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Perspective

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Wearable sensors for monitoring marine environments and their inhabitants

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Human societies depend on marine ecosystems, but their degradation continues. Toward mitigating this decline, new and more effective ways to precisely measure the status and condition of marine environments are needed alongside existing rebuilding strategies. Here, we provide an overview of how sensors and wearable technology developed for humans could be adapted to improve marine monitoring. We describe barriers that have slowed the transition of this technology from land to sea, update on the developments in sensors to advance ocean observation and advocate for more widespread use of wearables on marine organisms in the wild and in aquaculture. We propose that large-scale use of wearables could facilitate the concept of an 'internet of marine life' that might contribute to a more robust and effective observation system for the oceans and commercial aquaculture operations. These observations may aid in rationalizing strategies toward conservation and restoration of marine communities and habitats.

Certain marine animals may migrate over great distances[1,2], and tracking these movements offers an opportunity to observe the physical and biological environment in which these animals travel through. Cataloging these movements can improve our understanding of their ecology, the challenges they face in their interaction with human activities and inform conservation actions[2–5].

Sensor tags attached to marine animals are analogous to wearable devices ('wearables') carried voluntarily by humans[6–8] (Table 1). Certain human wearable devices are now small, unobtrusive and have transformed personalized assessments of physiology[9,10]. Wearables can potentially offer improvements to human health, livelihood and society, as evidenced by applications to track the spread of coronavirus disease 2019 (COVID-19)[11]. Wearable technology has now progressed beyond humans to monitor livestock movement and condition through, for example, sensing microfluids, sweat and saliva and serodiagnosis[12]. The value that wearables have provided for humans,

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Table 1 | Benchmarking of existing animal-borne sensor technology

Device	Cefas G5 Long-life	CTD–SRDL Valeport	DST CTD	LAT 1100	Onset HOBO U20	CTD Biotag, Florida University	MiniPAT-348	PTT-100 Microwave Telemetry
Parameters	Depth Temperature	Conductivity Temperature Depth	Depth Temperature	Depth Temperature	Depth Temperature	Conductivity Temperature Depth	Depth Temperature Light	Depth Temperature Light
Size (length × width or diameter)	36.5 mm × 12 mm	105 mm × 70 mm	50 mm × 15 mm	31.5 mm × 15 mm	150 mm × 24.6 mm	100 mm × 43 mm	124 mm × 38 mm	168 mm × 41 mm + 178-mm antenna
Mass in air (in water)	6.5 g (2.5 g)	545 g	21 g (13 g)	4.25 g (1.9 g)	210 g	104 g	60 g	78 g
Fastest possible sampling	1 s	1 s	1 s	>1 s in 1-s intervals	1 s	5 s	1 s	45 s
Operating temperature range	2–34 °C	−5 to 35 °C	−1 to 40 °C	−20 °C to 45 °C	−20 to 50 °C	5–35 °C	−20 to 50 °C	−4 to 40 °C
Temperature resolution	0.03125 °C	0.001 °C	0.032 °C	0.05 °C	0.1 °C at 25 °C	0.001–0.015 °C	0.05 °C	0.16–0.23 °C
Depth range	100–2,000 dbar	0–2,000 dbar	<2,400 m	<2,000 m	<76 m	<2,000 m	0–1,700 m	0–1,250 m
Pressure resolution	4–60 cm	0.05 dbar	60 cm	100 cm	0.87 cm	0.25% of the selected range	0.5 m	5.4 m
Conductivity range	–	0–80 mS cm^{-1}	3–68 mS cm^{-1}	–	–	2–70 mS cm^{-1}	–	–
Salinity resolution	–	0.002 mS cm^{-1}	0.02 PSU	–	–	0.04 PSU	–	–
Attachment method	Invasive clipping	Glue	Implantation or external tagging	Invasive clipping	Mounting hole	– (not field tested)	Towed	Towed via tagging dart

These commercially available devices provide data for understanding the ecology of marine life and are used to measure physical parameters, such as depth, temperature and light, and have varying dimensions, masses, sampling rates and resolutions. The invasive attachment methods of these devices, however, can cause physical harm or discomfort to animals, alter their swimming patterns and impede feeding or reproduction. This can ultimately affect the accuracy and reliability of the collected data. PSU, practical salinity unit.

their pets and other domesticated animals in terrestrial systems demonstrates the potential value that wearable technology might bring to sensing the marine environment as well as for humans voluntarily (for example, scuba divers) or accidentally (for example, castaways) entering the marine environment[13].

Relevant review articles have largely focused on progress in satellite telemetry tagging technologies and techniques in aquatic environments[1,2,5,6,8,14]. However, translation of advances in human wearables to marine equivalents still faces several barriers. Major limitations of wearable devices traditionally used in aquatic environments (Table 1) include limited functionality under pressure and with highly saline conditions, the relatively small number of tag types available (compared to human and other terrestrial wearables), the prohibitively large size of most tags, the fact that only a few biological or physical parameters can currently be measured when appropriately sized species are tagged, issues with data storage, transmission and processing and energy sources as well as biofouling and animal-welfare considerations.

In this Perspective, we outline how certain human wearables could potentially be adapted for improving marine wearables and toward expanding the range of potential target species and measurable parameters, while mitigating animal-welfare concerns (Fig. 1). We propose how a range of flexible, conformable and imperceptible sensor technologies could be modified through multidisciplinary approaches for use on diverse marine animals and reiterate the need for simultaneous consideration of compatible underwater communication systems to facilitate data recovery. Next, we discuss how wearable devices tailored specifically for the bodies of marine animals could advance understanding of the ecology and environment of marine life. Finally, we propose how large-scale use of marine wearables could give rise to the concept of an 'internet of marine life' and describe its potential benefits and limitations in aquaculture and long-term ocean-conservation and sustainability contexts.

Limitations of current marine wearables for ecology and conservation studies

Data obtained from electronic tagging have fundamentally changed our understanding of the ecology and behavior of marine megafauna such as sharks, turtles, tunas and seabirds[2,15]. However, these tags rarely comply with the definition of wearables because they tend to be bulky, their attachment may interfere with animal movements and well-being[16,17] and limited data transmission often prevents high sampling rates (Table 1).

Marine sensors have not typically benefited from innovation in technology for wearables used on land. For example, the conductivity–temperature–depth (CTD) sensor, the mainstay of oceanographic research, continues to look and operate mostly as it did 30 years ago. The relatively large size of tags suitable for marine animals remains a substantial barrier to research progress. On land, radiofrequency tags weighing only 2.5 mg allow tagging of insects[18]. By contrast, the smallest tag available for marine animals weighs 650 mg in air, thus limiting tagging of animals similar to or larger than turtle hatchlings[19] that have a body mass (19.5 g) almost 2,000 times that of a bee (0.01 g). Commercially available electronic tags designed for use in marine systems often exceed the cost of wearable sensors for humans by orders of magnitude[20] and lack the means to link external signals (physical and biological) to internal changes within the animal body (Table 1).

Another practical issue limiting deployment is the mechanical mismatch between an animal's soft, curvilinear body and wafer-based electronic sensor tags that are rigid and bulky. Flexible sensing techniques reduce the invasive and burdensome nature of electronic tags

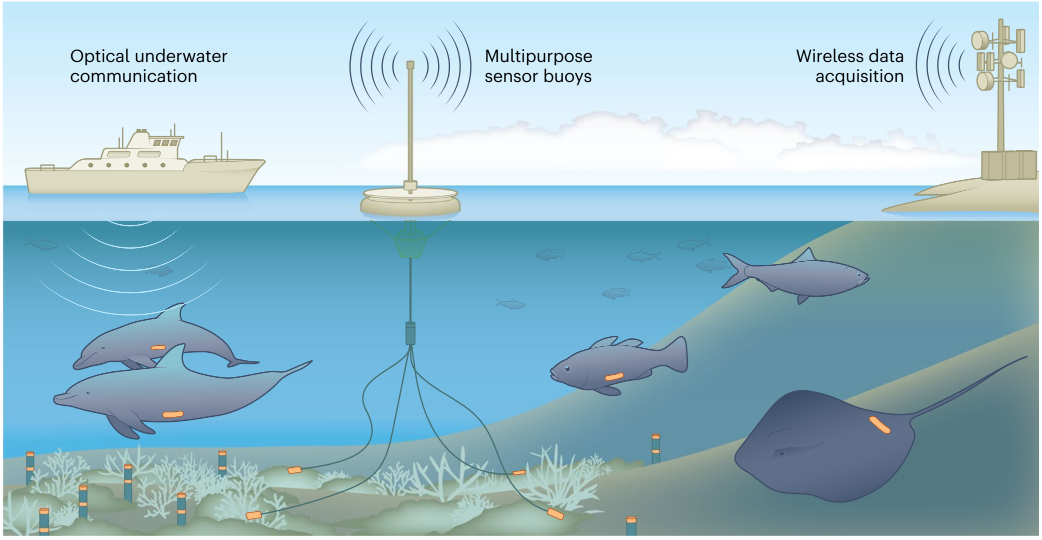

Fig. 1 | Current marine sensors and communication technologies. The developments highlight routes for collecting physiological parameters from the body fluid and environments of marine animals, such as pulses, hormones, temperature, antimicrobials or pollutants, using wearable sensors that could be combined with optical underwater communication, multipurpose sensor buoys, wireless data acquisition or other systems, such as acoustic–optical–radiofrequency hybrid underwater communication, to relay data.

through form-fitting sensors[20,21]. These fit the changing body form of moving and growing animals within certain limits. Packaging is a fundamental challenge to achieve overall wearability, whereby every single component in an electronic system is bendable, while also protecting delicate electronics from impacts of the marine environment. Development of impermeable, biocompatible and transparent polymer coatings offers materials that could be incorporated into the design of more practical marine wearables[20,21].

As tag technology for use in marine systems has evolved, the sampling frequency of sensors has also increased. For example, the time resolution of depth sensors has increased three orders of magnitude from about 0.1 to 10 Hz[22], whereas other sensors, such as accelerometers, now routinely sample at tens or even hundreds of Hz[23]. This advance is not trivial, given that depth sampling at 1 Hz by a tag on a penguin will only indicate how the bird allocates time to various depths, whereas sampling rates of 40 Hz provide sufficient resolution to understand the extent to which the body rises and falls within the water column with every flipper beat (Fig. 2). This allows assessment of the propulsion mechanism, how this varies with depth and consideration of energetic and metabolic consequences with respect to a penguin's frequency of flipper beats, speed and depth. This understanding informs biomimicry, design of adhesives and faster swimwear[24], but, most importantly, it informs on how animals alter their energy budgets in a changing environment. Examples of how high resolution (40 Hz and 16 bit) can elucidate aspects of marine animal biology are shown in Fig. 2. Increasing the sampling rate of animal-borne sensors is, therefore, a requirement to deepen our understanding of movement, metabolism and behavior.

Toward translating human wearables to marine animals

Translating innovations in human wearables to marine wearables requires substantial technological development because of challenges in assaying biochemical parameters in a marine context in a reliable, robust and minimally intrusive way. Nanomaterial-based sensors can enable assessment of physiological changes in marine animals by measuring internal parameters, such as hormone levels and metabolites[25] and the chemistry of body fluids and tissues[26] as well as the body temperature[27], respiratory rate[28], cardiac activity[29], neural activity[30] and locomotor activities[31] (Box 1). Incorporation of nanomaterials into flexible electronics, soft microfluidics, pain-free microneedles, electronic tattoos and point-of-care smartphone-based sensors has resulted in certain sensors that can externally assess an animal's internal condition through its skin, described below (Fig. 2).

Marine Skin

So-called 'Marine Skin' (refs. 20,21) is an ultra-lightweight (~2.5–6 g in air) and standalone wireless multisensory device designed to conform and adapt to the soft and irregularly shaped surfaces of marine animals (Fig. 2a). Based on polydimethylsiloxane (PDMS) polymer and integrated silicon CTD sensor arrays, Marine Skin was designed to simultaneously monitor diving behavior and the surrounding marine environment. The sinusoidal wavy architecture of metallic interconnects enables high stretchability in lateral directions to maintain stable performance after repeated twisting and bending of the device. The latest waterproof version of Marine Skin showed 500–1,500% enhanced sensitivity and endurance at a depth of 2 km in full-strength seawater compared to the initial version of the device[21]. A bracelet-like, featherlight jacket design was developed to non-invasively attach Marine Skin to fishes such as barramundi, sea bream and common goldfish without any glue or surgery[21]. A limitation of Marine Skin is the low-power Bluetooth transceiver that operates only when marine animals surface for a sufficient period of time; otherwise the system has to be retrieved to access the stored data. Further work should aim to integrate Marine Skin with advanced optical and/or acoustic transmitters as well as to incorporate a range of biochemical sensors for monitoring biomarkers such as cortisol, glucose and oxygen levels. Additionally, biocompatibility and susceptibility to biofouling must be thoroughly assessed before long-term deployment.

Implantable fluorescence nanosensors

Hybrid nanomaterials combining molecularly imprinted polymers with inorganic nanomaterials present a promising approach for concurrently acquiring previously inaccessible physiological datasets in marine organisms. These materials offer unique selectivity and affinity for target analytes, enabling the development of highly sensitive and specific sensors[32]. However, challenges remain due to the scarcity of in vivo measurements, complex marine environments and concerns regarding stability, biocompatibility and toxicity. Recently, near-infrared fluorescent nanosensor implants employing

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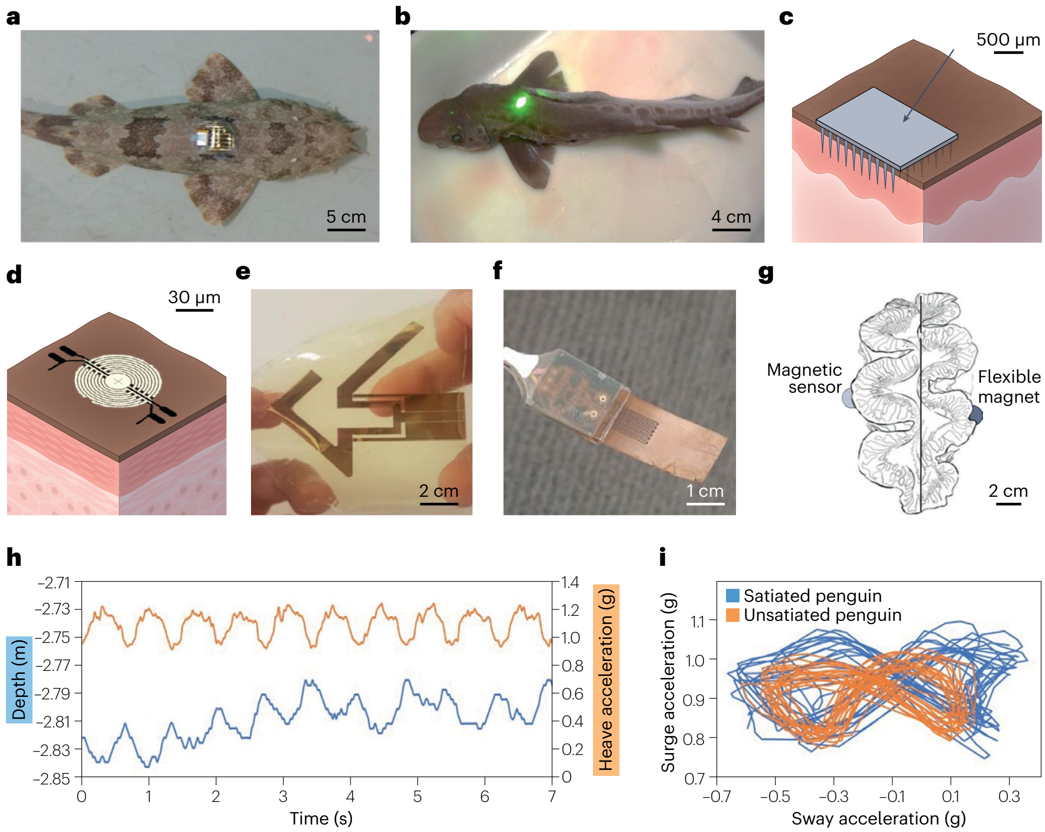

Fig. 2 | Wearable technology solutions and developments for monitoring marine environments and their inhabitants. a, Non-invasive, lightweight wearable 'Marine Skin'. **b**, Implantable fluorescent nanosensors. **c**, Schematic of a generic microneedle-based wearable device on the epidermis. **d**, Epidermal tattoo-like physiological sensors. **e**, Flexible antenna integrated with a wireless data-acquisition system. **f**, Multifunctional LIG sensors. **g**, Imperceptible magnetic skin system. **h**, Resolution of depth indicates how flipper beats in a Magellanic penguin (*Spheniscus magellanicus*) (indicated by pulses in the heave acceleration axis) result in the whole body oscillating in the water column by approximately 3 cm to provide insights into swim effort and efficiency (left). Change in walking gait between a satiated and unsatiated penguin manifest via the (smoothed over 0.25 s) surge and sway accelerations showing greater body oscillations for the period when the bird was heavier (right).

DNA-wrapped single-wall carbon nanotubes have been devised for continuous organismal monitoring[33]. These nanosensors are encapsulated within a biocompatible poly(ethylene glycol)diacrylate hydrogel for highly selective chemical detection through corona phase molecular recognition. Riboflavin (vitamin B_2), a cofactor for enzymes involved in oxidative phosphorylation, was used as a target analyte in tissue assessment in vitro and ex vivo[33]. The design characteristics for this riboflavin sensor such as implantation depth, sensor imaging, detection limits, fluence and stability as well as acute and long-term biocompatibility, were examined on species such as bony fish, sharks, eels and turtles. When combined with gels, single-wall carbon nanotubes could be detected up to a depth of 7 mm in the skin and muscle tissue of individual organisms without any observable changes in movement, tissue structure, swimming and feeding patterns[33]. Incorporating riboflavin status into the proposed internet of marine life would necessitate a multidisciplinary methodology encompassing the advancement of biochemical-sensing devices, data-management infrastructures and machine learning algorithms. This integration facilitates examination of feeding behavior, overall health and responses to environmental stressors across various temporal scales. The identification of seasonal and annual patterns provides insights into variations in, and anthropogenic influences on, marine ecosystems, while diurnal patterns elucidate specific periods of heightened feeding activity or changes in nutrient status during growth and reproductive phases.

Measurement of chlorophyll a and dissolved oxygen has gained popularity because these parameters provide valuable insights into the health and productivity of aquatic ecosystems[34]. Chlorophyll a plays an important role in global carbon cycling[35], and its concentration is a vital indicator of oceanic primary production. Deep-diving marine mammals, such as southern elephant seals, were equipped with combined CTD–satellite relay data logger (SRDL) and fluorometer devices to gather data on photosynthetic pigments in hard-to-reach areas where traditional methods fall short or research vessels may not be available[36]. Integrating CTD–SRDLs with dissolved oxygen sensors allows researchers to observe oceanographic conditions near marine animals (such as Atlantic salmon[37]), obtain more in-depth data on bottom-water formation as well as monitor oxygen thresholds required to maintain healthy animals in the face of ongoing ocean deoxygenation. The miniaturization of these multi-sensor loggers would enhance our understanding of marine ecosystems and the status and changes in previously unexplored environments of marine animals.

Meanwhile, wider use of implantable sensors requires overcoming limitations such as sensor signal normalization to account for the optical heterogeneity of various animal tissues, low signal-to-noise ratios, temporal resolution of measurements and movement artifacts. Subsequent removal of the nanodevice also requires recapture and further surgery with ethical and feasibility implications.

Microneedle-based sensor arrays

Microneedle sensor arrays (MSAs) allow painless transdermal extraction of interstitial fluid (Fig. 2c). A miniature MSA patch is typically composed of micron-sized electrode arrays (silicon, metals, polymers, glass, ceramics) arranged in a specific order and shape[38] (cylindrical, canonical, pyramids, spike, spear) for direct, real-time and continuous

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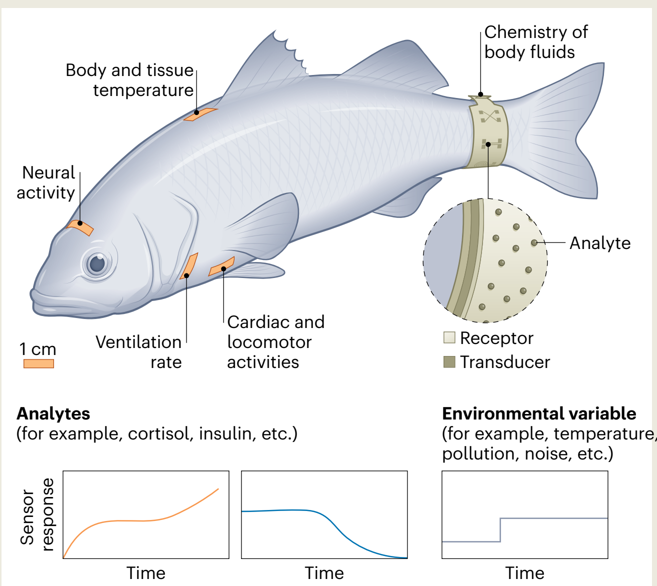
BOX 1

Biochemical sensors for marine monitoring

Chemical measurements in living organisms can generally be performed electrochemically or through physical adsorption, with the latter potentially offering more specificity and selectivity[137]. This general scheme can be described as

$$S + A \Longleftrightarrow S_A,$$

whereby a sensor site (S) reversibly binds an analyte (A), resulting in a state change that can be transduced as a measurable signal. The analyte in this case can be any physiological chemical constituent of interest, such as cortisol or insulin. One attractive method to design chemical sensors for molecules of interest is through the engineering of nanoparticle surfaces. The optical properties of these materials can often report the adsorption-induced state change, directly correlating measured optical intensity to the analyte concentration. As shown in human systems, detectable signaling molecules include insulin, dopamine and components of the steroidogenesis pathway[26].



measurement of analytes[39], metabolites[40], chemical threats[41], therapeutics[42], hormones[43] and gene delivery[44]. Despite MSAs offering a technique to study physiology in free-living marine animals, it has not yet been exploited. This is due to susceptibility to corrosion, fouling, poor biocompatibility and noisy signals caused by interactions with biological molecules of metallic MSA. By contrast, polymer MSAs suffer from problems with retaining tip sharpness, efficacy and stability of microneedles after contact with body fluids, particularly when relatively high insertion forces are used to penetrate the outer layer of the skin. Despite the barriers that have impeded deployment of microneedle sensors in aquatic environments, there are positive indications of their future potential for use in marine contexts with ongoing advancements in sensor design, waterproof and biocompatible materials and secure attachment methods for reliable data acquisition in harsh environments.

Tattoo-like epidermal sensors

Tattoo-like epidermal sensors are an ultra-thin and elastic wearable technology that closely adheres to the skin, resembling temporary tattoos. Wearability of these sensors could be extended to the microscopic morphology of epidermal skin via tattoo-like imperceptible sensors without application of artificial adhesives (Fig. 2d). This technique increases the contact surface area of the skin with the electrode and decreases contact impedance and susceptibility to motion, resulting in a higher signal-to-noise ratio. Liquid metal-based electronic tattoos have been the most popular option for electrodes and interconnects (~10–100-nm thickness) because of their excellent stretchability and self-healing ability[45]. At room temperature, metals such as eutectic indium gallium maintain a liquid form, allowing devices with this to be stretched over 300% without loss of conductivity[46]. Their unique surface chemistry allows for development of various devices in wearable form, while their biocompatibility holds potential in uses on the surface and internal applications for living organisms. An electronic tattoo could function as a diagnostic display by reflecting color changes within the visible spectrum in response to a given biochemical variable[46]. In biomedical applications, these variables can be recorded easily by a smartphone, but, in marine settings, an imaging device would need to be installed at sites that are routinely revisited by tagged species. This technique is therefore limited to species that are either regularly sighted (for example, turtle nests, species resident in marine protected areas, aquaculture animals) or remotely observed (shelf habitats and coastal settings). Because the color calibration of the sensor has been carried out under controlled lighting conditions, it is essential to conduct tests in the marine environment to assess sensor performance under ambient environmental conditions to support readout at distinct brightness, saturation and shades.

Tattoo-like epidermal sensors have the potential to non-invasively monitor various physiological and biochemical parameters in marine organisms, including cardiovascular function, respiration rate, muscle activity and hormone levels. A challenge in using tattoo-like and MSA sensors in marine contexts is effective integration with flexible antennas[47] as part of wireless data-acquisition systems (Fig. 2e). Evaluating underwater functionality, addressing the impacts of water conductivity, pressure and temperature on signal quality and devising encapsulation strategies to safeguard the sensors from harsh marine conditions are also essential considerations for the application of these sensing technologies in a potential internet of marine life.

Multifunctional graphene sensors

As the thinnest electrically conductive material, graphene has been widely exploited to fabricate flexible, electrochemically stable and biocompatible sensor solutions[48]; however, its usage has been hindered by costly and energy-intensive fabrication methods. Laser-induced graphene (LIG) has facilitated a simultaneous formation and patterning of porous graphene in a solid state and has permitted development of versatile, high-yield, low-cost and widely tunable physiological sensors[49–51]. Wearable LIG sensors have been developed for measuring various physical parameters in the marine environment[52–60] (Fig. 2f), are resistant to corrosion and fouling[61] and can function in challenging contexts such as monitoring movement behavior of dolphins and turtles[52]. Multifunctional LIG sensors still require improvements to packing density and elimination of interference among multiple stimuli present in marine environments. In addition, the use of LIG as an electrochemical sensor requires surface modification with heteroatom doping or composite formation[62]. Although there have been developments in this regard[60], none have yet been optimized for use in marine environments. Therefore, next-generation LIG sensors could be tailored for use within the internet of marine life with a specific emphasis on sensing a wide range of small molecules, including ascorbic acid (vitamin C), dopamine, uric acid, hydrogen peroxide, urea, bisphenol A, glucose and biogenic amines.

Magnetic skin system

The magnetic skin system integrates composite magnets and magnetic sensors onto a living organism and uses changes in the magnetic field resulting from differences in the magnet–sensor distance to detect body movements[63]. Advantages of a magnetic sensing approach include marine species being highly tolerant of magnetic fields and magnets exhibiting measurable magnetic properties underwater. Tunnel magnetoresistance sensors, the most sensitive solid-state sensors available today, in combination with flexible and lightweight composite magnets, were used to monitor the movement behavior of the bivalve *Tridacna maxima*[64,65] (maxima clam, Fig. 2g). In another study, the elastic modulus of the neodymium (NdFeB)–PDMS magnet was optimized for attachment to the curved surfaces of giant clams, crabs and turtles, and a parylene C coating provided enhanced underwater durability, biocompatibility and corrosion resistance[64]. Meanwhile, the next-generation magnetic skin made of NdFeB–Ecoflex is virtually imperceptible to wear due to its high stretchability (>300%), breathability and versatility in shape and color[66,67]. The system has several limitations, such as restricted measurement capabilities due to the limited maximum operational distance between the magnet and the sensor, and sufficient long-term testing of the devices is required to assess the reliability, durability and safety of the technology during extended periods of use.

Challenges for development of marine wearables

The marine environment poses several major physical, biological and technical challenges for using wearable sensor devices. The ionic composition of seawater conducts electricity and can corrode, galvanize and denature materials commonly used in wearables. All this is exacerbated by changes in pressure representing an increase of a whole atmosphere for every ~10-m increase in depth, together with temperatures that may vary between −2 and 35 °C. Beyond this, marine organisms that colonize surfaces and promote biofouling can also impede the functioning of marine wearables[68,69]. In addition, the transmission of radio waves, which in the air is far reaching and is used for data transfer from wearables on land, is negligible in seawater[6]. Acoustic transmission of data remains the most viable option for marine wearables, but this is limited to distances of up to 1 km (ref. 6) and slow rates of about 1 s across that distance.

Data transmission and recovery

Retrieving data from sensors attached to mobile animals is a major barrier in the design of marine wearables given the difficulties with wireless communication underwater. By contrast, acoustic technology does generally work well underwater, leading to the development of sensor networks and arrays. However, both acoustic tags and receiving stations are relatively large, have low data-transmission speeds (of kilobytes per second), long latency and high power consumption[70,71]. Radiofrequency communications rely either on the marine animal coming to the surface or use of a detachable, floating sensor node to transmit the data[5,36,47,72,73], for example, using Bluetooth Low Energy[47] or Wi-Fi modules[8]. However, because most of the open ocean does not have coverage by communication networks, satellites provide the only viable option. These are expensive and energy-intensive (few mA quiescent, several hundred mA transmitting) solutions that prohibit their large-scale use. These limitations could be overcome by developing a custom communication network composed of wearable tags, floating receivers and ground stations for studies of relatively resident animals[47]. Marine wearables with Bluetooth modules can be used for short-range (~100 m) and high data-communication rates (~2 Mbps) on marine mammals that breathe periodically on the sea surface[47]. Long Range (LoRa) low-power modules could be used on detachable marine wearables with improved communication distances (~15 km) but at the cost of a lower data rate (~30 kbps) than those of Bluetooth and Wi-Fi, although still higher than typical underwater acoustic communication rates. For both types of marine wearables, a multi-hopping communication network, including small Bluetooth floating receivers[74] and large floating receivers with multiple communication capabilities (Global System for Mobile (GSM), Bluetooth, LoRa and Global Positioning System (GPS) modules)[75], can relay data across a swarm of such floating receivers. This approach could enable coverage of large areas, forming the conceptual basis for the notion of an internet of marine life.

Underwater wireless optical communication (UWOC) also offers a potential approach for underwater communication and was developed to overcome the limitations of acoustic methods[76,77], with high bandwidth and communication speed above 1 Gbps. For example, downloading a 1-GB video underwater required a few seconds using UWOC, compared to a few days using acoustic technology. However, these data can only be directly transmitted across short distances. The current record of data transmission across the furthest distance underwater involves transmitting data across 20 m at 1.5 Gbps[78]. Several challenges remain before UWOC becomes a practical technology to use with marine wearables. These include the development of high-speed, low-power (or self-powered) transceivers capable of communicating with other devices or sensors in a non-line-of-sight fashion at a range of ~100 m in both clear and turbid waters[79–82]. Successful field trials for energy-autonomous receivers[82–84], a non-line-of-sight water-to-air communication system[85,86] and optical underwater internet[87] might permit further exploration of connectivity strategies for an underwater internet of marine life.

Accounting for data analysis in wearable design

Tracking underwater animals is a challenging task, especially when trying to do so accurately without using GPS or complex systems. Feasible, long-term and self-contained yet accurate tracking of marine animals requires hardware–software co-design and incorporation of 'hardware-aware' algorithmic pipelines[88]. Because marine tags can store large amounts of data and underwater data transmission is challenging, onboard processing is therefore a prerequisite before data transfer. This processing is, however, constrained by the small footprint of wearable devices.

Machine learning offers a promising avenue to address the challenge by processing data from an array of sensors integrated into marine wearables[88]. These wearables typically encompass accelerometers, gyroscopes and magnetometers, which provide insights into an animal's locomotion. Advanced machine learning methodologies facilitate deeper comprehension and interpretation of the animal's motion, thereby rectifying common errors inherent in conventional tracking techniques. The deep neural network (DNN) machine learning class has demonstrated strong efficacy in this domain[89]. DNNs are trained to estimate the displacement, heading or velocity of marine animals based on data obtained by the sensors embedded within the wearable device. Employing DNN enables researchers to input segments of sensor data into a network and subsequently extract crucial parameters such as initial velocity, gravitational forces and magnetic anchor direction. This approach results in enhanced accuracy when predicting an animal's movement trajectory[88].

Energy harvesting

At present, the lifetime of sensor tags is limited by the amount of energy provided by batteries, which are usually among the larger and heavier tag components. Harvesting energy from the ambient environment offers an alternative option for long-term power deployment of small marine wearables. The marine environment has many natural sources of energy to draw from including waves, tidal currents, salinity gradients, solar energy and thermal gradients.

For low-power marine wearables, autonomous energy harvesting could greatly increase sensor capabilities[90]. Advances in material science and nanotechnology offer some potential approaches such as battery-free wearable tags that use flexible piezoelectric beams[90–94] and triboelectric nanogenerators[95–98] to harvest energy from small-scale mechanical motions, such as animal swimming. Kinetic energy captured by a flexible triboelectric nanogenerator was sufficient to power several marine sensors[99]. Other self-powered approaches include a magneto–acoustic resonator that directly upconverts the low-frequency motion of marine animals (ranging from 0.15 to 100 Hz[100]) to a high-frequency acoustic signal and a bionic[101], stretchable nanogenerator with an output of more than 10 V[102].

Self-powering sensors can harvest energy from fish fin movement[92,95] and can avoid fatal damage to marine life caused by turboprop generators[103]. In addition, micro bacterial fuel cells for bioenergy harvesting via redox reactions have been also reported for residual biowaste[104], algae, bacteria and micro organ-based catalysis[105]. These self-powered electrolytic sensors have potential to be used for marine animal health technologies and underwater environmental-monitoring systems without the use of harmful external energy sources. Challenges remain regarding energy density and size reduction of systems for use in self-powered wearables.

Biofouling

Biofouling, the accumulation of organisms on surfaces submerged in seawater, arises from the transition of taxa such as microbes, algae and invertebrates from planktonic to sessile lifestyles[106]. This process involves adhesion of pioneer bacteria, secretion of polymeric extracellular substances and temporary soft and permanent hard macrofouling. Conventional antifouling agents, including tributyltin, copper-based molecules and zinc pyrithione, face challenges in microbial resistance and toxicity to marine life[107]. As a result, alternative strategies have been explored, such as incorporation of metallic nanoparticles, catalytic redox couples, nanoporous electrodes, electrochemical activation, biomaterials and graphene-based nanomaterials[108]. LIGs stand out due to the hydrophilic nature, texture and nanoporous structure that inhibits microbial attachment and reduces adhesion energy[109]. An alternative approach involves bio-inspired shark skin, produced using the PDMS-embedded elastomeric-stamping method, exhibiting microstructured ribbons on dermal denticles that decrease drag and enhance anti-biofouling performance[110]. Despite these advancements, no single biomimetic structure can withstand diverse biological ecosystems in uncontrolled maritime environments, necessitating further surface-engineering progress for the development of effective marine wearables.

Considerations for maintaining animal well-being while using wearables

The accuracy of the data collected by marine wearables relies on sensor deployment having no adverse effects on the animal[16]. The large size of conventional electronic tags and the attachment techniques that penetrate the skin of an animal can result in severe impacts that can extend from burdens on energy budgets to injury and in some cases death[16].

Attachment of flexible electronics to marine animals remains an important challenge. For rigid sensors, current attachment methods include internal implants or external implants via sutures for fishes[111], glue for crabs[112], turtles[113] and seals[114], suction cups for dolphins[115] and bolts or clamps for sharks[116] (Table 1). All these attachment options are invasive and affect animal behavior and well-being[25,117]. The ideal solution for marine wearables is light, flexible and biocompatible belt- or net-like architectures to secure a flexible device, depending on the shape and size of the animal. Advances in adhesive tapes designed for wet tissues offer promising attachment methods. Attachments for wearable sensor systems could also be improved through advances in three-dimensional (3D) imaging and printing technologies, such as those already used in human prosthetic design[118,119]. Whole-body or area-specific scans of animals will facilitate attachments that fit a 3D model negative, allowing devices to be tailored for specific individuals. High-density scans (for example, the Artec Eva made by Artec 3D has a 3D resolution of 0.5 mm) can be used in computational fluid dynamic models to determine the optimal, species-specific attachment location, thereby limiting excessive mechanical deformation and drag[114,120]. The models can also test the impact on hydrodynamic performance of the attachment of wearables. The value of 3D printing for wearable design and attachment is further enhanced as the materials available for printing expand, including flexible plastics and biocompatible options[121]. Major drawbacks of custom-printed sensors include the handling time needed to scan animals and the lag time in being able to customize the design in the field. These barriers could be overcome by creating multiple species- and size-specific sensors using museum specimens and captive individuals for fitting to wild animals with minimal adjustment, thereby reducing the time and stress that an animal is exposed to. Nonetheless, the success of this approach depends on interindividual variation in body dimensions, constitution (such as the thickness of fat layers), overall fitness and other factors such as parasite load, timing around breeding events and seasonality.

Bio-inspired solutions may offer alternative attachment strategies. Marine animals host symbiotic organisms that can persist for years on the body surface without causing major harm to the host. These organisms exhibit a unique form of attachment that offers inspiration for improving attachment of wearables. For example, a biomimetic tag-attachment system[122,123] is based on remoras that use a modified fin on the back of their heads as a suction pad to attach to large marine animals[123]. The remora disc prototype offers strong adhesion to various surfaces and enhanced frictional forces due to the combination of rigid spinules and soft-tissue overlay. However, current 3D printing technology cannot match the mechanical properties of remora disc soft tissues, and the detachment mechanism used is not biologically inspired, requiring further investigation of the natural detachment behavior of remoras. Apart from marine wearables, this system has other applications in contexts in which secure attachment is indispensable, such as marine archeology, oceanographic data gathering, underwater imaging and mapping as well as aquaculture and fishery management.

Generating an 'internet' of marine life

Networks collecting data mostly on physical observations of the open ocean from multiple sources have been achieved[124–126]. Ocean-observation systems rely on either airborne (for example, satellites) or in situ sensing systems, either tethered to mooring systems anchored on the sea floor or drifting or gliding along pre-defined routes[127]. Current use of animal-borne sensing systems is limited by the availability of suitable sensors and systems able to retrieve the data generated and is largely limited to tracking devices sporadically reporting position data for animals surfacing regularly through the Advanced Research and Global Observation (ARGO) satellite system[2]. Here, we elaborate on our vision for using wearables toward generating an internet of marine life in three distinct marine settings: aquaculture, the open ocean and coastal habitats (Fig. 3).

Industrial aquaculture began about 40 years ago, compared to the more than 1,000 years of large-scale food production on land. However, the pace of aquaculture development is rapid, with technology potentially leaping over the third industrial revolution to directly enter the 'fourth industrial revolution', which is characterized by sensor-rich operations networked through highly connected devices (the internet of things) that provide information to initiate interventions by robotized systems. For example, Norway has just established the first offshore, highly robotized salmon farm with the capacity to hold 1.5 million salmon, fitted with 20,000 sensors to monitor all aspects of the operation, supervised by only four humans (https://www.fishfarmingexpert.com/article/world-s-first-offshore-fish-farm-arrives-in-norway/). This farm still lacks animal-borne sensors to provide direct feedback about the state of animals.

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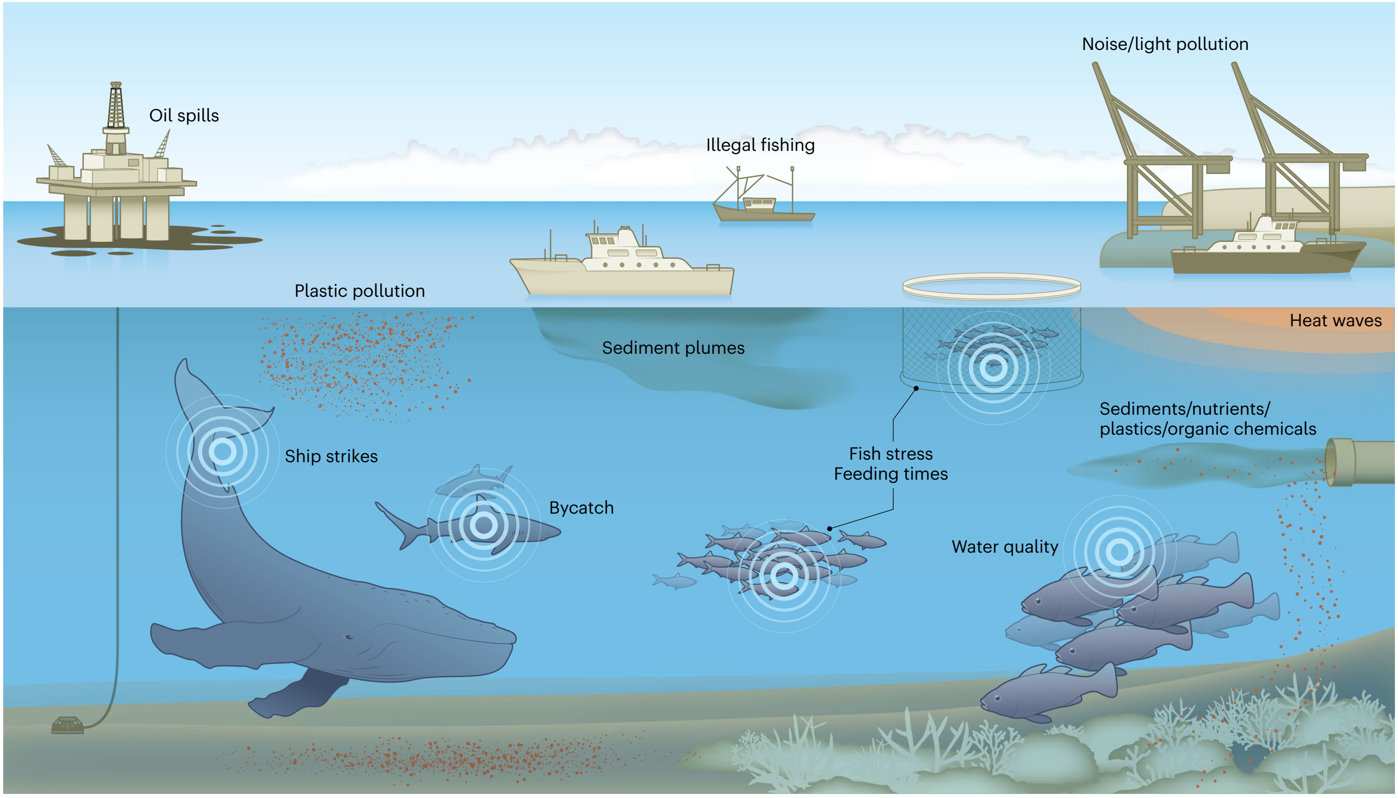

Fig. 3 | Anthropogenic impacts on the marine environment and examples of marine organisms that could potentially benefit from an internet of marine life. We envision that use of wearable sensing technology could span three distinct marine ecosystems: aquaculture, open oceans and coastal habitats. Wearables could provide information on animal health, nutrition, growth, reproductive stage and stress levels to maximize aquaculture yield and ensure animal well-being. The internal status of oceanic animals (concentric circles) and their environment could also be monitored using wearables with built-in energy-harvesting capabilities to ensure long sensor lifetimes. The proposed internet of marine life could also contribute to our understanding of coastal environments, particularly in or near urban settings, where anthropogenic impacts, such as habitat degradation and shoreline hardening, are a major concern.

Wearables for aquaculture ought to focus on measuring the health, feeding, growth, reproductive stage and stress markers of target animals with the dual goal of ensuring animal well-being and maximizing yield. A subsample of animals (10–20 animals) carrying wearables could be used in aquaculture facilities, where fish cages may hold thousands to hundreds of thousands of fish, as current technologies to monitor them using visual methods are limited. Movement data in controlled environments can inform on animal condition and stress, while metabolic activity also provides insights into animal condition and well-being. Analyzing these data in relation to relevant environmental parameters, acquired by fixes or animal-mounted sensors, may help define thresholds of environmental conditions, such as turbulence, temperature and oxygen, to provide an understanding that can be used to select and manage fish cages and, more broadly, aquaculture farms. Furthermore, animal behavior data can be used to precisely dose feed, thereby avoiding excess feed supply, which is a major driver of environmental impacts arising from aquaculture farms[77]. Fitting aquaculture animals with wearables would confer a precision farming approach to aquaculture, comparable to the emergence of precision livestock farming on land, which generates positive outcomes in terms of rangeland conservation, animal welfare and labor optimization[77]. Because most aquaculture occurs in confined areas, it is suitable for UWOC, which would allow large amounts of data to be transmitted and could integrate measures of animal well-being. Wearables would need minimal storage or onboard processing because all data could be collected by receivers attached to the enclosure and analyzed immediately to give farm operators real-time information about many individuals. Long-term power supplies would also be a low priority, as tags could be added or replaced when animals were moved among size-specific enclosures. In this situation, wearables might offer a realistic prospect to improve both the well-being of animals and the economic return of aquaculture facilities.

As seaweed aquaculture expands, the internet of marine life could also extend to monitoring seaweed, akin to use of sensors to monitor terrestrial crops[128]. Monitoring oxygen levels, blade movement, fluorescence as a function of chlorophyll *a* content, temperature and pH can inform on the productivity, growth and condition of farmed seaweed. However, capital investment in seaweed farming is currently modest; therefore, most seaweed farms are unlikely to invest in such technology in the medium term unless this assists to release additional revenue streams.

The open ocean remains poorly explored due to its vast size. Remote sensing by way of satellites or drones can only penetrate the top 50 m of the ocean, leaving the majority difficult to monitor, given that the ocean's mean depth is 3,870 m. Other options such as oceanic research vessels are cost prohibitive. Deployment of wearables to form an internet of wild ocean life could substantially increase our capacity for ocean exploration in a cost-effective manner, as shown by studies already using heavy sensors on large marine animals for oceanography data collection[129]. The low turbidity and long-distance, direct line of sight available for transmission in this habitat offer an opportunity to use UWOC for data transfer. Free-floating and anchored receivers could then collect data and transmit it to satellites. A system of buoys with sensors at multiple depths could measure physical variables (temperature, salinity, pH, pCO_2), while GPS tracks the location of data collection. Wearables could collect data on the internal status of animals, but the need for long sensor lifetimes would necessitate the use of systems that have autonomous energy-harvesting capacity. At present, animal tags that relay data via satellites through the ARGO system have transmission lifespans of 6–8 months, and their energy demands result in relatively heavy and bulky configurations[2].

Because battery size is a major constraint for tag design, energy harvesting would not only prolong the life of the wearable but also allow miniaturization. To reduce the necessity for wearables to detach and come to the surface for data collection, floating buoys would send initiation signals to trigger data transmission by the wearable whenever it came within communication distance. The ARGO float system, which already has 5,000 devices deployed across the global oceans[130], could provide such a network of receiving stations, although their feasibility as base stations for collecting data from animal-mounted sensors has not been explored. Designing a hybrid network of the internet of marine life coupled with mechanical sensors, such as ARGO floats, as receiving stations will require optimization as well as identifying what species need to be prioritized to target. In principle, highly mobile species that exhibit diving behavior are more likely to come within range of ARGO floats to download and relay data and would be more suitable for inclusion. Analyzing the current range of tagged marine animals, derived from portals such as MegaMove (https://megamove.org) along with the position of the ARGO floats will be required to assess the feasibility and design of such a hybrid system.

Continental shelf habitats and coasts offer a particularly important target for the internet of marine life because human pressures and threats to marine life are concentrated in these areas. Developing the internet of marine life in a coastal setting would come with different opportunities and challenges. Topographically complex habitats and turbid waters render UWOC unsuitable, and data transmission could instead rely on acoustics or communication occurring either when animals surface or from detached floating sensors. Shallow and complex habitats, such as coral reefs, seagrass meadows, oyster reefs and kelp forests, have high biodiversity and thus offer many potential target species for deployment of wearables. The data from sensors measuring environmental variables and the behavior and physiology of sedentary species can be hardwired to a moored station that can transmit live data via existing GSM or other satellite technology[131]. The station would also offer both a power source (solar cells) and battery backup to power all sensors. Environmental sensors could measure temperature, salinity, pH, pCO_2, water current and turbidity and include instruments such as hydrophones and cameras. Behavioral monitoring of sessile species such as bivalves or barnacles can be achieved using magnets and a magnetometer to measure the opening and closing of valves or plates. Similarly, the filtering rate of bivalves or sponges can be measured using bending graphite sensors to record water velocity[52]. The behavior of a multitude of small mobile species on reefs could also be measured, and data could be transferred to the station. For example, burrowing snapping shrimp can be tracked by attaching a miniature magnet to the animal and placing a magnetometer at the burrow opening to track the location of an animal from the opening to the far end of the burrow. A second example could be the use of an array of magnetometers deployed on the sea floor within the territory of a benthic species fitted with a small magnet, such as a damselfish. Three-dimensional movements could be tracked by triangulation of magnetic field intensity. Real-time data from the environment and the behavior of sedentary species, combined with data from more mobile species, could greatly enhance our understanding of coastal environments, especially in urban settings where the effects of anthropogenic impacts, such as habitat degradation, shoreline hardening and noise pollution, require urgent attention. High-biodiversity environments, such as coral reefs, may render the choice of which species to tag complex. However, choices should be guided by the role of the species in a given community and its conservation status and mobility. We contend therefore that resident apical predators are ideal targets of choice because of their capability to deliver data at scale. In a pioneer deployment of 360° cameras in tiger sharks, this led to the discovery of the largest seagrass meadow in the ocean[132].

Benefits of wearables for promoting a sustainable ocean economy

Wearables that are an integral component of the internet of marine life potentially offer an opportunity to use animals to sense the marine environment and, at the same time, gain insights into the internal status and behavior of animals as they respond to the ocean ecosystems that they inhabit. Such information is urgently required to improve our understanding of interactions between human activity and marine animals.

Real-time assessments of human impacts on marine animals, such as anthropogenic noise[133], vessel strikes on air-breathing animals (for example, cetaceans and turtles) and other species that feed near the surface (such as whale sharks) and bycatch in fisheries, can facilitate immediate management actions to reduce the risk of animal injury. Such capacity would be a major step forward to achieving the goals of UN Sustainable Development Goal 14: 'Life Below Water', developing a sustainable ocean economy and supporting more effective efforts at rebuilding marine life[134]. Human-based monitoring is vulnerable to bias and disruptions, such as the COVID-19 pandemic, during which the confinement of humans to mitigate spread of the virus led to disruption of research, monitoring, conservation and enforcement activities[135]. An internet of marine life could provide a more resilient and effective observation system for the oceans. The capacity to assess animal well-being in a non-intrusive manner through the use of wearables is also of fundamental importance to marine aquaculture and resource extraction, particularly as these industries move toward heavily robotized operations[136].

Technological developments in marine wearables are likely to lead to wider effects for all industries operating in the marine environment[9] as well as citizens venturing into the marine environment for recreational uses[13]. In addition, some of this technology may be translated to human wearables for extreme environments such as space exploration, mining and deep-ground operations and wearables for land animals. The ramifications of wearables are potentially vast, but, importantly, it is the size of the devices that will prove pivotal in informing us comprehensively about the status of animal life in ecosystems. This is because smaller tags are more easily tolerated by their wearers and are most easily affixed. Critically, the vast majority of animal species are 'small'; therefore, researchers working with animal wearables must strive to reduce system size to encompass a broader range of organisms. Indeed, minimizing tag size is likely the single greatest challenge to this approach in the future.

Addressing the potential challenge of wearable disposal and cleanup for marine animal tags is critical in minimizing their environmental impact. The most important challenge lies in replacing battery components containing potentially hazardous materials with ecofriendly alternatives. Future generations of metal-free batteries, such as those based on graphene or organic capacitors, may help overcome this. The unique aquatic environment demands customized solutions for responsible management of discarded wearables in marine ecosystems. Such solutions may encompass the use of biodegradable, ecofriendly and non-toxic materials, minimizing detrimental effects on marine life and their habitats. Additionally, the implementation of time-controlled release mechanisms or harnesses that safely detach from the animals after a predetermined period could aid in the retrieval and proper disposal of these devices. Enhancing environmental regulations and establishing comprehensive guidelines for the deployment and recovery of these devices will further contribute to the responsible management of electronic waste within marine ecosystems

Summary

In conclusion, as we enter the UN Decade of Ocean Science for Sustainable Development, an elevated ambition is required to move beyond traditional oceanographic surveys to develop a new approach toward sensing the marine environment and the well-being and movement of marine animals. The current technological gap between human operations on land and in space relative to those in our ocean cannot be perpetuated. Bringing the internet of marine life to fruition could be a major milestone toward improving our understanding of the ocean and our capacity to conserve and rebuild ocean ecosystems.

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Competing interests

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Additional information

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