NTNU
Centre for Autonomos Marine Operations and Systems

NTNU AMOS

Centre for Autonomous Marine Operations and Systems

Final Report 2013-2023

Norwegian Centre of Excellence
The Research Council of Norway

OUR VISION

- Establish a **world-leading research** centre on autonomous marine operations and systems
- Create **fundamental knowledge** through multidisciplinary research
- Provide **cutting-edge interdisciplinary research** to make autonomy a reality for ships and ocean structures, unmanned vehicles and marine operations
- AMOS has license to create knowledge, competence and values in terms of innovations and entrepreneurships

NTNU AMOS will contribute to improved international competitiveness of Norwegian industries as well as to safety and protection of the marine environment

excellent – generous – courageous

Editors: Live Oftedahl and Asgeir J. Sørensen

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DIRECTOR'S REPORT

Directly stated from the Research Council of Norway:

The Centre of Excellence (SFF) scheme gives Norway's best researchers the opportunity to organise their research activities in centres that seek to achieve ambitious scientific objectives through collaboration and with long-term basic funding. The research conducted at the centres must be innovative and have major potential to generate ground-breaking results that advance the international research frontier. The centres must work with ambitious ideas and complex problems that require coordinated, long-term research activities within or across disciplines to achieve their objectives.

The first research plans for the Centre for Autonomous Marine Operations and Systems (NTNU AMOS) were put in writing in 2010 in partnership between NTNU, SINTEF, DNV and Equinor. The research plans were founded on targeted mega trends, enabling technologies and comparative advantages identified by the key scientists and partners.

In 2012 we were rewarded with the SFF status with the start up in 2013. In June 2023 the 10 years SFF program has come to its end.

Since the start-up, we at NTNU AMOS have advocated for the importance of a holistic and sustainable approach to develop competence, knowledge, and innovations with relevance for:

- Global challenges related to global warming, degrading ecosystems and loss of biodiversity, natural disasters, de-oxygenation of the oceans, lack of energy, food, water, and minerals.
- Value creation in terms of greener and safer oil and gas exploration, maritime transportation, fisheries, aquaculture, offshore renewable energy, tourism, and coastal infrastructure.
- Governance and knowledge-based management of the oceans and coastal areas.

The targeted research areas at NTNU AMOS have been well aligned with national and international strategies meeting the transformations for environmental, economic, and social sustainability.

NTNU AMOS has been focusing on fundamental research within marine technology, control engineering and marine biology, leveraging ground-breaking results on autonomous marine operations and systems.

NTNU AMOS has two research areas: Autonomous vehicles and robotic systems, and Safer, smarter and greener ships, structures and operations. We started up with ten research projects that after mid-term evaluation was reduced into three projects:

- Project 1: Technology for the mapping and monitoring of the oceans;
- Project 2: Marine robotic platforms; and
- Project 3: Risk management and a maximized operability of ships and ocean structures.

The portfolio of associated projects and launch of several new associated centres for research-based innovations (SFIs), FME and VISTA CAROS in collaboration with national and international collaborators enhance the societal and science impact of the research and innovation activities.

The main deliverables are:

- 230+ PhDs
- 1000+ MSc
- 50+ Postdocs
- 2000+ Scientific publications
- The observation pyramid which consists of laboratory infrastructure of sensors and robotic platforms operating in space, air, sea surface and underwater.
- 8 spin-off companies

The upscale through research-based education leaves lasting traces of research originating from the NTNU AMOS research environment. The candidates leave for further career in the industry, public sector, and academia. Several of our PhDs and postdocs have succeeded to enter full time professorships in Norway and abroad.

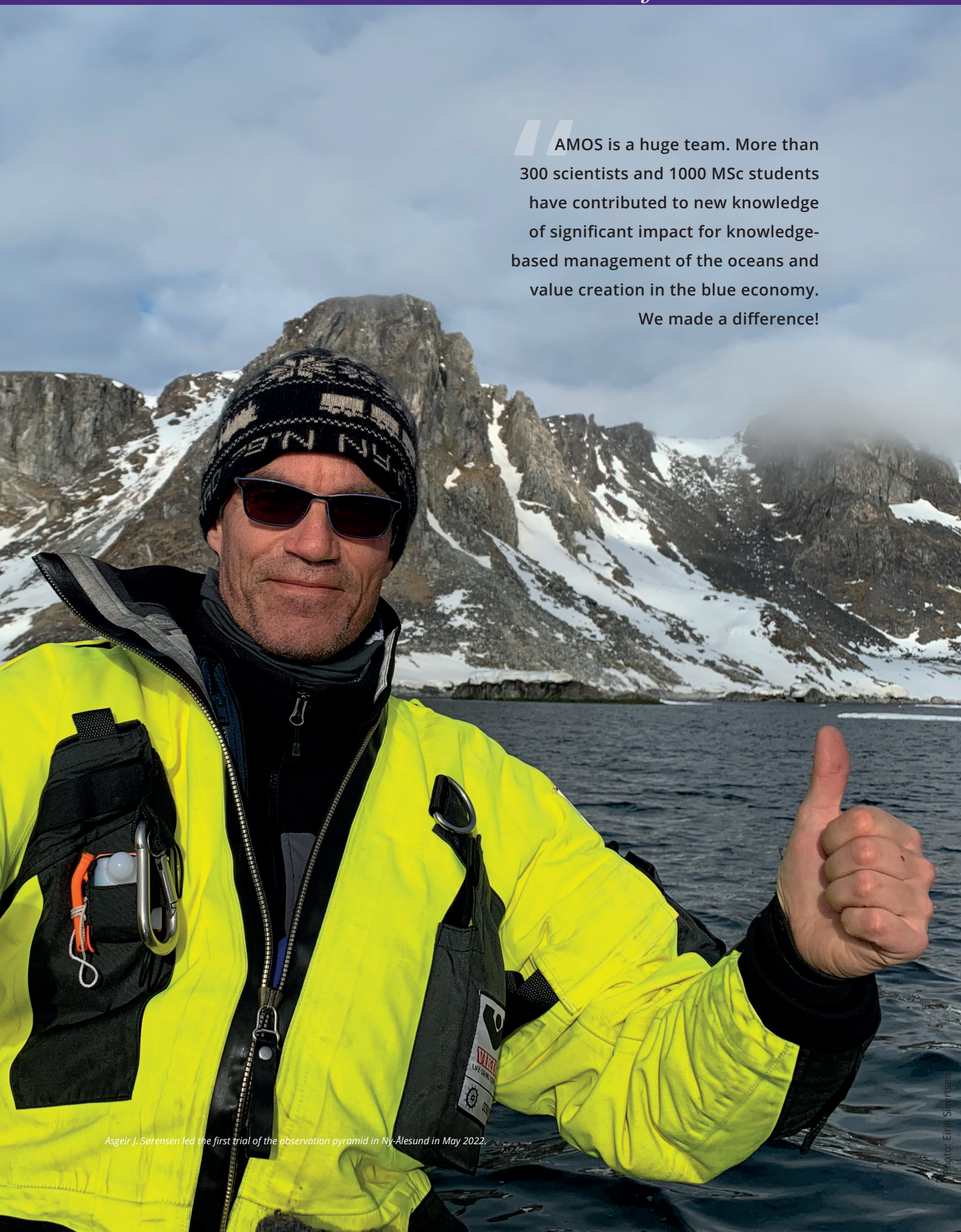
I am pleased to observe that the legacy of NTNU AMOS is well in place.

I would like to take this opportunity to thank all the colleagues, researchers, PhDs, postdocs and master students, partners, and collaborators for their efforts in creating competence, knowledge, and innovations for a better world. I will also emphasize the importance of the partnerships with SINTEF, DNV and Equinor. You have, together with NTNU, provided important support in terms of cash and in-kind contributions. Equally important you have also contributed to the leadership of NTNU AMOS chasing impact of the research outcome for the blue economy and management of the oceans.

Finally, I will also thank the Research Council of Norway for giving us the credentials and trust to become a Centre of Excellence having extended power of attorney *with licence to create*. Hopefully, the impact and outcome of NTNU AMOS gives recognition for investment in long-term fundamental research and innovations in the years to come.

Sincerely,

Professor Asgeir J. Sørensen
Director NTNU AMOS



AMOS is a huge team. More than 300 scientists and 1000 MSc students have contributed to new knowledge of significant impact for knowledge-based management of the oceans and value creation in the blue economy. We made a difference!

Asgeir J. Sørensen led the first trial of the observation pyramid in Ny-Ålesund in May 2022.

Photo: Eirik Sivertsen

MAIN RESEARCH AREAS AND PROJECTS

Pål Kvaløy, technical staff in the UAV-Lab during observation pyramid trial in Kongsfjorden May 22.

Photo: Asgeir J. Sørensen

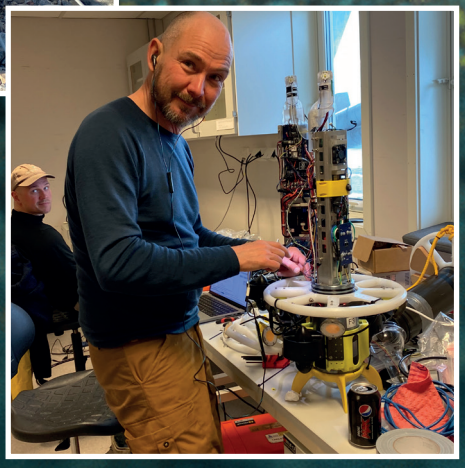
The NTNU AMOS has two research areas:

- **Autonomous vehicles and robotic systems**
- **Safer, smarter and greener ships, structures and operations**

Research at AMOS is organized as three major research projects

- **PROJECT 1: Technology for mapping and monitoring of the oceans.** Heterogeneous robotic platforms (underwater, surface, air and space) for mapping and monitoring the oceans in space and time.
- **PROJECT 2: Marine robotic platforms.** This project concerns the guidance, navigation and control of unmanned ships, underwater vehicles, aerial vehicles, and small-satellite systems, as well as optimization, fault-tolerance, cooperative control, and situational awareness; bio-mimics: bio-cyber-hydrodynamics, and multiscale and distributed systems for sensing and actuation are also included. The new emerging field of bio-cyber-hydrodynamics enables the development of novel concepts in marine robotics.
- **PROJECT 3: Risk management and maximized operability of ship and ocean structures.** The focus will be on the development of methods that maximize operability with improved risk management. This will be achieved by combining advanced numerical hydrodynamic and structural mechanical models for analysis, monitoring and control. Application areas include offshore wind turbines, aquaculture installations, oil and gas installations, coastal infrastructures, coupled multibody marine structures, marine operations, autonomous ships, inspections and installations.

AMOS LEGACY – THE SHORT SUM UP



You will find the complete interviews in our 2022 Annual Report

ASGEIR J. SØRENSEN
THE WIZARD OF AMOS

"We wanted to take chances and push the limits, be ground-breaking, cross barriers and go to places we have never been before, into the unknown, and foster innovations beyond imagination."

Photo: Live Ofredahl

TOR ARNE JOHANSEN
CROSS-DISCIPLINARY COLLABORATION CATALYST

"We created a research strategy focused on the gaps that were identified to be of national importance. Breakthroughs were made in several areas. I believe one of the prime outcomes of AMOS is the demonstration of the observation pyramid in several science missions."

Photo: Private

GEIR JOHNSEN
THE EDGE OF LIFE

"As a part of AMOS our master students, PhDs and post docs have had the possibility to go and examine habitats where we have never been before, in remote and extreme areas. We have obtained information that is totally new to science at nighttime, in the polar night, under the sea-ice, and at greater depths."

Photo: Live Oftedahl

KRISTIN Y. PETTERSEN
ACADEMIC FREEDOM IS IMPORTANT

"It is from basic research that the most innovative solutions may arise, but you won't get the momentum if you don't have the financial resources. NTNU AMOS gave resources to gain proper momentum in the research."

Photo: NTNU

THOR INGE FOSSEN
RISE OF THE ROBOTS

"It is a shame that of the approximately 60 Centres of Excellence that the Norwegian Reseach Council has funded so far, only three include engineering science. The biggest advantage of being av Centre of Excellence is getting funding for basic research, experimental testing, and fieldwork."

MARILENA GRECO
WAVE TO THE FUTURE

Photo: Live Oftegard, NTNU

"Within NTNU AMOS, I had the opportunity to work on topics I have never studied before, among them bioinspired studies involving fish hydrodynamics. Marine and maritime technology can directly and indirectly contribute to many of the UN 17 sustainable development goals and play a primary role for energy and food production."

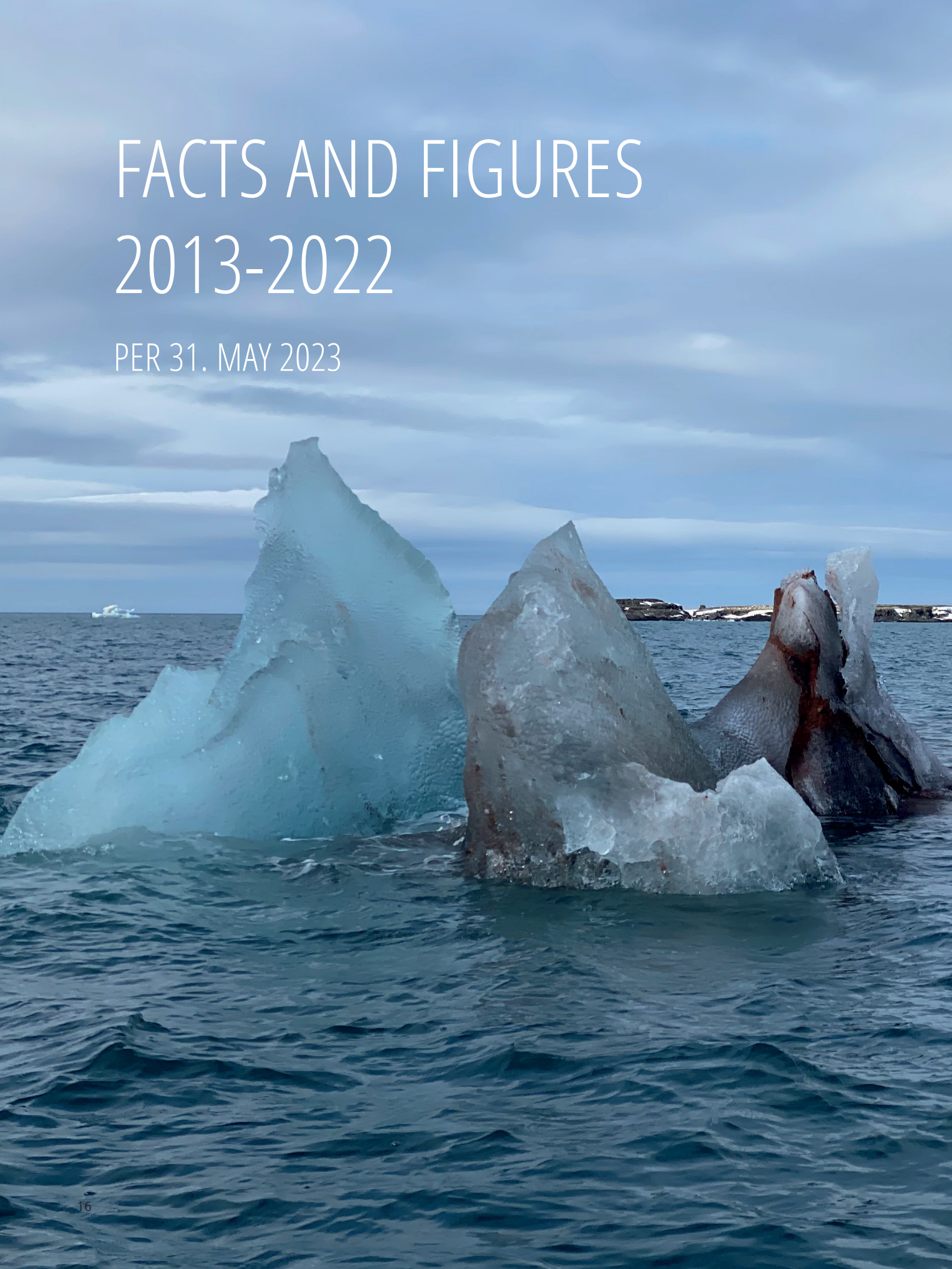
JØRGEN AMDAHL
DO THE MATHS!

"Do we have to change the rules and regulations because of the climate change? I am worried about the decades that are coming. I am also worried that the industry will get at desperate lack of people with the competencies of understanding hydrodynamics, ocean structures and loads in the years to come."

Photo: Private

FACTS AND FIGURES 2013-2022

PER 31. MAY 2023



	2013-2017	2018-2022	2023 ++	Total
Cost (direct and indirect) - MNOK	254,6	258,2	45,8	558,6
Graduated PhD – AMOS + Associated	57	79	7	143
Graduated MSc	-400	-500	-100	-1000
Books	3	4		7
Journal papers	370	485		855
Book chapters	21	28		49
Conference papers	556	377		933
Keynotes	42	42		84
Start-up companies	5	3		8

	AMOS total	
	Count	%
PhD		
Male	196	83 %
Female	39	17 %
Total	**235**	**100 %**
Postdocs/researchers		
Male	47	87 %
Female	7	13 %
Total	**54**	**100 %**

Total number of graduated PhDs: 143 **(289)**

Nationality	Count	%
Norway	161	56 %
Denmark	7	2 %
Italy	8	3 %
India	7	2 %
Brazil	5	2 %
China	22	8 %
France	3	1 %
Greece	4	1 %
Netherlands	7	2 %
Germany	17	6 %
Spain	3	1 %
Pakistan	1	0 %
Portugal	1	0 %
Poland	3	1 %
South Korea	2	1 %
Sweden	4	1 %
USA	6	2 %
Taiwan	1	0 %
Island	1	0 %
Czech republic	2	1 %
Great Britain	2	1 %
Iran	6	2 %
Switzerland	1	0 %
Finland	1	0 %
Lithuania	1	0 %
Turkey	1	0 %
Malaysia	1	0 %
Slovakia	1	0 %
Bulgaria	1	0 %
Vietnam	1	0 %
Hungary	1	0 %
Egypt	1	0 %
Indonesia	1	0 %
Sri Lanka	1	0 %
Montenegro	1	0 %
England	2	1 %
Japan	1	0 %
Total	**289**	

EQUINOR

Equinor is a proud partner of NTNU AMOS. Our interest in AMOS goes across all projects, and in support of advancing knowledge and solutions with higher levels of autonomy throughout the ocean space. We have been able to participate and set a strategic direction for AMOS that spurs unbiased basic research that can easily be implemented across industries.

While suppliers with market shares within segments covered by AMOS have been collaborating, we do see the unique position AMOS has kept throughout its existence, in which there is a genuine freedom to disrupt without concern for legacy products and technologies. It is believed that this freedom has been vital for the many innovations that have emerged from AMOS. We also see that suppliers and industry have stepped up to improve their own solutions based on the great work done in AMOS.

Bringing in end user perspectives to the research undertaken has proven to be a great virtue for activities in AMOS. End users set the bar on the quality and performance of systems, and hence spur AMOS researchers to rethink solutions – not at the cost of basic research, but rather fundamentally challenging the options provided by existing research and technology. AMOS has shown how basic research can grow from trying to radically improve given end-user objectives. Solution-agonistic approaches have the power to disrupt and fundamentally change industries.

The centre has consciously taken the approach of the rapid testing of ideas, technology and solutions. Such rapid testing of ideas with a high allowance for failure is essential for swift progress within the selected research areas. In this way, students get a chance to excel in their own research and theory, through corrective actions on hypothesis and models based on evidence. Such an approach increases the uptake of basic research from AMOS in research institutes and industry in general.

As industry partner to AMOS, it has been of the highest importance for us that AMOS became and stayed a daring research centre. Academia should have

PARTNER STATEMENT

that courage to test and fail in the quest for expanding the limits of what is, not humanly, but: scientifically or "robotically" possible. Fail in a safe way. This is a prerequisite for progress. If research does not fail in its early stages, it could indicate that the bar is set too low. Through 10 years of operation, AMOS personnel have been imprinted with this message, and need to aim high with their own research. The AMOS mantra has been: "Proud? Yes!, Satisfied? Never!" The constant quest for improvements, incremental as well as radical, has been the backbone of AMOS. Within the fast-moving research areas of AMOS, this is a prerequisite to stay as a world leader, which has served the centre well.

In academia, impact is often measured by the volume of scientific productions in high impact-rated journals. AMOS has shown great numbers in this respect, contributing to dissemination and awareness in a way that confirms NTNU and Norway as world leading on cutting-edge science and technology in the ocean space. This, however, offers only a limited view of the actual impact AMOS has had on academia, institutes, industry, and society as such.

AMOS provides great examples that interdisciplinary work is not in conflict with the scientific depth of single disciplines, but instead improves quality in such individual domains, as well as the collaboration across. Results are shown to be groundbreaking, in true honour of the intentions of the Centre of Excellence scheme. Profound impact is gained from the way AMOS has refined and educated its own students and employees to become polyvalent experts.

Even if the many new companies spun out from AMOS activities with the potential for a great impact on society, perhaps the greatest impact is still competence and mindset imprinted in the many MSc, PhD, postdocs and employees of AMOS. They are highly sought-after employees in industry, institutes, academia and with governing bodies. Fruits from their careers and future endeavors will last for many decades to come.

Equinor has throughout AMOS existence gained value from its production of insights, competence, solutions, and established spin-out companies. Our operations as well as rollout of robotic systems with increased level of autonomy in air, on sea surface, on the ground and subsea supporting petroleum as well as offshore wind business has been supported by AMOS competencies. As examples, this has aided environmental monitoring, inspection, maintenance, and repair as well as situation awareness for operators. Such systems and increased level of autonomy opens fundamentally new ways of operating. AMOS contributions have improved Equinor's ability to deliver according to the corporate strategy "Always safe, High value, Low carbon".

"As industry partner to AMOS, it has been of the highest importance for us that AMOS became and stayed a daring research centre. Academia should have that courage to test and fail in the quest for expanding the limits of what is, not humanly, but: scientifically or "robotically" possible. Fail in a safe way.

Dissemination into the public domain has also been in focus at AMOS. Over the last decade, a great number of TV broadcasts and news articles on AMOS activities have created curiosity, interest, pride, and enthusiasm to a wider audience. This increases the interest of youth to study and find a career within our industries.

AMOS has never been afraid of reinventing itself as a centre. Bringing in biology and archeology into AMOS, in addition to developing the observation pyramid concept, thereby proving its virtues and applicability, are just some. Conquering space with small satellites is another. Many more could have been mentioned, including robotic organizations. At the core of this is an ability to timely identify new and adjacent areas, white spaces on the map, as well as redefining and applying basic competencies to radically improve for high impact.

We would like to thank the Research Council of Norway, AMOS partners, the host institution and collaborators for an extraordinary and successful journey. The unwavering support from the host NTNU has been imperative for AMOS to succeed. We would like to thank the key scientists of AMOS, the administration, and the centre's director Asgeir J. Sørensen, who has created and maintained a sharp performing team.

Then finally: *"Now this is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning."* (Quote: Sir Winston Churchill)

On behalf of Equinor
Kjetil Skaugset
Board member of AMOS for 10 years

DNV

The maritime and offshore segments have always been important areas for DNV and we have been a member of AMOS since the beginning. The focus of AMOS on autonomous systems, marine robot platforms, and risk management of ships and ocean structures are well aligned with the direction that DNV is taking.

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We acquired Marine Cybernetics in 2014 as a means of providing new ways of testing and assuring software control systems. With digital twins of the sea states and the ships, we could now simulate the performance of the control system against these twins rather than test onboard the real ship. Such hardware-in-the-loop testing added additional capabilities to the conventional way of assuring control systems.

The collaboration with AMOS has strengthened our capabilities in this field beyond testing of control systems. Today, we see that cybernetics and simulation-based approaches is essential in assuring any kind of digital system, be it a full autonomous ship, a digital twin of the ship, a machine learning algorithm providing a function, etc. In our journey towards a digital class offering, we explore all these possibilities.

We test how ships can be assured based on standardised 3D models (digital twins) combined with simulations and use of operational data. The collaboration with AMOS has been important for DNV to advance these areas. To further harvest from the work in AMOS, DNV has also acquired a minority stake in the AMOS spin-off ScoutDI, who provides drone-based inspections.

DNV is a knowledge-based company. We therefore need to collaborate with academia to stay close to the scientific developments. One of our instruments to connect us to NTNU are the DNV-funded professors: We sponsor fulltime professors at NTNU that work on topics of special importance to DNV.

Three DNV-funded professors have been part of AMOS over the years: Edmund Brekke, Zhen Gao and Børge Rokseth.

> **"AMOS is important not only to DNV, but also to Norway as a maritime nation. Through this Centre of Excellence, we have been able to take a leading role internationally in areas of special importance to Norway."**

These professors have been helping to advance the scientific work in AMOS, and also helped DNV in our harvesting of knowledge into our own work. Through AMOS and the professors, we have been able to shape and engage in scientific work, supervise students, recruit candidates, and deploy results from AMOS.

AMOS is important not only to DNV, but also to Norway as a maritime nation. Through this Centre of Excellence we have been able to take a leading role internationally in areas of special importance to Norway. This demonstrates that Norway has a competitive advantage on collaborations between government, academia, and industry.

Together one can have a fast cycle from development of regulations, development of concepts, testing on use cases, qualification of new technology and adaptions. This fast cycle from research to innovation is also the trademark of AMOS. In addition to doing cutting edge research, AMOS has created several spin-off companies. The ability of AMOS to make use of the whole value chain, from research to innovation through pilots and finally commercialization is truly impressive.

We would like to take this opportunity to thank AMOS and NTNU, the partners and everybody involved in AMOS for a project well done. AMOS is a success.

On behalf of DNV
Frank Børre Pedersen
Partner of AMOS for 10 years

PARTNER STATEMENT

SINTEF OCEAN

Norway is and has always been a nation relying on ocean industries. Fisheries, shipping, and petroleum has expanded to aquaculture, renewable ocean energy and other new industrial segments. The basis for this adventure has been the resources of the ocean and knowledge. In modern times NTNU and the entire Norwegian community of research organizations have contributed to the development of the ocean industries through education of students and world leading research.

SINTEF Ocean has been a partner of the Centre of Excellence NTNU AMOS since its start, and we have proudly participated in the research activities across all scientific areas in the centre. NTNU has taken strong leadership and challenged us and the other partners on experimenting with radical new ideas and solutions to support the future ocean industries. We cannot rely on the past to form the future, and we need to support the existing industry to perform significant shifts in their operations and value chains. The current climate crisis, biodiversity crisis and shifting positions in geopolitics underpins this.

The global ocean industries will need to renew their license to operate in the future. Many solutions to the climate crisis will be found in the ocean industries, and the new businesses will have to operate with minimal disturbance of the ocean ecosystems. The future scientists and employees in ocean industries will have to find new solutions with this in mind, and new technology is going to be developed and implemented in future value chains on new premises. AMOS has proved that new solutions can be found, and the students and researchers involved in AMOS will have the mindset and insight to take the development further in the future.

SINTEF Ocean has already recruited many of the students from AMOS, and they are doing industrial research supporting ocean-based businesses. They are a source of new ideas and solutions, and they are working in close collaboration with the industry. AMOS has been vital for establishing new research activity, and many new centers have been started based on results and proposals from AMOS. In addition, many industrial research projects have also been established from AMOS results, and we foresee that many solutions will have their industrial implementation in the near future.

AMOS has also been vital in building research infrastructure, as ideas from AMOS has been translated into future needs for education and industrial research. For example, The Norwegian Ocean Technology Centre has been developed with inspiration from AMOS, and the OceanLab infrastructure has been built on the needs to take AMOS' results into the future.

The collaboration between NTNU and SINTEF has been strong for more than 70 years. AMOS has been vital in strengthening this partnership, and new scientific areas have been developed to create values on future opportunities. SINTEF Ocean is grateful for the opportunity to work with NTNU and the other partners of AMOS. NTNU's strong leadership in the centre has been of particular value because "Excellent – generous – courageous" have been the real guideline for the work performed.

> **"The global ocean industries will need to renew their license to operate in the future. Many solutions to the climate crisis will be found in the ocean industries, and the new businesses will have to operate with minimal disturbance of the ocean ecosystems. The future scientists and employees in ocean industries will have to find new solutions with this in mind"**

SINTEF Ocean would like to take this opportunity to thank AMOS and NTNU, the other partners and connected companies and researchers involved in AMOS for excellent cooperation. AMOS will stand out in history, and we are proud of the results.

On behalf of SINTEF Ocean
Vegar Johansen
Partner of AMOS for 10 years

PARTNER STATEMENT

PERSPECTIVES **BEYOND** AMOS


Jørgen Amdahl
Thor I. Fossen

Marilena Greco
Geir Johnsen

Tor Arne Johansen
Kristin Y. Pettersen
Asgeir J. Sørensen





Norway plays an important international role as one of the main actors in the blue economy. More than ever, a holistic and sustainable approach is needed to address global challenges, value creation and knowledge-based management of the northern regions and oceans. We are in the United Nations Decade (2021-2030) of Ocean Science for Sustainable Development – The Science We need for the Ocean We Want (Intergovernmental Oceanographic Commission, 2019). Another important achievement was the UN Biodiversity Conference, COP15, in Montreal in December 2022, concluding with a "historic" deal to protect one-third of the world's biodiversity to help strengthen the web of life, the protection and restoration of land and seas, and the launch of platforms for accelerating action.

A holistic and sustainable perspective of the blue economy (see Figure 1) that encompasses all stakeholders, including policymakers, is needed to achieve both the impact and implementation at the speed we require. The changes that take place in Arctic regions and ocean areas increase in speed and extent, and are strongly interconnected to activity on land and coastal areas around the globe. The oceans connect and belong to all of us (humans and other organisms), so we are in a hurry to understand and take proper actions. We must create incentives for *demand* and *deliver* across the entire value chain, stimulating the stakeholders from a think-tank to an executional do-tank to develop competence, knowledge and innovations subject to:

- *global challenges* related to habitat degradation, climate change, lack of energy, minerals and food, acidification and pollution of the oceans, a biodiversity crisis, natural disasters and a need for green logistics;
- *value creati*on (products, services, etc.) in terms of fisheries, aquaculture, maritime transport, oil and gas exploitation, offshore renewable energy, marine minerals, tourism, coastal and urbanization infrastructure;
- *governance and knowledge-based management* of the oceans, coastal areas, seabeds, and the Arctic; and
- *enabling technologies* such as information and communication technology (ICT), material technology, biotechnology, autonomy, big data cybernetics, nanotechnology, and interdisciplinarity.

When it comes to preserving and developing human health and well-being in the short- and long-term for the generations to come, we face a few dilemmas. Increasing occurrences of habitat degradation, extinction of species, extreme weather, accelerated melting of ice on land and sea, rising sea levels, pollution, and global diseases should indeed motivate us to develop more sound and sustainable human activities. The cost of overlooking this fact will simply be too high, both in economic and humanitarian terms.

Indeed, it is our belief that knowledge and competence can contribute to technology innovations and policy in two ways. To create changes fast enough in the desired direction, technology innovations may be implemented as a transformative process, while others may be more disruptive. Start-ups supported by academia, industrial and financial partners are often the most effective way to go, as no strings are attached to legacy products and services. Successful implementation relies on political leadership that enforces incentives and regulations. Fortunately, long-term responsible industry actors and investors that are looking beyond the next quarterly economic reporting also have similar interests. There does not need to be a contradiction between value creation and sound knowledge-based governance. For instance, for the fisheries and aquaculture industry, it

> **"There does not need to be a contradiction between value creation and sound knowledge-based governance**

is obvious that a healthy ocean is not only good for, but a precondition for business.

In being proactive, both for existing industry and start-ups, we may regard the 17 United Nations (UN) Sustainable Development Goals (SDG) as the largest and most systematic market study of the world, providing possibilities for economic growth and a better future. Knowledge and competence will be instrumental for the development of technology and services contributing to improved solutions.

Decades of systematic ocean science research using ships, landers and buoys, and lately advanced marine robotics and sensors, have told us how extensive and vulnerable the ecosystems are in the High North and Arctic Ocean. Even during the winter and polar night season, the marine ecosystems are fully functional and active. Threats to these ecosystems span from the discharge of toxic substances, the inflow of warm water and the intrusion of invasive species from the south.

During the polar night, we have also studied how sensitive the behavior of zooplankton and fish are to artificial light pollution (e.g. ships, settlements). The light climate influences the hunting and escape strategies for many species, such that they easily become disturbed by artificial light several kilometers away from the source, as well as ten folds of meter into the depth. The same behavior using large ships emitting light may also be an error source in the quantification of marine resources for research and management (fish stock surveys) purposes during the night and winter season (polar night).

We may claim that the advection pump of warm Atlantic water into the Arctic Ocean and the corresponding outflow of cold Arctic water, both taking place in the Fram Strait between Greenland and Svalbard, are of crucial importance for life in the northeastern Northern Atlantic and the Arctic Ocean. Any changes in these water fluxes not only directly affect the local climate, but have ramifications all over the Northern hemisphere. In simple terms, we can regard the Fram Strait as an oceanographic and biological

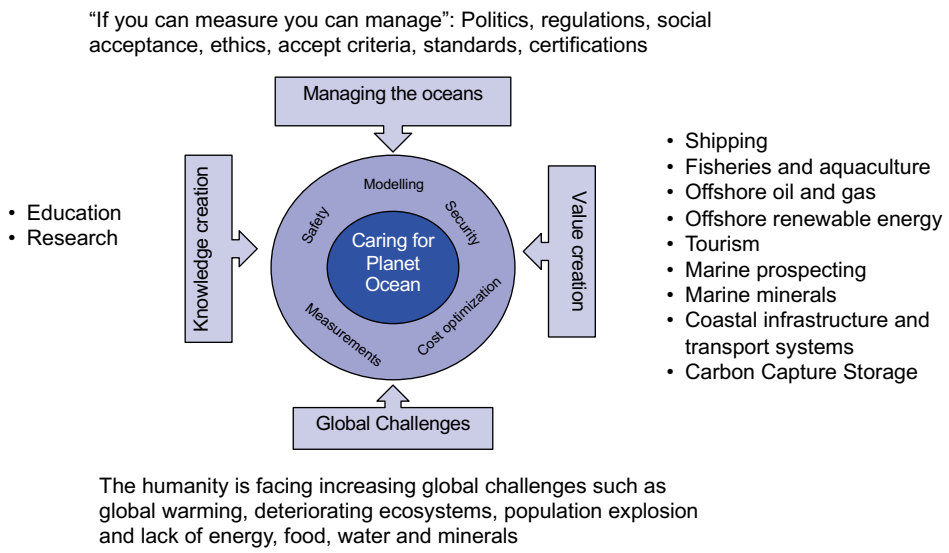

Figure 1: Sustainable value creation requires a holistic approach

"war zone" between the south and north. Today's climate change moves this war zone further north, with possible devastating effects on Arctic sea life, including sea birds.

As in the ancient times of the ice age, the pressure by the human exploitation of resources in the Arctic regions literally follows the ice edge. This also applies today for whaling, fisheries, shipping, tourism, mining, oil and gas, defined as the blue economy. In some few decades, we may experience that Arctic Ocean going from an iced covered white ocean to becoming a blue ocean during the summer, with little or no multi-year ice present.

The blue economy

The Norwegian economy is dominated by the blue economy (see Figure 2). Common factors for the blue economy are that the activities are taking place in the oceans, and that they are both local and global in their presence and trade. Concerning a more accessible new Arctic Ocean, we may foresee a global race for securing access to potential valuable fisheries, hydrocarbons and mineral resources. In addition, less multi-year sea ice will open new Arctic shipping routes. Hence, the level of human activities and possible environmental impact are expected to increase in a vulnerable environment, in which our knowledge is still rather limited. The sustainable exploration and exploitation of the ocean require hydrodynamically efficient, highly maneuverable, low intrusive, autonomous vehicles, so as to cope with long-distance missions, hostile environmental conditions (e.g. high pressure, low visibility) and fragile eco-systems; bio-inspired underwater vehicles can be crucial in the engineering implementation of these skills.

> **"We can regard the Fram Strait as an oceanographic and biological "war zone" between the south and north. Today's climate change moves this war zone further north**

Offshore oil and gas, the maritime industry, fishery and aquaculture are the three largest sectors of the Norwegian blue economy. They are all of great importance for Norwegian well-being, providing an important contribution to the world in the supply of energy, transportation and food. Emerging business areas are offshore renewables (primarily offshore wind), tourism and marine mining. Benefitting from ocean science and bioprospecting (the process of discovery and the commercialization of new products based on biological resources), we may also see huge potential in new marine species, bacteria, molecules, etc. to produce new pharmaceutical substances, such as antibiotics that kill antibiotic-resistant bacteria.

Reduced emission footprint in oil and gas

National oil and gas activities mostly take place in three areas - the Arctic region, the Norwegian Sea and the Barents Sea. Defining the border line for the sea ice edge in the Norwegian Arctic regions, restricting how far north oil and gas activities on the Norwegian continental shelf can take place, has been highly important. Oil and gas activities in the High North are not only of concern in Norway, as there are also large terrestrial and offshore activities in Russia, Canada and the US. The exploitation

> The exploitation of hydrocarbons is not sustainable. Carbon capture storage (CCS) may be methods to reduce the problem

of hydrocarbons is not sustainable. Carbon capture storage (CCS) in ground reservoirs and other capturing methods in the ocean (e.g. kelp and micro algae production) may be methods to reduce the problem. The work to replace polluting energy sources, such as coal and heavy oil, with cleaner sources using renewables has intensified. Regardless of how the energy transition will occur, the 50 years of experience and knowledge gained from designing and operating offshore oil and gas installations, and conducting marine operations in harsh environments, will be instrumental in developing offshore renewables and offshore aquaculture.

Toward zero carbon shipping

Maritime transport is probably the most environmentally friendly method to transport large amounts of goods and humans to secure primary logistics needs. However, in global terms, shipping is still a severe single source of greenhouse gases and black carbon, unintentionally causing the spread of invasive species with ballast waters and hull fouling. The UN International Maritime Organization (IMO) has therefore enforced a plan to reduce emissions in international shipping by a total of 50% in 2050 compared to the 2008 level. A reduction of up to 50% may not look ambitious. However, it will indeed create changes in the organization of logistic chains and motivate new ship concepts with hybrid power plants, using greener fuel mixtures, batteries, hydrogen, ammonia, etc. Green fuels are supposed to be produced by renewables, by limiting the capacity and speed of transition. An attractive substitution for some years is the production of blue hydrogen products based on hydrocarbons and CCS. Nevertheless, the cost of energy may rise on the order of 3-10 times, compared to today's use of conventional fuels.

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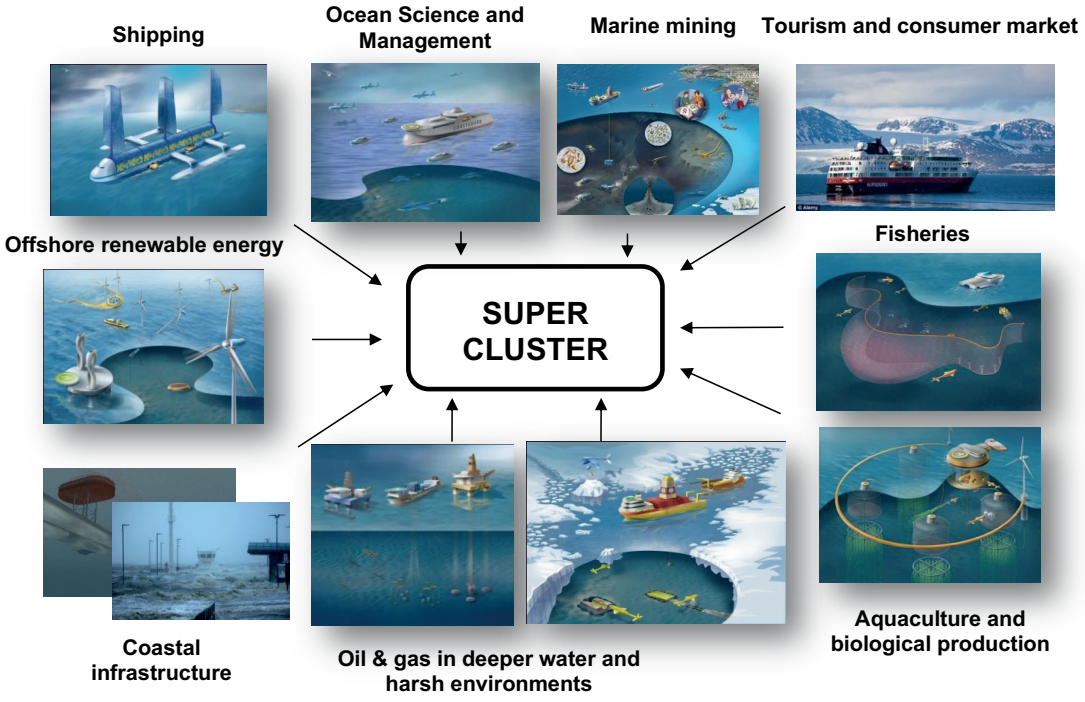


Figure 2: The blue economy (Courtesy: NTNU AMOS/Stenberg)

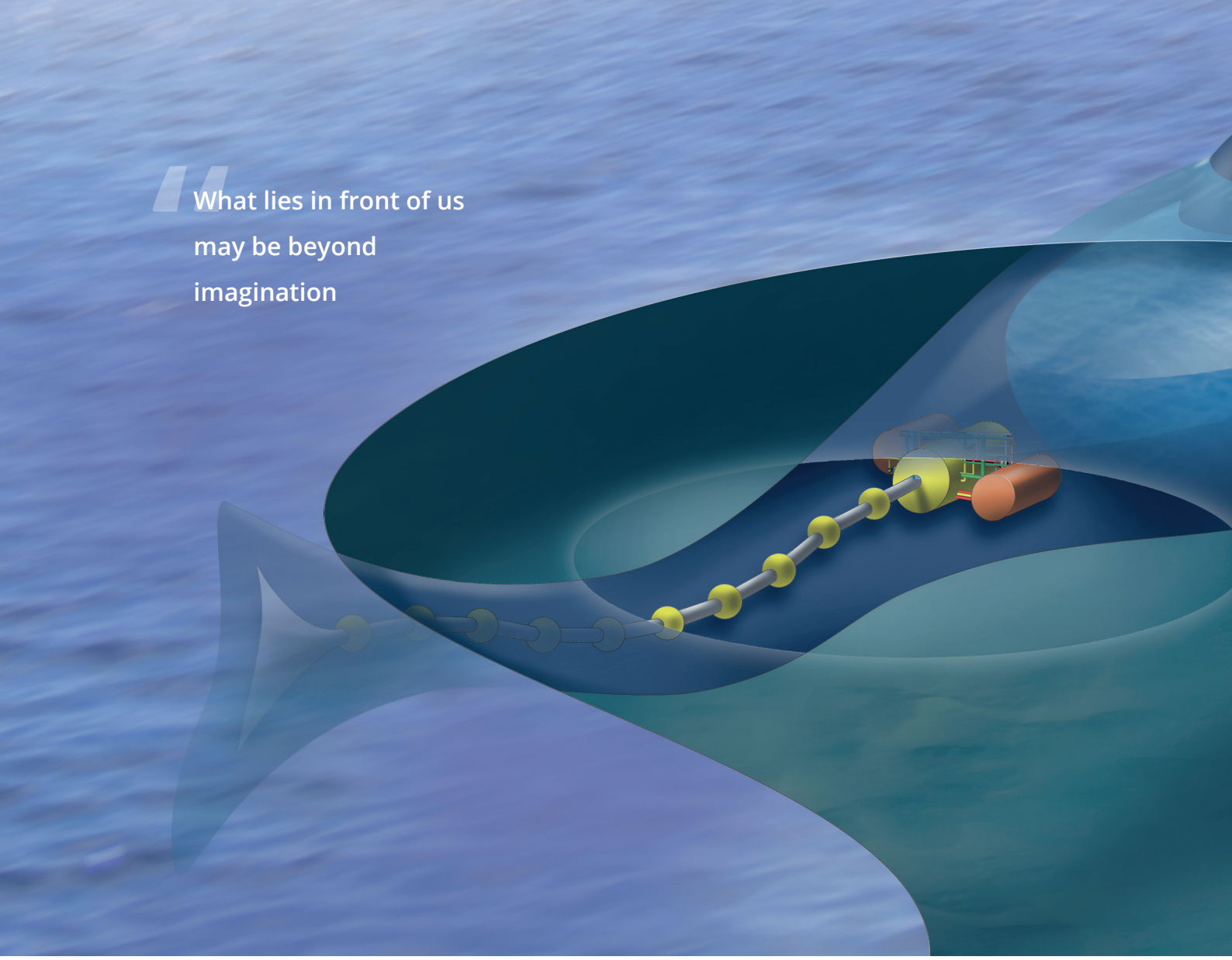


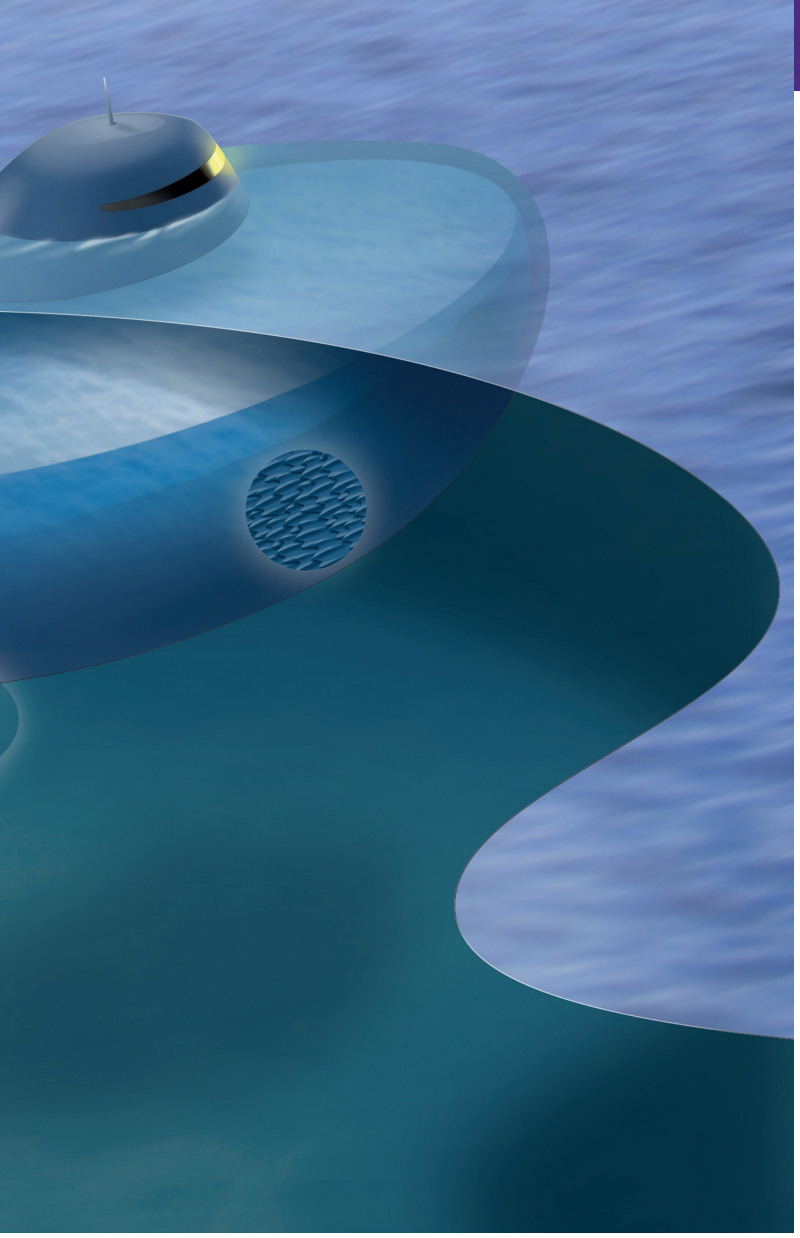
Figure 3: Disruptive innovations beyond imagination from micro to macro scales *Illustration: NTNU AMOS/Stenberg*

Reducing ship speed and selecting unmanned autonomous ships will represent possible solutions. A driver for a rapid transition towards zero carbon shipping may be to enforce even stricter requirements for reduced emissions in all maritime activity. This may be regulated by authorities using, e.g., a tax on emissions and creating a commercial *demand* and *delivery* mechanism from customer to producer through the entire supply chain. The combination of regulators and financial institutions is a significant driver for the transition. A license to operate and financial security are closely interconnected. For the various shipping segments, from deep sea shipping, regional shipping, domestic shipping, short sea shipping and urban transportation, it is evident that new commercial positions are to be taken, and we therefore see a race for innovations and investments in new technology, services and infrastructure. The response in the market is seen in, e.g., the form of innovation and spin offs, where:

- owners and logistic suppliers of goods to be transported commit to using zero-carbon shipping fuels (ref. Amazon and Ikea);
- partnerships between established and new actors develop a demand for knowledge, solutions, global infrastructure and distribution systems, thus supporting green fuel types on ships (e.g. the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping[1]);
- existing and new actors set up and develop production and distributions systems for green fuel types, batteries and charging systems; and
- novel logistics and ship concepts are developed for the various shipping segments.

The more capital-intensive innovations are often handled by the established enterprises, which may enter into joint ventures with

1 Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping: https://www.zerocarbonshipping.com



other companies or investors by developing solutions for batteries and new fuel types (e.g., Aker[2], Yara[3]), while the smaller start-ups seek more disruptive and less capital-intensive opportunities, e.g., autonomous urban ferries (e.g. Zeabuz[4]) and energy-efficient high speed crafts using an air cavity to reduce resistance (e.g. SES-x Marine Technologies[5]).

Towards offshore aquaculture

Coastal aquaculture is currently struggling with ectoparasites and harmful algae blooms. In addition, the environmental impact of aquaculture is of concern in many fjords. Offshore aquaculture in more exposed areas has become the next step for growth in this business. It is likely that the activity level will move northwards, and to areas with better access to a natural supply of food for farmed fish, such as the dominant zooplankton species *Calanus finmarchicus*. Important research areas may be related to spatial and localization planning, a co-existence with other industries, environment monitoring, novel structures, fish welfare, extreme hydrodynamic loadings and response, precision farming, autonomy and marine operations.

Towards offshore wind

When it comes to climate, biodiversity and short-term profit, we obviously face several policy and economic dilemmas, and possible conflicts of interest. For instance, more costly offshore wind turbines may have a less negative impact on biodiversity than developing cheaper wind turbine parks on untouched land. Still, going offshore may potentially increase spatial area conflicts with fisheries. In economic terms, we may ask how to evaluate and price limited resources, such as land and terrestrial ecosystems, when setting up cost balance sheets for new energy projects. Similarly, unless we increase our mining activities, a shortage of minerals may challenge the further growth of green alternatives, such as solar energy and batteries, for energy storage in, e.g., cars and ships.

Electrifying remote settlements and ports

Today, the settlements on Svalbard are dependent on hydrocarbon-driven power plants for the production of electricity (local coal and transported diesel). It is really a contradiction that one of the most environmentally sensitive areas in Norway is not supplied with greener and more renewable energy. We may turn this contradiction to an opportunity, where Svalbard and other remote areas can be a destination for developing and testing hybrid power plants, combining solar and wind driven energy production with energy storage, and the possible production of green fuel types such as ammonia becoming a green port for ships as well. The use of hydrocarbons is hence limited to a minimum. Smart hybrid power plants that work autonomously off-grid without large transmission networks may be a natural next step powering societies and ships on a global scale with greener energy, with less of an impact on climate and biodiversity. Why not start at remote areas such as Svalbard, and then use this

> **"Offshore aquaculture in more exposed areas has become the next step for growth in this business**

2 Aker: https://www.akerasa.com
3 Yara Marine Technologies: https://yaramarine.com
4 Zeabuz: https://zeabuz.com
5 SES-X Marine Technologies: https://sesxmarinetechnologies.com

> **Smart hybrid power plants that work autonomously off-grid without large transmission networks may be a natural next step powering societies and ships on a global scale with greener energy**

experience for the further export of knowledge, products and services on a global scale for remote areas.

Climate adaption of coastal infrastructure
Climate adaptation as well as novel concepts for the crossing of fjords and bays are increasingly important for the coastal economies. Most of the world population lives in urban settlements close to the sea. We can hardly comprehend the cost of adapting these cities and land areas to increasing sea level of only a few decimeters due to melting of land fast ice. Global and local infrastructure enterprises must look for innovative solutions for damage reduction.

Enabling technology

As we have seen, we face both challenges and enjoy opportunities where technology and its use play important roles for human activities and corresponding impact on life and environment. There are many drivers for technology developments such as market needs, exploration needs (and dreams) accessing new and maybe extreme environments, as well as policy-driven rules and regulations. Game-changing technology is often provided through so-called enabling technologies. Enabling technology may be defined in different manners. Here, it is technology that can be applied to drive radical and thorough changes of public and industry inventions and innovations. For instance, drivers for technology developments for improved mapping and monitoring of the oceans in the High North including the Arctic Ocean may be improved operability, access to remote and harsh environments (deep water, under ice, extreme coldness, etc.), long distance with limited ability to communicate, demand for improved coverage and higher resolution of data in spatial and temporal scales, reduced cost, improved safety, etc.

In this context we may categorize the following as enabling technologies with relevance for the ocean technology

- Information and communication technology.
- Nanotechnology.
- Biotechnology.
- Material technology.
- Big data cybernetics and data analytics.
- Autonomous systems.

Combined with fundamental knowledge fields such as mathematics, physics, chemistry, biology, computer science and engineering and by integrating disciplines and technologies we may become in the position to conduct research and innovations based on disruptive, game changing technology. What lies in front of us may be beyond imagination. Examples could be to develop technology inspired by nature that are far more efficient and effective than today's solutions, e.g. applying multi-scale and distributed systems for sensing and actuation: Micro-to-macro (see Figure 3).

We have so far only witnessed the early start of an era where digitalization, artificial intelligence (AI) and robotics substantially contribute to our society: The next opportunities and research challenges lie in embodied artificial intelligence. Embodied AI is AI that controls something physical, like a robot arm or an autonomous vehicle. It is able to move through the world and affect a physical environment with its actions. This opens a new era of opportunities. Such embodied AI needs to become resilient and field-hardened. We can then see embodied AI contribute on roads, tracks, waterways, and in the air transporting passengers and cargo. In precision farming and forestry. At industrial sites, performing inspection, maintenance, and repair. Flying above land and water as well as swimming under water.

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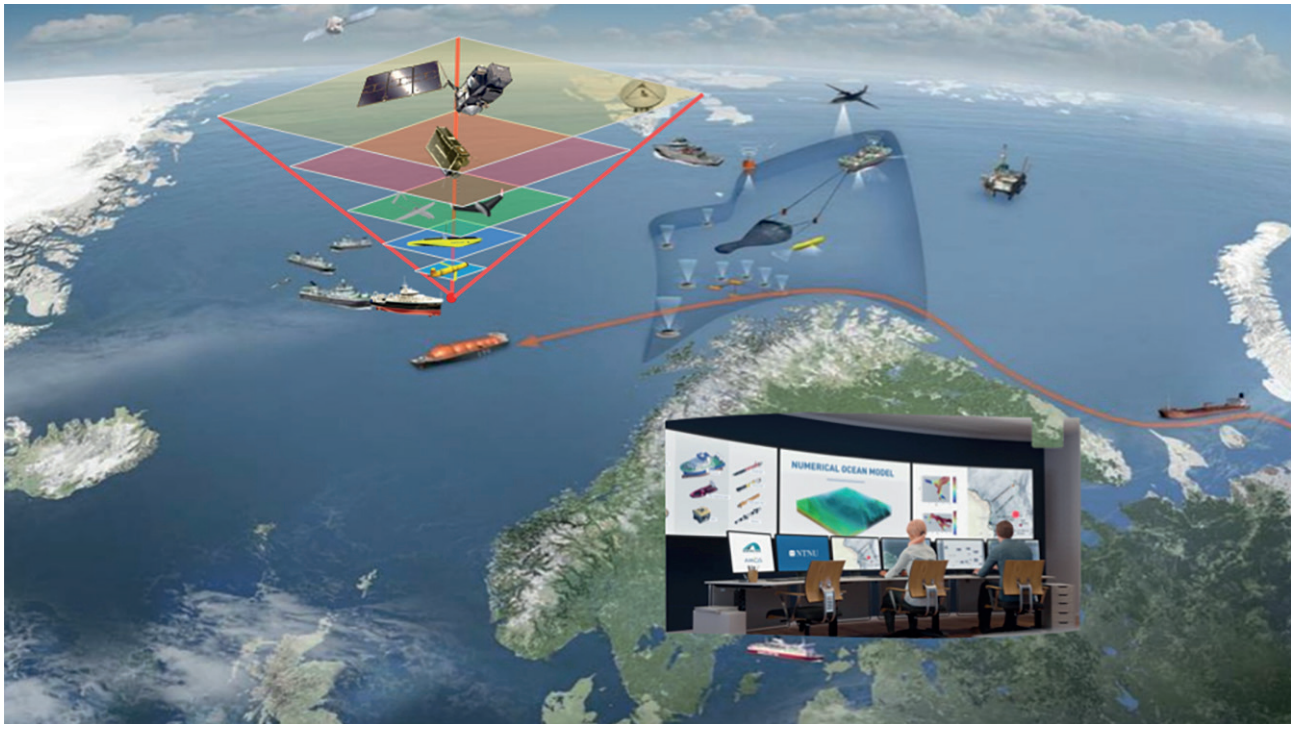

Figure 4: Observation pyramid

Enabling technologies such as information and communication technology, autonomy and microelectromechanical (MEMS) systems provide new possibilities for the development of sensors, sensor carrying platforms creating and observation pyramid (Figure 4), connectivity and big data analytics. The sensor carrying platforms operating from space to ocean space are:

- Underwater: Landers and buoys, remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), gliders and profilers.
- Sea surface: Ships, and unmanned surface vehicles (USVs).
- Air and space: Satellites, unmanned aerial vehicles (UAVs) and airplanes.

Low-cost small satellites and in particular *nano* (1-10 kg) and *micro* satellites (10-100 kg) carrying customized payload sensors and communication devices have opened for a step change for remote sensing and communication in polar orbits at altitude of 450-500 km with about 3-6 hours for each passing. Constellations of satellites will provide a significantly improved spatial and temporal coverage. NTNU has decided to launch two small-satellites as a pilot: one for hyperspectral imaging of ocean color and one for supporting Arctic IoT communication.

Environmental mapping and monitoring may be carried out by single platforms, swarms of platforms or combination of several types denoted as *heterogeneous sensor carrying platforms*. Each platform and sensor have various capabilities in terms of spatial and temporal resolution and coverage. By combining them we face a paradigm shift in terms of capabilities that may be 100-1000 times higher than the state-of-the-art technology only some years ago. The entailed increase in data harvesting does also create new challenges in handling big data sets. To take full benefit of the data and develop efficient adaptive strategies for sampling and measurements for the sensor carrying platforms, refinement of models and co-simulation with numerical simulation models of the oceanography and ecosystems is essential.

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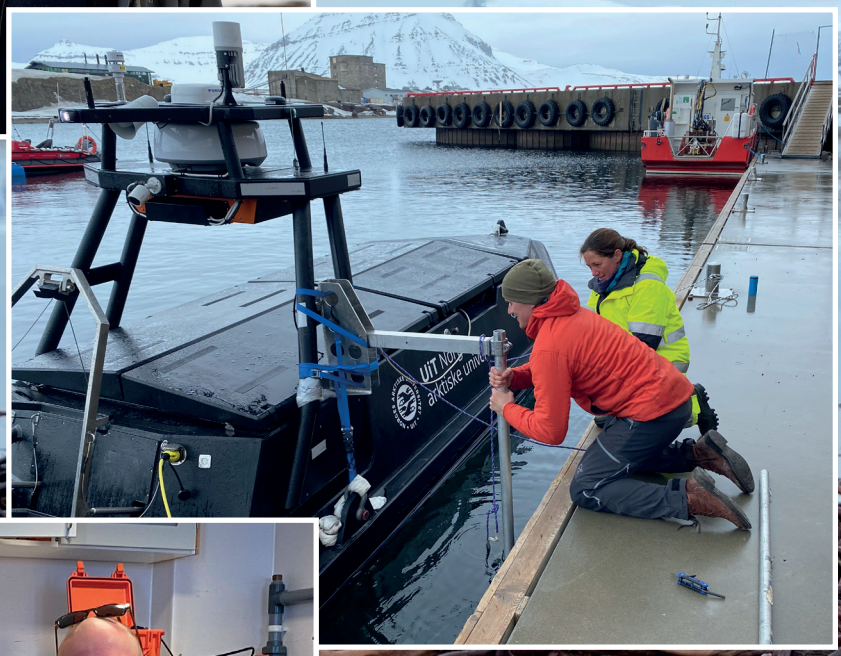

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