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Introduction

The technological advancements introduced through the last decade have brought disrupting effects in modern society, often offering solutions to practical problems that would otherwise remain devoid of sustainable answers. The core principle of this revolution revolves around achievements attained in the field of semiconductors which underpinned subsequent developments in the design of small-sized chipsets able to support the functioning of computing devices and infrastructures more efficiently and requiring moderate amounts of power compared to former designs. This has played a seminal role in the strides covered by industries in the formulation, development and rollout of enabling factors such as cloud computing, Internet of Things and revolutions in the field of satellite-based telecommunications bridging the gaps of intensively data-centric processes spanning any field of science and governance. This is particularly true in the domains relating oceans and seas, where technologies are now changing the kind, definition, amount and reliability of information collected and made available for monitoring, control, management and scientific purposes which, coupled with emerging frameworks and methodologies based on artificial intelligence (AI), contribute to the daily work of national authorities and institutions including Regional Fisheries Management Organizations (RFMOs) in carrying out their mandates.

Fighting illegal fishing and streamlining fisheries management through modern hardware, software and technology services - recent developments and opportunities

Since the early 2000s the need to ensure effective control measures to curb Illegal, Unreported and Unregulated (IUU) fishing activities prioritized the introduction and use of cutting-edge technologies in the field of Monitoring, control and surveillance (MCS). The most evident of these effects relates to the evolution of on-board transponder units applicable to vessels, especially those engaging in fishing activities, where upfront costs, size of equipment and technical requirements were progressively reduced over time while enhancing their ability to more reliably address their control role by leveraging multiple telecommunication networks (i.e. satellite and cellular) and incorporating short/medium-range communication interfaces based on IoT technologies (i.e. Bluetooth Low Energy, LoRaWAN etc.) that also enabled these devices to collect and relay real-time data on the use of fishing gears and fuel consumption. All of this radically changed the spatio-temporal perspective from which it was possible to collect, process and analyze these quantities, with clear beneficial effects for scientific and management practices aimed at attaining rational exploitation of marine living resources and moderating the environmental impact of anthropogenic factors in general. IoT tools designed for the MCS domain also improves opportunities to protect marine environment, as is the case for electronic gear tagging, which can help reduce IUU fishing, track lost gears and curb ghost fishing.

Modern electronics leveraged by on board MCS tools depend less and less on employes, high-capacity batteries or stable power sources for transmission of location data and this has opened the door to the design of solutions tailored for small-scale fishing (SSF) vessels based on satellite or cellular connectivity. This can be of particular relevance in some regions, such as the Mediterranean and the Black Sea, where SSF vessels still constitute roughly 80% of the overall fishing fleet and, beyond mere monitoring and control, this kind of on-board devices could also be employed to enhance safety at sea, for instance by implementing features able to trigger distress alerts through the Global Maritime Distress Safety System (GMDSS). On the other hand, fitting modern features on SSF-specific devices still implies expensive design solutions to extend battery life and optimize operational continuity (i.e. by using embedded, high-performance solar panels).

The strive to formulate affordable monitoring solutions that may turn acceptably accurate for SSF vessels created the conditions to seek the reutilization and modernization of tools originally conceived for collision avoidance purposes, as in the case of AIS, for which the MCS industry has been rolling out, over the last six years, transponder solutions based on low-power (Class-B) AIS. While these solutions clearly relieve vessel operators from recurring airtime costs, the presence of a high noise floor due to the density of surrounding telecommunications in certain regions make this approach suitable for a limited array of cases and most certainly requires the use of signal detection/reconstruction services hosted on Low-Earth Orbit (LEO) satellites incorporating AI algorithms able to detect tampered or spoofed AIS signals. The same generation of LEO constellations recently enabled the capacity to detect radiofrequency emissions (RF) from vessels' navigation equipment and, while fingerprinting these signals is still not viable, the accuracy of detection rates is rapidly increasing and some MCS data providers are already able to combine resulting data with satellite imagery including Synthetic Aperture Radar (SAR) and Visible Infrared Radiometer Suite (VIIRS) to spot vessels that may purposefully have deactivated or tampered their vessel monitoring system (VMS) and AIS transponders.

Such novelties were coupled with advancements that have impacted another crucial pillar of MCS solutions, namely VMS platforms used by national fishery monitoring centers (FMCs) and RFMOs, which benefited from the advent of cloud computing in many ways. Cloud platforms had an important impact on the software industry, which has streamlined its delivery models, development frameworks and design practices: the most visible effects for MCS purposes are the presence on the market of VMS platforms that are now modular by design, thus allowing the gradual introduction of additional features (i.e. compatibility with new transponder models, gear sensors, data representation functions or interoperability provisions with 3rd party systems) without implying major redesign in most cases. In addition, these software solutions are nowadays cloud-ready (if not cloud-native), thus delivering the possibility to either host them on a cloud infrastructure managed by competent national authorities/RFMOs or even be made available by VMS software providers in a Software-as-a-Service (SaaS) model. Either case allows to avoid upfront monetary commitment for underlying physical server infrastructures (that formerly required on-premise to host these systems), ensures fault tolerance more affordably and often benefit from the intrinsic elasticity of cloud architectures that can support growing computational needs (as can be the case when covering additional fleet segments with MCS tools, increasing reporting frequency, introducing electronic logbooks or the use of ancillary sensors reporting on gear status or fuel consumption). All of this also provides the possibility to leverage the flexibility of cloud infrastructures to apply AI frameworks to the analysis of real-time and historical datasets of diversified nature, thus enabling correlation and forecast of unprecedented accuracy and complexity which can help identifying anomalous patterns and spot potential IUU activities (like unauthorized/unreported transshipment). It is reasonable to believe that such instruments could, in time, also help rationalize time and resources devoted by control authorities to effectively perform their duties.

Integrating MPAs, OECM and VMEs maps into VMS system for improved MCS

Since the introduction of VMS, multiple studies have assessed the collected data as a tool to estimate the fishing effort and potential impacts from fishing activities on habitats and species and the impacts of regulatory and protected or conservation areas. The VMS technology has proven effective for offshore fleet monitoring and surveillance, but there is little data on the interaction of smaller fleets in near shore areas, where most of the coastal protected and conservation areas are set. There is a need to incorporate the spatial data of marine protected and conservation areas listed by World Database on Protected Area WDPA1 into the VMS chart/plotting systems. This will reduce the administrative burdens and potential conflicts of overlapping authorities among different national agencies, as often protection and conservation are under the tutelage of a different administration than fisheries. This overlap often leaves grey areas and opportunities for IUU activities for fisheries, under the pretext that they were not informed. Hosting the maps or boundaries of protected and/or conserved areas as built-in feature on VMS would void any excuse by fishers/skippers that they were not aware of the boundaries or measure of conservation applied. Acquiring the maps is an easy and reliable process, WDPA is an authoritative source of data on protected areas and other effective-based conservation measures (OECM). Maps are provided by governments and other stakeholders to map, monitor and report data on protected areas and OECMs.

Hurdles in the implementation of MCS tools and practices

Despite the significant drop in prices of the component and hardware used for VMS, in most cases the technology itself is still niche and expensive for inshore fisheries and developing/low-income countries. Often it relies on satellite connection packages which are costly and require annual subscription and in certain countries military or ministry of defence clearance. Moreover, the bulk of existing solutions on the market today are addressed, in terms of design and features, to commercial and offshore fishing fleets. Some suppliers have ventured into localized solutions for in-shore fisheries and small-scale fisheries, but the lack of clear region-wide technical requirements and the limited market opportunities are often hampering investments by manufacturers to optimize device design for modular and mass-production processes that might allow for cheaper products for the end users. In this respect, the role of RFMOs is pivotal to ensuring cooperation with member countries in identifying clusters of cross-cutting MCS needs at regional level, while taking into account specificities of national fleets, that may be helpful to prepare harmonized technical specification frameworks to possibly incentivize participation from local tech-startups and cater tailor made solutions.

With the increasing probability of becoming a mandatory solution on all fishing vessels, VMS service providers will have to adapt to the various needs, vessel types and operational spans. The role of RFMOs is crucial to determining if and how this technology can be used in fisheries operating within confined areas such as harbours, estuaries and associated MPA boundaries. Also, the reporting rate will have to be tailored to the different operations, seasonality of the work, as small-scale fisheries do not have the same year-round operation and trip time as the commercial fleet: this crucial point might be addressed by alternate (pooled) connectivity pricing schemes negotiated for the whole fleet in terms of overall Kilobytes (KB) transmitted. This would allow the compensation of extra costs deriving

[1] World Database on Protected Areas; https://www.protectedplanet.net/en/about

from the need to employ transmission intervals narrower than those used in traditional MCS scenarios. National authorities must also adapt. Deploying VMS solutions is not only about the hardware and connectivity, but a set of policies, regulations and legislations needed to steer the operation and achieve desirables results. There are national regulations for the domestic fleet, and special regulations governing the international fleet operating in territorial or EEZ of each country based on existing agreement and arrangements. Investing in human capital is crucial to ensure that the flow of data received by the transponders to the monitoring centre is not only processed and addressed in real-time, but appropriately leveraged for MCS, fisheries management and safety at sea.

Use of MCS data to bolster fisheries management and scientific research – challenges and emerging opportunities

MCS tools were conceived for control and safety purposes, especially given the high costs implied in early implementations of underlying technologies. For this reason, resulting information systems (i.e. VMS software platforms and equivalent) were often built as information siloes with limited interoperability provisions, mostly required for very specific applications, such as FMC-to-FMC or FMC-to-RFMO location/logbook data exchange, as it the case for the North Atlantic Format (NAF) which for a long time played the role of de-facto industry standard for this purpose. Due to this, integrating MCS data with information gathered and collated by national fisheries information systems (FIS) often resulted in complex data which, ultimately, made data exchange with 3rd parties (i.e. RFMOs) a difficult task. This had limiting effects on the possibility to exploit such information, even at aggregate level, for scientific purposes of management advice on a regional scope.

The need to bridge this and other gaps stemming from the lack of scalable regional and global data exchange formats and exchange standards inspired the United Nations to develop, through the UN/CEFACT2, the “United Nations Fisheries Language for Universal eXchange” (UN/FLUX) a single, universal standard with global coverage harmonising technicalities stemming from data exchange needs for fisheries. This standard, consisting of a many-to-many content-agnostic "Transport Layer” (TL) and a growing set of “Business Layers” (BL) addressing information domains spanning, helping to track fisheries activities, improve traceability of related products from catch to sale and underpin sustainable fisheries management, in line with the principles of the UN Sustainable Development Goals (SDG) 12 (responsible production and consumption) and 14 (life below water). This instrument has been already embraced by several governments, control and enforcement authorities and RFMOs and is paving the way to facilitate the integration with fisheries information systems and analytical platforms able to combine, for instance, fisheries, control and environmental data, thus supporting the assessment of the status of fish stocks, suggesting richer correlation scenarios between anthropogenic and environmental factors and ultimately underpinning the formulation of effective management measures.

Cutting-edge technologies and multi-purpose, autonomous oceanographic stations: Smart Buoys

Recent technological trends and innovation in several fields including IoT have allowed the development of solar-powered smart buoys equipped with sensors and designed for the collection of in-situ marine environmental data. Depending on the specific design and specialized purpose, this tool can monitor traffic and hydrometeorological conditions, sample the water and communicate with its surroundings. By integrating IoT and satellite connectivity, smart buoys provide a physical solution for

[2] UN/CEFACT, an intergovernmental body of the United Nations Economic Commission for Europe (UNECE)

Remote Monitoring System (RMS) and deliver precious information to support the functioning of cutting-edge cloud-based solutions allowing real-time monitoring of multiple parameters at sea from basic factors such as sea surface temperature to more complex parameters like fluorescence, dissolved CO_2, cetaceans clicks, harmful algae blooms (HABs) and even underpin monitoring vessel activities in the proximities of areas of management concern. The combination of modular and customizable solutions in a smart buoy architecture allows for rich and frequent sampling throughout the water column, in addition to surface meteorological data. As in the case of VMS transponders tailored for SSF, electronic components underpinning the functioning of a smart buoy must be carefully selected on the basis of respective energy consumption and available renewable power sources to ensure operational continuity.

All these data can be continuously transferred and stored on cloud-based systems and can ideally be made available through secured web interfaces in real-time, thus contributing to the monitoring and understanding of the marine environment especially where an array of smart buoys is equipped with multiple sensors in different areas and deployed on a permanent basis in areas of scientific or governance interest, with a view to obtain high-definition time series that can complement satellite images and data where applicable. It can be the case, for instance, to bolster environmental monitoring for coastal areas in support to the management of human activities such as marine aquaculture. At present, small networks of smart buoys exist in the Mediterranean and Black Sea, yet their permanence is envisaged in the framework of fix-term specific projects and, while a small set of them have intended for long-lasting monitoring, they still require dedicated financial resources to ensure due maintenance, reliability of collected information, and airtime.

Earth Observation and related remote sensing technologies simplifying the complexities of the oceans

The expanding constellations of satellites and nanosatellites, the growing array of software features supported by their on-board hardware bring them to the forefront of ocean management, providing exceptional capabilities to monitor activities at seas, and improve protection and conservation measures. Modern satellites offer a wide array of ocean measurements from temperature to wave height, through sea level, sea ice, salinity, phytoplankton and edge recognition algorithms facilitating the identification of oil spills, potential IUU activities, tracking wildlife and spotting near surface cetaceans, to list a few. Recent technological advancements made satellite imagery helpful to forecasting and understanding ocean acidification by monitoring the behaviour of phytoplankton, one of the main ocean oxygen providers and building blocks in the food chain, essential for the survival of fish stocks.

Satellite imagery has helped identify large cetacean hotspots and related derivative data is valuable for conservation and fisheries management as it reveals the presence and movement of whales. Aside from earth observation data, satellites provide telecommunication features compatible with telemetry devices used to support marine animals tracking and understanding. Multiple satellite tags have been used on sharks, whales, seals and other marine life, thanks to the increasing versatility, affordability and autonomy granted by modern technologies.

Technological trends in support to decarbonization of the fishing fleet

Recent advancements in several technological fields as well as improved engine and fishing gear designs are supporting efforts towards the decarbonisation of fishing activities. These efforts intend to reduce CO_2 emissions resulting from human activity, with eventual goal of eliminating them altogether. In 2015 the Paris Agreement set ambitious targets to limit global warming level to well below 2°C and to achieve net carbon neutrality by 2050. The substantial reduction of global greenhouse gas emissions (including CO2) will limit the increase of global temperatures. At present, decarbonization relies on short and long-term modifications of existing practices to achieve these ambitious targets. It is reasonable to think that, based on priorities expressed by several member countries, RFMOs might facilitate the identification and test of innovative solutions and assess their impact on the catch and the fuel consumption and emissions.

In the long term, the need to shift towards alternative fuels raises logistical issues that need to be considered in relation vessels engines, port infrastructures requiring recharging / hydrogen refilling stations, specialized maintenance and crew training. This in turn requires that RFMOs and governments work closely with relevant stakeholders to evaluate specificities at the regional and subregional level to ensure sustainability and operational performance comparable to fossil fuels.