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Addressing the Sustainable Development Goals with a System-of-Systems for Monitoring Arctic Coastal Regions

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Abstract. Norway has a large coastal industry and a strong motivation for developing systems to enable sustainable management of ocean resources. Recent advances in collaborating autonomous systems, Internet-of-Things, microsatellites, data fusion, and sensor development have led to initiatives for a more concerted and coordinated effort through the establishment of an ocean studies research project. Applying a System-of-Systems perspective on the project highlights the challenges in terms of interoperability and communication interfaces, as well as revealing the use-cases stakeholders rely on to enable informed decision-making.

Introduction

The United Nations sustainable development goals (UN SDG) are drivers for development activities and national strategies across the world. The Director of the UN Office for Outer Space Affairs (UNOOSA), states that *"close to 40 % of the targets underpinning the 17 UN SDGs rely on the use of space science and technology"*, based on research conducted in 2018 (Pippo 2018). Since water covers 70 % of the planet, it is no surprise that many of the SDG address ocean challenges. *"Understanding the ecology, biogeochemistry and hazards of our oceans in a varying and changing climate is critical to sustaining Earth as a habitable planet"* (IOCCG 2008: p.7).

Developing systems for monitoring the Arctic coastal regions allows decision-makers to develop strategies for sustainable management of these resources. The vastness and challenging environment of these regions mean that it is not cost-effective to base the administration on a single technology for monitoring with the required spatial, spectral, and temporal resolutions. This paper looks at a specific project, from a System-of-Systems (SoS) perspective and describes how it can support the sustainable management of the Arctic coastal regions of Norway.

The MASSIVE (Mission-oriented autonomous systems with small satellites for maritime sensing, surveillance, and communication) is a project funded by the Research Council of Norway (RCN) and the Norwegian University of Science and Technology (NTNU). MASSIVE studies how observations of the ocean can be coordinated between different sensor systems by developing systems to accomplish the goals of effectively monitoring oceanographic phenomena and for distributing data to the scientific community and the relevant decision-makers. It considers small satellites, autonomous vehicles, and both data processing in the sensor nodes and data fusion in operations centers. In the light of MASSIVE's intended capabilities, the question addressed by this paper is: *How can viewing the MASSIVE project as an SoS produce a system that supports the scientific community and informs decision-makers?*

The MASSIVE project concept in Figure 1 gives an overview of included systems and interfaces. The constituent systems (CS) are unmanned aerial vehicles (UAVs), buoys, autonomous surface vehicles (ASVs), autonomous underwater vehicles (AUVs), small satellites (SmallSats), ground station system (GS), and a data processing system. While not shown in the figure, data from monolithic satellite systems such as Copernicus will contribute data to the data processing system. The concept of operation is that the satellite (constellation) will monitor the coast from space, and the autonomous assets from air and on/below the water surface. The operations control center can accumulate and process data collected and provided by the various agents about the ocean.

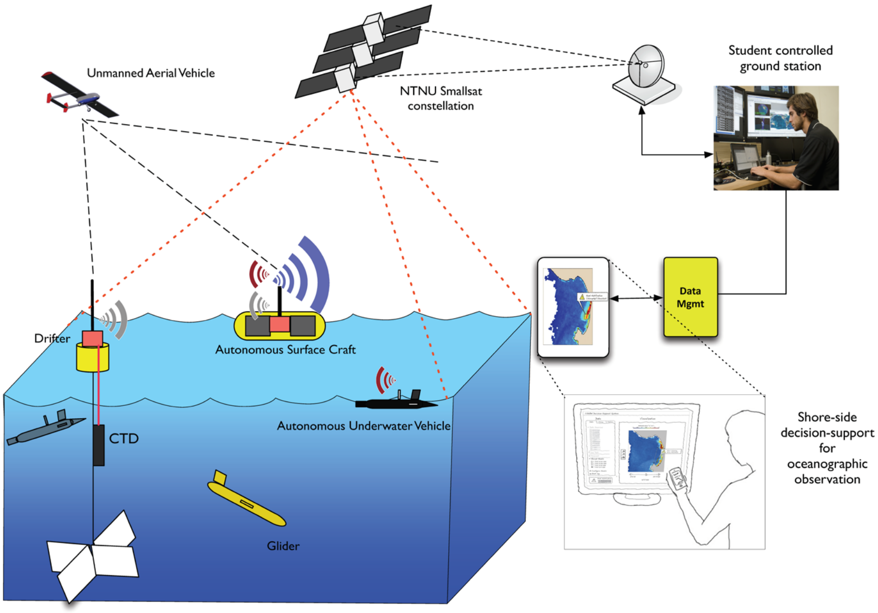


Figure 1. MASSIVE project concept, from (Rajan et al. 2017).

The paper is organized as follows: The first section gives background information on the management of coastal regions and a brief theoretic description of SoS. The next section describes the method used to analyze the MASSIVE project, followed by the analysis and an evaluation of how the MASSIVE SoS can support the scientific community and inform decision-makers in developing strategies for managing Arctic coastal regions.

Background

Managing Coastal Regions

A variety of oceanographic phenomena can be detected with different types of sensors, such as small or large monolithic earth-observing satellites, from ships during scientific cruises, swarms of drones or other autonomous vehicles equipped with sensors, manual tests, physical installations at various points of interest in the region or data gathered as secondary products from other systems. Each of these sensors provides valuable data, but they have characteristics such that no single source can satisfy the needs of the stakeholders.

Norway has a long coastline compared to its population (80,000 km, approx. 5.4 million inhabitants) and a high Gross Domestic Product (GDP) per capita (International Monetary Fund 2019), enabling the government to invest significantly in infrastructure. The Northern coast of Norway has a low population density, making it challenging to rely on human resources to support the surveillance and monitoring needs of the coast. Additionally, the country's industry is mainly offshore oil/gas, fisheries, and aquaculture, which means that the nation has a strong dependence on the coast for sustaining the high standard of living and national income.

The past years have seen an increase in sea temperature and a dramatic loss of ice in the Arctic, leading in part to a rise in ship traffic and a push to explore new oil fields further North. To ensure continued health and viability of the Arctic coastal areas, sustainable monitoring is needed. The need for sustainable monitoring drives the demand for better systems to monitor the Arctic in near real-time so that we can understand the impact of increased human and machine activity on the environment. Furthermore, more activity means a higher risk of loss of life or devices in the Arctic, which is a region underserved by communication and infrastructure, which also poses challenges for search and rescue activities.

RCN has awarded the following research initiatives related to ocean and coast monitoring, signaling how important the coastal areas are for Norway: *"Norwegian Infrastructure for drone-based research, mapping and monitoring in the coastal zone" (7.8M€)*, *"The Norwegian node for the European Multidisciplinary Seafloor and water column Observatory" (7M€)* and *"Ocean Space Field Laboratory Trondheimsfjorden" (18M€)* (Wel 2019).

System-of-Systems

System-of-Systems (SoS) is often used to describe the increasingly complex systems developed today. Maier's definition of an SoS from 1998 is widely cited and is used as a basis for this research. An SoS includes components that are in themselves systems and have operational and managerial independence (Maier 1998). An SoS is distributed, interoperable, and adaptable, and can consist of technical and human components (Madni and Sievers 2016). It is helpful to view the integrated system as an SoS, ensuring the consideration of the whole context when developing the constituents. However, there are additional challenges associated with an SoS which are not present in a system. Firstly, components may reach their own decisions without considering their role in the SoS. Secondly, inherent complexity makes it challenging to model emergent behavior. And thirdly, that testing and verification of the SoS may not be feasible due to its scale and complexity (Madni and Sievers 2016).

Existing systems can be integrated into an SoS, bringing challenges of mismatched interfaces and decentralized operations management (Lindman 2015). Decentralized management creates programmatic problems such as ownership, governance, and data policies. For example, changes to the CS can influence the required capabilities of the SoS and the other CS and requires coordination to manage risk, maintainability, and reliability of the CS and SoS as a whole. An SoS may be a temporary assemblage to satisfy a specific short-term mission or can be adaptable to fulfill a combination of mission objectives that change over time.

There are different types of SoS: virtual (*"…no central management…* (or) *agreed-upon purpose"*); collaborative (*"…interact more or less voluntarily to fulfill agreed upon central purposes")*; acknowledged (*"…independent ownership, objectives, funding, development and sustainment")*; or directed (*"…built and managed to fulfill specific purposes"*) (Madni and Sievers 2016: p.6). The SoS can change or bridge types over time, by adding or removing constituents or if the mission objectives change.

The SoS described in this paper can be classified as something between a collaborative or an acknowledged SoS as the CS have independent management but act together to fulfill the mission objectives.

Analysis Method

The SPADE (Stakeholders, Problem, Alternatives, Decision-making, Evaluation) methodology (Haskins 2008) was applied when analyzing the project. The methodology captures the essential systems engineering principles and can be used continuously at multiple maturity levels of a project. SPADE's focus on stakeholders and analysis of these is relevant when dealing with SDGs, which are so large that there are multiple governmental and private stakeholders involved. This section gives a short description of the method and usage for the case study.

Stakeholders are actors, entities, and anyone affected by the system. They are managed throughout a project's lifecycle, and their involvement can vary continuously depending on the phase (Welford 2018). Stakeholder identification, understanding their level of involvement and contribution, analysis of needs, and management are relevant both to the systems engineer and to the project management. The stakeholders were identified from publications related to the MASSIVE project, and from research news items related to oceanography from RCN. They were assessed according to their interest-influence. The needs from the stakeholders were derived from public documentation review and informal talks with some of the researchers involved in MASSIVE.

The **Problem** definition or description activity is to understand the stakeholders' needs, to uncover the state-of-the-art solutions, and to determine how to measure whether the system solves the problem through metrics of performance and success criteria (Haskins 2008). The problem formulation will vary and change according to the viewpoint taken, the degree of involvement of a stakeholder, and the changes in context from the environment and state-of-the-art development. The context is limited to the MASSIVE project and the Arctic coastal regions, which limits the problem space in which the stakeholders' needs are analyzed. The problem is described from the perspective of oceanographic research and how the MASSIVE project can address the problem by providing new capabilities and information. Specific use-cases were created to contextualize the needs of the stakeholders. This does not rule out future use-cases that expand on the capabilities of the project.

Alternatives are generated based on the different viewpoints from the stakeholder analysis and problem formulation. The alternatives are subject to modification to accommodate the discovery of new options and the changing problem description. The alternatives described are different CS relevant to the overall project, various architectures, and the allocation to meet the system requirements.

Decision-making is a continuous process in a development project, where the people making the decisions determine the quality of the solution chosen (Haskins 2008). It is essential that the decision-making method applied is related to the overall problem formulation and stakeholder analysis, and that it can be tested for validity (Peniwati 2007; Rostaldås et al. 2015). This paper looks at how the project can inform decision-makers for Arctic coastal regions.

Evaluation is key to the whole SPADE framework. Continuous assessment of stakeholders, alternatives, problem formulation, and state-of-the-art solutions allows the project team to adjust the performance metrics and success criteria of the project to meet the changing conditions that arise.

Stakeholders: Private and Public Stakeholders

The multitude of stakeholders with varying degrees of interest contribute to the SoS complexity. The following stakeholders were identified and categorized according to type and level of influence (Schmeer 1999) as used in previous natural resource studies (Reed et al. 2009; De Lopez 2001). An interest-influence map (Eden and Ackerman 1998) was developed to map the stakeholders and visualize the assessment of the level of influence and interest, shown in Figure 2. While the public has an interest in the sustainable management of the oceans, they are indirect stakeholders represented through ministries (elected officials). The stakeholder analysis to-date has been performed based on a documentation review (Faisandier, Roedler, and Adcock 2019).

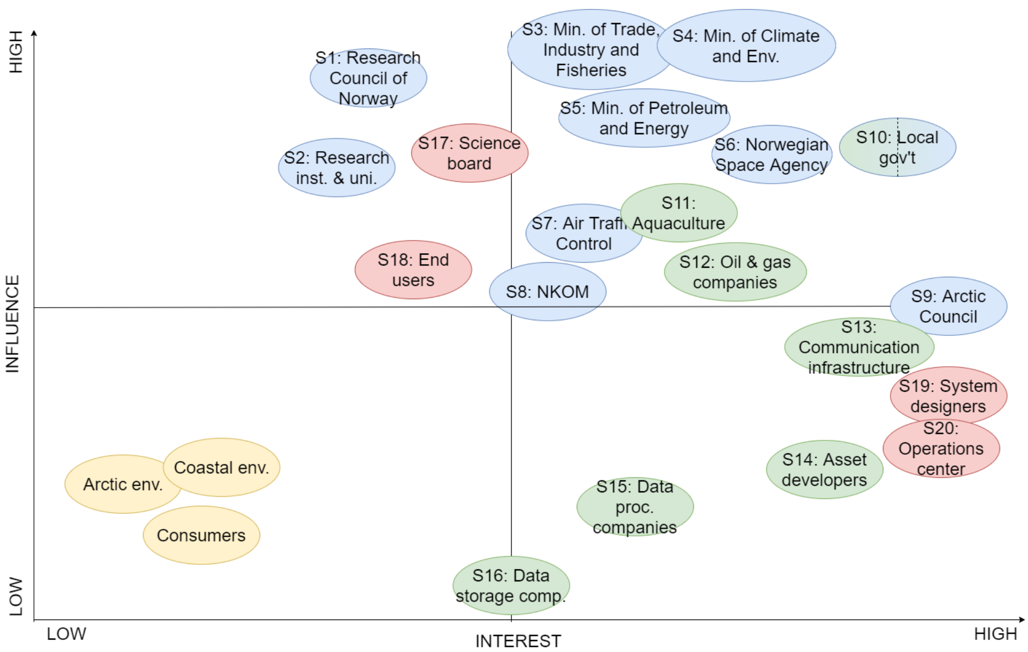


Figure 2. Interest-influence map. NKOM is the Norwegian Communications Authority. Red: MASSIVE; Blue: public; Green: enabling technology; Yellow: passive. Size for readability.

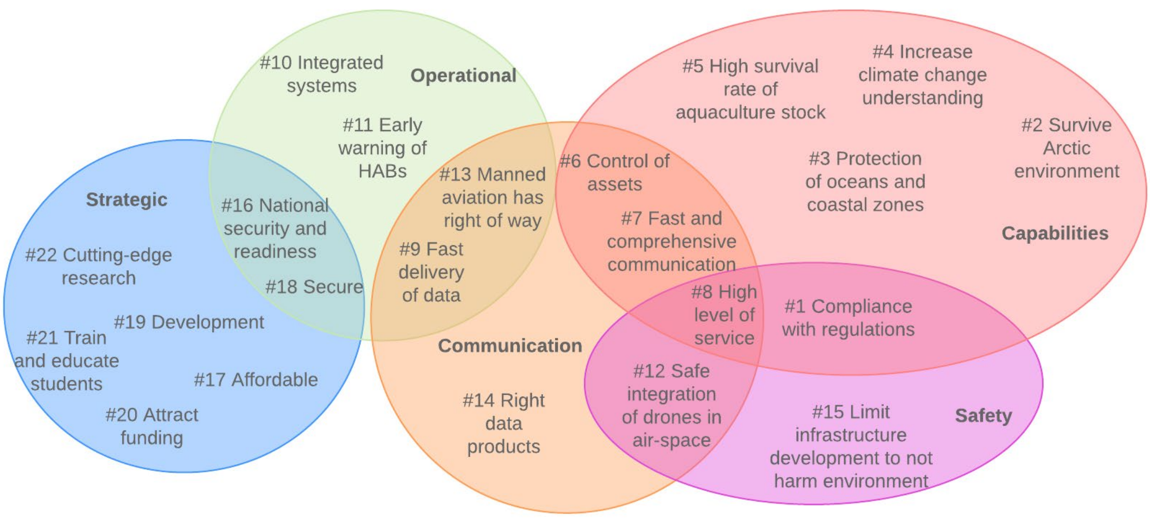


Figure 3. Diagram of stakeholder needs/constraints categorized in Operational, Capabilities, Communication, Safety, and Strategic.

The interest-influence map shows a high concentration of stakeholders in the two right quadrants. The large mass of public bodies in the upper quadrant should move to the bottom quadrant over time as the concept matures, as these have a more substantial influence at the beginning of a project than during the execution. Likewise, the system developers/enablers should move to the upper quadrant in the establishment of the SoS, when these stakeholders have a direct impact on the CS development.

The stakeholder analysis revealed a few high-level needs for an oceanographic monitoring system shown in Figure 3. Cross-mapping of stakeholders and needs are given in Table 1. To measure that the SoS meets the needs, they will be refined and quantified during decomposition into requirements. However, in their current state, they help direct the focus of capability development (upper right corner) while understanding the constraints.

Table 1. A mapping between stakeholder ID (from Figure 2) and needs/constraints (from Figure 3).

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20
#1			X	X	X		X	X		X	X	X	X		X	X				
#2									X		X	X		X			X	X	X	
#3	X	X	X	X	X	X			X	X	X	X		X			X		X	
#4	X	X	X	X	X	(X)			X	X	X	X					X		X	
#5			X								X									X
#6							X	X			(X)		X	X					X	X
#7							X	X		X	X	X	X						X	X
#8	X		(X)	(X)	(X)		X	X		X	X	X	X		X	X				X
#9							X	X			X	X	X		X	X				X
#10		X											X	X	X				X	X
#11			X	X	X				X	X	X				X		X	X	X	X
#12	X						X	X		X				X					X	X
#13							X	X					X						X	X
#14			X	X	X						X	X								
#15									X	X			X					X		
#16	X		X	X	X	X	X	X	X	X	X	X	X		X	X			X	X
#17	X									X	X	X		X	X	X		X		
#18	X		X	X	X		X	X	X	X	X	X	X	X	X	X				X
#19	X	X								X				X	X	X			X	X
#20		X	X	X	X									X	X	X			X	X
#21	X	X																	X	X
#22	X	X									X	X		X	X	X			X	X

Problem: Detecting Oceanographic Phenomena

Observing oceanographic phenomena and understanding the ecosystem is complex. While on land, humans can easily see biomass (such as planta and animals), in water microscopic phytoplankton or fish, and sea-mammals hidden under the water are challenging to monitor. This section will discuss the problems associated with detecting oceanographic phenomena and current approaches.

According to the International Ocean Color Coordinating Group (IOCCG), the presence of phyto-plankton is the leading property for understanding the aquatic ecosystems: *"(...) phytoplankton biomass is a key ecological property (...). Ocean-Color Radiometry (OCR) quantifies the base of the* *marine food chain"* (IOCCG 2008: p.7). OCR is used for detection because phytoplankton reflects light. A high spectral resolution provides more biomass information for researchers to better understand the ecosystems and provide information on species type. Algal blooms can move quickly because of ocean currents and having high temporal resolution enables better mapping and understanding of the blooms.

Other phenomena of interest are sea surface temperature (SST), ocean currents, wind data, salinity, sea surface height (SSH), and marine suspended sediments. These phenomena can be viewed in tandem to provide early warning systems for harmful algal blooms (HABs), optimal drilling times for oil and gas operations, safe swimming and diving conditions, stormwater and sewage release able to cause algal blooms, monitoring response of the ecosystem to oil spills, data to optimize competitive sailing paths (e.g. Volvo Ocean Race (IOCCG 1998)) and measure port sea depth.

Sky- and space-based sensors face the challenge of clouds obstructing the view, which can be especially prevalent in the region of interest. A study for the feasibility of optical communication estimated cloud coverage in Norway's Arctic regions, which approximated 25-30% cloud-free days in a year in Arctic land-regions (Bråten and Rytir 2019). The study concluded that there is a lower percentage of cloud-free days over the ocean than over land. On cloudy days, knowledge of oceanographic phenomena and models of how chlorophyll and sediments develop, and move is important to enabling better and timely usage of other sensor systems based on predicted paths.

One of the most significant challenges with the existing systems is that they are not coordinated in what they observe or how. Each system was created with a specific mission or with specific funding but may not have considered other existing or planned systems and how they could cooperate or utilize each other's data to perform the mission. Also, there are significant communication infrastructure challenges with fjords and mountains between the areas of interest, and vast distances to be covered along the Norwegian coastline.

Specific use-cases (UC) were developed as a basis for discussion and to highlight how the MASSIVE concept addresses the needs of the stakeholders. Specific requirements, in addition to the needs in Figure 3, are highlighted.

- **UC-1: Nominal (low resolution) monitoring of the coast (large coverage area).** Requirements: multispectral imaging; medium-scale distributed SST, SSH, salinity, ocean current, and sediment data; edge computing capabilities and low data rate (LDR) OR high data rate (HDR) and ground system computing.

- **UC-2: On-demand high resolution monitoring of HABs (medium coverage area).** Requirements: hyperspectral imaging with high temporal and spatial resolution, plus UC-1.

- **UC-3: Aquaculture monitoring (small coverage area).** Requirements: high frequency oceanographic phenomena monitoring; multispectral imaging; off-board HDR.

- **UC-4: High-resolution monitoring of the coast (various coverage area).** Requirements: high frequency oceanographic phenomena monitoring; hyperspectral imaging with high temporal and spatial resolution. LDR or HDR is dependent on edge computing capabilities.

Constraint: Communication gaps

Most of mainland coastal Norway is covered by mobile communication services such as 4G (LTE, NB-IoT, LTEm) up to some kilometers off the coast. In some deep fjords, there are spots without coverage due to the horizon obstruction and lack of base stations. Satellite services are also available (Iridium, Inmarsat) along the coast, but in narrow fjords, especially GEO-stationary services are limited. Offshore areas south of 70°-75°N can have coverage from GEO satellite services usable for ships, but not usable for smaller platforms/sensors because of the size of the equipment. New satellite solutions such as Norwegian HEO or proposed mega-constellations eventually may offer complementary services (Birkeland and Palma 2018). Around Svalbard, the situation is different from the mainland. Only a small portion of the archipelago has coverage from 4G, limited to areas near Longyearbyen (Telia 2019). A maritime broadband radio network has been tested to provide coverage in central parts (Gulbrandsen et al. 2017). Coverage from geo-stationary systems cannot be relied on for use above 76°N (Plass, Clazzer, and Bekkadal 2015). Thus, much of the Norwegian maritime area, including large parts of the sector above 65°N, is without adequate communication services both for oceanographic research and for Norwegian Search and Rescue (SAR) activities.

UC-1,2,4: Communication with sensors deployed in remote locations: For sensor nodes, several options exist depending on the size of the node, power available, and the amount of data collected (Quintana-Diaz 2019). For sensors with little data (<100 MB/month), systems like Iridium, Argos and OrbComm may provide a solution today. Dial-up Iridium can give a 2.4 kbps link, whereas Iridium SBD, Argos, and OrbComm are message-based systems with message sizes of a few bytes, typically 32 bytes as for Argos. For larger sensors producing more data, there currently is no option to transfer all data over satellite.

UC-3: Communication infrastructure for aquaculture: As aquaculture (fish-farms) move away from the fjords and the coast, the communication systems must move with them. For near-shore installations, custom microwave links can be installed between the shore and the aquaculture site. At the installation site, the network can be distributed through one or several local base stations and provide either specialized data links or other standard communications, such as WiFi and 4/5G. When the distance from the coast increases, satellites may be needed because relaying terrestrial radio signals over long distances and multiple hops offshore is complicated. Inmarsat from GEO-satellites or the upcoming Norwegian HEO-satellites, or services from the proposed mega-constellations, can serve as options if these systems fulfill cost and capacity requirements.

Alternatives: Multi-robot, space-based and ground-based systems

This section will describe different systems that are already in use for coast management, which needs they cover, some of the advantages and disadvantages with the systems, and possible further development needs to satisfy the problem definition. An explanation of the symbols used in the following sections, and of types of ASVs are given in Appendix A.

Multi-robot systems (MRS) consist of different types of robots, such as UAVs, ASVs, and AUVs. An MRS is defined as a system composed of multiple assets where each asset has an individual and a collective task and must have knowledge about the other assets and their movements and performance to achieve the collective mission. There may be multiple MRS' in an SoS, and each MRS can be considered a constituent system.

MRS may be homogeneous (same type of assets with similar characteristics and interfaces) or heterogeneous (combining assets from multiple classes with different interfaces). Much research has been done on both homogeneous and heterogeneous composition and control of assets, as recently discussed in the research and review papers (Birkeland, Zolich, and Palma 2017) and (Zolich et al. 2019). A summary of characteristics is shown in Table 2, where X means that it applies to a range, + means well suited, - not suited to a property assessed.

To utilize MRS to address the use-cases, there are specific communication needs. Drone operators need at least two communication links that could have quite different properties. (1) **The Command & Control (C2) link.** This link will allow the drone to fly beyond-line-of-sight. For this link, controlling the Quality of Service (QoS) is essential. The link must minimize delays, and loss of connection may cause the mission to abort. Iridium provides a basic solution today for the C2-link for some types of flights. Depending on which kind of airspace the drone operates in, Air Traffic Control may require that the operator has a live video feed from the drone to fulfill operations under visual flight rules; hence a broadband link will be needed. (2) **Link for payload data**. This link may not be required for all missions. It will be used for the transmission of payload data, allowing the mission control system to act on payload data during the flight. QoS-requirements for this link may be more relaxed if the data is not critical. In coastal areas near shore, the links can be provided by LTE or 5G, and the mission must be planned according to predicted coverage. Further offshore, satellite systems like proposed mega-constellations could be useful.

Table 2. Unmanned vehicles for coastal and Arctic environments, based on (Zolich et al. 2019). [a]) Depends on wind conditions, it may be difficult to control in strong wind.

	UAV			AUV			ASV		
Type / **Range**	<25 kg	>25 kg	Fixed wings	Light AUV	AUV	Gliders	Renew. energy	Boats	Vessels
0-10 km	X		X	X	X			X	
10-100 km		X	X		X	X	X	X	
>100 km		X	X			X	X		X
Property									
Arctic env.	-	-	+	+	+	+	-	-	-
Precise obs.	++[a]	+	-		+	-	+	-	-
Communication	-	+	+	-	-	-	+	++	++

The ground-based systems are the aquaculture installations, which can host multiple sensors depending on the mass and energy available. These will satisfy many of the UC-3 needs. Other ground-based systems can be buoys with sensors for oceanographic phenomena and a computer with a communication system to interface with other CS. In the Arctic, the challenges are environment and energy for edge computing and data transmission (Quintana-Diaz et al. 2019).

The space segment is dominated by large monolithic communication and by *Earth Observation (EO)* satellites such as the Copernicus program. The Copernicus program supports many of the SDGs, especially when coordinated with a navigation system (UNOOSA 2018). However, the Arctic regions are not addressed as much because of the lack of observation in higher latitudes. There are a growing number of small satellites (<500 kg) and microsatellites (<100 kg) for *EO* and communication. Stratospheric UAVs are a new technology with low maturity that straddles the UAV and space segment. It is expected that payloads on microsatellites today can be deployed eventually on stratospheric UAVs. The cost of a mature stratospheric UAV is not known, but it is expected to be lower than for a monolithic satellite and higher than for a small satellite. A summary of the space segment properties is given in Table 3, where + means suited and - not suited or negative property.

Table 3. Space segment properties. The properties are evaluated in the Arctic context. Payloads are the instruments observing Earth. [a]) Payload properties are not relevant to asses for C2 and datalink. [b]) Spectral availability is related to C2 and payload datalink, not applicable for EO.

	Monolithic satellites			Small satellites			Stratospheric UAVs		
Type / **Range**	C2	Payload datalink	EO	C2	Payload datalink	EO	C2	Payload datalink	EO
Maturity	+++	+++	+++	++	-	-	---	---	---
Cost	---	---	---	++	++	++	--	--	--
Field-of-view	++	++	++	+	+	+	+	+	+
Payload size > 10 kg	N/A[a])	+++	+++	N/A	-	-	N/A	-	--
Temporal res.	-	-	-	++	++	++	+	+	+
Payload spatial res.	N/A[a])	N/A	++	N/A	N/A	+	N/A	N/A	-
Payload spectral res.	N/A[a])	N/A	+++	N/A	N/A	+	N/A	N/A	+
Spectral avail.	+++	+++	N/A[b])	+	-	N/A	+	-	N/A

Decision-Making

Decision-making for project development is complex because there is managerial and operational independence. Achieving interoperability and ensuring that the right data products are delivered to the end-users so that informed decisions can be reached are the main objectives.

Reasons for viewing the MASSIVE project as a System-of-Systems are twofold:

1. The project team desires to avoid the failure to recognize and benefit from synergies between CS in the solution space such as coordinated ocean observations, and,
2. The number of CS and their communications are too complex to handle as a single system

The stakeholder analysis presented in Figure 3 describes which capabilities the project must provide that the existing CS cannot achieve individually (Axelsson 2015). The current CS have different capabilities and constraints, which must be understood to develop an integrated SoS. Further, the required capabilities given by the stakeholders should be traced to requirements and functions that can be performed by the SoS through decomposition, use-case development, and functional allocation to the different CS, both old and new. Managing an SoS is more complicated than a system because both beneficiary stakeholders and the specific CS stakeholders are involved, sometimes with conflicting expectations.

Looking at MASSIVE as an SoS can increase the understanding of the project management challenges to meet the objectives. This perspective can assist in addressing interoperability and allocation of functions to ensure that the SoS can fulfill the needs. To assess if the MASSIVE project is an SoS, Maier's dimensions were applied to the characteristics of the project in Table 4.

Table 4. The MASSIVE project as a System-of-Systems according to Maier's five dimensions (1998)

Dimension	**Description of MASSIVE**
Operational independence of the elements	Each of the CS are developed to operate independently and can reach decisions without the other elements to perform their own mission objectives.
Managerial independence of the elements	The CS are developed in different phases, and some have higher maturity than others because of this. As an example, the satellite system can be developed and perform independently as a sensor system without the presence of other parts of the MRS.
Evolutionary development	Evolutionary development of the CS allows the SoS' capabilities to evolve with technological advancements, which in turn motivate new capabilities.
Emergent behavior	No single CS can monitor the coastal and Arctic regions with the timeliness and level of detail required without cooperating within the SoS.
Geographical distribution	The developing organizations are not co-located. Also, the CS only interact through information or data exchange and do not rely on physical interactions.

Within each of the CS, there are also decisions to be made, such as energy trade-offs, data budgets, level of autonomy, architecture, and sensor technology. Zolich et al. (2019) discuss possible solutions for the communication infrastructure of heterogeneous multi-robot systems, which are related to the degree of autonomy chosen. However, when the CS are viewed as a part of a larger SoS, the trade-offs become more complicated but may become less complex for technological and architectural decisions. High spectral resolution EO in the space segment could provide more coverage with less cost than equipping all UAVs with high spectral resolution EO. Or, the many small multi-rotor UAVs could carry different sensors for fast response (UC-2, UC-4) while larger fixed-wing UAVs carry several sensors to give an overview (UC-1, UC-3). AUV communication underwater largely relies on the acoustic link to a relay hub which can have a 10-20 km range, but a low bandwidth (<1 kbps). Light UAVs have limited mass available for communication equipment. ASVs can support many communication interfaces depending on the mission (Birkeland, Zolich, and Palma 2017).

The MASSIVE project has focused on developing two of the assets during the first phases; a research ASV called AutoNaut and HYPSO, a small satellite system with a hyperspectral payload. A small satellite designed for Low Earth Orbit (LEO) was chosen because of its low cost, relatively fast development time, and high temporal and spectral resolution. Some stakeholders emphasized that the data collected must be the "right data" and that it is verified. The AutoNaut was chosen because of its multiple onboard scientific instruments for in-situ measurements and can operate autonomously for long periods, which air-borne MRS cannot. While complementary, they are managed and funded separately. Additionally, an operations center is being established that includes command and control of the assets and prediction of oceanographic phenomena by fusing satellite, meteorological, and ocean model data. Future large monolithic satellites may satisfy some of the needs, and new data products may be developed that reduce the need for the MASSIVE entities or be fused to support the more extensive decision-making system.

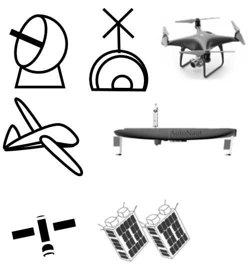
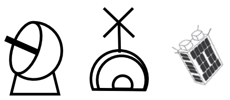
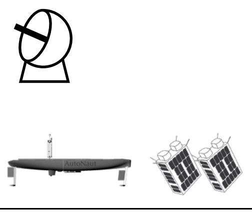
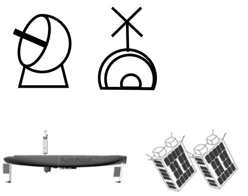
Decision-making for the Arctic coastal region takes place on multiple levels. While there are international committees and directorates concerned with ocean resources, there is no global decision-making body. Decision-making on a multinational scale, a *macro* level, is nearly impossible, and at best tough and time-consuming. At the macro level, agreements between nations can be decided upon, while the actual management of this falls to the lower meso-level. The *meso* level is typically national and local governments and allows for the control of the systems and activities.

Furthermore, at a *micro* level, the local governments can delegate authority to specific companies to perform the actual actions and interactions for making the systems. For example, the local governments (meso) can choose where to build infrastructure for monitoring their harbors, or if a drone-based system should have a deployment site there. The local governments can also act on anyone breaking the local regulations, for example, by having the local police (meso/micro) banning individual shipping companies or fisheries. Providing information may inform decision-makers but does not necessarily result in a structured decision-making process. The political environment and the influential power of the stakeholders affected influence the effectiveness of enacting regulations.

Evaluation

The stakeholder analysis was primarily based on documentation publicly available from the constituent system organizations. Many stakeholders were identified in the first stage of the study, showing the scope of the problem. Not all stakeholders will participate actively in the execution of developing the final solution, but all of them must be allowed to join through gateway reviews or reporting. To strengthen the validity of the analysis, interviews could be conducted with key persons in each of the organizations and other stakeholders. This and other techniques may also uncover needs not expressed in the documentation but relevant to developing the MASSIVE project. For example, the stakeholder list could be expanded based on a recent paper that recommends including peoples whose way of living and observations could contribute to traditional ecological knowledge to help improve marine ecosystem management (Kaiser et al. 2019).

Table 5. Evaluation of how the MASSIVE end-state SoS addresses the specific use-cases.

UC	Systems involved	Evaluation of MASSIVE
All		Requires development of infrastructure and technology sourced both locally and internationally. The project's communication needs will influence infrastructure development. MASSIVE SoS will gather oceanographic data products that can be utilized in understanding climate change. The combination of high temporal, spectral, and spatial resolution through satellite imaging and autonomous asset deployment gives the possibility to gather data cost-effectively. AUVs can be used for fish tracking with optical/radar sensors.
1		**Nominal (low resolution) monitoring of the coast:** The small satellites can be equipped with multi/hyper-spectral imaging sensors. A trade-off must be made between edge computing power requirements and downlink capabilities. Buoys along the coast can provide data on the other oceanographic phenomena.
2		**On-demand high resolution monitoring of HAB:** In addition to UC-1, the ASV can inspect and patrol fjords/coastline where there is some probability that HAB may develop. Will most likely require a small constellation of satellites to provide on-demand monitoring or stratospheric/fixed-wing UAVs equipped for Arctic conditions with multi/hyper-spectral imaging sensors.
3,4		**Aquaculture monitoring, High-resolution monitoring of the coast:** MASSIVE SoS can inform responsible production through better oceanographic data with higher temporal and spectral resolution than existing systems. Requires coordination with end-users to deliver correct data products to inform decisions. Relies on in-situ measurements (ground-based sensors).

The problem description combines aspects from a science community and the Norwegian government. There is not much high-temporal resolution data on oceanographic phenomena available because of the difficulties collecting them. The use-cases selected are based on knowledge of how the CS may interact and to address specific capability needs from Figure 3. An assessment of how the MASSIVE project currently addresses use-cases is shown in Table 5. The use-cases focus the solution work but may also limit the solution space because of specificity. The communication analysis shows that the use-cases are underserved today, and it is difficult to predict when the future systems will be operative. Some initiatives may close these gaps and provide better services.

There should be an aspect of flexibility in the design to address the changing needs of the environment and the development of new technology (Fricke and Schulz 2005), which is more straightforward to assess as an SoS than if it were looked upon as a system. The flexibility can then be built-in through adapting or adding to the CS.

The alternatives listed were limited to autonomous assets because this is the focus of MASSIVE. These CS are being developed in parallel to be integrated or coordinated in the future. It is expected that more MRS will be included, as well as multiple satellites. One of the most challenging aspects is to ensure a good communication infrastructure for the different use-cases and the different CS. Furthermore, the relevance of MASSIVE may change over time.

Conclusion and Future Work

The next decade will be the "United Nations Decade of Ocean Science for Sustainable Development (2021-2030)" (UN General Assembly Resolution 2018). In keeping with the criticality of this topic, this study looked at how an SoS perspective can be used to create solutions that support decision-makers in making informed decisions for the management of Arctic coastal regions. The SoS is challenging to define and describe, to develop, and to test and verify because of the complexity and distributed management of the constituent systems.

Future work on this MASSIVE project should address:

- The sociotechnical aspects of implementing an SoS for monitoring coastal and Arctic regions. On the one hand, there is the technology development and increased infrastructure, which will generate more jobs and a higher level of safety and security. On the other hand, it may be looked upon negatively because it means even more infrastructure in an untouched landscape. Furthermore, the way humans will interface with the SoS, which consists of several assets with varying levels of autonomy, will need to be addressed, for example, avoiding maritime collisions.
- Operational deployment and management of the SoS. Ensuring that the CS are interoperable through agreements and data exchange protocols is critical future work. The SoS viewpoint can be modeled to map out and specify interfaces and to ensure the allocation of functions.

These problems are not specific to the Norwegian Arctic coastal regions and apply to other areas, such as Greenland and Canada, where similar research efforts are underway. Furthermore, the needs will change over time, and technology will develop, supporting the case for the flexibility provided by an SoS perspective. There is an increasing drive for collaboration, cooperation, and interoperability of systems. Different environments give different constraints and performance drivers, and the combination of constituent assets aims to utilize their characteristics to improve the overall solution.

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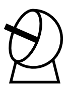
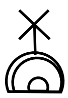
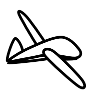
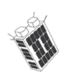
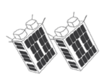
Appendix A

AUV classes: a “Light AUV” is an AUV that can be carried by one man (e.g. <20 kg), “*gliders are long-endurance underwater vehicles”* (Zolich et al 2019). ASV classes: “renew. energy” are often wave and solar-powered, very restricted in power and speed but may have good endurance, “vessels” are large boats/ferries such as a tanker, “boats” are smaller in size, typically up to 10 m.The following icons are used throughout the discussion.

Legend							
							
Ground station	Sensor node	UAV	Fixed-wing UAV	Renew. energy ASV	Monolithic satellite	Small satellite	Small satellite constellation

Biography

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