 2 Photo credits: Alfredo Martins

The availability of these testing infrastructures ensures, within a reduced territorial area, the adequate conditions to perform tests and trials, covering the full range of Technology Readiness Levels (TRL), from the lowest levels to the pre-commercial level. In this sense, recent dynamics associated with Leixões Blue Hub, Companhia de Energia Oceância, and the announced Technological Free Zone in Viana do Castelo (with the support of local municipalities i.e., Matosinhos, Póvoa de Varzim, and Viana do Castelo), bring new ambition to the region in terms of testing and trials in the maritime sector. We'd like to present some of the features of said infrastructures:

LEIXÕES BLUE HUB[8]

The Leixões Blue Hub (HAL) is a project promoted by a consortium led by INESC TEC, featuring CIIMAR, INEGI, APDL, Fórum Oceano, and the Matosinhos City Council. It is funded by the PRR (Recovery and Resilience Plan) and it aims to establish an infrastructure for testing technologies, products, and systems in the fields of ocean engineering, maritime logistics, and blue biotechnology (blue biobank of the North and scientific diving centre) - within the perimeter or the Leixões port, and featuring the expertise of the various partners. HAL will encompass a diverse range of complementary actions that will address the needs of different sectors within the blue economy, in a wide range of domains, including the following:

- Research and Technological Development in smart energy management systems, renewable energy production at sea, port structures, new propulsion systems for vessels, automation, development of new materials, valorisation of marine bioresources, environmental sustainability, and the incorporation of waste and by-products from maritime industries into new products.

- Prototyping and testing of solutions, by providing a set of equipment and conditions that enable the testing and trials of prototypes developed by the partnership's entities and third parties.

- Innovation and technology transfer, applying innovative solutions to companies, which is crucial to boost competitiveness and strengthen the value chains of the blue economy.

- Provision of technological services, training, and information on financial instruments, both public and private, available to support the blue economy.

- Promotion and support for ideation and business acceleration programmes that contribute to generating new products and services in the areas covered by HAL, adding value and consolidating different sectors of the blue economy.

Figure 3 CEO Substation at the Aguçadoura Test Site – tower to support communications and surveillance. (Photo credits: INESC TEC)

HAL stands out due to a set of features that address the challenges set forth by the PRR, particularly in terms of multidisciplinarity (combining biology and engineering), collaborative approach (involving multiple promoters gathered in a consortium), and vertical integration (encompassing research, technological development, testing, technology validation, innovation, training, and entrepreneurship). HAL is expected to be completed by the end of 2025.

COMPANHIA DE ENERGIAS OCEÂNICAS - AGUÇADOURA TEST ZONE[9]

In 2022, INESC TEC and WAVEC acquired a majority stake in Companhia de Energia Oceânica SA by purchasing a significant percentage of shares previously held by EDP Inovação SA. This acquisition reflects the shared understanding between INESC TEC and WAVEC regarding the transformation of the Aguçadoura infrastructure into a reference test and demonstration centre for ocean technologies at the European level. This infrastructure focuses on renewable energy technologies, as well as underwater robotics, ocean digitalisation, and offshore aquaculture.

The Aguçadoura Test Zone, located in an environment with abundant renewable resources, in proximity to Viana do Castelo and the port of Póvoa de Varzim, features relevant assets. These include associated usage licenses (TUPEM - Permits for Private Use of the National Maritime Space and TRC - Grid Capacity Reservation Title, which enable the connection of devices under test to the power grid), available equipment (electric substation with a 4 MW connection capacity and offshore power cable with a 3.2 MW export capacity), a wealth of oceanographic and oceanic data accumulated over the infrastructure's history - where wave energy technologies such as AWS (2000-2004) and Pelamis (2007-2008) were tested, as well as the floating wind energy technology WindFloat (2011-2016). To these success cases, we can add a promising near future, with the testing of the wave technology CorPower Ocean AB (CPO) scheduled to start during the first semester of 2023 and extend for another six years. This will simultaneously contribute to initiating operations in the infrastructure and placing it on the map of European test facilities.

The Aguçadoura Test Zone can benefit from the development of floating offshore wind power, which is expected to become a reality during this decade - both in terms of commercial projects and innovative technological advancements. This includes the development of 15 MW and 20 MW turbines, the creation of cheaper and more flexible floating platforms in terms of mooring requirements, the integration with other economic activities in the same space (e.g., aquaculture), the development of Artificial Intelligence/Machine Learning (AI/ML) based technologies to support Operations and Maintenance (O&M), and the creation of new dynamic power cables and modular submerged electrical substations.

VIANA DO CASTELO TECHNOLOGICAL FREE ZONE

Within the organisation and operation of the National Electrical System, a Technological Free Zone (TFZ) for offshore and nearshore[10] renewable energies was created in Viana do Castelo. It aims to carry out research, demonstration, and testing activities in a real environment for technologies, processes, products, and services related to electricity production and storage.

The public discussion on the delimitation of the Viana do Castelo TFZ ended recently, and further development of the process is expected. The Viana do Castelo TFZ presents significant potential for synergy with the Aguçadoura Test Zone. It is considered essential that both infrastructures are managed by the same set of entities to leverage said synergies.

CONCLUSION

The ocean represents a relevant domain for the development of the new wave of deep innovation; in this sense, the country, particularly the Northern region, along its coastal stretch between Porto and Viana do Castelo, has the potential to become internationally attractive for testing, technology development, and prototyping activities, as explained above. The points discussed earlier highlight the existing potential, the progress made so far, and the determination of regional stakeholders to work collaboratively and engage in cooperative projects. However, there are certain conditions to fulfil and challenges to overcome to reach this potential, including:

Figure 4 CEO Substation at the Aguçadoura Test Site - transformer and the subsea cable connection point. (Photo credits: INESC TEC)

- The challenge of network governance, strategic and coherent, namely in terms of managing the set of testing infrastructures and support services, to ensure a high-quality service and meet demand.
- The challenge of investment and financing, as some of the infrastructures still require investment - for which financing is not yet secured (as is the case with HAL). It is expected that such financing will be possible with continued support within the framework of the new period of EU funding programming.
- The challenge of developing an innovation ecosystem focusing on marine renewable energies and the blue bioeconomy, particularly regarding the improvement of conditions for hosting, incubating, and accelerating companies that provide technological services.
- The challenge of concerted and strategic international promotion of the set of infrastructures and their capabilities, to attract companies and tech experts and let them test their products, services, and technologies.
- The challenge of attracting public and private capital to support the financing of new companies operating in these areas.
- Finally, but not least, the challenge of training, attracting, and retaining talented and human resources to meet the demand for new skills that these projects will certainly require.

[1] COM (2022) 332 from the EC, 05/07/2022
[2] ENEI 2030, ANI, October 2021
[3] Regional Agenda for the Sea – Action Plan for the Sea, CCDR-N, 2009
[4] S3 Norte 2027, CCDR-N, January 2023
[5] Thematic Agenda for Marine Research and Innovtion, FCT, March 2019
[6] National Ocean Strategy 2021-2030, DGPM, 2020
[7] TEC4SEA, infrastructure created by INESC TEC and CINTAL
[8] Adapted from an application submitted and approved within the scope of the PRR
[9] Adapted from the 2023 Plan and Budget, Companhia de Energias Oceânicas
[10] Decree-law 15/2022, January 14

SHARING RESOURCES
THE CASE FOR OPEN MARITIME TECHNOLOGY INFRASTRUCTURES

Shared resources can include everything from research vessels to ROVs and AUVs, sonar systems, and other specialised equipment. By sharing resources, we can reduce duplication and waste, making the most efficient use of available technology. Overall, creating such capable technological infrastructures, whose resources can be openly used by interested entities can lead to large synergies and lower costs, making it easier and more cost-effective to operate at sea. This, in turn, can foster the growth of the blue economy, as more companies and organisations will be able to develop maritime activities.

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Figure 1 Photo credits: Alfredo Martins

1. INTRODUCTION

With over 70% of the Earth's surface covered by water, the ocean constitutes a vast and largely unexplored frontier, holding untold potential for scientific discovery and innovation. It is also a still dormant source of much needed resources. Exploring the ocean may be one of the most dauting, fascinating and complex tasks that human beings have ever attempted.

The need for systematic ocean exploration and survey is clear and pressing. The ocean is a vast and greatly untapped resource that holds enormous potential, both for economic development and as an environmental protection agent. It is a critical source of food, energy, and minerals, and it plays a vital role in regulating the Earth's climate. Obtaining a better understanding of the ocean's vast resources and its ecological importance will, therefore, help us develop sustainable strategies for managing our planet's natural resources.

However, the ocean's vastness, depth, and complex environment present unique challenges. Exploring the deep sea is an endeavour inevitably associated with extreme and inhospitable conditions, especially those found at great depths. Factors such as crushing pressure, frigid temperatures, and near-total darkness create an environment that is exceptionally challenging and dangerous for humans to navigate. By incorporating advanced automation in deep-sea exploration, we can minimise the exposure of humans to these harsh conditions, significantly reducing the risk of accidents or injuries. Furthermore, automated systems can perform tasks with greater precision, efficiency, and endurance than human operators, which enables the gathering of more accurate data and a better understanding of this realm.

Many of the obstacles involved in ocean exploration can therefore be overcome by using ever more advanced technology. However, developing technology for maritime environments poses its own set of harsh problems and difficulties, which are often insurmountable.

TECHNOLOGICAL CHALLENGES

The technology used for ocean exploration must be durable and resistant to the harsh conditions of the ocean environment. Namely, it must be able to withstand extreme conditions, operate at great depths, survive considerable temperature and salinity changes,

Figure 2 Photo credits: João Martins

Figure 3 Photo credits: INESC TEC

and endure the combined effects of a multitude of corrosion agents. Second, it must be precise and accurate. Not only is the ocean a dynamic and constantly changing environment, but it also presents severe environment-related constraints, a notable one being the omnipresent difficulties of underwater positioning and navigation. Third, it must be versatile and adaptable, as different areas of the ocean require different types of technology. Finally, it imposes high degrees of endurance on the equipment. The vast ocean expanses that require further exploration, and the great depths involved in deep-sea research — with the associated long dive times — impose high levels of on-site endurance to the used platforms and equipment. Operating unassisted for long periods becomes, therefore, a crucial requirement for deep-sea exploration equipment and robotic platforms. The used devices and platforms not only need to function autonomously and efficiently, with minimal need for human intervention or maintenance, but they must do so for extended periods of time.

Naturally, such technology comes with a hefty price tag, making ocean exploration (or use) an expensive endeavour. This cost difficulty is also compounded by the fact that the set of equipment and resources required to operate at sea is vast and eclectic and poses immense logistic challenges. Acquiring such assets and capabilities is expensive for any individual organisation. The harsh and hostile marine environment is also very unforgiving and can take a heavy toll on ships and equipment, with direct implications on maintenance and replacement costs. Additionally, there is a vast amount of expertise involved in maritime operations, which cannot be easily created or transferred. Together, these difficulties pose severe—and often insuperable—hurdles to any economic or scientific agents that might otherwise bring their operations to sea.

THE ROLE OF OPEN INFRASTRUCTURES

One way to mitigate these costs is to create shareable technological infrastructures containing all the necessary skills and resources needed for successful maritime operations, and make them available to any interested entities. By using those resources, facilities, and skill sets, the economic agents will drastically lower their individual operating costs, have the capability to use more advanced scientific equipment and highly skilled personnel than what they themselves possess, and allow their business teams (be it industry or research) a greater focus on their operational goals, rather than on equipment, logistics, and support.

Shared resources can include everything from research vessels to ROVs and AUVs, sonar systems, and other specialised equipment. By sharing resources, we can reduce duplication and waste, making the most efficient use of available technology. Overall, creating such capable technological infrastructures, whose resources can be openly used by interested entities can lead to large synergies and lower costs, making it easier and more cost-effective to operate at sea. This, in turn, can foster the growth of the blue economy, as more companies and organisations will be able to develop maritime activities.

A lateral—but also vital—effect of sharing such resources is that it will lead to a more natural and easier sharing of data and research findings, facilitating collaboration between researchers and promoting scientific discovery. By creating a more accessible and collaborative approach to ocean exploration, we foster the unlocking of the ocean's potential for innovation and discovery, benefiting all of humanity.

THE TEC4SEA INFRASTRUCTURE

One example of a direct answer to the mentioned difficulties is the TEC4SEA Research Infrastructure, founded in Portugal by INESC TEC and CINTAL. It is an open distributed research infrastructure, whose skills, equipment, resources, and facilities can be used by the external academic and industrial communities, to support them in their research, development, and validation of maritime technology. It possesses a set of skills and resources which range from pure conceptual research to field deployment missions, with strong industrial and logistic capacities in the middle tier of prototype production. As such, it constitutes an invaluable asset for the research and industrial communities requiring support for their operations at sea.

Being an innovative scientific infrastructure, and considering the immense impact it may have in the ocean-related scientific and industrial fabrics, its strategic interest has been recognised by the Portuguese agency for science, research and technology (FCT), which led to its inclusion in the National Roadmap of strategic Research Infrastructures. It is certainly an example to be followed.

THE IMPORTANCE OF CREATING **A TECHNOLOGICAL FREE ZONE**

The establishment of TFZ INFANTE D. HENRIQUE was a historic milestone of national pride, and a moment of affirmation of the Armed Forces - and the Navy in particular - in the Innovation sector. Its approval made it possible to operationalise the first national and European experimental and operational testing infrastructure for dual-use technologies and sensors in the maritime environment.

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INTRODUCTION

The Decree-Law No. 67/2021 published in July 30 of 2021, established and defined the regime and governance model for the promotion of tech-based innovation through the creation of Technological Free Zones (TFZ).

According to this decree, TFZ are perceived as "test sites, geographically located, intended for testing of innovative technology, products, services and processes, by their promoters, in a safe manner, with the support and monitoring of the respective competent authorities, namely in terms of testing, provision of information, guidelines and recommendations, corresponding to the concept of regulatory sandbox".

On July 19, 2022, the Navy - together with the Portuguese National Innovation Agency (ANI) - presented the first Technological Free Zone (TFZ) created in Portugal, named INFANTE D. HENRIQUE; the event took place at the Maritime Operational Experimentation Centre (CEOM), in Tróia.

Acting as the testing authority, ANI is responsible for coordinating and managing the TFZ network in Portugal, in liaison with the national regulatory bodies. There are other TFZs under analysis, that ought to be implemented in the short-term; those new TFZs aim to experiment and test projects in areas like Mobility, Fintech, Communications, New Materials, and Environment, among others.

There is also a significant interest in developing and deploying them in the Portuguese archipelagos, which will allow the creation of a national network of TFZs, thus bringing together the regional industrial and academic sectors around the technological acceleration that Portugal requires.

Figure 1 **Photo credits: Marinha**

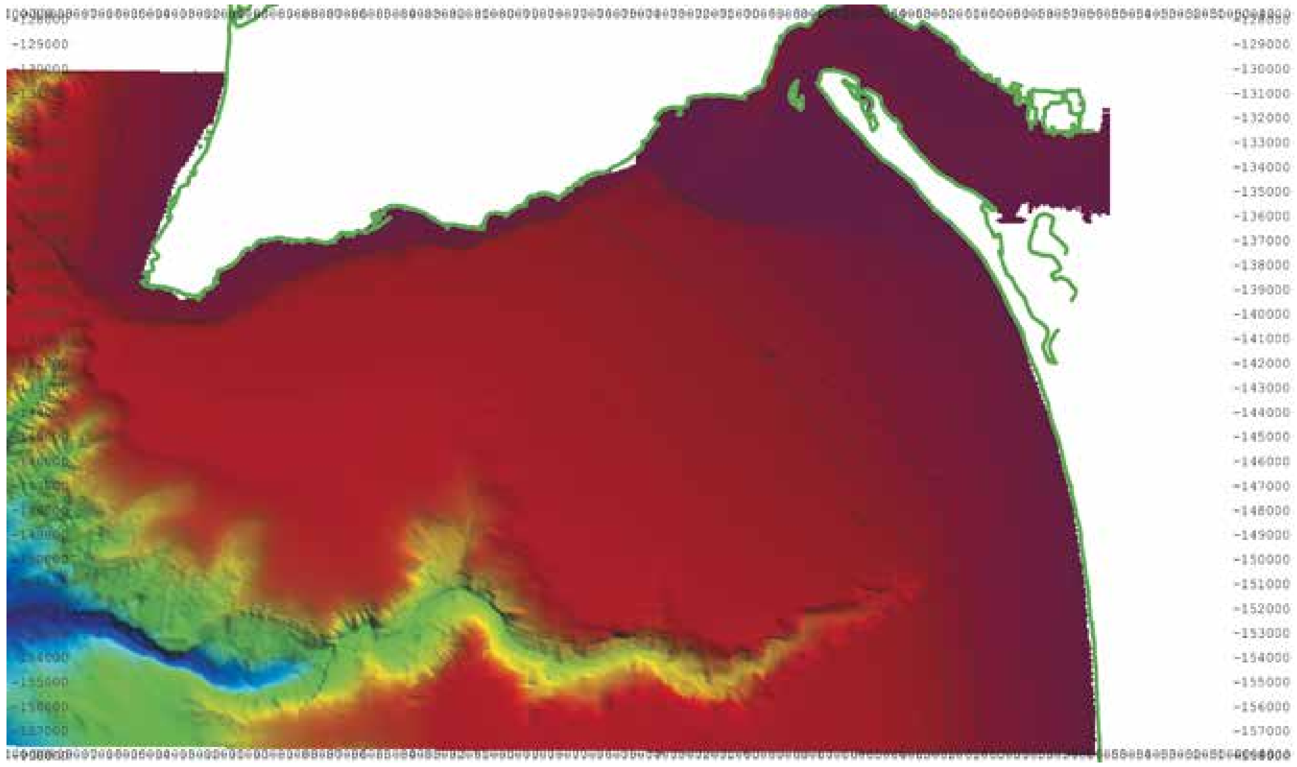

Figure 2 Photo credits: Marinha

Figure 3 Photo credits: Marinha

THE TFZ INFANTE D. HENRIQUE

The TFZ INFANTE D. HENRIQUE occupies an area of more than 1000 square miles (2590 square km), covering the municipalities of Sesimbra, Setúbal and Grândola; it is monitored at CEOM. In order to establish an area dedicated to the experimentation and operational testing of solutions with application on maritime environments - focusing mainly on Security and Defence, but also with dual use applications - the TFZ INFANTE D. HENRIQUE allows open-sea and real-world testing of unmanned security and defence systems, as well as technologies for subsurface, surface (land and water) and aerial environments.

This TFZ follows a regulation established by ordinance 189/22, of July 25. This Regulation stems from the collaborative work with multiple entities, namely the testing authority (ANI), the regulatory bodies (AAN, ANAC and ANACOM) and other stakeholders (DGRM, FAP, ICNF, APA and IdD Portugal Defence).

Due to the geophysical characteristics of this area, where the Setúbal canyon is located, it is also important to highlight that the TFZ INFANTE D. HENRIQUE will provide access to various types of seafloor and deep environments, enabling deep-sea exploration - which will be leveraged with the installation of an artificial island.

Although the sensing of this entire maritime area is not complete, the existence of a digital twin provides access to vast data (big data), meeting the ideal conditions for the safe validation of new applications and the testing of unmanned systems in subsurface, surface, and aerial environments (and associated technologies) at CEOM. In this sense, it will be possible to test these systems before they are implemented at sea, thus reducing the carbon footprint. Moreover, it allows the development of software using historical and real-time data and create simulation tools.

In order to strengthen the national business fabric, this TFZ promotes an effective and active collaboration with the industry, the academia, and end users. In fact, since its creation, dozens of tests have been carried out, alongside innovative experimentation projects featuring emerging and disruptive technologies with application in the maritime environment. We would like to highlight the K2D project, with the participation of INESC TEC and the Robotic Experimentation and Prototyping augmented by Maritime Unmanned Systems exercise, with numerous national and international participants from industry, academia, and the Navy - currently considered the largest NATO experimentation campaign, which featured, in 2022, 26 countries and almost 2000 participants on board vessels and ashore. The characterisation of the activities that can take place at this TFZ are available on the CEOM portal (ceom.marinha.pt) and in the Regulation approved by the aforementioned ordinance.

A BRIEF TALE OF TFZ INFANTE D. HENRIQUE.

After the presentation ceremony of the TFZ applications, which took place on November 30, 2021, in Matosinhos - with the presence, among other entities, of the Minister of Economy, the Secretary of State for the Digital Transition, and the President of ANI - the authors, realising the importance of the project to the country, debated, filled out and submitted the application of TFZ Infante D. Henrique on the ANI portal while driving to Lisbon. That act, somewhere between Aveiro and Leiria, configured the soul of the project that formally began there. In fact, the gathering of entities, the enthusiasm of the team composed of its representatives, and the collaborative work developed, represented a body in constant acceleration that culminated with the formal creation of this TFZ on July 19, 2022.

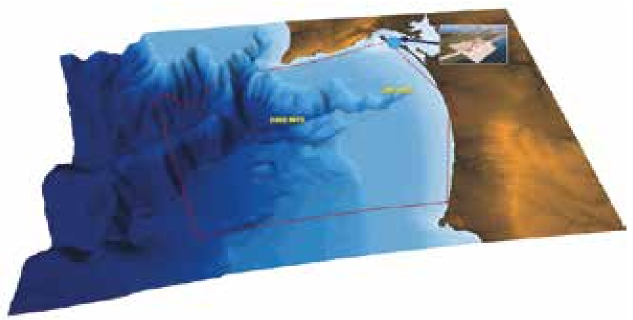

Figure 4 Photo credits: Marinha

CONCLUSION

The establishment of TFZ INFANTE D. HENRIQUE was a historic milestone of national pride, and a moment of affirmation of the Armed Forces - and the Navy in particular - in the Innovation sector.

Its approval made it possible to operationalise the first national and European experimental and operational testing infrastructure for dual-use technologies and sensors in the maritime environment. In this sense, the Navy and all those entities that collaborated - and still collaborate - within the scope of the TFZ take on a leading role in this specific project, focusing on the creation of a technological development accelerator in Portugal, and in Europe.

The creation process, also pioneering, currently encourages the creation of other TFZs in the continental territory and islands, thus favouring the possibility of building a network of infrastructures that, in collaboration, allow access to various TFZs for the design and development of products that use different technologies.

The promotion of this network must bring together industry, academia, and end users, joining efforts to create an innovation-friendly ecosystem, with added value to the country.

CHAPTER

TACKLE WITH SEA POLLUTION

Photo credits: Alfredo Martins

Rising pressure on social organisation leads to the increased probability of large-scale accidents with considerable environmental damage. This pressure emerges from the continuous asymmetric population growth, making the collection, analysis, and production of information on the state of the oceans, land, atmosphere, and their respective dynamic interactions a priority.

TACKLING MARINE LITTER WITH TECHNOLOGY

THE ROLE OF INNOVATION IN ADDRESSING A GLOBAL PROBLEM

Marine litter refers to any human-made solid material that is discarded, disposed of, or abandoned in the marine environment, including plastic, metal, glass, rubber, and other materials. Marine litter is a serious problem with significant environmental, economic, and social impact. It harms marine wildlife, degrades marine ecosystems, and negatively impacts human health.

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Figure 1 Photo credits: Hugo Silva

The world's oceans are facing a growing problem of marine litter, which is affecting marine life and the ecosystems that support them. The problem is so significant that it has been identified as a global issue that requires a coordinated effort from governments, industries, and individuals to mitigate its impact. While many initiatives and programmes have been put in place to address marine litter, can technology play a crucial role in tackling this problem? This article explores the potential of technology in addressing marine litter and the types of technology that can be used.

WHAT IS MARINE LITTER?

Marine litter refers to any human-made solid material that is discarded, disposed of, or abandoned in the marine environment, including plastic, metal, glass, rubber, and other materials. Marine litter is a serious problem with significant environmental, economic, and social impact. It harms marine wildlife, degrades marine ecosystems, and negatively impacts human health.

TYPES OF MARINE LITTER TECHNOLOGIES

There are three types of marine litter technologies that can be used to address the problem: preventing, monitoring, and cleanup technologies.

PREVENTING TECHNOLOGIES

Are an essential aspect of mitigating the problem of marine litter. These technologies primarily focus on reducing the amount of litter produced in the first place, by implementing measures that discourage littering and encourage responsible waste disposal practices. One example of such technologies is smart waste management systems, which use sensors to monitor and optimise waste collection and processing. These systems can help reduce the amount of litter that ends up in our rivers and oceans by ensuring that waste is collected promptly and processed appropriately.

Another approach to prevent marine litter is the use of biodegradable materials. These materials are designed to break down naturally in the marine environment, reducing the impact of litter on marine life and ecosystems. Biodegradable materials can be used in a wide range of applications, from packaging to fishing gear, and they are

SOME FACTS AND FIGURES

- An estimated eight million tons of plastic waste enters the oceans every year. (Source: UN Environment Programme)

- Plastic waste has been found in all parts of the ocean, including the deep sea and remote areas such as the Arctic and Antarctic. (Source: National Geographic)

- Marine litter can harm and kill marine animals, such as sea turtles, whales, and seabirds, through ingestion or entanglement. (Source: Ocean Conservancy)

- Plastic waste can take hundreds of years to break down in the ocean, leading to long-term environmental damage. (Source: National Geographic)

- Marine litter can also have a significant economic impact, such as damage to fisheries and tourism industries. (Source: European Commission)

- It is estimated that by 2050, there will be more plastic in the oceans than fish by weight if current trends continue. (Source: World Economic Forum)

- The cost of the global impact of plastic pollution on marine ecosystems is estimated to be at least $13 billion per year. (Source: The Pew Charitable Trusts)

sustainable alternative to traditional materials that take decades or even centuries to break down.

Technology-based education and awareness campaigns connected to citizen science can also help prevent marine litter. These campaigns can be used to educate people about the impact of litter on the marine environment and encourage responsible waste disposal practices. Citizen science programmes can also involve the public indata collection and monitoring, providing valuable insights into the extent and sources of marine litter.

MONITORING TECHNOLOGIES

Are critical for understanding the extent and sources of marine litter. These technologies provide valuable data on the movement and amount of litter in the ocean, allowing researchers and policymakers to identify patterns and develop targeted strategies for prevention and cleanup.

One of the most promising monitoring technologies is the use of "smart" sensors e.g., radar, hyperspectral cameras, which can be deployed on satellites, drones, and airplanes. These sensors can capture high-resolution images and other data on the location, size, and composition of marine litter. The data can then be processed using artificial intelligence methods and analysed to identify hotspots of litter accumulation and track the movement of debris in the oceans. This information can help researchers and policymakers develop effective strategies to tackle marine litter.

In-situ sensors are another important monitoring technology. These sensors can be installed in buoys or other long-term permanent infrastructures in the oceans, providing real-time data on water quality, temperature, and other environmental factors that can affect the distribution and movement of marine litter. By monitoring these factors, researchers can gain insights into the sources and pathways of marine litter, enabling targeted intervention strategies.

CLEANUP TECHNOLOGIES

Are crucial to remove existing marine litter from the ocean and preventing it from causing further harm to the marine environment. These technologies include a range of tools and strategies, each with its own strengths and limitations.

Figure 2 Marine Litter Accumulation Targets for performing development of monitoring technologies using satellite and drone data at Porto Pim, Azores (Photo credits: Hugo Silva)

Figure 3 Photo credits: Hugo Silva

Figure 4 INESC TEC Drone equipped with hyperspectral camera for detecting marine litter during a mission at Porto Pim, Azores (Photo credits: Hugo Silva)

Autonomous Surface Vehicles (ASVs) are one type of cleanup technology that has gained increasing interest in recent years. These vehicles are equipped with nets or steppers that can collect debris from the surface of the ocean. Some ASVs are also designed to navigate autonomously, allowing them to cover large areas of ocean and collect debris in hard-to-reach locations. ASVs can be especially effective in areas with high concentrations of litter, such as around coastal cities and shipping lanes.

Another type of cleanup technology is barriers, which can be fixed or mobile and placed in waterways to prevent marine litter from reaching the ocean. Fixed barriers are typically installed across rivers or other waterways that flow into the ocean, while mobile barriers can be deployed in areas with high concentrations of litter. These barriers can be effective in preventing litter from entering the ocean, but they require ongoing maintenance and may not be suitable for all locations.

In addition to these technologies, manual cleanup efforts are also critical for removing litter from the ocean. These efforts involve teams of volunteers or paid workers who collect litter from beaches and other coastal areas. While manual cleanup efforts can be time-consuming and labor-intensive, they can be especially effective in removing smaller items of litter and debris.

WHEN, HOW, AND WHERE TECHNOLOGY CAN BE USED

The deployment of technology to address marine litter depends on the specific technology and the location and extent of the litter problem. Some aforementioned technologies are already being used in certain parts of the world, while others are still in development. Governments, non-governmental organisations, and private companies play a role in the development and deploying of technology to address marine litter. Collaboration and coordination between stakeholders will be important to ensure that technology is used effectively to tackle this global problem.

In conclusion, the problem of marine litter is a pressing issue that demands urgent action from governments, industries, and individuals worldwide. The deployment of advanced technology is a critical component in addressing the issue of marine litter. Preventing technologies, monitoring technologies, and cleanup technologies are all viable solutions to mitigate the problem. However, successful implementation of these technologies requires a concerted effort and collaboration between all stakeholders involved. It is imperative that we work together to ensure that technology is harnessed effectively to tackle this global problem and safeguard our oceans and marine life for future generations. Let us act now and take the necessary steps towards a cleaner and healthier marine ecosystem.

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MARINE PLASTIC POLLUTION

WHY IS IT A GLOBAL CONCERN? AND HOW CAN TECHNOLOGY HELP?

Plastic pollution poses significant risks to the marine environment and to the health and wellbeing of both marine life and humans. Several organisms have been harmed by plastic debris, including marine mammals, seabirds, fishes, corals, crustaceans, molluscs, as well as marine plants like macroalgae and seagrass.

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1. CURRENT SITUATION OF PLASTIC AND MICROPLASTIC POLLUTION

Plastic is undoubtedly one of the most significant innovations of the last century. With its exceptional properties such as durability, resistance, and inertness, it has become a widely used material. This associated with its low production costs and versatile nature lead to an unprecedented overuse of plastic, resulting in an alarming amount of plastic waste in our ocean.

Marine plastic pollution has become a global concern in recent years, as the magnitude of the problem has become increasingly clear. Plastic pollution is the accumulation of plastic materials in the natural environment, particularly in the ocean. Plastics do not biodegrade, but rather break down into smaller particles. Nowadays, plastic debris is one of the most significant and long-lasting pollution issues worldwide due to its durability and persistence (Villarrubia-Gómez et al., 2018), being able to last in the environment for hundreds of years. Plastics, namely microplastics (i.e., plastic particles smaller than 5 mm) have become ubiquitous in aquatic environments, and plastic debris is now found in all of the world's regions; it has been documented in remote and previously untouched locations, like the Arctic and Antarctic (Mihai et al 2022). The Great Pacific Garbage Patch (GPGP), situated in the eastern region of the North Pacific Subtropical Gyre,

Figure 1 Photo credits: Alfredo Martins

is one of the areas with the highest levels of oceanic plastics, with approximately 45-129 thousand tonnes of plastic debris floating within an area of 1.6 million km2 in this location (Lebreton et al., 2018).

Inadequate waste management practices, combined with the continuous production of new plastic items, contribute to a constant build-up of plastics in various marine and coastal environments (Ramos et al., 2023). Despite ongoing environmental concerns, society continues to maintain a high demand for plastics. Plastics are widely used in food and drink packaging, medicines, cosmetics, detergents, and other products (Wang et al., 2016; Anjana et al., 2020). Plastic invention dates back to the 19th century (Figure 1), but its massive production began in the 1950s (Velez et al., 2019). It is still supported by a linear economy, which is gradually shifting into a circular economy in some regions of the world. In 2020, it was estimated that between 4.8 million and 12.7 million metric tons of plastic waste entered the ocean annually (Jambeck et al., 2015). Although numerous regulations and initiatives are currently in place to mitigate plastic pollution, it has not yet been possible to significantly reduce plastic litter. Furthermore, the COVID-19 epidemic has caused a recent setback in the progress made on reducing plastic use, with plastic consumption increasing dramatically (Govender et al., 2020).

IMPACTS
OF MARINE DEBRIS

INGESTION
Animals mistakenly eat palstic and other debris

ENTANGLEMENT & GHOSTFISHING
Marine life gets caught and killed in ghost nets, trapped in dereflict gear, and entangled in plastic bands and other marine debris

HABITAT DAMAGE
heavy marine debris crushes sensitive habitat, such as coral reefs and see grass

NON-NATIVE SPECIES
marins debris transports alien and invasive species from one region to another

2. MAIN THREATS OF MARINE PLASTIC POLLUTION

Plastic pollution poses significant risks to the marine environment and to the health and wellbeing of both marine life and humans. Several organisms have been harmed by plastic debris, including marine mammals, seabirds, fishes, corals, crustaceans, molluscs, as well as marine plants like macroalgae and seagrass.

Plastic debris can entangle marine organisms, leading to suffocation, drowning, or other fatal injuries, and cause habitat damage. Plastic waste can also be ingested by marine organisms, which can cause injury or death by blocking their digestive system or causing other internal injuries.

Figure 2 Photo credits: José Oliveira

The main threats posed by marine plastic pollution are numerous and manifold, and they vary according to the type and size of plastic debris. In general, macro-sized marine debris has more lethal impact compared to smaller particles like micro- and nano-sized debris (Ramos et al., 2023). However, in some cases, small debris (nano and micro) can be lethal by restricting also the feeding ability of smaller planktonic organisms like zooplankton and ichthyoplankton (Botterell et al., 2019). Microplastics may also have biological effects at low concentrations, especially for mollusks, crustaceans, and amphibians.

Moreover, the chemicals and pathogens adsorbed to microplastics and nanoplastics can also cause significant noxious effects (Ramos et al., 2023). Smaller ingested debris particles, including micro and nano particles, can indeed have sublethal effects due to plastic-associated chemicals. Hazardous polymers like polyurethanes, polyacrylonitriles, polyvinyl chloride, epoxy resins, and styrene contain mutagenic and carcinogenic monomers. Plastic additives such as phthalates, bisphenol A, and polybrominated diphenyl ethers leach out, affecting reproduction and causing genetic and hormonal imbalances. Plastics can also adsorb metals and persistent organic pollutants (POPs) like polychlorinated biphenyls and polycyclic aromatic hydrocarbons. These POPs act as endocrine disruptors and carcinogens. Microplastics may serve as carriers of hazardous pollutants, which are then released upon ingestion by marine organisms. Microplastics can also transport pathogenic bacteria as well as alien and invasive species from one region to another, thus causing ecological issues.

Also, plastic pollution can impact the food chain, as smaller organisms ingest microplastics, which are then consumed by larger predators. This can lead to the accumulation of plastic particles in the bodies of these organisms, which can ultimately be passed on to humans who consume seafood.

Furthermore, plastic pollution can also influence the health and wellbeing of humans directly. Plastic waste can wash up on beaches, posing a physical hazard to beachgoers and potentially causing injury. It can also affect the aesthetic appeal of coastal areas, leading to reduced tourism and economic impact. Additionally, plastic pollution can have significant economic costs, as it can damage fishing nets, vessels, and other marine infrastructures.

3. SOLUTIONS TO PREVENT AND MITIGATE PLASTIC POLLUTION

Addressing the growing threat of marine plastic pollution requires teamwork within the science-policy-society interface to combine the know-how of the different actors involved, towards successfully solve the marine litter global environmental crisis. Numerous regulations and initiatives are currently in place to mitigate plastic pollution, such as educational and citizen science projects and environmental NGO initiatives, as well as international policies and agreements, resolutions,

Figure 3 Photo credits: Alfredo Martins

and other international instruments, processes, commitments, and treaties that directly or indirectly target marine litter and microplastics (Ramos et al., 2023).

Technological solutions are also being developed and implemented to help tackle plastic pollution. These solutions range from innovative new materials to advanced waste management technologies. One example of an innovative material is biodegradable plastic, which is designed to break down more quickly than traditional plastic, reducing the amount of plastic waste in the environment. In addition to these materials-based solutions, technological advancements in waste management are also being developed to reduce the amount of plastic waste that enters the environment, for example, microplastic capture technologies, which can filter out tiny plastic particles from wastewater before it is discharged into the ocean. Moreover, some countries have implemented extended producer responsibility (EPR) schemes, which require manufacturers to take responsibility for the end-of-life disposal of their products. This encourages manufacturers to design products that are more easily recyclable or compostable, reducing the amount of waste that enters the environment. Other waste management technologies under development include waste-to-energy technologies, which convert plastic waste into energy, reducing the amount of waste at landfills or incinerators.

Although the great majority of marine litter comes from activities that take place on land, sea-based activities also contribute to pollution, though to a lesser extent. The primary sea-based sources of marine litter are aquaculture, fishing, shipping, and offshore oil and gas platforms. In fact, abandoned, lost, or otherwise discarded fishing gear (ALDFG) is a critical item of plastic marine debris (Richardson et al., 2019), responsible for the entanglement and injury of several marine wildlife (Brown and Macfadyen, 2007). There are several initiatives taking place worldwide to recover ALDFG from the oceans and prevent fishing nets from becoming lost. Tagging fishing nets has been presented as a reliable solution to prevent their loss (Balk and Lindem, 2000), with important technological improvements being made in this field. For example, acoustic tagging with transponders technology, as those developed by the EU funded NetTag project is a reliable technological solution to locate, track and recover fishing gears in case of loss.

NetTag project aimed to reduce and prevent marine litter derived from fisheries, bringing together scientists, engineers and the fisheries industry. The project combined two different types of preventive measures:

- new technology to prevent lost gears;
- awareness actions to promote best-practices for on-board waste management

NetTag developed new technologies to track fishing gears in case gears got lost, fostering a reduction of lost gears. The technology included low cost, miniature and environmental-friendly acoustic tags and acoustic transceivers for uniquely localization (with fisher's personal ID) of lost gear and an automated-short-range robotic recovery system. For the later, autonomous underwater vehicle/remotely operated vehicle (AUV/ROV) were adapted to assist in the recovery of the gear. Participant fishers from the NW Iberia Peninsula coast then evaluated the new technology in a dedicated demonstrative field action acknowledging the easiness and usefulness of it.

The project will now have a follow up, the NETTAG+ project, dedicated to develop thre solutions to Prevent, avoid and Mitigate the environmental impacts of fishing gears and associated marine litter. This new project will scale-up the technological solution to locate, track and recover fishing gears in case of loss and expand its applicability to different types of fishing gear and scenarios, namely the Mediterranean Sea. NETTAG+ will also continue to work with the fisheries sector, co-producing activities to promote their role as key-actors to prevent and reduce marine litter. Moreover, NetTag+ will also develop new technology to detect and map ALDFG, facilitating their retrieval and, consequently, reducing their negative impacts.

While technological solutions translate into promising pathways to reducing marine plastic pollution, there are still significant challenges to overcome. One major challenge is the cost of said solutions, which can be unaffordable to some communities and countries. Additionally, the implementation of these technologies requires significant infrastructure and regulatory support, which can be difficult to achieve in many parts of the world.

5. CONCLUSION

In conclusion, marine plastic pollution is a global concern that poses significant risks to both the marine environment and human health and wellbeing. The status of the problem is bleak, with significant amounts of plastic waste entering the ocean each year. However, several mitigation actions are being implemented targeting the responsible use of plastic and improving the circularity of these materials. It is important to stress that preventing plastic pollution is key to solving the current crisis. Additionally, technological solutions offer promising pathways to reducing this pollution, through innovative new materials and advanced waste management technologies. While challenges remain, continuous research and development in this area could lead to a cleaner and healthier future for our planet.

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COMBINING **BIOTECHNOLOGY AND ROBOTICS** TO TACKLE OIL SPILLS

First-line responses typically include physical (e.g., controlled burning; absorbing) and chemical (e.g., dispersing) removal of oil, which is largely constrained by maritime conditions. Though these treatments are important to rapidly control the diffusion and drift of the oil, they are not suitable for ecological restoration.

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Figure 1 Photo credits: Alfredo Martins

Marine oil spills are catastrophic events that lead to high losses of marine life and ecosystems. Oil spill incidents occur regularly during the exploration, production, refining, transport and storage of petroleum and petroleum products. In recent years, several oil spill disasters have occurred, with Deepwater Horizon (2010) being considered one of the largest accidental marine oil spill in the history of the petroleum industry, leading to the spill of over 500.000 tons of crude oil, at the Gulf of México. In the last 50 years, several major spills occurred in the NW Iberian Peninsula, one of the main routes of oil cargo in Europe, because of tanker accidents. In 1975, the oil tanker Jakob Maersk, which was loaded with 80.000 tons of heavy crude oil and 4.000 tons of heavy fuel, hit a sandbank while entering the sea harbour of Leixões (Porto, North of Portugal) and ended up exploding and breaking apart. As a result, around 50.000 tons of oil were consumed by fire, 25.000 tons were drifted at sea and 15.000 tons came to shore. More recently, in 2002, the oil tanker Prestige sank 250 km from the coast of Galicia (North of Spain) spilling more than 60.000 tons of crude oil, polluting thousands of kilometres of coastline and causing great harm to the local fishing industry. This was considered one of the larger environmental disasters in the history of Iberian Peninsula. Jakob Maersk and Prestige cases occupy the 13th and 20th position, respectively, at the ranking of the worldwide major oil spills (ITOF 2015).

The occurrence of such incidents requires immediate, simple, effective, and eco-friendly actions to minimise environmental damages. First-line responses typically include physical (e.g., controlled burning; absorbing) and chemical (e.g., dispersing) removal of oil, which is largely constrained by maritime conditions. Though these treatments are important to rapidly control the diffusion and drift of the oil, they are not suitable for ecological restoration. Recently, bioremediation using microorganisms to degrade the remaining spilled oil,

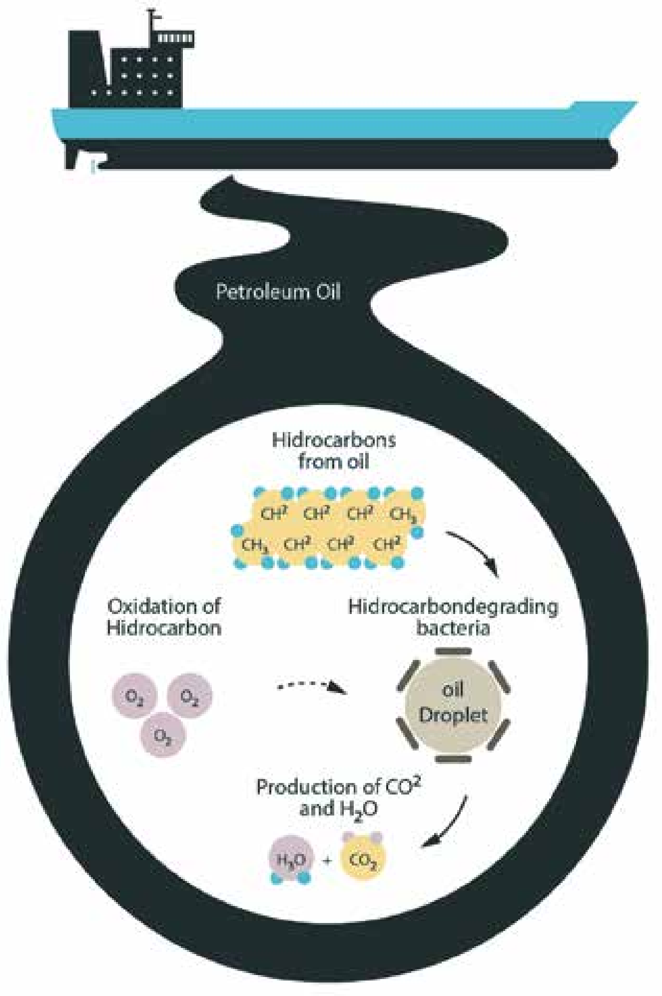

Figure 2 General process of petroleum hydrocarbons biodegradation

Figure 3 Photo credits: Alfredo Martins

has been proposed as a cost-effective alternative to the use of chemical additives. The use of microorganisms with a natural capacity to degrade petroleum is highly advantageous, since it is an environmentally friendly process and allows complete decomposition of complex petroleum hydrocarbons (Fig. 1). The efficient biodegradation of oil spills requires a jointed action of a consortium of microorganisms, i.e., a group of diverse microbial species with a complementary range of metabolic capabilities, rather than the action of individual microbial species.

The success of bioremediation to improve petroleum removal and reduce clean up time and costs, relies on two major approaches: (i) addition of nutrients to stimulate the growth of the microorganisms that break down oil (Biostimulation) and (ii) the addition of pre-grown microbial cultures/consortia to enhance microbial populations (Bioaugmentation). The use of native microorganisms is highly beneficial because they are better adapted to the affected environment, leading to a more efficient degradation of complex hydrocarbons. Plus, this technique avoids the unpredictable ecological impact of introducing non-native organisms into a particular environment.

The natural cooperative partnership in microorganisms is a key element that must be considered when planning to develop bioaugmentation strategies to degrade highly diverse and complex compounds e.g., oil and petroleum products. The efficiency of this strategy has already been demonstrated for crude oil in beach sediments - in microcosm [1] and mesocosm [3] experiments - by CIIMAR researchers, within the scope of the project OILDEBEACH (Buried oil in the intertidal beach zone: coupling between beach morphodynamic, natural degradation, forcing mechanisms and biological activity), this is an FP6 project implemented to address the Prestige oil spill. Recently, within the projects Spilless (First line response to oil spills based on native microorganisms cooperation), ROSM (Robotic Oil Spill Mitigation) and BIOREM (Bioremediation of hydrocarbon pollutants by autochthonous microorganisms in aquatic environment), the researchers from CIIMAR and INESC TEC developed innovative approaches to oil spills mitigation, based on the production of native microbial consortia with bioremediation capacity, and the adaptation of unmanned and autonomous vehicles for in-situ release of autochthonous microorganisms (bioaugmentation) and nutrients (biostimulation). Such innovative solutions aim to:

- be environment-friendly, by using native organisms to naturally degrade oil spills, and avoid the introduction of additional chemical or biological additives;
- integrate first line responses to oil spill incidents, by using unmanned and autonomous vehicles, which are able to operate under unfavourable and harsh conditions with low human intervention;
- set-up holistic pollution combat missions, by jointly combining air, surface and underwater vehicles;
- increase the overall efficiency of the oil spill combat missions, by acting on defined targets and areas;
- provide valuable data, by equipping the vehicles with sensors, which can perform environmental monitoring (before, during and after oil spill combat missions);
- decrease the overall time to reaction and mission costs, by using unmanned and autonomous vehicles, whose deployment is faster and less costly than using boats, planes, or helicopters.

The scientific strategy of these projects included a new concept of georeferenced library of native microbial consortia (Fig. 2), with capacity to degrade petroleum compounds, which could be applied by autonomous vehicles (aerial, surface and underwater) at specific geographic areas. More than 800 hydrocarbon-degrading bacteria were isolated from the NW Iberian Peninsula coast [3], for future use in bioremediation of oil spills in specific geographic areas. These bacteria are cryopreserved in a georeferenced library that is part of the CIIMAR Microbial Culture Collection (CM2C) (Fig.3). Some of said bacteria were already used to optimise the conditions for biomass production, leading to the formulation of a lyophilised microbial product [4] for application in oil spill scenarios. In addition, containers and autonomous release systems [5] were developed for application of bioremediation treatments by aerial, surface and underwater vehicles (Fig. 4). This includes mechanisms to release bacteria and nutrients from three distinct ways: (i) from an unmanned aerial vehicle (UAV), and for rotary wing with high positioning accuracy, to tackle leakages from the surface "inner" areas; (ii) from an autonomous surface vehicle (ASV) to release microbial consortia on the stroke border areas; (iii) from an autonomous underwater vehicle (AUV) / remotely operated vehicle (ROV) to release microbial consortia in the water column and the seabed. Finally, all the vehicles were tested for their operability under different environmental conditions [6].

Figure 4 Hydrocarbon-degrading bacteria isolated from the NW Iberian Peninsula coast and preserved at CIIMAR Microbial Culture Collection (CM2C).

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[5] Dias, A., A. P. Mucha, T. Santos, D. Pedrosa, G. Amaral, H. Ferreira, A. Oliveira, A. Martins, J. Almeida, C. M. Almeida, S. Ramos, C. Magalhães, M. F. Carvalho, and E. Silva. 2019 "ROSM - Robotic Oil Spill Mitigations". In: OCEANS 2019 – Marseille, pp. 1–7. https://doi.org/10.1109/OCEANSE.2019.8867213

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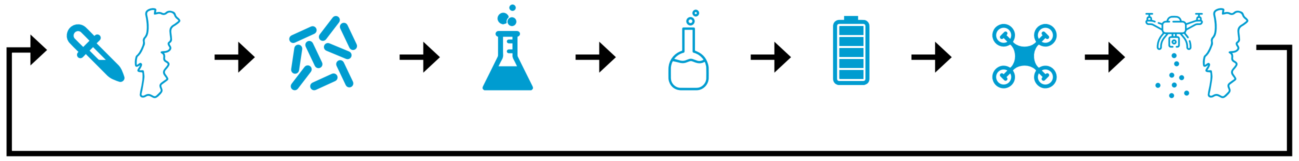

Figure 5 Workflow for the development of georeferenced library of native microbial consortia for bioremediation of oil spills

MARINE RESOURCES

Marine resources are in the critical path for enabling the green transition and the continuous societal development avoiding major disruptions. Developing and gathering knowledge on these living and non-living resources, where they can be found and their conditions for existence, monitoring their status and evolution, their dependence on different environmental factors and interdependence is critical for their protection, utilization and for conscious future decisions that we may have to face.

Photo credits: @Hypersea

RECENT PORTUGUESE TECHNOLOGICAL ADVANCES BENEFITING THE DEEP SEA BIOLOGICAL RESEARCH

Recently the exploitation of deep-sea resources, particularly the mesopelagic species, is gaining interest, as they are perceived as assets with significant potential for the pharmaceutical and food industries. But, despite some research programmes focused on their study, the existing technologies and methodologies are a major drawback, especially in Portugal. To increase the knowledge on deep-sea species, the HiperSea project developed competences and technologies through the construction of a hyperbaric system to capture living specimens in the seabed and the water column at high depths, transferring them to the surface and maintaining them alive in a hyperbaric aquarium.

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Figure 1 The hyperbaric diving chamber being deployed during the sea trials. (Photo credits: Alfredo Martins)

The deep sea and the mesopelagic zone (between 200 and 1000 m deep) in particular comprises more than 60% of the planet's surface and 20% of the ocean's volume, constituting a large part of the total biosphere and still representing an unknown world. Most of the world's fish species live in the mesopelagic zone, both in terms of number and biomass. Moreover, the mesopelagic zone presents a great diversity, with the dominant groups being crustaceans, gelatinous organisms, and cephalopods, in addition to fish. These species are generally small, dark in colour (black or red), have luminescent organs and/or, large eyes and mouths. Recent studies indicate that the globally calculated total mesopelagic fish biomass has been grossly underestimated, possibly by a factor of 10. The new assessment suggests a biomass around 10,000 million tons, roughly equivalent to 100 times the annual catch from the fishery (about 100 million tons).

Although much is known about the mesopelagic and the deep-sea communities and their functioning in marine ecosystems, much remains unknown, especially the role of many species in deep sea carbon sequestration. Advances in knowledge are relatively recent. For example, the discovery of hydrothermal vents and cold vents with unique ecosystems, which was only made in 1971. These hydrothermal ecosystems studies have revolutionised the knowledge of marine biology, by discovering modes of life different from those existing at low depths, and their potential for economic exploitation.

This advance in knowledge is only feasible due to the development of technologies that can take humans to depths where they cannot survive and/or technologies that make it possible to bring specimens from the deep sea and provide a set of conditions to keep them alive at the surface, so that studies and experiments can be carried out. Technologies for studying deep-sea organisms have improved significantly in recent years. Remotely operated vehicles (ROV) or autonomous underwater vehicles (AUV) are equipped with vision systems (cameras and light) and other mechanical systems, that allows them to acquire data, capture specimens, and perform in situ experiments.

A major difficulty preventing studies, on environmental and biological traits, of deep-sea species, is the low hydrostatic pressure at surface, causing that specimens captured at deep sea and brought to the surface usually arrive dead or dying. In this sense, one of the main needs identified was the development of a hyperbaric system with controlled high hydrostatic pressures, capable of simulating the environmental conditions unique to deep sea organisms allowing said experiments.

This need led to the HiperSea hyperbaric system, developed by a multidisciplinary team consisting of biologists from the Portuguese Institute of the Sea and Atmosphere (IPMA) and the Interdisciplinary Center

Figure 2 Photo credits: Alfredo Martins

Figure 3 The Hipersea system. The diving chamber attached to the mesopelagic net. The hyperbaric aquarium and the diving chamber at the bottom of the sea. (Photo credits: @Iris)

for Marine and Environmental Research (CIIMAR), as well as electrotechnical engineers in the field of robotics and autonomous systems from the Institute for Systems and Computers Engineering, Technology and Science (INESC TEC), the Polytechnic of Porto - School of Engineering (ISEP) and by the company A. Silva Matos Metalomecânica, which led the technological development project.

With the objective of capturing deep-sea species and keeping them in good physiological conditions in the laboratory, allowing their reproduction in captivity at the surface, the project proposed to develop a mobile hyperbaric infrastructure. The hyperbaric infrastructure collects the specimens in the deep sea (to 1000 m deep) and transports them to surface, where another hyperbaric chamber mimics (high pressure, low temperature or extremely high, in the case of proximity to active volcanoes, and low luminosity) their habitat. The system developed will allow the survival, maintenance, and reproduction in captivity, at the surface.

The HiperSea hyperbaric mobile chamber, the transfer chamber and the hyperbaric aquarium, developed under the project "HIPERSEA - Hyperbaric System for Collection and Maintenance of Deep Sea Organisms", was built and tested to be used on the bottom of the sea and/or coupled to a mesopelagic trawl, to capture mesopelagic species as well.

We started with the biological requirements and technical specifications that the hyperbaric chambers should have. The planning and construction of the hyperbaric system was carried out at the premises of the company A. Silva Matos Metalomecânica, in Aveiro.

The hyperbaric aquarium (Figure 2) can support a small number (up to six) of medium-sized species (up to 400 g), maintaining a specific pressure, the desired temperature, the adequate physical-chemical parameters of the water (pH, PCO2, PO2 and ammonia) and the control of photoperiod. It also enables the administration of food.

The hyperbaric diving chamber is versatile and can be used to capture deep-sea pelagic and benthic species. When capturing benthic species, the diving chamber acts as a trap on the seabed. When capturing pelagic animals, the system is placed at the end of a mesopelagic trawl. The fabric of the net is luminescent to attract species. The depth at which the net is operated is decided with the help of an acoustic probe.

The entire prototype system was tested at sea on board the NI Mário Ruivo (Figure 1), in the Lisbon and Setúbal canyons, at depths that varied between 40 and 906m. All the captured species were deep-sea crustaceans (Figure 3), using the HiperSea prototype system on the seabed. Organic and luminous baits were tested, the latter using different frequencies and light intensity to attract the species. The mesopelagic trawls we were not so successful to capture species. The crustaceans captured in the two benthic dives were successfully transferred to the HiperSea prototype aquarium and remained very active after the transfer. Later, unexpected problems related to changes in the voltage of the electric current supplied to the prototype led to difficulties in maintaining the temperature of the water inside the chamber, which rose unexpectedly and led to the death of the animals.

After the at sea tests, we verified that the first prototype of the HiperSea hyperbaric system supports depths of up to 1000 m. In fact, we were able to place it on the sea floor at a depth of 906 m, corresponding to a pressure of 92 bar, always maintaining communication with the system and properly monitoring the environmental and biological parameters. Therefore, the tests at sea were extremely positive. Finally, it was also possible to verify the aspects that we can improve, such as the transportation of the system, its format, and the conditions for capturing and maintaining the species. Thus, the survey was crucial to assess the work and technological development carried out and to plan future developments.

The project is now concluded, but the prototype built is still operational. It is now imperative to find a way (research funds and/or opportunities) to pursue this technological development.

More about the project on: https://www.compete2020.gov.pt/noticias/detalhe/Proj33889-HiperSea-NL227-14112019 and https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9706082

More about sea trials: https://www.youtube.com/watch?v=A7gQ3ai9ZlU

Figure 4 The red arrow highlights one of the deep-sea crustaceans inside the diving chamber swimming (Photo credits: @Hypersea). Meganyctiphanes norvegica, one of the crustaceans that was captured and successfully transferred to the hyperbaric aquarium (Photo credits: Antonina dos Santos). A fish photographed approaching the diving chamber. (Photo credits: @Hypersea)

POWER FROM THE SEAS
WHY WIND FARMS WILL TURN INTO MULTI-SOURCE OFFSHORE ENERGY PARKS

It's crucial to explore innovative technology solutions that play a vital role in Europe's offshore energy system of the future. The key requirements for these technologies are (1) an easy integration in the business case of offshore energy operators, (2) the potential for co-location with offshore wind farms, without strong interference on energy yield from either technology, (3) a high technology maturity, to allow an implementation in the near future, during which spatial plans, electrical infrastructure and tenders for offshore energy projects will be designed.

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The European offshore energy system is in the middle of a massive transformation that is driven by the ambitious large-scale targets for offshore wind expansion. In order to ensure a sustainable long-term development of the energy system on- and offshore, it's crucial to foster a continuous innovation. With offshore floating solar and wave energy, the EU SCORES project demonstrates the integration of two innovative offshore energy technologies in offshore wind farms. To this end, the project demonstrates the technical feasibility while addressing key stakeholder challenges and specific scenarios for the large-scale implementation of multi-use energy parks.

THE CHALLENGES OF OFFSHORE WIND

While Europe is moving towards a fully renewable future, a lot of focus and expectations are placed on offshore renewable energies. Rightfully so, since the European seas provide a vast amount of space, as well as highly favourable conditions, especially for wind turbines. With no hills, forests or cities in the way, the wind is not only more powerful but also more predictable and consistent. This makes much larger wind turbines, of 15 and maybe even 20 MW, a possibility over the next years; despite their extreme height, they barely impact people on their everyday lives, due to their remote location, far out at sea.

Over the last years, the first offshore wind projects have reached commercial feasibility and no longer depend on government subsidies to compete with electricity prices on the energy market. These aspects have driven many European countries to commit to increasingly ambitious offshore wind targets, most recently culminating in the Oostende targets. At this meeting, the heads of state from most North Sea countries published a joint target of 120 GW of offshore wind capacity by 2050.

However, this growth does not come without complications. Even in the more stable conditions offshore, wind is still a weather phenomenon, which changes on a daily basis, and according to seasonal patterns. Together with the necessary maintenance of wind turbines, this means that, on average, a wind park will produce at around 50% of its total capacity throughout the year. Consequently, the offshore cables (accounting for 50-60% of the infrastructure costs of these projects) are only used for 50% of their capacity. With innovative technologies, this cable capacity could be used more efficiently and allow a more stable electricity supply, with a much lower additional investment.

At the same time, these patterns in wind availability also affect the stability of the electricity grid and the energy market. With the current target, and by 2050, around 80% of European electricity will come from renewable energy sources. Due to this, prices are expected to reach extremes, especially during periods where only little wind occurs. A more diverse set of energy technologies could reduce these peaks by providing energy even at times when the wind does not blow.

Lastly, it's important to point out that, despite seeming vast, offshore space is also not an unlimited resource. In busier areas, like the North Sea, there are many different activities competing for space: cargo transport, fishery, and offshore energy. With this rapid increase in activities, another crucial aspect is to ensure enough space for nature. With more areas serving for energy production, fully protected Natura 2000 areas are becoming more and more scarce. According to the current plans for wind parks, turbines will be spaced more than 1 km apart, leaving vast room for other activities.

Considering the massive changes over the upcoming years, it seems obvious that all opportunities to minimise these potential effects need to be explored. For governments, stakeholders, and commercial operators alike, it is vital to pursue the most sustainable solutions for the offshore energy system, ecosystem and the limited space available.

OFFSHORE RENEWABLE ENERGY INNOVATIONS

As a key solution to these challenges, it's crucial to explore innovative technology solutions that play a vital role in Europe's offshore energy system of the future. The key requirements for these technologies are (1) an easy integration in the business case of offshore energy operators, (2) the potential for co-location with offshore wind farms, without strong interference on energy yield from either technology, (3) a high technology maturity, to allow an implementation in the near future, during which spatial plans, electrical infrastructure and tenders for offshore energy projects will be designed.

Two innovative energy technologies in development are particularly well suited for these requirements.

Offshore floating solar
Floating solar panels have been operating on large water bodies, such as lakes and reservoirs, for several years. As the cheapest renewable energy source on land with an immense scaling potential, solar energy's extension to water is a logical development for areas with little land space. Not only does this avoid disputes about the often-discussed aesthetics of onshore farms, but the available space in general is much less limited. At the same time, many existing offshore wind farm operators are already familiar with the technology from onshore PV projects. Extensive offshore tests have been pursued by several companies during the last few years. For example, Oceans of Energy from The Netherlands have operated an ever-growing number of offshore floating PV modules in the North Sea since November 2020, surviving serious winter storms. In addition, a few research organisations like SINTEF (Norway) and TNO (the Netherlands) have pursued the development of offshore solar concepts over the last years. These developments have shown that one of the core aspects in the survivability of these structures are the connection points between different modules.

Offshore solar systems are following several different design philosophies, which are primarily distinguished by the materials used for the floaters, as well as the positioning of the panels, relative to the water surface. While some structures are designed to follow the water movement and accept overtopping waves, others are built to have the solar panels high above the sea level.

Wave Energy
Many researchers, as well as energy companies, have pursued the development of machines to extract energy from the movement of waves since the oil crisis in the 1970s. Ocean waves, which are generated by wind blowing over the surface of the sea, can travel for large distances with little to no energy loss. With a theoretical potential of 3700 GW of installed capacity, wave energy presents the largest untapped resource of renewable energy today. Extensive tests over the years of different technology concepts have taken place, for example at the European Marine Energy Centre (EMEC) in Scotland, as well as at the Wave Energy Centre (Wavec) in Portugal. One of the biggest challenges is the engineering of machines which can produce energy economically, while surviving in the harshest offshore conditions.

From many different device concepts, one of the best studied to date are point-absorbers. These are round or hexagonal buoys operating on the water surface or just below it, to follow the surface movement and to operate (ideally) in a state of resonance to maximise the extracted energy. Given the rotational symmetry of these devices, they operate with the same efficiency with waves from all directions, and do not need to be yawed to match the mean wave field. This reduces complexity in the design and control of the device.

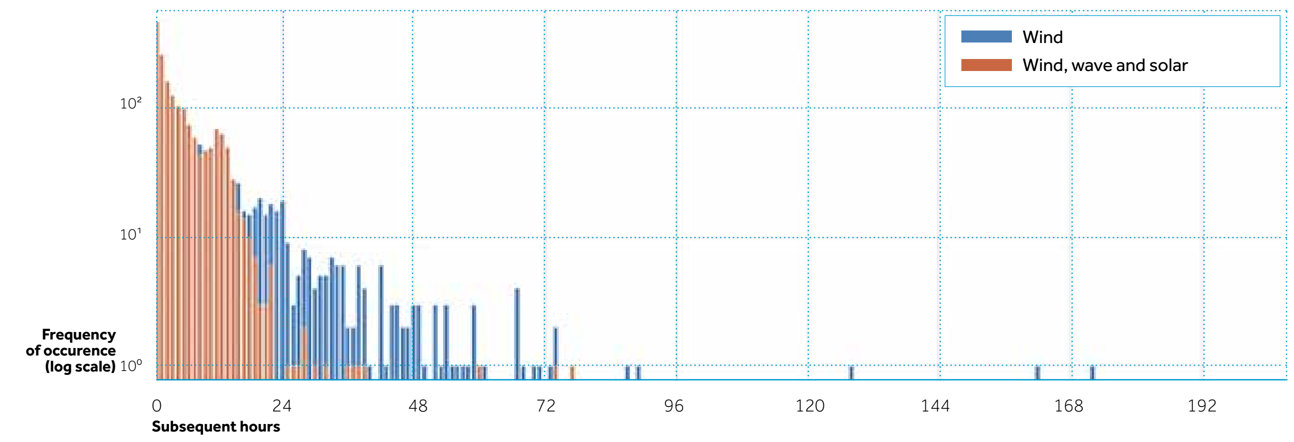
The reference point for these devices to move against is the seafloor. Other concepts are based on multiple floating bodies which move relative to each other and are connected e.g., using hinges.

Given the nature of their potential, as well as associated challenges, offshore floating solar systems are best suited to operate in an environment with a low to moderate wave climate. This will enable technologies to build a strong supply chain and achieve cost reduction before stepping into more challenging waters. Obviously, for wave energy devices, the economics dictate a strong wave climate to maximise power production.

Due to this, and considering their current stage, offshore floating PV is most suited for integration in bottom fixed wind parks in the relatively shallow North Sea. To ensure high availability, these wind parks are often located in areas with a low wave climate, so that maintenance vessels can easily access the turbines.

A high-power production for wave energy devices can especially be achieved if the waves are not exclusively generated by local weather systems. With an exposure to swell from the entire Atlantic Ocean, the Atlantic coast presents an ideal environment for these devices. These areas are, in most cases (for example in Ireland

CONSECUTIVE HOURS WITH OUTPUT BELOW THRESHOLD (=0.2GW)



and Portugal), too deep for bottom fixed wind turbine concepts. Therefore, the most likely integration scenario can be found between floating offshore wind turbines and wave energy devices.

To demonstrate the technical feasibility of wave and offshore solar energy and their integration in offshore wind parks, the EU SCORES project combines two demonstration projects.

At the Belgian coast, close to the harbour of Oostende, a 2.5 MW demonstrator of Oceans of Energy will be installed to operate in the challenging environment of steep waves in shallow water. This demonstration focuses not only on the feasibility of manufacturing, installation and operation of multi-MW offshore floating solar, but also on the integration of an export cable with onshore substations of existing offshore wind farms.

At Aguçadoura (Portugal), a wave array, consisting of three full-scale devices of CorPower Ocean, will be assembled in a mobile manufacturing unit, tested on site and deployed offshore, for a total installed capacity of 1.2 MW. Due to the proximity of the wave array to the Wind Float Atlantic offshore floating wind park, an integration with the power export cable will be implemented.

THE VISION FOR MULTI-SOURCE OFFSHORE ENERGY PARKS

Next to technical feasibility of the technologies, the key aspect of offshore multi-use is an increased power production, as well as an improved power profile. In this context, we'd like to highlight a model of the Dutch offshore wind zone Ten noorden van de Waddeneilanden (North of the Wadden islands) TNVW, which demonstrated the characteristics of a multi-use park.

The model describes potential park designs, based on the available space in the offshore wind park, and according to exclusion zones around wind turbines andmaintenance pathways.

This model shows that the energy density of a floating wind zone double when integrating other technologies. In this configuration, it is possible to raise the nominal capacity of the 750 MW offshore wind park by nearly 150%, with 980 MW of offshore floating solar, and 120 MW wave energy. In a park like this, it's possible to generate around 40% more electricity annually. But, and more importantly, longer periods with a low power output can be reduced drastically. While a pure wind park experiences around 13 events over a 3-year period, in which little to no power.

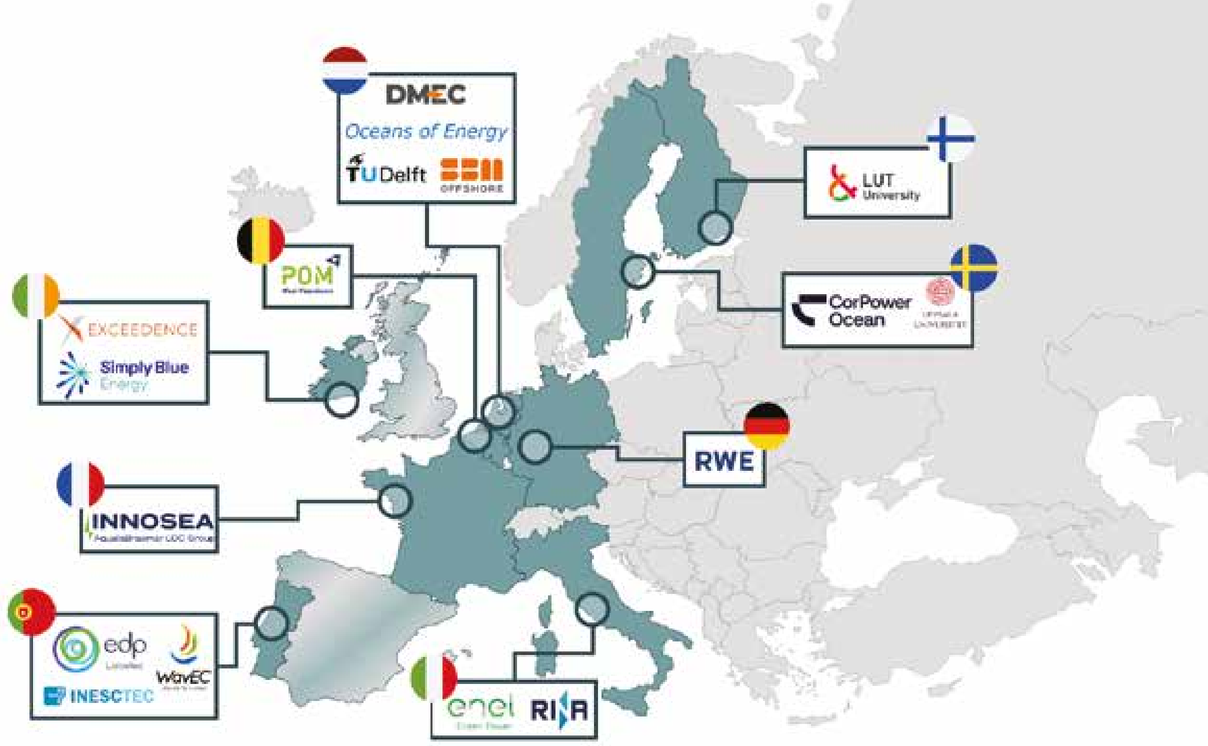
Looking at the number of times throughout a 3-year period in which only little power is available for more than 48 hours, it becomes very clear that the multi-source park is a much more reliable solution.

This shows that multi-source parks are a more efficient solution to ensure a stable power supply, even in an area with only limited wave resources. At the same time, the wave energy devices could show another positive effect on farms: while passing through the row of wave energy converters, the wave field loses energy and height. This could lead to more favourable conditions for offshore operations, namely crew transfers, or even reduce loads on the wind turbines and their foundations.

THE CHALLENGES ADDRESSED BY EU-SCOURES

While the benefits of more efficient use of offshore space and an increased energy production are clear, it is important to address a number of challenges in the process of commercialising multi-use offshore parks.

One key aspect is the high speed with which the offshore wind project pipeline develops. Not only government tenders and cable connections, but also commercial contracts are being designed to develop

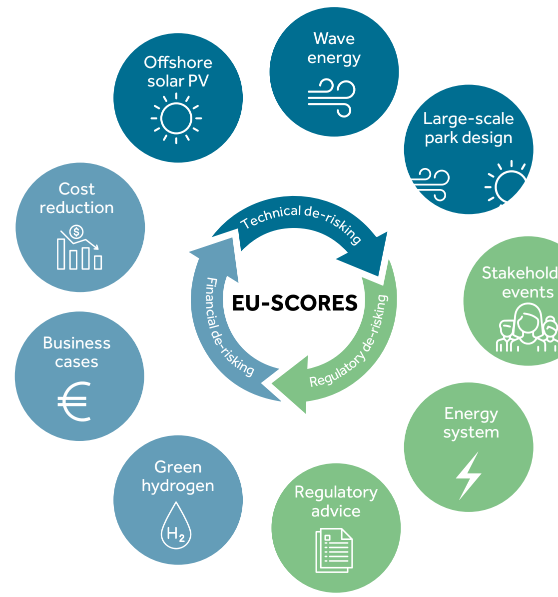


and operate offshore wind projects. Adding other energy technologies, later in this process, poses challenges and might make other technologies e.g., offshore energy storage, necessary to avoid the need for additional cable capacity. In this sense, it's crucial to promote early contact and collaboration with all stakeholders. The EU SCORES project combines a total of seven offshore wind developers to exchange challenges and lessons learned, and to support the design of legal frameworks for future multi-use parks.

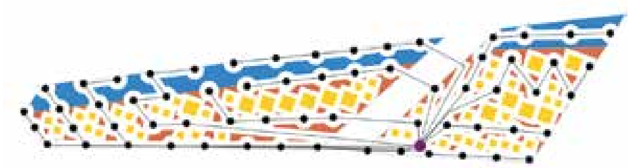
On the technical side, operators and contractors need to start gaining experience with these new technologies. The safe and efficient operation of multi-use parks relies significantly on the efficiency of maintenance processes, as well as on a clearer understanding of the core risks of new technologies. Both are the result of extensive operational experience and data collection on systems operating in the offshore environment. Therefore, more and larger scale pilot projects will be a key enabler for the success of multi-use parks.

Lastly, governments, TSOs and wind farm operators must ensure that they make long term plans. With current issues around grid congestion and the need for more interconnection between European countries, wind parks are already becoming hybrids. By combining a transmission function with their energy production role, wind parks can play a dual role in enabling the energy transition. To play this role more effectively, all potential technologies and future needs, covering not only electricity generation but also storage and eco-innovation and protection of the environment, need to be part of the plan.

If you are interested in learning more about the EU SCORES project, following the demonstrations taking place in the project, or participating in stakeholder meetings or events, please visit www.euscores.eu or follow the project on LinkedIn.



MULTI-USE PARK DESIGN



Wind turbines

Offshore floating solar installations

Wave energy machines

Combination of offshore energy production systems

CAN **DEEP-SEA MINERALS** HELP PROPEL THE WORLD TOWARDS NET-ZERO

The best-case scenario, using the latest in battery technologies for electric vehicles, requires 126 years of production for cobalt, 62 years' of global production for neodymium, 45 years' of global production for lithium, and 31 years' of global production for copper. Let us now assume these electric vehicles are powered by zero-carbon renewable energy. If the electricity is generated by wind turbines, then they would require 20 years' worth of neodymium and dysprosium global production in their permanent magnets or, if using CdTe-type photovoltaic solar energy, they would require 2000 years' of the current global production of tellurium.

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Figure 1 Cobalt-rich crusts being sampled on the summit of Tropic Seamount, NE Atlantic, obtained by remotely operated vehicle. The crust forms a layer of a few tens of cm thick underlain by a substrate of phosphorized carbonate and basalt.

INTRODUCTION

It is widely accepted that the use of fossil carbon-based fuels is environmentally unsustainable, causing significant and increasingly adverse effects on climates and ecosystems worldwide. As a result, there is a growing demand for alternative sources of energy, that are either renewable or carbon neutral. The aim, set by many industrialised nations, is to reach zero-net carbon by the second half of the 21st Century [1]. This ambition will require a huge increase in production of base metals like copper, nickel, zinc, as well as scarcer minerals and elements critical to enabling a transition to low-carbon energy generation and transport.

Many of these elements are relatively rare or restricted to very few areas of the globe and include: cobalt and lithium (used in batteries for electric vehicles); tellurium (used in cadmium- telluride thin-film, photovoltaic electrical energy generation); neodymium and dysprosium (used for permanent magnets in wind-turbines and electric motors); heavy rare earth elements (used in electronics), and platinum group elements (used in fuel cells and hydrogen catalysers).

For example, and by way of illustration of the magnitude of the demand, we can compare the mineral resources needed to electrify the world's estimated two billion private cars with today's worldwide land-based mining production rates for some of these critical and base metals [2].

The best-case scenario, using the latest in battery technologies for electric vehicles, requires 126 years of production for cobalt, 62 years' of global production for neodymium, 45 years' of global production for lithium, and 31 years' of global production for copper. Let us now assume these electric vehicles are powered by zero-carbon renewable energy. If the electricity is generated by wind turbines, then they would require 20 years' worth of neodymium and dysprosium global production in their permanent magnets [3] or, if using CdTe-type photovoltaic solar energy [4], they would require 2000 years' of the current global production of tellurium.

Whether this projection proves accurate or not, it is increasingly clear that there is a potential supply crisis for a range of critical elements, currently sourced from land-based mines, to reach any meaningful target for net-zero carbon emissions this century. However, the deep-seafloor hosts billions of tonnes of metalliferous mineral deposits, rich in these critical elements, that may hold part of the solution.

TYPES OF DEEP-SEA MINERALS OF INTEREST

There are three main types of deep-sea mineral deposit: polymetallic nodules, cobalt-rich crusts, and polymetallic massive sulphides.

Polymetallic nodules
Polymetallic nodules are iron-manganese oxide concretions, rich in nickel, copper, titanium, cobalt, and heavy rare earth elements (Figure 2). They are variable in shape and size, typically 1–12 cm in maximum dimension, and are most abundant on the ocean's abyssal plains at water depths of 4.000–6.500 m.

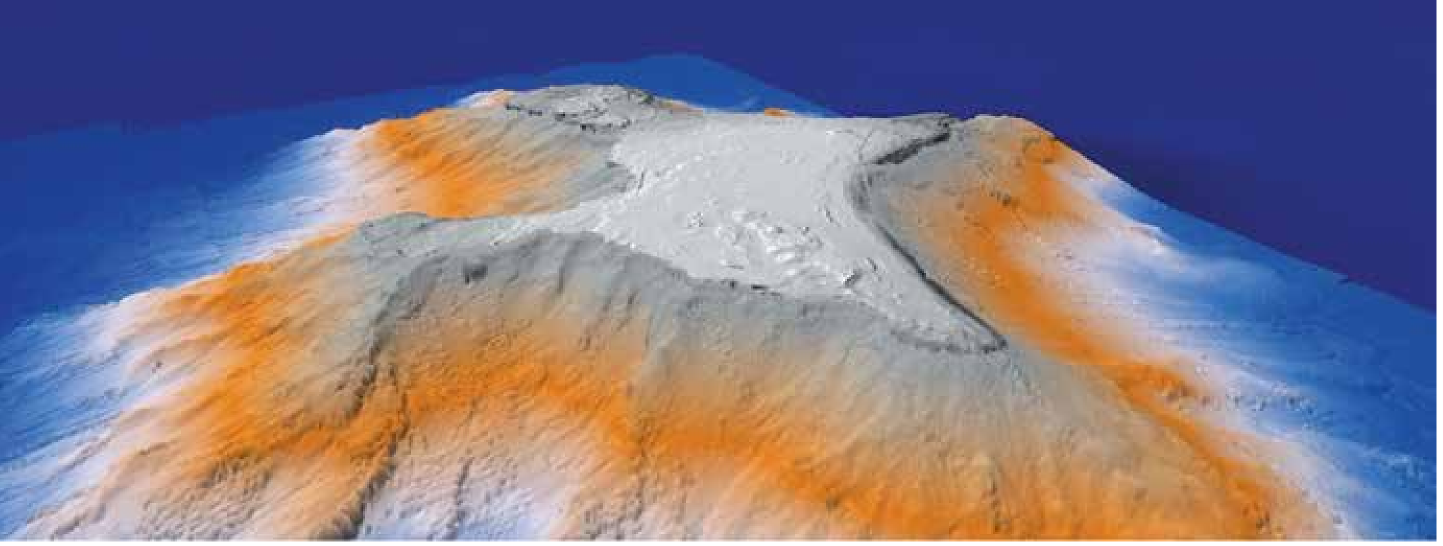

Figure 2 3D bathymetry image of Tropic Seamount, NE Atlantic, obtained by autonomous underwater vehicle, with a resolution of 1m on the summit. The summit is 12 km wide and contains a widespread deposit of cobalt-rich crusts.

where they lie on or immediately below the sediment-covered seafloor. Here, Fe and Mn oxide colloids slowly precipitate over millions of years around a hard nucleus, such as a shark's tooth or fish bone, from the overlying seawater (hydrogenetic nodules) and/or pore waters released from the underlying sediment (diagenetic nodules).

The best-known deposits are from the Clarion-Clipperton Zone (CCZ), between the west coast of Mexico and Hawaii, where there are an estimated 20-30 billion tonnes of nodules. The Peru Basin in the south-eastern Pacific has about of ~6-9 billion tonnes, while the Penrhyn Basin, also in the Pacific and located near the Cook Islands, has an estimated 5-7 billion tonnes of nodules with a resource potential of ~21 million tonnes of cobalt (i.e., 210 years' worth of global land-based production).

In the Indian ocean, nodule fields contain lower average abundances ~5 kg/m2. Worldwide, polymetallic nodules present an enormous source of metals, with 10 times more manganese, 6 times more cobalt, 4 times more tellurium and yttrium, 3.5 times more nickel, and a third more copper compared with land-based reserves [5].

Cobalt-rich crusts
Cobalt-rich crusts are another type of iron-manganese oxide-oxyhydroxides deposit. They commonly form layers, up to 25 cm thick (Figure 1), on rocky substrates such as seamounts and underwater ridges (Figure 2). They are rich in cobalt (0.5-1.2%) and other critical elements such as tellurium, platinum, rare earths, titanium, thallium, and nickel [6]. These crusts occur through- out the global ocean, at all depths below 700 m, but are thickest on the oldest areas such as the Prime Crust Zone of the northwest Pacific. They contain more than half the nickel, a fifth of the titanium, over 3 times the yttrium (and other rare earth elements), 7 times the cobalt, 23 times the tellurium, and 3000 times the thallium compared with all known land-based reserves [5].

Polymetallic massive sulphides
Polymetallic massive sulphides and their metalliferous sediments are the product of intense seafloor volcanic activity and form rapidly from high-temperature hydrothermal fluids. Hydrothermal venting of metal-rich fluids (known as black-smokers) is associated with volcanic activity, typically at the boundaries of tectonic plates such as mid-ocean ridges, and occurs in all the oceans at depths down to 5,000 m (Beaulieu et al. 2013). This phenomenon is one of the most spectacular examples of geology in action where we can witness the release of metal-saturated fluids from the ocean floor at temperatures of up to 450°C where they instantly mix with cold ambient seawater, at 2-4°C , resulting in the formation of spectacular chimneys and mounds of sulphide typically 30-50m high and 100-200 m in diameter (Figure 5).

Geophysical studies and drilling show these hydrothermal systems form extensive deposits both on and below the seafloor, down to depths of a few hundred metres. They are primarily rich in iron (up to 32%), zinc (up to 17%), copper (up to 13%), gold (up to 13 ppm), silver (up to 2000 ppm) and have elevated concentration of cadmium, gallium, germanium, antimony, tellurium, thallium, and indium [7].

Previous estimates suggest about 600 million tonnes of accessible seafloor massive sulphide [8], however, hydrothermally inactive deposits may be 10 to 20 times more abundant than active ones with between 3 and 5 times more sulphide under the seafloor than above it [9], hosting 20 to 30 billion tonnes of ore worldwide. One of the largest deposits known is found on the Mid-Atlantic Ridge, at the Semenov Field at 13:30'N, where it forms mounds of sulphide up to 200 m high and 500 m in diameter (Figure 4).

CHALLENGES

Without deep-sea minerals there is unlikely to be sufficient supply of critical raw material to enable a net zero-carbon economy this century. However, there are three major challenges facing the nascent deep-sea mining industry. First is the uncertainty around the regulations that the United Nations International Seabed Authority is drafting. Second, there remains considerable technological challenge to deep-sea mineral exploration and mining. Thirdly, protecting the environment is key to gaining social license, for which much needs to be done to identify potential harm and how to mitigate it.

Much work is required to enable the technologies for environmentally sustainable extraction as well as environmental monitoring. In response to the urgent need for environmental monitoring, a new research project has been initiated by Europe horizons. Involving researchers from across Europe, collaborators across the world and led by Portugal's Institute for Technology, INESC TEC. Project Trident is developing the technological knowhow to enable in situ monitoring and forecasting of potential impacts from seafloor activities including deep-sea mining. Such monitoring is essential if there is to be transparency in the work of the operators to allow the public and regulators alike to check on what is being done to the seafloor.

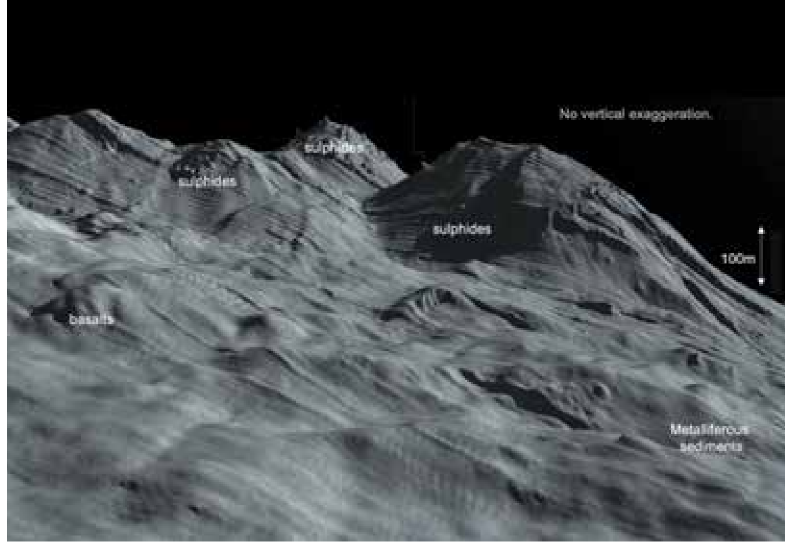

Figure 4 Perspective view of the Semenov 4 PMS hydrothermal mounds, located above a major fault system on the Mid-Atlantic Ridge at 13°30'N MAR, viewed from the south to north. These PMS mounds are hydrothermally extinct and contain an estimated 100 MT of sulfide ore (courtesy of John Jamieson).

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Figure 3 Polymetallic nodules on the floor of the Atlantic Ocean. The nodules are 5-20cm in diameter.

Figure 5 'Black-smoker' chimney venting high-temperature hydrothermal fluids (at 390°C) from the Mid-Cayman Rise, at a depth of 5050m. The dark colour of the fluids is a result of saturation of metal sulphides as the vent fluids mix with seawater.

SOCIETAL CHALLENGES AND MARINE GEOLOGY

Understanding the origin of current changes in the ocean, to anticipate the future, implies a better understanding of the ocean's interior - about which one has very little knowledge. Modern ocean studies range from the use of satellites to direct sampling studies through human diving, vessels or research vessels with mechanical drilling towers that can operate in up to five km of water column, and drill several hundred of meters from below the ocean floor.

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Figure 1 Photo credits: Hugo Ferreira

The ocean is not only vast, but also complex. Nowadays, we cannot perceive it exclusively as a part of the Earth's hydrosphere - although this notion alone makes the ocean a complex system, consisting of water masses with specific physical and chemical properties, which move in different directions and at different depths.

The ocean is the most important subsystem of the climate system, since it covers about 71% of the earth's surface; its surficial and deep circulation distribute energy throughout the planet; produces close to 50% of the global primary production, which makes it the source of a large amount of oxygen; supports a great biodiversity. It contains 60 times more carbon than the atmosphere, and it holds a higher thermal capacity than the atmosphere. In this sense, it plays a very important role in regulating the climate and the carbon and nutrient cycles that are crucial to the organisms that form the basis of the ocean food chain, the primary producers.

Among the anthropogenic risks, the most important are those caused by the increase in the concentration of greenhouse gases in the atmosphere. The discovery that the CO2 concentration in the atmosphere was increasing happened in the early 1970s from the analysis of the records of the Mauna Loa Observatory in Hawaii (Keeling, 1960). After this unveiling and the scientific community's understanding of the disastrous consequences of this phenomenon for the biosphere, the paleosciences community (Palaeoceanography/ Paleoclimate) immediately understood that it was necessary to verify whether the phenomenon was recent or just a repetition of some event that had already happened in the geologic past.

The study of the concentration of conserved CO2 in the air bubbles that are trapped in the ice sheets deposited annually in the Arctic and Antarctic revealed that the exponential increase in concentrations began around 1850, at an unprecedented rate over the last 125.000 years, proving in 1987 (Barnola et al., 1987) that urgent action was necessary. Today, the ice record reaches 800.000 years, and the data remains correct.

Figure 2 Joides Resolution Platform where drilling of sediments from under the ocean floor takes place. IODP Exp397 Iberian Margin Paleoclimate. (Credit: Sandra Herrmann, IODP, JRSO)

The ocean absorbed more than 90% of the excess energy accumulated by the climate system between 1971 and 2010, and about 30% of the anthropogenic CO_2 emitted in the same period, which causes an increase in energy and heat in the ocean waters, a decrease in oxygen concentration and the ocean water acidification (Sabine et al., 2004). Changes that have a deep environmental impact and are of great concern, because they can result in the decline of a large part of the microorganisms (primary producers) that are at the base of the marine food chain (Feely, 2004). This process will affect the most important sources of fishing in the world, which are concentrated in about 1% of the ocean - with Portugal being part of this area (Fiúza, 1983; Barton et al., 1998). All fisheries - particularly sardines - could suffer from these environmental changes.

Understanding the origin of current changes in the ocean, to anticipate the future, implies a better understanding of the ocean's interior - about which one has very little knowledge. Modern ocean studies range from the use of satellites to direct sampling studies through human diving, vessels or research vessels with mechanical drilling towers that can operate in up to five km of water column, and drill several hundred of meters from below the ocean floor (Figure 2). The studies of seafloor rocks provide information on the frequency of major earthquakes, tsunamis, meteoritic impacts, biological extinctions, and climatic variations.

The recent technological developments allow for the installation of observatories on the ocean floor that also record information along the entire water column; together with data collected by a whole range of small robotic autonomous vehicles, which collect data at different ocean depths, will warrant a significant progress in this domain (Favali et al., 2015). Moreover, the commitment of the international community to uphold the principles of "knowing to preserve" and "acquiring data once and using it many times" will certainly contribute to accelerate knowledge and better preserve the environment.

Just like the trees, which record the environmental conditions that occur annually in their tree rings allowing high temporal resolution climatic reconstructions, the marine sediments that accumulate on the ocean floor permit the same type of reconstruction but with lower temporal resolution. However, they constitute the only records from which we can study the climatic variability during older periods (from hundreds to millions of years).

Continuous and long data series constitute a consensual support to evaluate the behaviour of natural systems, e.g., seismicity and tsunamis (Miranda et al., 2015). Estimating the impact of humanity's interaction on the climate system involves generating time series beyond instrumental data and using a geological retrospective from the past, thus allowing to understand the present and anticipate the future.

The sediments of the Portuguese continental margin are crucial for the reconstruction of past climate, as they simultaneously record the millennial climatic variability occurred in the Arctic and Antarctica during the Quaternary (last 2.6 milhões de anos). Hence, they have the potential to extend this record to times prior to the ones recorded in the polar ice caps. Moreover, in addition to the reconstruction of the climate for long periods (hundreds of thousands to millions of years (e.g., Rodrigues et al, 2017; Hodell, Abrantes et al., 2023); they also provide valuable information about the last 2.000 years (e.g., Abrantes et al, 2005, 2011, 2017), or even extreme weather events (e.g., Salgueiro et al., 2010; Naughton et al., 2021).

Despite the desire to preserve pristine or untouchable natural systems, the exploitation of non-living resources in the oceans is urgent due to the extensive occupation of the territory by societies and to political conflicts. Hence, and to address these risks, simultaneously with the development of exploratory capacity and effort, through direct bottom sampling platforms and indirect methods, several endeavours are taking place with the objective of understanding how the impact of the exploration of mineral occurrences on the ocean bottom can impact the general ocean environment and the deep ecosystems in particular (Silva et al., 2023).

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Emília Salgueiro (sedimentologist) describes a sedimentary sequence just collected. IODP Exp397 Iberian Margin Paleoclimate. (Credit: Sandra Herrmann, IODP, JRSO)

Fátima Abrantes(co-chief) at a results presentation meeting during the IODP Exp397 Iberian Margin Paleoclimate. (Credit: Sandra Herrmann, IODP, JRSO)

The ship Joides Resolution, working for the IODP (International Ocean Discovery Program), in the port of Lisbon in October 2022, with the group of researchers who participated in Expedition 397 – Iberian Margin Paleoclimate. (Credit: Sandra Herrmann, IODP, JRSO)

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THE OPPORTUNITIES, CHALLENGES AND ADVANTAGES OF **DEEP-SEA MINING**

Approximately 70% of the earth is covered by seas and oceans, and a lot of the higher quality easy-access minerals on land have already been found and mined out. So, moving to the oceans is in many ways logical. As time and technology advancement progresses and exploration continues, more and more viable mineral reserves will be found in the deep sea.

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BACKGROUND

Mining in the sea is not a new activity. It has been done since the times of the Roman Empire, an example being with the mining of copper-bearing ores around parts of the coast of Cyprus. Mining underneath the seafloor is also not a new activity, with historic mining of coal underneath the seafloor having taken place off many coastlines across the world. The safety and environmental standards that society expects to be met have become tougher to meet over time and what was once deemed as socially acceptable is not necessarily acceptable today. Currently, dredging in relatively shallow coastal areas for aggregates, tin, titanium, gold, diamonds, salt and other minerals takes place at many places across the world and is considered by many as socially acceptable. Deep-sea mining, often classified as beyond 500m water depth, is not being carried out on an industrial scale, although there have been several prototypes and tests done at various ocean sites.

In recent times, advances in offshore exploration technology have enabled anallowed the increase in our knowledge and understanding of remote deep-sea mineral deposits. This increased knowledge has occurred not just in terms of mapping and measuring the physical characteristics of the mineral deposits and their potential value, but also in terms of mapping the presence and nature of any associated flora and fauna. The interactions and dependencies between sub-sea species is also being actively studied. Nevertheless, the deep-sea environment is still a relatively unexplored space compared to the earth's land masses.

MINERAL OPPORTUNITIES

The main types of ore in the deep sea are ferro-manganese crusts, polymetallic nodules, and mineral rich sulphide deposits. There are some potentially attractive crusts on the top of submerged seamounts. These crusts are relatively thin, but potentially extractable and some areas have attractive concentrations of cobalt and other metals needed for electric vehicles and green energy applications. Nodules have been found to cover vast areas of the abyssal plains. Some of the more attractive resources from a metal content perspective are at a depth of up to 6000m. In addition to manganese and iron, the crusts and nodule resources in the deep sea are in some cases rich in cobalt, copper and nickel. Sulphide ores are often found adjacent to hydrothermal vents. These can be active or dormant subsea volcanic areas and the more attractive resources may typically contain good concentrations of copper and gold.

Figure 1 Photo credits: Alfredo Martins

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Some of the subsea areas have rare earth minerals, but to the author's knowledge, heavier rare earth minerals have not, so far, been found in sufficiently desirable concentrations to justify exploitation, other than perhaps as a by-product or co-product.

CHALLENGES

Challenges remain from environmental, legal, technical and practical perspectives;

Environmental
Fundamentally, all types of mining activity - whether on land or at sea - have an environmental footprint and impact of some sort. Concerning deep-sea mining, the question remains as to whether the impact can be minimised to an extent that would prove to be environmentally and socially acceptable. Some areas of the seabed are more environmentally sensitive than others and some are relatively barren other than with respect to the micro-fauna and microbes found there. Also, some ore deposits are easier to mine than others and the process of extracting the ore can in some cases be more akin to "collection" than to digging - which could, in some cases, potentially minimise impact. This is particularly the case of polymetallic nodules.

Care needs to be taken with the design of the mining or collection machines to minimise plume generation. This is a particular challenge in deposits with fine sediments and slow currents, as any plume generated would tend to hang in the water column before settling. The generation of plumes can hamper visibility and may also influence the local environment in some areas.

Legal
Granting of licences and oversight of mining in international waters is governed by the International Seabed Authority. In the case of polymetallic or manganese nodules, exploration licences are typically awarded for quite large areas with some being the size of small countries. Approximately half of a licence area is typically reserved for the "benefit of mankind". This is designed to ensure that larger developed countries do not dominate future extraction of the world's shared resources. Significant areas around the licence area are also set aside, as what could be described as environmental impact monitoring zones. Obtaining a lease in international waters also requires the sponsorship of a state which must be signed up to UNCLOS (the United Nations Convention on the Law of the Sea).

Technical and practical
There are many technical challenges due to the depth of the operation – particularly if the wave-height is significant. A mining/collection machine needs power, which is generally supplied by a large vessel when working in remote offshore areas. Getting power to a mining or collection machine - which is between 0.5 and 6 km away vertically - is not easy in a submerged and remote environment. This is also challenging for electrical and hydraulic control systems. There can also be large energy requirements for lifting the ore to the surface vessel or platform in deep areas.

Any mining equipment needs to be maintained from time to time, so there are also energy and equipment requirements to lift the mining machine back to the surface vessel. And on-boarding large machines in high seas can be a difficult and risky task. The weight of any lifting wire/cable, even when submerged, can be very high due to its high suspended length. Some of the subsea equipment would typically need high-quality syntactic foam buoyancy blocks.

With depth comes pressure; so, key electrical and electronic equipment on the mining machine may need to be enclosed in a very strong pressure-resistant vessel.

Care also needs to be taken in limiting the amount of unwanted sediment taken on-board the mining machine, as this may dilute the product and potentially require separation circuits on the machine – making it bigger, heavier and in need of more power. And of course, any unwanted sediment taken onboard the mining machine, or the surface vessel, would need to be placed back carefully to the seabed in a manner which encourages rapid settlement.

As is the case on land, variability of ore grade can be a challenge. If this is anticipated as a problem, then the design of the mining equipment and overall system needs to be able to rapidly assess the ore grade and react in a timely manner. With very deep areas, transportation of the mined/collected material to the surface may take significant time, in which case it would be preferable to analyse the metal content at the seabed – either in advance of mining, or directly on the mining/collection machine to ensure that the receiving hoppers on the vessel at the surface do not fill up with silt or low grade ore (which is difficult or costly to treat and process to extract the final product).

Some subsea areas have very corrosive environments. Sulphides are formed during subsea volcanic activity. The ejecta/smoke streams from hydrothermal vents can also cause increased corrosivity nearby. Some of the prototype mining machines used have been equipped with cathodic protection. The deep sea is a dark place. Sound travels a long way in water, but light does not. The smoke streams can also cause visibility issues or indeed interference to navigation systems that use smart sonar or LIDAR systems.

ADVANTAGES OF DEEP-SEA MINING

Deep-sea deposits of minerals are relatively untouched and many of them are shallow, laying with no requirement to remove substantial overburden material, whereas the stripping ratio (overburden material to ore) on land has gradually increased over time as the easy access deposits have been mined.

As the world's population grows and the underdeveloped parts of the world modernise, new sources of high-grade minerals will be required. It is unlikely that we would be able to recycle sufficient metals to cater entirely for the demands of the future, particularly if the current trends in population and mineral requirements per capita persist. While recycling and re-purposing of metals and other materials is improving, the costs and environmental footprint of the recycling activities themselves can become cost prohibitive.

Our understanding of the oceans and the life in it is also increasing. Approximately 70% of the earth is covered by seas and oceans, and a lot of the higher quality easy-access minerals on land have already been found and mined out. So, moving to the oceans is in many ways logical. As time and technology advancement progresses and exploration continues, more and more viable mineral reserves will be found in the deep sea. Navigation, visualisation, and other perception system technologies are improving. Sub-sea vehicle design and prototype deep-sea mining systems are starting to mature and advancements in robotics continue.

THE UNITED NATIONS CONVENTION ON THE LAW OF THE SEA AND THE INTERNATIONAL SEABED AUTHORITY **CONTRIBUTIONS TO RESPONSIBLE OCEAN MANAGEMENT**

The International Seabed Authority (ISA) is an autonomous international organization established under the 1982 United Nations Convention on the Law of the Sea (UNCLOS) and the 1994 Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea (1994 Agreement).

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The world oceans cover 361.90 million square kilometres, representing 70.9% of the Earth's surface. While about half of the oceans are part of coastal countries and under national jurisdictions, a total of 181.63 million square kilometres does not belong to any country or entity; or better, belong to everyone. Similar to the better known Antarctic treaty which regulates legally the international status of Antarctica, the United Nations Convention on the Law of the Sea (UNCLOS), adopted in 1982, regulates the international areas of the world oceans – called the 'Area' - in terms of navigational rights, territorial sea limits, economic jurisdiction, the legal status of resources on the seabed beyond the limits of national jurisdiction, the passage of ships through narrow straits, the conservation and management of living marine resources, the protection of the marine environment, a marine research regime and binding procedures for settlement of disputes between States. The Convention is an unprecedented attempt by the international community to regulate all aspects of the resources of the sea and uses of the ocean as the common heritage of humankind. UNCLOS outlines the areas of national jurisdiction as a 12 nautical-mile territorial sea, an exclusive economic zone of up to 200 nautical miles and a continental shelf. The international seabed Area is defined as "the seabed and ocean floor and the subsoil thereof, beyond the limits of national jurisdiction."

The International Seabed Authority (ISA) is an autonomous international organization established under the 1982 United Nations Convention on the Law of the Sea (UNCLOS) and the 1994 Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea (1994 Agreement). ISA, which has its headquarters in Kingston, Jamaica, came into existence on 16 November 1994, upon the entry into force of UNCLOS. ISA is the organization through which States Parties to UNCLOS organize and control all mineral-resources-related activities in the Area for the benefit of humankind as a whole. In so doing, ISA has the mandate to ensure the effective protection of the marine environment from harmful effects that may arise from deep-seabed-related activities. ISA provides a critical platform for knowledge generation on the deep-sea, its resources and ecosystems. As of 1 May 2020, ISA has 168 Members, including 167 Member States and the European Union.

ISA has undertaken work to develop regulations for exploration and exploitation of mineral resources in the Area since its existence in November 1994, through expert workshops and studies and discussion papers. The draft regulations are considered by organs of the ISA, namely the Legal and Technical Commission and

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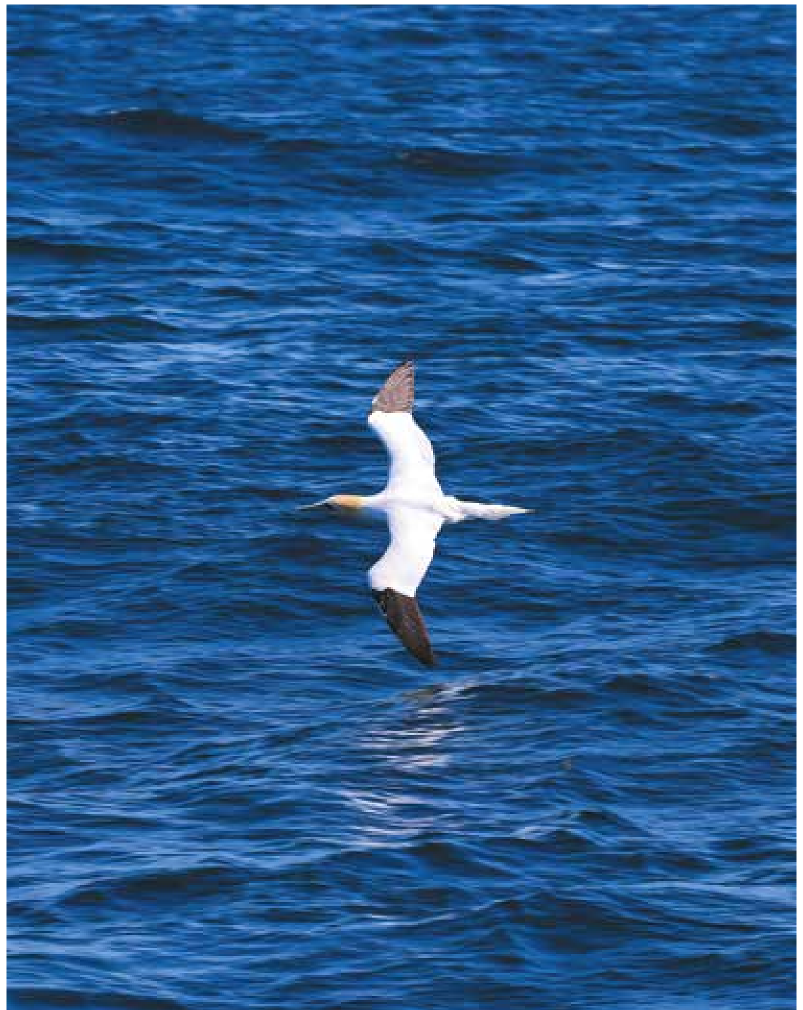


Figure 2 Photo credits: Alfredo Martins

the Council, and finally decided by the Assembly. Open stakeholder consultations are held throughout the process. ISA has issued regulations on prospecting and exploration for marine resources in the Area, that are polymetallic manganese nodules (PMN, adopted on 13 July 2000, updated, and adopted on 25 July 2013; polymetallic massive sulphides (PMS, adopted on 7 May 2010); and cobalt-rich ferromanganese crusts (CFC, adopted on 27 July 2012). Draft exploitation regulations are under development and negotiation since 2014, with current negotiations provided in the open access document ISBA/27/C/3.

The first global marine scientific project dedicated to research of the world's oceans started with the Challenger expeditions in 1872. The expeditions included mapping and sampling programs and it created the first evidence for the geological continuum between land masses and oceans. It became evident that complete maps of the ocean floor are required. The identification of magnetic stripes on the seabed in the 1950s and 1960s by scientific magnetic surveys soon led to the development of the theory of plate tectonics. And contributed scientific evidence to the seafloor map. All these efforts have led to a solid, sometimes detailed understanding of the world's geomorphology and geology. The large variations and numerous details, however, make it necessary to improve mapping to resolutions which allow for better knowledge, understanding, assessments, identifications, and quantifications – both, on land as well as at sea. Satellite altimetry and advanced echo-sounding data at higher resolutions from a variety of different scientific and commercial data providers form the base for the open access General Bathymetric Map of the Oceans (GEBCO) which today provides a constantly updated global terrain model. Bathymetry largely contributes to the effective implementation of a sound and stringent regulatory framework. Based on extensive high-resolution bathymetric measurements, coastal countries are enabled to define their exclusive economic zones and potentially propose the extension of the continental shelf and the marine area of national jurisdiction.

The GEBCO data were and still are the first step for the identification of seabed mineral resources, marine habitats, potential natural hazards, but also assist in the definition of a regulatory framework. Marine scientific research contributes a significant amount of detailed bathymetry in the different parts of the oceans – particularly along the mid-ocean ridges with the alignment of PMS occurrences, abyssal plains with the potential enrichment of PMN and seamounts with CFC. ISA has entered into 15-year contracts for the exploration for PMN (n=19), PMS (n=7) and CFC (4) in the deep seabed with 21 contractors and 30 contracts. The contracted license areas cover 1.45 million square kilometres representing 0.8% of the entire Area or 0.4% of the world oceans. In the time frame between 2001 and 2021 the contractors spent the amount of USD 1,579,901,917 for their exploration activities, environmental surveys, the development of marine technologies and metallurgy processes, capacity building trainings for scientists from developing countries and other activities. Exploration programmes by ISA furthermore attract significant scientific activities including bathymetric mapping and environmental baseline studies in and around contract areas, for example the area between the Clarion and Clipperton fracture zones (CCZ) in the Central Pacific and the Mid-Ocean ridge system in the northern Atlantic Ocean. Biodiversity in the CCZ is protected by 13 Areas of Particular Environmental Interest (APEIs) which cover 1.97 million square kilometres or 44% of the entire zone. Technological developments and contractors' activities led recently to the development of ISA's draft technology roadmap defining areas of priority for member countries to engage in developments for (i) ocean observation and communication, (ii) monitoring, (iii) automation, autonomy, and robotics, (iv) machine learning by artificial intelligence (AI), (v) mining, energy and metal processing. EU Horizon's currently funded TRIDENT project greatly contributes to several aspects of this roadmap cross-fertilizing the identified priorities for the aim of developing and establishing a robust monitoring approach for any seabed activities.

ISA contributions to ocean management covers a wide range of aspects including the seabed mineral resource base, biodiversity and habitat identification and protection, marine science, and knowledge management as well as potential new resources including sustainable and net zero geothermal, current, wave energy sources, potential new food resources and fish farming in the deeper water column and future potential in advanced pharmaceuticals from marine microbiome sources.

CHAPTER

1 2 3 4 5

SEA TECHNOLOGY

INESC TEC aims to be a reference in the development of advanced technologies and methodologies supporting the sustainable growth of the Blue Economy in emerging areas like energy, natural resources, water and ocean management, environmental monitoring (climate change), and safety. The comprehensive activities of supporting and promoting research and development, while addressing new societal problems on a global, national, or regional scale, contributes for promoting a reference for human development.

Photo credits: Alfredo Martins

UNDERWATER ROBOTICS
SUSTAINABLE EXPLORATION AND EXPLOITATION OF RAW MATERIALS

The need to explore new raw material sites and re-evaluate existing prospecting sites is increasingly becoming a key element for the success of the green transition and for reducing Europe's dependence on raw material imports. The importance of exploring raw material sites is intrinsically associated with the need to optimise the extraction and exploitation of finite resources, mitigating the environmental impact linked to these activities - in which underwater robotics plays a key role, as it is crucial for said harnessing.

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The prospecting and exploitation of underwater minerals has emerged as an important subject over recent years, due to the growing global demand for resources. Over the past decade, we've witnessed a significant global transition towards more sustainable practices and the pursuit of environmentally responsible solutions. This sought-after green transition puts pressure on the supply chain of much-needed raw materials to increase energy production and storage capacity, thereby reducing the use of fossil fuels, and consequently decreasing dependence on non-renewable natural resources. The need to explore new raw material sites and re-evaluate existing prospecting sites is increasingly becoming a key element for the success of the green transition and for reducing Europe's dependence on raw material imports. The importance of exploring raw material sites is intrinsically associated with the need to optimise the extraction and exploitation of finite resources, mitigating the environmental impact linked to these activities - in which underwater robotics plays a key role, as it is crucial for said harnessing.

INESC TEC, in particular the Centre for Robotics and Autonomous Systems, has dedicated more than a decade to underwater robotics, motivated by the search for new knowledge and the ability to study deep-sea and inaccessible flooded areas. Research, development, and innovation play a key role in creating technologies for the identification and exploitation of new raw material sites. The Institute has developed innovative robotic solutions for complex environments and multiple operations, including data collection, inspection, mapping, surveillance, or intervention.

In this sense, INESC TEC has played an active role in several projects related to underwater prospecting and exploitation. INESC TEC was involved in the project ¡VAMOS!, which ended in 2019 and whose main objective was to allow access to European top quality reserves of underwater minerals, providing a novel, safe, and clean mining technique with low environmental impact. In addition, the project has proven the environmental and economic feasibility of harnessing currently inaccessible mineral deposits, encouraging investments and helping to safeguard EU access to strategically important minerals.

The exploration of ore in abandoned and flooded open pit mines was made possible thanks to the development

Figure 1 Photo credits: @Turtle

Figure 2 Photo credits: UX1 Rocky Shore

of a robotic system, composed mainly of an underwater mining vehicle, an Autonomous underwater vehicles to support the operations, and an operations' support vessel. The larger vehicle is a 25-tonne robot equipped with a drilling machine (with the ability to break up rock and pump the extracted material to the surface) on one side, and a hydraulic arm with interchangeable tools on the other. The smaller one, called EVA, moves around the mining site, constantly updating a 3D map of the area and transmitting this cartography data to the larger vehicle, thus improving navigation. The EVA robot was developed entirely by INESC TEC researchers, as well as all sensing, perception, and navigation systems that power an operating environment based on a digital twin. This environment allows the operation of the 25-ton robot in an intuitive and friendly way, like a game.

EVA (Figure 1) is a versatile, multifunctional vehicle that combines high-precision positioning and navigation capabilities with a unique set of observation sensors e.g., 3D multi-beam sonars, cameras, and structured lighting systems for three-dimensional environmental perception with omnidirectional motion capabilities. These features, quite unique considering the robot's dimensions, allow its effective use both in mapping applications during initial surveys, and in the detailed inspection and support to the operation of the mining machine.

INESC TEC has played a major role in this flagship project. But it wasn't the only one. INESC TEC also participated in the European project UNEXMIN.

The UNEXMIN (Autonomous Underwater Explorer for Flooded Mines) focused on the development of underwater robotic systems capable of autonomously exploring and mapping ancient underground mines, without the need for direct human intervention.

There are thousands of abandoned mines in Europe that pose environmental and safety risks but can also contain valuable resources to be recovered. At the time of their decommissioning (in many cases, several decades ago), the technology and interest in high-demand minerals were not the same as today. Therefore, it is urgent to analyse and explore whether the once abandoned mines are likely to be mined again today.

The project involved the creation of three prototype robotic systems for the exploration and autonomous mapping of flooded mines' galleries in Europe. The UX-1 was equipped with advanced cameras, sensors, and navigation systems, allowing it to map the submerged mines and collect data on their condition and economic potential.

During the project, the team carried out tests and exploration missions at several abandoned mines in Europe, including quartz and feldspar mines in Finland, uranium mines in Portugal, mercury mines in Slovenia, and copper mines in the United Kingdom. The underwater robots were able to navigate through the mines' narrow and complex tunnels, collecting geological data, water samples and 3D images.

The first prototype of the UX-1, UX-1a, was developed and assembled in April 2018. During that year, the robot was tested and improved in Kaatiala (Finland, June) and Idrija (Slovenia, September) mines. The second prototype (UX-1b) was built and optimised in March 2019. Both robots were tested in the mines of Urgeiriça (Portugal, March/April), Ecton (United Kingdom, May) and in the Molnár János cave (Budapest-Hungary, June/July).

The results obtained by the UNEXMIN project were quite significant. The exploration missions provided valuable insight into the condition of submerged mines, the presence of mineral resources, and the technical and environmental challenges associated with their retrieval. In addition, the project contributed to the development of advanced robotic technologies and improved our understanding of underground and underwater environments.

The company UGR – UNEXMIN GEOROBOTICS was established because of the UNEXMIN project, with INESC TEC as one the partners, providing mapping and exploration services for mines or other flooded non-oceanic environments.

In addition, a D&I leverage project (upscaling) of the UNEXMIN – UNEXUP concept was accepted for financing in 2020; it focused on increasing the level of operability and robustness of the UX-1 robot by advancing to the development of a product and the provision of services by UGR. This UNEXUP project was completed at the end of 2022 and could not have had better results. The UX-1neo can now navigate up to 500m deep, which is equivalent to 50bar of pressure, while the UX-2deep can operate at 1500m deep. Both feature navigation sensors optimised for state-of-the-art exploration and mapping processes, and they're accessible to anyone through the services provided by UGR.

The increase in global demand for raw materials is not limited to inland mines alone. The possibility of deep-sea underwater mining is also considered. In this sense, it's important to emphasise the relevance of monitoring the impact assessment to ensure sustainable resources' extraction practices. Prior to any type of deep-sea exploration activity, it is crucial to foster competencies to inspect and assess the potential environmental impact of said activities on ecosystems. The European project TRIDENT, launched in 2023 and coordinated by INESC TEC, aims to develop

Figure 3 Autonomous vehicle EVA deployment at sea. (Photo credits: Alfredo Martins)

technologies capable of promoting a significant advance in the assessment of deep-sea environmental impact, in the identification of mitigation solutions, and in the development of new methodologies and operational techniques, while contributing to a solid legal framework (together with the International Seabed Authority – ISA); the goal is to promote the access to the marine mineral deposits in a safe, ecological, industrially viable and socially accepted way.

Besides requiring heavy and expensive logistical support for installation, maintenance, and operation (which limit the effective monitoring capacity), the current monitoring systems for deep-water do not favour the effective network integration for the creation of a real-time monitoring and alerting system.

The TRIDENT project aims to go beyond the current state of the art by bridging existing technological limitations and gaps and establishing advanced methodologies for real-time monitoring of environmental impact and the adoption of mitigation measures in the context of deep-sea mining. TRIDENT will provide a fixed and mobile (modular) wireless network of sensors and autonomous robots that enable real-time environmental monitoring and data transfer from remote deep-sea areas to remote onshore monitoring systems, validated in relevant scenarios (TRL 5). Although the project is still in an initial stage, TRIDENT proves to be promising, and is already considered a flagship project for its ambition and capacity for innovation. The next five years will be challenging for the consortium, but they will certainly be a big step forward in terms of autonomous robotic deep-sea technology.

Most INESC TEC robots are primarily developed to address and solve specific challenges (considering the problems and objectives of the projects that fund them). However, after reaching some functional maturity, the prototypes are quickly integrated into other projects, thus proving the versatility of the technological solutions developed at INESC TEC. The robots previously presented, developed within the scope of projects already completed, are currently being adapted for their use in the open sea, with increased pressure resistance capacity, as well as the ability to withstand currents and environments harsher than controlled environments inside mines.

The EVA robot has been upgraded and developed for open sea operations, with increased autonomy (currently capable of operating up to about seven hours), and movement elements capable of supporting open sea currents. In addition, it has been optimised in terms of resistance to pressure, and it can now reach

Figure 4 UX-1neo operating at the Kőbánya mine in Hungary. (Photo credits: UX1 Rocky Shore)

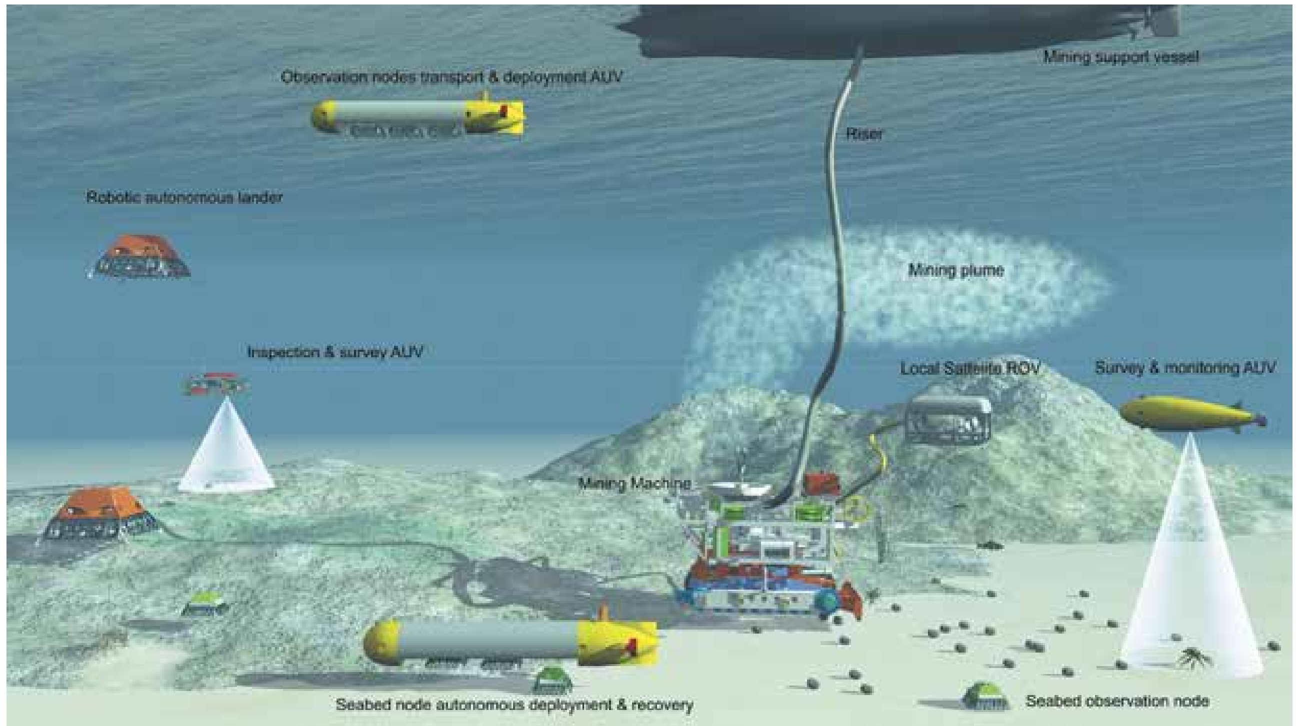

Figure 5 Concept picture of the environmental impact assessment system of deep-sea activities.

depths greater than 1000m - also featuring sensors capable of submerging up to 4000m deep. Recently, it has been equipped with new high-resolution cameras for seabed observation.

The UX-1neo is designed to operate in complex underground environments. However, the applications for this type of system are much more comprehensive. The robotic platform uses non-invasive methods for autonomous 3D mapping of mines, in order to collect essential geological, mineralogical and spatial information. This action can open new exploration scenarios, in which strategic decisions on the reopening of Europe's abandoned mines can be supported by up-to-date data that cannot be obtained in any other way, without great costs and/or risks.

The line of technology employed in the UX1 is only possible thanks to recent scientific advances in autonomy, which allow the development of a completely new class of mining service robots, capable of operating without remote control. Said robots do not exist at the time, with UX-1neo being the first of its kind - having already broken depth records in non-oceanic inland waters, in the Hranice Abyss (Czech Republic).

The main development challenges are related to autonomous operation in complex environments, high accuracy navigation and 3D mapping, miniaturisation and adaptation of open-sea robotics technologies to new applications and environments, and the interpretation of geoscientific data.

The instrumentation carried by the UX1-neo gathers the necessary equipment to obtain valuable geoscientific, spatial, and visual data, while performing basic activities like movement and control.

The UX-1neo's subsystems need to work together to ensure that the robot's features work in any conditions. Together, the sensors, subsystems, and processing/autonomy elements allow the collection of valuable data, which cannot be obtained otherwise. It's also important to emphasise that the use of underwater robots allows operating in flooded mines without the need to remove water from said mines, a task with significant operational costs.

In short, the technological developments of INESC TEC in Underwater Robotics have a great impact on a global scale, with concrete applications in terms of underwater exploration and mining - both in flooded environments on land and in the deep sea. The developments presented always carry an intrinsic societal impact, and they aim to provide a global perspective on the subject, shedding light on the challenges, advancements, and potential benefits associated with underwater mineral prospecting and exploitation, and the monitoring of environmental impact assessment. By understanding the complex dynamics at stake, policymakers, scientists and stakeholders can make informed decisions to mitigate environmental consequences and promote the responsible and sustainable use of these valuable resources.

DIGITAL TWINS OF THE OCEAN

A UNIFIED TECHNOLOGICAL APPROACH TO UNDERSTAND, MANAGE, AND PRESERVE OUR FUTURE

A Digital Twin of the Ocean (DTO) can leverage on existing science assets to provide consistent high-resolution, multi-dimensional descriptions of the ocean, and to unravel its underlying processes. The DTO aims at being a place of digital co-creation, bringing together different disciplines and communities. It benefits from IoT data collection and transfer, including novel sensors, Big Data analytics and Artificial Intelligence tools.

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The oceans are the main regulator and stabilizer of the planetary ecosystem and its primary source of life.

Presently, many factors associated with human action (rising temperature, acidification, overuse of plastic...) are putting the homeostasis of such complex system at risk, seriously compromising the future habitability for humans and other species. In this context, we need to monitor a diversity of physical and chemical parameters at a global scale, to better understand, and learn to modify our actions in ways that promote the natural balance and regeneration capability.

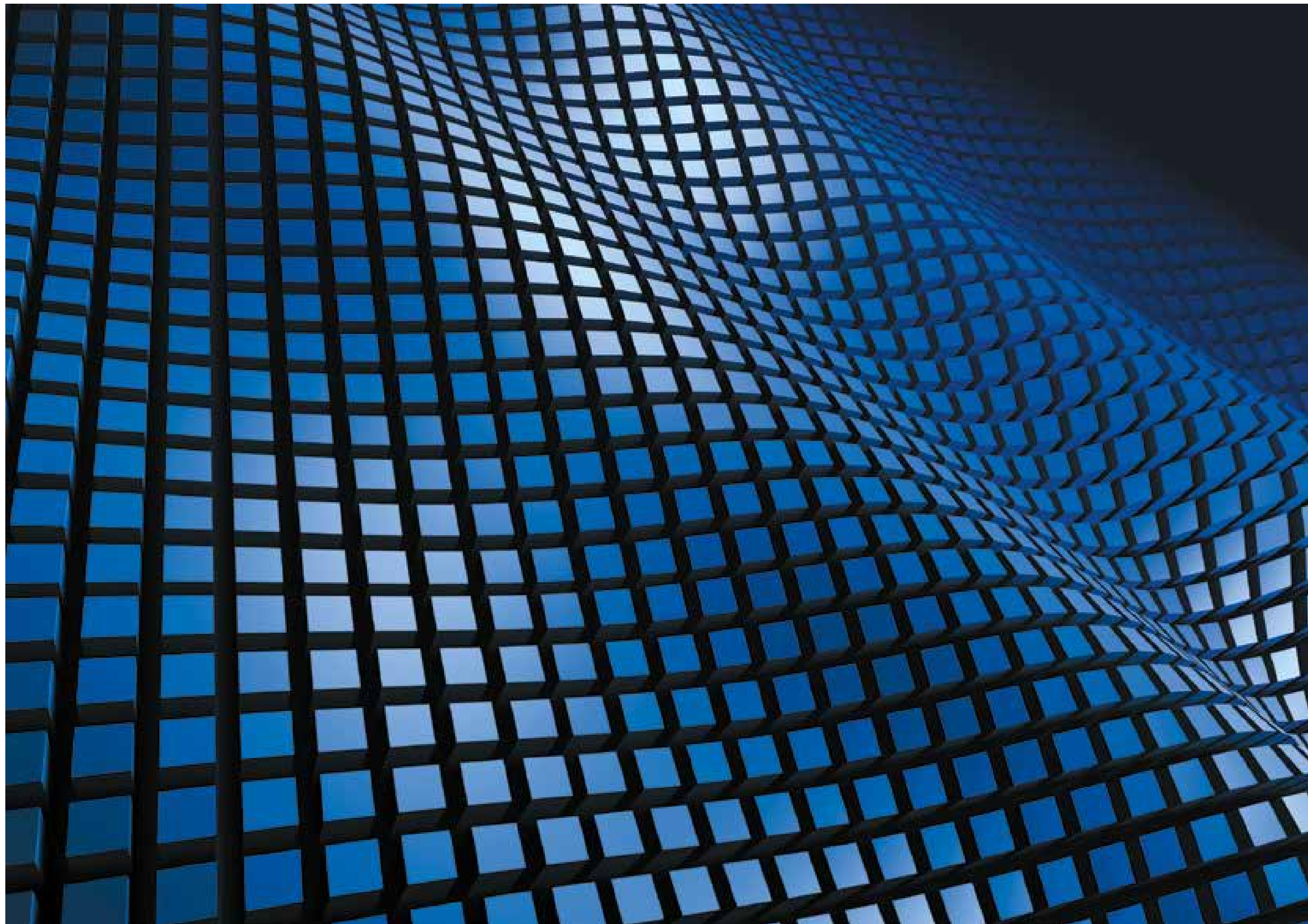
Ocean monitoring presents a diversity of challenges, starting from its vastness and dynamic nature, imposing the need for technological solutions that can cope with very demanding requirements. Continuous monitoring, covering large areas and a variety of depths, over extended periods of time, and measuring a multiplicity of parameters, such as temperature, pH, biodiversity or plastic content, requires a diversity of technologies, able to sustain performance under harsh conditions, and capable of gathering, storing and sometimes conveying huge amounts of data. It adds to this the huge logistic difficulties and costs of deployment, operation and maintenance.

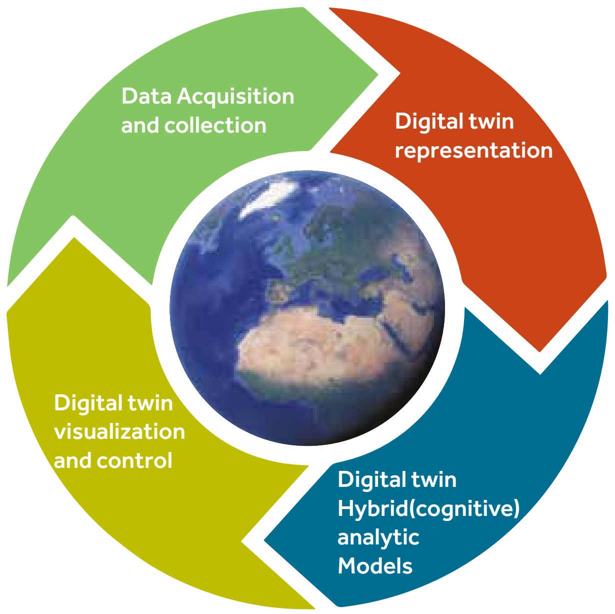
Considering the diversity of operational requirements, a large variety of solutions is being explored, both in what concerns the deployment platforms and sensing technologies.

While satellites enable remote planetary coverage, the cost and deployment challenges of such platforms are very high. In addition, their efficacy strongly relies on the development of more capable instrumentation, and present efforts include, for instance, developing sensors with wider spectral coverage, and strategies to circumvent atmospheric interference.

In this context, a large global initiative is in place to enable widespread development of Pico and nano satellites, standardise small-sized (<10kg) cube shape platforms, deployable at affordable prices, opening new possibilities for rapid technology testing, and increased participation in space missions by developing nations, small companies, and educational institutions.

Surface and underwater monitoring are more challenging, particularly in what concerns spatial and temporal coverage. For these reasons different platforms and sensing technologies are needed. Continuous monitoring of physical, chemical, and biological parameters in the marine environment over extended periods requires permanent or long-term operating systems.





Permanent ocean observatories include fixed subsea observatories, moored buoy systems, coastal monitoring stations and deep-sea observatories, and are often localized in strategic regions, providing focused monitoring rather than comprehensive coverage. Indeed, even if a growing number of such infrastructures is installed, the ocean area covered by permanent observatories is still relatively small in the context of the vastness of global oceans.

In this regard, mobile autonomous or drifting platforms, such as gliders and drifters, enable the coverage of much larger areas. The latter are buoyant instruments that move passively with the ocean currents, while the former are autonomous vehicles designed to move through the water column by adjusting their buoyancy. In addition to these, larger mobile autonomous platforms, such as landers, are a new and promising tendency that can enable reconfigurable observatories, that can actively get data from where it's most needed.

Ultimately the quality of collected data relies on the reliability of the sensor technology. Most common sensor technologies used include, acoustic, CTD (conductivity, temperature and depth), dissolved oxygen, fluorometry (indirectly measuring chlorophyll), and a diversity of detectors for optical properties such as turbidity, irradiance, absorption and scattering, from which different properties of the ocean waters can be inferred.

Present tendencies include miniaturisation of sensor technologies, enabling new functionalities such as automatic collection of samples for e-DNA analysis and multiparameter sensing. More robust and compact optoelectronics, coupled with advanced machine learning are empowering spectroscopic analysis such as plasma spectroscopy, hyperspectral or holographic imaging. Furthermore, the fusion of information from several platforms and/or sensors, coupled with artificial intelligence is greatly improving the quantity and quality of information that can be extracted from the data.

The creation of digital models is particularly relevant, materialising a platform where information can be integrated, interpolated and/or extrapolated, eventually bridging the gaps of the physical layers, and enabling a more holistic approach to the study of the ocean ecosystems.

Hence, a Digital Twin of the Ocean (DTO) can leverage on existing science assets to provide consistent high-resolution, multi-dimensional descriptions of the ocean, and to unravel its underlying processes.

The DTO aims at being a place of digital co-creation, bringing together different disciplines and communities. It benefits from IoT data collection and transfer, including novel sensors, Big Data analytics and Artificial Intelligence tools.

Digital twins shall make use of real-time and historical data to represent the past and present, as well as models to simulate future scenarios and support decisions about human interventions on the ocean.

The DTO is an asset that aims at servicing multiple types of users, such as researchers, entrepreneurs, decision-makers and citizens alike. As an example, researchers will be able to use the DTO to predict how climate change and human activity will affect marine ecosystems. Based on this knowledge, decision-makers will assess different management plans to choose the most efficient one.

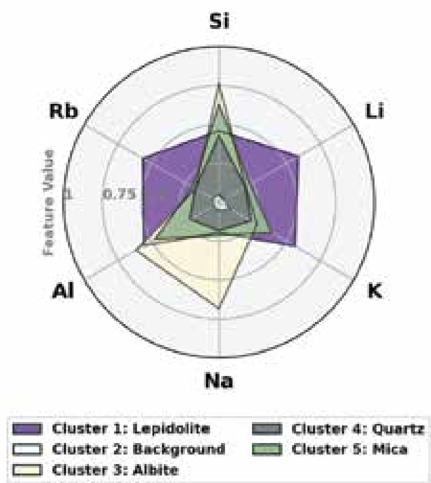
In the same manner, entrepreneurs will be able to use this asset to plan their activities at sea, accelerating the implementation of marine renewable energies, optimizing production and minimising negative impacts.

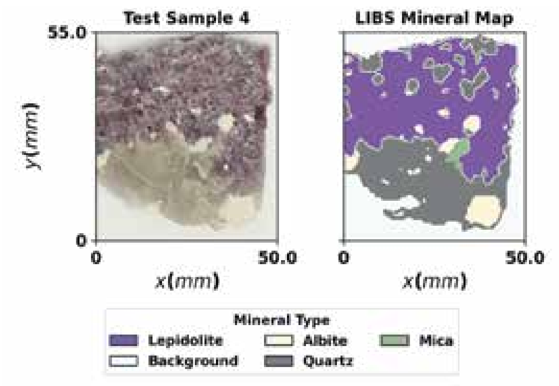
Last but not least, citizens are a vital part of this digital ecosystem, they will be able to contribute to biological and ecological observation campaigns which can be used to improve models. These models can then be applied for other purposes such as generating alerts for extreme weather events, predicting local jellyfish blooms, or identifying safe and clean swimming spots.

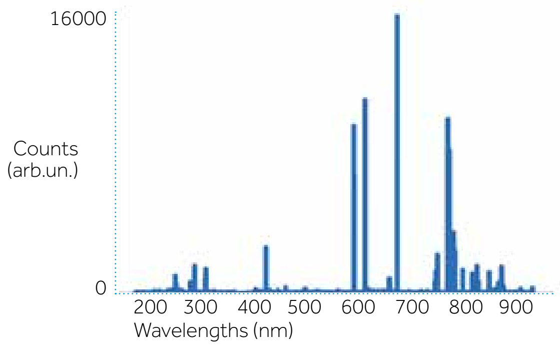
Beyond the wealth of high-quality data, the DTO will also make scientific state-of-the-art models representing different components of the ocean system more accessible and easier to combine, enabling transdisciplinary scientific approaches, revolutionizing work practices, and helping to make science-based, informed decisions.

The completion of these scenarios heavily relies on a well-planned and maintained network of multiples observational platforms, overlayed with an effective communication network, and a powerful computational capability.

The challenges at hand require substantial critical mass in terms of technology, financial support, and political engagement. For these reasons, most relevant initiatives are promoted either by governmental agencies of large rich countries or private-non-profit organisations. In both instances, they tend to operate at an international level, tackling not only the technological problems but also socio-economic and environmental sustainability, influencing policy making and promoting public knowledge and initiatives. These initiatives should also be fostered and promoted, at a private level because such a global challenge can only be met by a united global response. It is time to unite or perish.







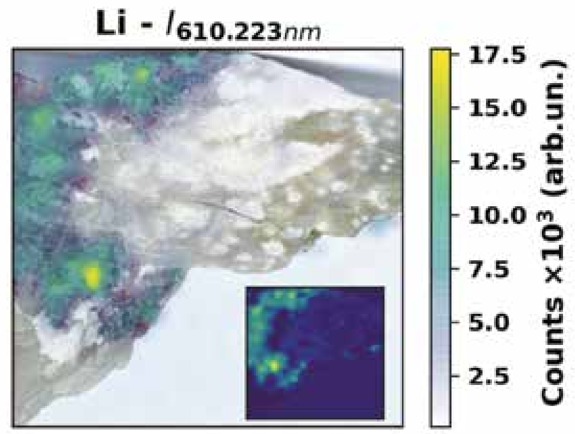


Figure 1 Contributions towards augmented reality an autonomous mining systems. The fusion of Laser induced Plasma Spectroscopy, with machine learning and advanced processing techniques, enable automatic mineral identification, and 3D visualization of the analysis result on the real object.)(Photo credits: Tomás Lopes, Nuno Silva, Pedro Jorge).

THE ROLE OF ROBOTICS IN THE ASSESSMENT AND PROTECTION OF MARINE ECOSYSTEM SERVICES **A REFRESHING LOOK AT THE OCEANS**

The use of robotics in the evaluation and protection of marine ecosystem services enables a more efficient and precise approach, contributing to informed decision-making and the development of more effective preservation strategies. With the sustained advancement of robotic technology, new solutions and innovations are expected to take place, further advancing the positive impact of marine robotics on the protection and preservation of marine ecosystems.

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Oceans play a key role in society and are extremely important to our well-being and survival. They provide a wide range of essential ecosystem services, like regulating global climate, absorbing a significant amount of carbon dioxide, providing food and marine resources, and harbouring an impressive diversity of marine species. However, the oceans face several challenges, e.g., overfishing, pollution, climate change and the degradation of coastal habitats. Protecting and assessing ocean ecosystem services is crucial to ensure the health of marine ecosystems and the livelihoods of coastal communities. This involves creating marine protected areas, establishing sustainable fishing practices, reducing marine pollution, and promoting the preservation and requalification of coastal habitats. The assessment of ocean ecosystem services allows for an in-depth understanding of the benefits provided by marine ecosystems, facilitating informed decision-making for the sustainable management of marine resources and the preservation of marine biodiversity.

Protecting and assessing ocean ecosystem services is essential to ensure the health and resilience of marine ecosystems, as well as the well-being of human communities that depend on these valuable resources.

This is where robotics comes into play! Robotics plays a crucial role in assessing and preserving marine ecosystems, allowing access to remote and hostile areas that would rather be difficult to access or dangerous for humans. INESC TEC's Centre for Robotics and Autonomous Systems has been developing several types of robotic systems capable of operating in various scenarios with a direct impact on marine ecosystem services.

There are several ocean ecosystem services; in this sense, the robotic applications developed by INESC TEC are also diversified, with applications in different scenarios.

Remote monitoring is one of the main focuses of INESC TEC underwater robotics solutions. Underwater robots equipped with advanced sensors can collect real-time data on water quality, temperature, salinity, pH, and other environmental parameters. This data is crucial to understand changes in marine ecosystems while identifying potential threats like ocean pollution or acidification.

In this context, it's important to point out INESC TEC version of the EGIM (EMSO Generic Instrument Module), a system developed by EMSO consortium and optimised by INESC TEC allowing its integration

Figure 1 **Photo credits: Hugo Ferreira**

Figure 2 Turtle III in operation on the seabed off Sesimbra (Portugal).(Photo credits: @Iris)

with robotic systems as well as standalone operation. This system is focused on ocean monitoring and observation. The EGIM system is designed to collect data continuously and consistently, from the water column and seabed. The European Multidisciplinary Seafloor and Water Column Observatory (EMSO) aims to implement EGIMs in several underwater observatories in Europe for the collection of standard and quality data. The EGIM consists of a standard set of sensors, which allows its integration into any node of the system of underwater observatories of the EMSO network. One of the objectives of EMSO is the distribution of EGIMs in various ocean locations to collect a set of variables that are measured homogeneously, using the same sensors, hardware, processes, and data format, enabling the use of standard analysis methods and the exchange of data – namely that related to conductivity, temperature, pressure, dissolved oxygen, turbidity, acoustic hydrophone, high-precision pressure, speed and direction of ocean currents. This data supports the Global Ocean Observing System – Essential Ocean Variables, the marine strategy framework directive for assessing environmental status and marine environmental changes.

Another type of device used for ocean monitoring is the TURTLE.

TURTLE[1] is a hybrid robotic lander, capable of remaining on the seabed for long periods of time, moving autonomously and emerging for maintenance operations. This robotic system is also capable of descending and ascending the water column with high energy efficiency, and its autonomous resources allow for reduced operating costs and flexibility.

TURTLE is the first deep-water robotic system fully developed in Portugal, operating since 2015. Since the first version, three newer versions have already been developed: the TURTLE II in 2018, the TURTLE III in 2019 (Figure 2) and the Turtle IV in 2022. The most significant changes were in the variable buoyancy system and batteries, which allowed a significant reduction in weight and size - with the first version weighing about one and a half tons and the most compact 600 kg. These robotic landers can withstand pressure up to 4km deep, with an autonomy that can go up to several months. This type of robotic system is very versatile and can be used for longer periods of time and in different application scenarios: transport and deployment of materials and tools to the seabed; communications and navigation support for underwater systems; ocean observatories; marine biology monitoring; oceanography; seismic and acoustic activity monitoring; port protection; border monitoring and intrusion detection; etc.

Other crucial elements to monitoring and evaluating ecosystem services is mapping and cartography, together with the oceans' bathymetric information.

Figure 3 Photo credits: Alfredo Martins / André Dias

Underwater robotics can support the mapping of the seabed, coral reefs, ocean floor and other geographical features. The ROAZ Autonomous Surface Vehicle (ASV) has been operating for more than 20 years, and is mainly used for bathymetry operations up to 100m deep, as well as to support other missions. Concerning the scenarios that require the mapping of deep sea with higher resolution, INESC TEC has developed several Autonomous Underwater Vehicles (AUV), like EVA (figure 4) - which allows the exploration and autonomous mapping of the seabed with high resolution, up to 1500m deep. Unlike ASV, these types of vehicles can navigate close to the seabed, providing them with an extremely detailed observation and mapping capability. These detailed maps are vital to understand the distribution and diversity of marine habitats, as well as to identify sensitive areas that require further preservation.

From another perspective, the Space-Atmosphere-Ocean interaction is also a very important subject to understand the climate and associated changes. The low clouds that extend over large areas over the oceans significantly influence the terrestrial radiative balance and, consequently, the regional and global climate. These processes are complex and involve multiple interactions, including connection between surface flows of heat and humidity, and interactions between clouds, aerosols, and precipitation - which are influenced by the electrical properties of the atmosphere, as well as by interactions between the Earth and the Sun. The understanding of these processes is still very incomplete, partly due to the lack of observations on the ocean, resulting from the difficulty of performing marine measurements in situ. The SAIL project focused on integrating equipment into the NRP Sagres vessel for its circumnavigation expedition in 2020, with a series of sensors dedicated to atmospheric properties (electric field, visibility, ions, and radioactivity) and space-related parameters (GNSS, gamma radiation and irradiance).

Biodiversity studies are also crucial to the current assessment of ecosystem resources. Underwater robots can be used to collect biological samples like marine organisms, sediments, and water. These samples allow the analysis of marine biodiversity, the identification of endangered species and the understanding of ecological patterns.

Concerning this area, it's worth highlighting the MarinEye project [2], which focused on the development of an autonomous and integrated marine chemical, physical and biological monitoring system. This system combines high-resolution imaging systems, acoustics, sonar, water filtration systems for DNA collection, and sensors in a modular and compact system that can be deployed on fixed and mobile platforms. Hence, the autonomous monitoring system developed combines

Figure 4 Photo credits: Alfredo Martins

a set of technologies capable of providing data that allow an integrated view of the different areas of the ocean (physical, chemical, biological), according to different types of knowledge (from genomics to biogeochemistry and from micro to macro dynamics of communities), synchronised in time and space. The ability to simultaneously monitor biological, chemical, and physical data allows us to answer questions about how organisms interact with their environment and with each other, and how these interactions influence the overall stability of the ecosystem. The integration of an image sensor capable of observing zooplankton and phytoplankton, together with the possibility of simultaneous DNA collection, allows the identification and visual classification of microorganisms with associated DNA information. These features are particularly important to study the organisms that constitute the vast majority of ocean biomass and are at the base of the entire trophic chain - therefore critical to the health of marine ecosystems.

MarinEye also includes a centralised database infrastructure that aggregates all the various data sources (physical, chemical, biological) collected by the different modules. This database powers a data visualisation and summarisation platform that provides synthetic summaries of major system events to simplify data analysis. In addition, the platform also implements several modelling tools to discover unsuspected and useful patterns that may exist in the physicochemical and biological data sets generated. This device will increase knowledge of the oceans, complementing existing ocean observatories by providing new integrative data not currently provided. MarinEye will play an important role in the consolidation of infrastructures dedicated to the observation of the marine environments. The biological sampling component has gathered a great deal of interest from the scientific community. With this in mind, INESC TEC's Centre for Robotics and Autonomous Systems has put in substantial actions to optimise the bio-sampler and DNA collection system.

This innovative bio-sampler and DNA collection solution, integrated into the Marineye system, can also be used as an autonomous sensor: in fixed moorings situations, in ddeployments from small vessels, or integrated with robotic vehicles.

A particularly relevant example of the application of this type of sensors is the study of the impact of climate change on sensitive marine ecosystems like the polar regions. This sensor will be used as early as the summer of 2023, integrated with the underwater robotic vehicle IRIS, namely in biological data collection campaigns in the Arctic Ocean.

IRIS is an AUV that can also be used in remote operation mode. The AUV IRIS, characterised by its small dimensions, combined with the positioning and autonomous navigation, on-board data processing and acoustic and optical sensors, is the ideal vehicle for operations in polar environments. It combines reduced logistical and operational needs with significant data collection cabilities, as well as the transport of specific sensory payloads e.g., the DNA bio-sampler.

Characterisation and monitoring of vulnerable ecosystems: robots equipped with cameras and sensors can monitor and help characterise areas with vulnerable ecosystems, which must be protected from overfishing or the use of destructive methods. These systems can support decision-makers in implementing fishing legislation and preserving fish stocks. Concerning these processes of monitoring and evaluation of ecosystem services, it's worth mentioning the campaign carried out with the EVA robot for the evaluation of vulnerable marine ecosystems (VME), in an area with depths between 550 and 640m, off the coast of Sines.

Waste cleaning: the development of underwater robots to detect and remove waste and debris from the oceans, including plastics and other pollutants, is also a solution. This action contributes to the preservation of marine ecosystems and the reduction of the negative impact of pollution.

INESC TEC participated in the NETTAG project, whose main objective is the reduction of fishing gear lost by fishermen, raising that community's awareness of the topic, and creating a technological solution that can be inserted into the fishing nets, enabling location and recovery. Moreover, the project focuses on the development of acoustic tags and a robotic system capable of locating the lost fishing nets.

Also in the field of marine pollution it's worth highlighting the SPILLESS project, which explored the identification and remediation of hydrocarbons in water close to port areas. The project featured a drone that mapped and released bacteria with bioremediation traits, supported by the aforementioned ASV ROAZ.

In conclusion, marine and underwater robotics has proven to be a powerful ally in the protection and preservation of marine ecosystem services. Through the development of underwater robots equipped with advanced sensors and autonomous systems, it is now possible to remotely monitor marine ecosystems and collect real-time data on various environmental parameters.

Said data is crucial to understand the changes taking place in the oceans, while identifying potential threats like pollution and ocean acidification. In addition, underwater robotics plays a key role in the study of marine biodiversity, enabling exploration of remote and hazardous areas for humans, providing valuable data for the preservation of marine life.

The use of robotics in the evaluation and protection of marine ecosystem services enables a more efficient and precise approach, contributing to informed decision-making and the development of more effective preservation strategies. With the sustained advancement of robotic technology, new solutions and innovations are expected to take place, further advancing the positive impact of marine robotics on the protection and preservation of marine ecosystems.

Therefore, investing in the development and application of marine robotics is crucial to ensure the health of the oceans, the preservation of marine ecosystem services, and the well-being of communities that depend on these vital resources. Only through an integrated approach, combining scientific knowledge, advanced technology, and preservation actions, can we meet today's challenges and ensure a sustainable future for our precious marine ecosystems.

[1] Eduardo Silva; Alfredo Martins; Jose Miguel Almeida; Hugo Ferreira; Antonio Valente; Mauricio Camilo; Antonio Figueiredo; Claudia Pinheiro. "TURTLE - a robotic autonomous deep-sea lander". 2016.

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MODULAR ROBOTICS FOR OCEAN ASSESSMENT
A RESEARCH PROGRAMME AT INESC TEC

INESC TEC is leveraging the modularity of the vehicles and docking stations to validate an innovative ocean observation paradigm. This approach involves combining the mobility of the vehicles with the advanced capabilities of a new generation of "smart cables."

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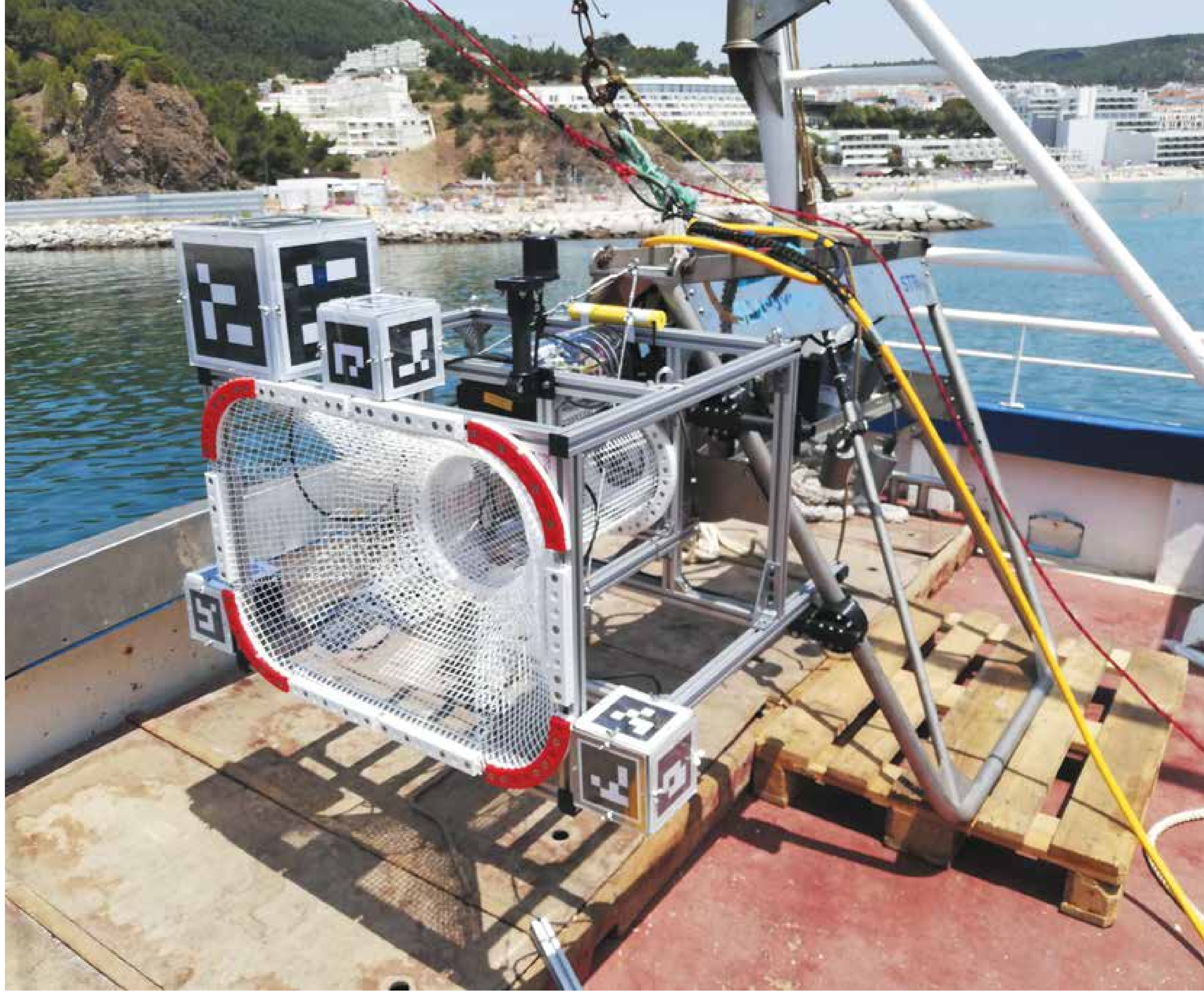

Figure 1 Photo credits: Nuno Cruz

The adoption of autonomous robotic platforms for the exploration and exploitation of the ocean has been steadily increasing throughout the last decades. The benefits of these platforms in terms of costs reduction, gains in amount and quality of gathered data, time and space extension of operations, or the increase of operations safety are already field validated, highly contributing to the maturity of this technology.

There are already multiple commercial solutions, addressing different applications and several operational scenarios. Hundreds of end-users worldwide are currently employing and benefiting from platforms. At the same time, they bring novel requirements and opportunities pulling new developments and novel research questions.

The continuous progress of autonomous underwater robots mainly lies on the innovation results on the underlying technologies. Major advances in electronics (miniaturisation, power efficiency, etc.), batteries (increase of energy to volume or energy to mass ratios), perception sensors (increased resolution and sensitivity in digital cameras, higher resolution and frequency bands in hyperspectral cameras, and better resolution in sonar systems.), or navigation sensors (improved accuracy of inertial systems and acoustic based speed sensors), among others, are at the basis of the ever increasing capabilities of these platforms.

But taking fully advantage of such underlying technologies is not a trivial task. It requires extensive and in-depth research leading to the proposal of novel solutions to fundamental robotic operation questions: navigation – determination of position, attitude, and velocity of the robot; guidance – definition of a plan towards the attainment of a mission goal; and control – implementation of actions defined in the plan.

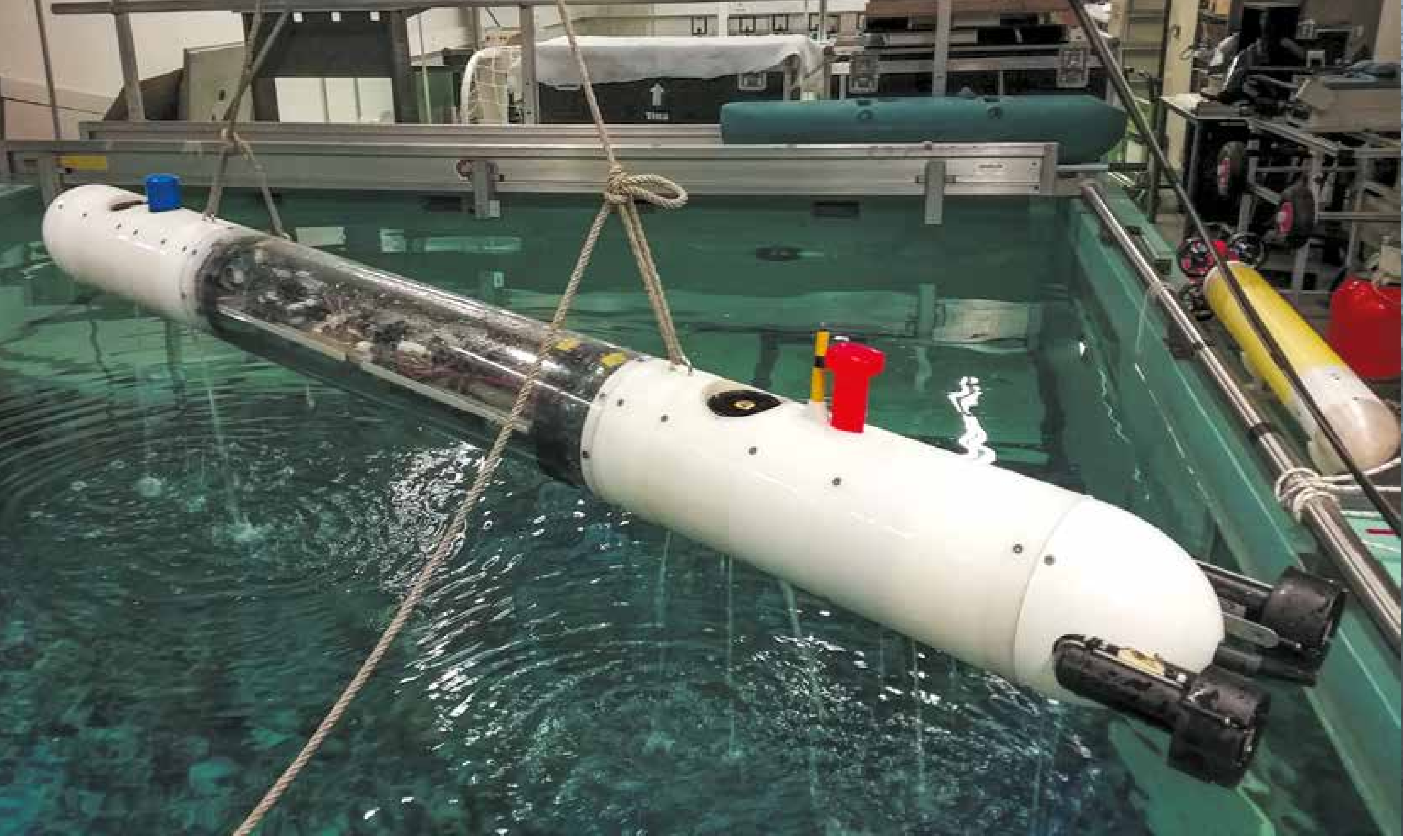

Figure 2 Photo credits: Nuno Cruz

Figure 3 Photo credits: Nuno Cruz

Additionally, as these platforms have specific mission goals, research efforts also address issues related to the acquisition of payload data or with end-effector operations.

Furthermore, as oceanic environments are harsh and not yet fully characterised, all these research efforts require experiments, ultimately in real operational scenarios.

Considering these aspects, a sustainable research programme in underwater robotics must not only address the more fundamental research questions, that naturally evolve with time and are partially driven by the available underlying technologies, but also to be supported in an experimental setup that enables a systematic validation of proposed solutions.

In this article we describe how modular solutions for underwater robotic applications have played a critical role in the research that has been carried out at INESC TEC for the past 15 years.

AUV MODULES

The roots of these developments emerged during the 1990s, when a research group explored the development of control algorithms and acoustic tracking systems for partner institutions' autonomous underwater vehicles (AUVs). The experience gained from utilising these vehicles played a crucial role in identifying key characteristics for a new generation of AUVs. Firstly, it was essential for the vehicle to possess a highly modular design, enabling easy reconfiguration (such as sensor swapping or addition) and independent subsystem development. Additionally, a streamlined construction was necessary to minimise drag in the desired direction of movement. Size and weight reduction were also prioritised to facilitate deployment and recovery from smaller support boats, eliminating the need for complex and costly logistics.

Regarding manoeuvrability, conventional portable AUVs featured a torpedo-shaped body with rear propellers and control surfaces (fins) for diving and steering. Although efficient during motion, these systems required a minimum forward velocity for the control surfaces to be effective. Consequently, people realised that this new generation of vehicles should possess full attitude control, even at zero velocity, allowing for unrestricted approaches to underwater targets.

The development of these small-sized AUVs relied on the use of modular building blocks. This modularity encompassed various aspects, including hardware construction, electronic subsystems, software, and control. The most clear sign of modularity in these building blocks stemmed from the design of the hull sections. To assemble AUVs using modular components and achieve a seamless overall profile, the sections were designed with matching edges and consistent cross sections, featuring an outer diameter of 200mm. This dimension struck a balance between a compact size for manageability and enough space to accommodate dry compartments for electronics and a diverse range of wet sensors. Additionally, a variety of materials, such as plastics and common metals, available off the shelf as rods or tubes, could be machined to meet this dimension.

The modules were engineered with an identical male/female coupling system, secured in place by evenly distributed radial set screws along the perimeter to allow rotation. They were divided into three classes: 1) Dry compartments, which were cylindrical enclosures designed to withstand hydrostatic pressure and featured connectors in the end caps; 2) Wet extensions, consisting of water-filled cylindrical sections with a male termination at one end and a female termination at the other, facilitating stacking, interchangeability, or direct attachment to the dry compartments; 3) End sections, encompassing water-filled nose cones and tails that formed the bow and stern of the AUV, accommodating various configurations of propulsion thrusters.

MODULAR AUVS

Using these building blocks, the initial vehicle was the MARES AUV (Modular Autonomous Robot for Environment Sampling), a portable AUV capable of hovering. Since its inception, in 2007, the MARES AUV has undergone continuous updates and has been deployed in various configurations in the field. The primary objective behind its design was to create an open architecture system for conducting underwater robotics research, specifically tailored for operations in coastal waters, with the ability to hover within the water column.

The MARES AUV consisted of a single dry compartment, measuring 60cm in length, housing all electronic boards, while the batteries were positioned at the bottom to lower the centre of gravity. Attached to each side of the dry compartment were the wet extensions, which incorporated payload sensors, communication devices, and through-hull thrusters, enabling independent control of vertical velocity and pitch angle. This setup allowed for operations in highly confined areas, with virtually separate horizontal and vertical motion even at 0 m/s velocities. This unique feature distinguished the MARES AUV from other AUVs of similar size and weight: depending on configuration, MARES versions ranged from 1.5 to 2 meters in length, with 35 to 45kg of dry mass. Furthermore, the system's modularity facilitated the integration of additional sensors or thrusters, such as those used for sway control. Additionally, a module with vertical and horizontal fins could be added to enable more traditional control modes.

Over the course of 15 years, the adaptable MARES architecture has been instrumental in collecting oceanic data across diverse application scenarios, spanning from pollution monitoring to traditional and cutting-edge mapping techniques. These endeavours have taken place not only in Portugal, but also internationally. Simultaneously, this programme has provided support for the experimental validation of outcomes derived from PhD theses and MSc dissertations over the past decade.

In 2011, a significant milestone was achieved in testing the maturity and versatility of the system components with the development of TriMARES. TriMARES, a 75kg, 3-body system, was designed to meet the specific requirements of a Brazilian consortium seeking a hybrid ROV/AUV solution. This innovative system incorporated high-definition cameras and sonars, enabling efficient inspections of hydroelectric dams. Leveraging the modularity of the MARES architecture and the simplicity of the building blocks, the development of TriMARES was successfully completed and transported to Brazil within an impressively short timeframe of just over six months.

Subsequently, in 2017, another significant milestone was accomplished through the development of DART (Deep Autonomous Robotic Traveler), a portable AUV designed for operations up to 4000 meters deep. A notable breakthrough was replacing the original dry compartment, constructed from polyacetal copolymer (POM), with a pressure housing composed of borosilicate glass, carefully adapted to align with the coupling of the wet extensions. Additionally, all sensors and actuators that came into direct contact with water were substituted with versions capable of withstanding pressures of at least 400 bar. This vehicle played a pivotal role within the system and notably contributed to the successful participation of the Shell Ocean Discovery XPrize, resulting in the Portuguese team receiving a share of the $1 million prize awarded to the finalists of the competition.

EXPANDING THE USES OF AUVS

One prevalent constraint of AUVs is the limited onboard energy, which imposes a maximum endurance for the vehicle. Another limitation pertains to communication, as electromagnetic signals experience significant attenuation in saltwater, effectively blocking RF-based technologies. To overcome these limitations, the concept of underwater docking stations has gained popularity. These stations function as underwater garages, providing mechanical protection against the elements while also serving as wireless charging stations and facilitating short-range, high-data-rate communications for AUVs. INESC TEC has conducted extensive testing of diverse docking station versions, including both the conventional "funnel-shaped" design

Figure 4 Photo credits: Nuno Cruz

and the innovative "cradle" configuration, capitalising on the hovering capability. These enable secure docking and recharging for AUVs assembled using the building blocks. In fact, the inherent modularity of the building blocks provides significant advantages in accommodating independent developments that evolve at different paces. In the context of these docking stations, bespoke modules were specifically designed and validated to seamlessly integrate close-range communication devices, underwater structure perception sensors, and wireless power transfer functionalities.

Within a broader scope, INESC TEC is leveraging the modularity of the vehicles and docking stations to validate an innovative ocean observation paradigm. This approach involves combining the mobility of the vehicles with the advanced capabilities of a new generation of "smart cables." These enhanced fibre optic communication cables span across the oceans, equipped with distributed sensors that enable ocean observations on a basin scale. Under this new paradigm, the repeaters positioned along the communication cables serve as anchors for local observatories and function as "service stations" for AUVs. These repeaters not only provide energy to recharge the AUVs' batteries but also serve as information gateways, facilitating internet access for data exchange. This integration of modular vehicles, docking stations, and smart cables establishes a symbiotic relationship that promises to revolutionise ocean observation capabilities on a global scale.

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