SMaRC

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R O B O T I C S
C E N T R E

MID-TERM EVALUATION REPORT 2020

SMaRC

SWEDISH
MARITIME
ROBOTICS
CENTRE

ABOUT THIS DOCUMENT

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ISBN

978-91-7873-672-0

SERIES

TRITA-SCI-RAP-2020:006

DOI

10.30746/TRITA-SCI-RAP-2020.006

IMAGE CREDITS

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ABSTRACT

This is the midterm report of the project SMaRC (Swedish Maritime Robotics Centre), which is one of four industrial research centres (IRC) funded by the Swedish Foundation for Strategic Research (SSF). SMaRC is a unique collaborative research environment consisting of key industry, academia, and governmental partners in Sweden. The focus of the centre is to enable a transformational/disruptive shift towards the next generation of marine robots.

The aim of this report is to describe how SMaRC will provide industrial outcomes that deliver into societal benefit areas, by linking user-defined scenarios with capabilities. This will strengthen the research focus as well as create a transparent mapping from scientific activities to end-user needs.

The SMaRC project has now reached its midpoint and is running according to plan. The initial start-up process is now passed and key milestones of the project have been reached and demonstrated at the joint workshop and demonstration periods. SMaRC has already participated in very challenging Antarctic expeditions, developed and tested its own underwater robots, and demonstrated new capabilities for perception, navigation, endurance and autonomy in both simulator environments and in field experiments.

For the upcoming second half of the project period, the focus will be on integration and demonstration to move closer to the industrial and end-user needs. The future research plan is connected to six targeted scenarios highlighting key capabilities to reach within the research projects. The demonstration of these scenarios also supports enhanced cooperation with both national and international partners.

TERMS AND ABBREVIATIONS

AI	Artificial intelligence
AUV	Autonomous underwater vehicle, a vehicle with less degree of autonomy
BTS	Breaking the Surface, a conference
CTD	Conductivity, temperature and depth
DVL	Doppler velocity logger
ECTS	European Credit Transfer and accumulation System in higher education
ENV	Environmental monitoring, used for the scenarios
EU	European Union
FM	Swedish Armed Forces
FMV	Swedish Defence Materiel Administration
FOI	Swedish Defence Research Agency
CNSS	Global Navigation Satellite System
GPS	Global Positioning System
GU	Gothenburg University
IPR	Intellectual property rights
IRC	Industrial research centre
JWS&D	Joint workshop and demonstration periods
KTH-AVE	Royal Institute of Technology, department of Aeronautical and Vehicle Engineering
KPI	Key performance indicators
KTH	Royal Institute of Technology
LoLo	Long-range long-endurance robot, name of one of SMaRC's in-house-developed robots
Maritime Robot	A vehicle with larger degree of autonomy
MBES	Multi-beam echo sounder
MMT	Marin Mätteknik
MSEK	Million Swedish crowns
NOC	National Oceanography Centre, in Southampton UK
NRIA	National research-and-innovation agenda
NTNU	Norwegian University of Science and Technology
OES	Ocean Engineering Society
OP	Ocean production, used for the scenarios
PC	Polar codes
PG	Project group
PhD	Doctor of philosophy
Ran	Name of the commercial AUV that is part of SMaRC
ROS-WHOI	Robot Operating System from Woods Hole Oceanographic Institution
ROV	Remotely operated vehicle
RV/IB	Research vessel/icebreaker
SAB	Scientific advisory board
SAM	Small and affordable maritime robot, name of one of SMaRC's in-house-developed robots
Scenario	Guiding principle defined by the end users showing what to achieve
SEC	Safeguarding society, used for the scenarios
SLAM	Simultaneous localisation and mapping
SMaRC	Swedish Maritime Robotics Centre
SME	Small and medium-sized enterprises
SSF	Swedish Foundation for Strategic Research
SWOT	Strengths, weaknesses, opportunities, threats
SP	Sub-project within SMaRC
SU	Stockholm University
TCPM	Trellis code permutation modulation
TRL	Technology readiness level
R&D	Research and development
UDT	Undersea defence technology
UN	United Nations
WASP	Wallenberg Artificial Intelligence, Autonomous Systems and Software Program
WARA-PS	WASP Research Arena for Public Safety

1

Background, Objectives and Organisation

1.1 BACKGROUND, MOTIVATION AND LONG-TERM VISION

The ongoing changes in the Earth's climate and ecosystems, our scarce resources and our dependence of the oceans for survival on this planet, demand sustained, continuous and integrated observations of the oceans. For the past centuries, oceanographic observations have been dominated by ship-based technologies, resulting in limited spatial and temporal resolution of the data collected. To address today's and tomorrow's challenges, there is a need for much greater automation – globally as well as nationally in Sweden.

DISRUPTIVE TECHNOLOGIES

Maritime robots enable a disruptive technology shift towards completely new capabilities, that will enable us to sustainably utilise the oceans' resources, to maintain territorial integrity, and to learn more about how to protect and preserve marine ecosystems, and the role of the oceans in a changing climate.

By removing humans from the vehicles and from the control loop, maritime robotics offer key services to society in a disruptive way such as: improved coverage and access, improved sampling capacity, reduced costs, and reduced risk to humans. This leads to enhanced capacity to collect scientific data from previously inaccessible areas as well as controls and monitors the underwater domain in both space and time at a scale and cost-efficiency not possible without maritime robots. These activities support sustainable exploitation of marine resources, increase our defence capacity in the marine domain, and address key environmental challenges. They will also lead to new products and markets, e.g. within ocean-farming robots, surveillance robots, and research tools.

Sweden is a country with a long coastline and many companies and

governmental bodies involved in topics related to the maritime and underwater domain. This includes development of advanced technological systems such as submarines and underwater robots, undertaking large-scale ocean operations such as high-accuracy mapping of the ocean floor, and participation in global research campaigns for a better understanding of climate change. Further, the Swedish government has declared underwater technology to be of vital national strategic importance. Despite all of these activities, prior to the industrial research centre SMaRC, there was no academic node in Sweden connecting research with industry and governmental strategic needs. Thus, SMaRC is of broad national interest and fully aligned with the recently published Swedish governmental maritime strategy¹ and the National Research and Innovation Agenda for Underwater Technology². This will help Sweden meet current political, economical and ecological key challenges of national and international importance.

SMARC'S VISION

SMaRC's vision is to enable and demonstrate a technology transformation towards the next generation of maritime robots, able to operate in unknown environments for longer duration and with less need for human intervention than currently possible.

Maritime robotics is a huge market to explore. There is great potential to further expand it by entering new markets and developing new products as well as new services. SMaRC strengthens the competitive potential of Sweden in these global markets. It will also have spin-off effects for maritime technology development and access to marine resources and as such will have economical relevance for Swedish industry. By bringing together the national key industrial and academic partners and stakeholders in Sweden, SMaRC is, in an international context, a unique collaborative environment that can be leveraged to contribute to global initiatives for climate research and climate actions.

¹ regeringen.se/regeringens-politik/maritim-strategi

² subtechsweden.se/agenda-nria-u-2019

Figure 1: Graphical illustration of research plan including sub-projects structure.

1.2 CONCRETE GOALS AND OBJECTIVES

1.2.1 SUMMARY OF GOALS/OBJECTIVES

The research plan is organised as illustrated in figure 1 to help SMaRC reach its main goal (E) of developing the next generation of maritime robotics. The scope has three societal benefits (A), which are the main focus areas for a substantial part of the industrial and academic maritime endeavours:

- **ocean production,**
- **safeguarding society, and**
- **environmental monitoring.**

To deliver benefits within these three areas via maritime robotics, we identify three main **challenges (B)**:

- **reducing the need for operator interaction,**
- **enabling long-term presence, and**
- **enabling operations in unknown waters.**

These are the key challenges that need to be overcome for maritime robotics to take the next big step. To address these challenges, we focus

on four different **research disciplines (C)**, which together deliver into all benefit areas and challenges:

- **Autonomy** – the ability to adapt actions based on sensed data.
- **Endurance** – the ability to stay on mission for a prolonged period of time, typically weeks/months/years.
- **Perception** – the “eyes and ears” of the maritime robotics, not only for mission-related tasks but also for navigation.
- **Communication** – the notion of sending and receiving data, typically in extremely challenging underwater environments.

Within these research areas, we are working cross-disciplinarily to develop the capabilities needed for maritime robotics to address the challenges. The developed capabilities are demonstrated, tested and proven through the use of a **demonstrator programme (D)** including hard- and software platforms, infrastructures and test environments, with strong links to existing facilities within the participating research organisations and industrial partners. Feedback from testing and demonstration is fed into the research areas. The demonstrators naturally bridge the different research groups within SMaRC and also link to the industry. The demonstrator programme is crucial from this aspect as well as for testing concepts and ideas in real ocean environments.

1.2.2 APPROACH

During the first year, we established the structure of the sub-projects, recruiting personnel and further sharpening the key challenges following a systems-engineering approach. This approach enabled us to identify key capabilities and thereby associated research questions for each societal benefit area. Originally nine **scenarios** (later ten) were designed (see table 1) to resemble real-life situations within the three benefits areas, incorporating all the challenges and highlighting the need for development in our four research areas (constituting our

system boundary: autonomy, endurance, perception, and communication) and further to specific technology areas such as robotics, artificial intelligence, electrochemistry, vehicle design, electronics, oceanography, and software.

The scenario work started with a two-day workshop in the Stockholm archipelago with participation from all key partners in SMaRC. Working with these scenarios was a major achievement during the start-up year of SMaRC (2017). The focus was to systematically identify and strengthen the goals and objectives of SMaRC and to encompass both the future disruptiveness and industrial needs. An

Table 1: SMaRC's scenarios in short.

Benefit area	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Ocean Production	OP01: Site Survey	OP02: Infrastructure and Productivity Monitoring	OP03: Risk and Environmental Assessment	OP04*: Pipeline Inspection
Safeguarding Society	SEC01: Long-Range Reconnaissance	SEC02: Multi-Agent Home Reconnaissance	SEC03: Home Surveillance	
Environmental Monitoring	ENV01: Glacier-Front Monitoring	ENV02: Below-Glacier Monitoring	ENV03: Substance-Cloud-Tracking "Sniffer"	

The scenarios are developed and described in detail in SMaRC's internal documentation and have been instrumental in the identification of the robotics-related capabilities necessary to realise them.

* A fourth scenario was added within the Ocean Production benefit area due to large interest from SMaRC's industrial members.

ENVIRONMENTAL MONITORING

The icy parts of the polar regions are important components of the climate system, controlling not only local environments and climate processes, but also global ones including sea-level rise. When the glaciers reach the oceans they begin to float. The cavities under these floating glacier tongues play a key role in controlling the stability of the Antarctic and Greenland ice sheets. To send a robot under the floating glacier tongue is difficult, but not impossible. It requires robots that can navigate over large distances without GPS and communication nodes. A robot that succeeds in this is also of military interest.

Figure 2: Illustration of example scenario for below-glacier monitoring (ENV02).

example of a scenario is illustrated in figure 2.

For each scenario, vision and goals, operational environments, stakeholders, concept descriptions, and typical assignments, were defined in order to generate a list of desirable key capabilities (see fact box and appendix A). A key finding in this phase was that these nine scenarios, from our three different areas of societal benefits, produced notably coherent capability requirements. The research needed to develop these capabilities was thus identified as a means of realising the scenarios. The next logical step was to use the identified capabilities to establish a suitable basis for the design of the sub-projects. In this way, full logic and traceability exists between SMaRC's sub-projects and society's and industry's needs (see figure 1).

In appendix A, we present a mapping between scenarios and capabilities, the mapping between capabilities and SMaRC's sub-projects, and the mapping of which robots are chosen as demonstrator platforms as well as to which research areas the capabilities mainly belong. As proven by these mappings, a conformity with the initial proposal was achieved between the scenarios, capabilities, sub-projects and demonstrator platforms.

- Firstly, this mapping approach encompasses in a clearly traceable way the scope of the societal benefit areas and industrial needs.
- Secondly, this shows that focus on a limited number of capabilities satisfies the entire scope and enables disruption.
- Thirdly, and decisive for success, this also clearly shows the need for collaborations between the different stakeholders in SMaRC, as most of the relevant research questions and needed key capabilities are the same regardless of whether the need is national security, marine science or ocean production. For SMaRC as an IRC, the research focus is centred on the goals for the industrial partners; however, these goals also align very well with the needs of the robots for natural sciences.
- Fourthly, the inherent logic of the design indicates that the scenarios do not need to be demonstrated in full; our assessment is that successfully demonstrated capabilities will implicitly mean that the scenarios are feasible.

SMaRC'S 15 CAPABILITIES – IN SHORT

These are the 15 capabilities identified as key building blocks in the nine scenarios. With these capabilities in place, the fulfilment of all scenarios is assessed to be within reach.

- 1. Navigation** Capability to navigate safely in unknown and dynamically changing environments without access to the surface while retaining a total navigation accuracy better than 10 m.
- 2. Payload deployment/retrieval** Capability to deploy (and preferably retrieve) payloads to well defined positions and in typical ambient conditions from "Mother AUV".
- 3. AUV deployment/retrieval** Capability to deploy and retrieve small AUVs from an underwater garage, "Mother AUV" (preferably moving), ships, submarines, and piers (including parking on the bottom).
- 4. Swarm intelligence** Capability to use collective swarm behaviour to, for instance, localise the source of pollutants, map the extension of a polluted area, create a perimeter around an object of interest.
- 5. Precision manoeuvring** Capability to manoeuvre safely, with precision, without entanglement, in an underwater environment with obstacles such as pillars, anchors, rigs, and similar.
- 6. Mission adaptation/re-planning** Capability to adapt and re-plan a mission for instance if an anomaly is detected, if mission profile and tasks are modified, or in case of an emergency.
- 7. Surveillance** Capability to survey, pursue and gather data from fixed and moving targets with minimised risk of losing the object.
- 8. Communication** Capability to perform optimised underwater communication and data transfer with for instance seafloor nodes, "Mother-AUV", and networks of other moving or static nodes/vehicles.
- 9. Operation in severe conditions** Capability to robustly and with minimised risk operate in extremely dynamic and challenging environments with an underwater robot for close-range mapping.
- 10. Long-range operation** Capability to perform missions with a range of >1.000 km or 30 days at optimal speed and >400 km at 5 knots.
- 11. Long-term operation** Capability to perform long-term continuous operations in a predefined area and perform multiple missions: docking, transferring data, recharging and repeating mission.
- 12. Pollutant detection** Capability to detect pollutants on molecular level in the water column with an advanced sensor suite.
- 13. Accurate localisation** Capability to accurately localise surrounding objects for operating in dynamic ocean conditions without GPS.
- 14. Identification/classification** Capability to autonomously, in real-time, accurately identify features and classify objects, both natural and man-made.
- 15. Anomaly detection** Capability to autonomously, in real-time, identify a deviation from a "normal state" and monitor and detect variations from a "normal state" in the underwater domain.

Table 2: SMaRC board members

Name	Organisation	Role in SMaRC
Hans Wicklander	Saab Kockums	Head of board
Mats Elofsson	FMV	Board member
Peter Forhaug	MMT	Board member
Stefan Östlund	KTH	Board member
Tina Elfving	SU	Substitute board member
Matts Gustavsson	FOI	Substitute board member
Anna Wählin	GU	Substitute board member
Per Johansson	Saab Dynamics	Substitute board member

1.3 ORGANISATION

1.3.1 PARTNERS, BOARD, AND MANAGEMENT

SMaRC is a triple-helix constellation bringing together partners from industry, academia and governmental bodies (figure 3). The academic partners are KTH Royal Institute of Technology, Stockholm University, and University of Gothenburg; industrial partners are Saab and MMT Sweden; governmental partners are FMV (the Swedish Defence Materiel Administration) and FOI (the Swedish Defence Research Agency). This constitutes a unique constellation of partners within multiple disciplines, combining engineering sciences with natural sciences, industry, and defence.

The organisational structure of SMaRC is depicted in figure 4. SMaRC is organised under a centre board (table 2) predominantly populated by members from the top management of the industrial partners (SSF-IRC requirement) to ensure industrial relevance of the research. The centre board meets four times per year for updates on the progress, economic status and input to the planning of main activities.

The centre is coordinated by a principal investigator (Ivan Stenius, main project applicant) and a co-PI (Peter Sigra, hired Oct 2019) with support from a Project Group (PG) (table 3) and a scientific advisory board (SAB) (table 4). There is also administrative support from KTH as well as an appointed industry coordinator (Roger Berg) and an appointed demonstrator-programme coordinator (Nina Kirchner)

in the management of SMaRC. The SAB meets at least once a year to get an update on the current status of the activities within SMaRC and to give recommendations for future work (see appendix B). The SAB meetings are typically planned back-to-back with a joint workshop and demonstration period (see section 2.3.3) giving the SAB also the opportunity to participate in the workshop. The PG contains at least one representative from each partner in SMaRC and meets regularly (approximately once per month) to share information and for more detailed planning of the centre activities. The members of the PG, in turn, coordinate and lead a number of sub-projects that covers the research areas. Figure 1 illustrates the overarching view of how the sub-projects connect to the research areas and the demonstrator programme as well as to the joint workshop and demonstration periods.

1.3.2 PARTICIPATING RESEARCHERS

The participating researchers (senior researchers, post-doctoral researchers etc.) are from the Royal Institute of Technology (KTH), Stockholm University (SU), the University of Gothenburg (GU), and the Swedish Defence Research Agency (FOI) as listed in tables 3–7.

Table 3: Project-group members and responsibility areas.

Name	Organisation	Role in SMaRC
Katarina Abrahamsson	GU	ENV03, SP10
Roger Berg	Saab Kockums	SEC01, SP01, Industry coordinator
John Folkesson	KTH	SP05, SP06
Fredrik Gröndahl	KTH	OP01-OP03
Joakim Holmlund	MMT	OP04
Per Johansson	Saab Dynamics	SEC02, SP02
Nina Kirchner	SU	ENV01, Demonstrator-programme coordinator
Jakob Kuttenkeuler	KTH	SP03, SP13
Carina Lagergren	KTH	SP09
Lena Lundh	FOI	SP11, SP12
Magnus Nordenvaad	FOI	SP11
Stina Palmeby	MMT	OP04
Matteo Perrone	FMV	SEC01-SEC03
Peter Sigray	KTH	Co-PI, SP12
Ivan Stenius	KTH	PI, SP04, SP14
Robert Wigert	FMV	SEC01-SEC03
Anna Wählin	GU	ENV02, SP15
Petter Ögren	KTH	SP07, SP08

1.3.3 ADJUSTMENTS TO STRENGTHEN THE ORGANISATION AND COLLABORATIONS

At the start of SMaRC, the top-level management was short-staffed, which was also pointed out at the SSF hearing as part of the evaluation process of the SMaRC application. As a response to this, the organisational structure of SMaRC was adjusted. There is now a management group consisting of the PI (Ivan Stenius), a co-PI (Peter Sigray) and a project manager from the industry (Roger Berg) responsible for the overall management of SMaRC with help from the project group (PG). The role of the industry coordinator is to deepen the interactions with the industry partners to support involvement and knowledge transfer. We are also proud to have engaged an additional partner in SMaRC, Cadson Production AB, contributing with key competence in electronics and sensor design.

Table 4: Scientific advisory board.

Name	Organisation
Prof. João Sousa	Porto University
Prof. Martin Ludvigsen	NTNU Institutt for marin teknikk
Dr. Louise Newman	University of Tasmania

Table 5: Post-doctoral researchers.

Name	Organisation	Role in SMaRC
Nils Bore	KTH	SP05-SP08
Lazáro Moratelli	KTH	SP13

Table 6: PhD students.

Name	Organisation	Role in SMaRC
Ariel Chiche	KTH	SP09
Christopher Sprague	KTH	SP07
Clemens Deutsch	KTH	SP03
Elias Strandell	FOI/KTH	SP12
Filip Söderling	Saab Kockums/KTH	SP01
Ignacio Torroba	KTH	SP06
Louise Fuchs	Saab Dynamics/KTH	SP02
Sriharsha Bath	KTH	SP04
Viktor Lidström	FOI/KTH	SP11
Özer Özkahraman	KTH	SP08

Table 7: Research engineers.

Name	Organisation	Role in SMaRC
Adela Dumitrascu	GU	SP10
Carl Jung	KTH	SP14
Josefine Severholt	KTH	SP14
Sebastian Thuné	KTH	SP13
Niklas Rolleberg	KTH	SP13

2 Research Results

2.1 MAJOR SCIENTIFIC ACHIEVEMENTS

An industrial research centre with deep collaboration between academia and industry requires a finely tuned balance between academic excellence and usefulness for industrial development. The centre focuses on producing results that match society's needs with industrially relevant research questions. SMaRC's scope is about research for producing the tools necessary for industry to be able to address society's needs with technological systems.

Some of the major scientific achievements of our research are:

- A potential breakthrough in utilising side-scan sonars for accurate bathymetric mapping. This has the capacity to revolutionise the performance of small and cost-efficient underwater robots.
- The development of unique and very powerful artificial-intelligence (AI) tools for mapping of sonar data between different sensors (multi-beam and side-scan) and their alignment to identify overlapping patches, can drastically enhance the performance of terrain-aided navigation and simultaneous localisation and mapping (SLAM).
- The contribution to new knowledge about the ocean-glacier interaction in the sub-ice cavity in Antarctica, where SMaRC researchers and the AUV Ran (see more details about the AUV Ran in section 2.3.1) have participated the first-ever measurements underneath the Thwaites glacier.
- The in-house development of underwater robots (the SMaRC AUVs LoLo and SAM, described in detail in section 2.3.1) for testing and demonstration of research results, fully accessible for the SMaRC researchers and integrated in simulation environments.
- The development of an integrated cyber-physical research environment, integrating multiple hardware, sensors, actuators, software, simulations and humans into a system including the mission-planning interface, behaviour trees, controllers, and navigation. The software architecture is tightly coupled with the simulation environments across multiple platforms, which is an essential part of the transition from single robots to systems of autonomous robots.

2.2 SUMMARY OF SCIENTIFIC ACHIEVEMENTS IN RELATION TO RESEARCH DISCIPLINES

This section summarises the scientific achievements so far in relation to the application and the target research areas perception, autonomy, endurance and underwater communication. This summary also highlights some of the main publications while the full list of all publications is presented at the end of this report in the Bibliography section.

2.2.1 PERCEPTION

The main achievements have been made regarding the use of the cost-effective side-scan sonar. We have made progress on understanding how to model the sonar signals both analytically and using data driven methods, see Xie et al. (2020). The goal is to use the more affordable side-scan sonar for surveys that normally require a much larger and expensive multibeam sonar. Using data-driven methods we have investigated representations of the seafloor bathymetry that can encode information for generating side-scan images and vice versa, see Bore and Folkesson (2020). The generated side-scan images from these models were indistinguishable from real images when presented to professionals in the field. Using side-scan to generate the 3D depth contours is being further investigated to include other information to bring the uncertainties to a level that would interest the industrial partners. Analytic modelling of the diffuse reflection returned from the seafloor has been fit to empirical data (collected in collaboration with sub-project 15) using models for the sonar-beam pattern. This will help us in pre-processing the signals to transform to a canonical side-scan image with pixels that have more uniform spatial and intensity distributions, removing much of the dependence on details such as altitude, range, and velocity from the images, see Folkesson et al. (2020).

2.2.2 ENDURANCE

SMaRC has been working towards optimising vehicle performance with respect to endurance, e.g. by identifying and developing optimal propulsion and energy storage solutions. The performance of underwater vehicles is improved through system optimisation, effectively enabling missions with extended range and endurance. System optimisation deals with both hardware and software design, including hydrodynamic design, propulsion methods and propulsors, energy and power systems, and vehicle-control strategies. In addition to fundamental research on underwater vehicle technology, new control methods are also developed and modern artificial intelligence (AI) algorithms are applied. The research methodology comprises a holistic approach with the study of vehicle-related performance factors such as flight mechanics, hydromechanics, velocity effects and scale factors, manoeuvring-control strategies, and payload-usage operational parameters.

The transit flight performance of underwater gliders has been studied by Deutsch et al. (2020). SMaRC has further been focusing on developing agility without the cost of endurance by studying hydrobotic capabilities of a slender-flight-style AUV, potentially offering disruptive designs in how to optimise the utilisation of onboard sensors and manipulators as well as extending the operational range (Bhat and Stenius 2018, Bhat et al. 2019 and Bhat et al. 2020).

Electrochemical energy storage systems, able to meet the need for energy onboard the vessel during long-term underwater missions, have been investigated in Chiche et al. (2018). Fuel cells in combination with batteries is an attractive solution for this purpose. Key issues studied are how to store the needed hydrogen and oxygen in an optimal way, how to combine the fuel cell with a battery and how to integrate the system on board and adapt it to the different applications and missions (Deutsch et al. 2020b, Chiche et al. 2019, Chiche et al. 2020).

2.2.3 AUTONOMY

Navigation A study was carried out using multi-beam echo sounding sonar (MBES) to correct the trajectory of the AUV. One significant result, is how overlapping patches of the seafloor mapped using MBES can be efficiently aligned using a fully Bayesian approach using sparse Gaussian processes, see Bore et al. (2018). Another related result systematically compares the most commonly used algorithms for point cloud registration on MBES data. These most commonly used algorithms for point cloud registration have then been used as part of a SLAM framework and demonstrated on several real data sets including some from the Antarctic missions, see Torroba et al. (2019). A novel approach to faster, accurate estimation of the relative strength of constraints arising from MBES registration has also been demonstrated, see Sprague et al. (2019). This approach employs a neural network to learn the covariances from point clouds of a patch. We showed that this results in a better SLAM estimate than other methods of comparable speed and comparable to much slower methods.

Mission planning In SMaRC we have developed algorithms for robust, efficient and transparent mission planning and execution for AUVs. These qualities are especially important in the underwater domain, since the areas of operation are often very large and hard to access by human users, making the retrieval of a malfunctioning vehicle very costly. Furthermore, end users such as oceanographers or underwater-farm operators need to be able to adjust and extend the decision-making framework without in-depth knowledge of all details. The robustness to disturbances was investigated in Colledanchise et al. (2019) and Ögren (2020), analysing behaviour tree structures using tools from planning and control theory, and the efficiency was explored in Sprague and Ögren (2018) and Sprague et al. (2019) where neural networks with near optimal performance were combined with robust behaviour trees. The transparency is given by the behaviour tree structure, which in earlier work have been shown to be editable by non-experts. Further, we have explored methods to improve the AI and decision-making capabilities of groups of smaller autonomous marine robots. It is well known that in some mission types, flexibility, performance and robustness can be increased by using a group of robots. Flexibility by deciding how many robots to assign to each task,

performance by enabling sensing from different locations at the same time, and robustness by limiting the consequences of a single failure to one robot, enabling the rest of the group to complete the mission. In Sprague et al. (2018) and Özkahraman and Ögren (2020a) we have explored the use of behaviour trees in a setting with multiple robots doing underwater coverage of a given area. The agents collaborate in doing the coverage, while staying within communication range of each other. At the same time, they also keep track of their battery level, and pause the mission to return to the charger when needed, always making sure they have enough battery to reach the charger. In Özkahraman and Ögren (2020b) the robots collaborate to create an optimal improvised barrier around the estimated position of an intruder, then iteratively shrinking this barrier until the intruder can be localised with certainty.

2.2.4 UNDERWATER COMMUNICATION

The focus of underwater communication is to develop methodologies related to the SMaRC underwater scenarios. Two types of physical links have been developed and tested in situ. The first utilises Trellis Code Permutation Modulation (TCPM) and the second Polar Codes (PC). The TCPM was used in situ for testing bit-rate error as a function of sea state (Lidström et al., 2019). The PC was used to test block code, utilising channel mapping where it has been shown that communication can reach near to the theoretical limit (Lidström, 2020). Protocols for ad-hoc networks have been implemented and tested in a simulator environment as well as in situ. The research targets sensor nodes, networking with maritime robots as well as with ships and other systems for data transfer and navigational support. Relaying techniques and underwater dynamic networking as well as deployment of network nodes/sensors were studied. The technological focus is centred on developing a sonar-array transmitter to investigate directive communication. A prototype transmitter consisting of five elements has been developed in-house. Beam-steering capability was incorporated in the transmitter using an FPGA in late 2019. Testing of beam steering was done during spring 2020. Moreover, a small energy-efficient navigational beacon has been developed. This unit was designed to fit in the larger SMaRC AUV LoLo. An automated deployment of a navigational beacon from LoLo on mission at depth was performed at the JWS&D 2020 at Askö and the distance between the AUV and the beacon was repeatedly estimated.

2.3 DEMONSTRATOR PROGRAMME

The demonstrator programme is the cohesive glue between the various research areas and groups, and comprises three main components:

- **Demonstrators:** This includes underwater robots as well as key sub-components such as sensors and underwater communication nodes.
- **Simulations:** A cyber-physical simulation environment framework for testing and evaluating the robots.
- **Demonstrations:** Joint Workshop and Demonstration periods (JWS&D).

These three components together function as the bridge between the two types of academic partners involved in SMaRC: the (developing) engineering sciences and the (requirement-setting) natural sciences, with institutes and industry in between, crafting the mediating demonstrators and aiding in testing and verification. The progress and results achieved thus far within these three components are described below.

2.3.1 DEMONSTRATORS

Within SMaRC, demonstrators are essential tools of the research to test and evaluate research results within all technology areas (Autonomy, Perception, Endurance and Underwater Communication). These demonstrators can be entire robots as well as sub-systems or sensors depending on the status of the research project at hand. The current

status of the various demonstrators within SMaRC are described below.

The main physical platforms for demonstrating our capabilities are three **underwater robots** (see fact boxes on the next pages). Two of these robots were developed within SMaRC, providing unique abilities for testing and development with full access to all core components of the robots and ability to modify these according to our needs. The first SMaRC-developed robot focuses on long range and long endurance (LoLo, see page 18), and the second robot focuses on small size and affordability (SAM, see page 19). The third robot (Ran, see page 20) is a large commercial Hugin robot developed by Kongsberg, representing current state-of-art in advanced work-horse underwater robots, mainly used in the off-shore industry.

In addition to these robots, we are also developing sensors and other demonstrator types, such as a Raman-spectroscopy “sniffer” sensor; a small-scale fuel-cell test bench; and underwater communication nodes for research on the communication link and communication networking (figures 5 and 6).

In the demonstrations to come (2021–2024), we will also include more robots from our partners MMT and Saab to demonstrate our research progress (see scenarios and milestones in the future research section 2.5). For example, from MMT the S-ROV (scenario OP04) will be utilised in the pipeline-inspection scenario, from Saab the AUV62 (scenario SEC01) will be used in the long-range reconnaissance scenario, and also from Saab the Sabertooth may be used together with Saab sensor nodes in the multi-agent scenario (scenario SEC02).

Figure 5: The newly developed directive transmitter for underwater communication.

Figure 6: The underwater communication node used for test of network protocols.

ROBOT: LOLO

DEVELOPED BY

SMaRC

SWEDISH
MARITIME
ROBOTICS
CENTRE

Basic data

Length: 4.0 m

Width: 1.05 m

Height: 0.6 m

Weight: 300-600 kg
depending on
configuration

Depth rating: 1,000 m

**Range/power capacity/
endurance:** depending
on payload

Max speed: 8 knots

Among the unique features of this long-range, long-endurance (LoLo) robot are her modularity and flexibility in terms of payload options and control options. A large payload bay allows for fast and easy tailoring for various missions. The capability to house an extra onboard computer gives SMaRC's scientists a powerful tool for easy integration and testing during research missions.

**Forward-Looking
Sonar/Anti-Collision
System:** BlueRobotics
Ping Sonar Altimeter
115kHz

**Multi-Beam
Echosounder:** R2Sonic
2020, 200-400kHz
with 700kHz option
1° x 1° beam width,
swath-coverage up
to 130°

**Variable Bouyancy
System:** 4x ballast
tanks à ±3 kg.

**Underwater
Communication:**
Evologics S2C 7/17
Hydroacoustic
modem with USBL for
positioning.

**Underwater
Communication:**
Evologics S2C 7/17
Hydroacoustic
modem with USBL for
positioning.

Other Sensors: Valeport SVP. **Other Systems:** VBS (Variable Buoyancy System) +- 12kg. Payload deployment system capable of dropping payload such as acoustic nodes or sensors on command either from mission-based trigger or via Hydroacoustic modem. Captain-Scientist-configuration based on open-source in-house internal node-based network allowing a very flexible backseat-driver control setup tailored for scientific missions.

ROBOT: SAM

DEVELOPED BY

SMaRC

SWEDISH
MARITIME
ROBOTICS
CENTRE

Basic data

Length: 1.4 m

Diameter: 125 mm

Weight: 16 kg

Depth rating: 50 m

Range: 50 km

Power capacity: 1 kWh

Endurance: 8 h

Max speed: 12 knots

This is the small and affordable maritime robot (SAM) developed within SMaRC. The aim of this platform is to push the boundaries of what is doable with a small size and easily portable AUV. SAM is carried by one person and all necessary equipment for SAM can be fitted in a regular station-wagon car. Unique for SAM is the manoeuvring capacity for this type of slender AUV, allowing relatively long range and advanced use of sensors that can be aimed at a target of interest. SAM is based on the open-source Robot Operating Software (ROS), which together with the robot's small size and portability makes it a perfect tool for the robotics researchers to easily bring out in the field for testing.

Payload sensor bay:

E.g. multi-sound chemical sensor EX01 from YSI or a small gripper from Blue Robotics

Navigation:

Doppler velocity log (Deep Vision), IMU (STIM300), AHRS (ELLIPSE Micro series), GPS and CTD (Star-Oddi)

Side-Scan Sonars: Dual-frequency side-scan sonars in rails from Deep Vision

Internal trim systems:

LCG for pitch, TCG and variable contra-rotating propellers for roll, and a variable buoyancy system for depth adjustment

Manoeuvring:

Thrust-vector steering with individually controlled contra-rotating propellers

Forward-looking multibeam for collision avoidance:

Custom design by Deep Vision as part of SMaRC

Cameras: 2x forward-looking and 1x downward-looking cameras integrated in nosecone

Bottom-looking multibeam: Custom design by Deep Vision as part of SMaRC

Surface communication: Wifi, 4G

Batteries: Rechargeable Li-ion batteries

ROBOT: RAN

Basic data

Length: 7.5 m
Diameter: 875 mm
Weight: 1,850 kg
Depth rating: 3,000 m
Range: 300 km
Power capacity: 32 kWh
Endurance: 36 h
Max speed: 6 knots

The AUV RAN is a Hugin type AUV purchased from the Norwegian company Kongsberg. It gives SMaRC access to polar environments as well as coastal seas. During 2018-2020, RAN performed in total 35 missions in the Gullmar Fjord, in the Koster Fjord, and in the Amundsen Sea, Antarctica, for the SMaRC project. RAN collected the first-ever data from underneath the Thwaites glacier in 2019. The mission data, including fine-scale bathymetric data and a wide range of environment parameters, is used to develop software and navigation tools that will be used on the other two platforms in the second half of the project.

Navigation: IMU (Honeywell Hg9900), GPS Receiver (AUV: Novatel), Compass (Leica DMC), Doppler velocity log (Nortek 500 kHz)

Underwater Communication: USBL (HiPAP Transponder), cNODE Command Link and Data Link

Batteries: Rechargeable and swappable lithium-polymer batteries

Surface Communication: WiFi, Iridium, UHF radio link

Forward-Looking Sonar/Anti-Collision System: Imagenex sonar and KM algorithms for improved contour following and obstacle avoidance

Sub-Bottom profiler: EdgeTech DW-216, configurable chirp pulses

Sidescan Sonar: EdgeTech dual-frequency, 75 kHz and 410 kHz

Multi-Beam Echo-sounder: Kongsberg EM2040, 200-400 kHz, 0.7° × 0.7° beam width, swath-coverage sector up to 140°

Altimeters: Kongsberg Mesotech 200/675 kHz forward- and down-looking

Other Sensors: Upward-looking DVL / ADCP, Contros HydroC CO₂, Sea-Bird/Wet-Labs ECO Triplet (FLBB CD), Sea-Bird/Satlantic Deep SUNA (max 2000 meter), 2x Sea-Bird combination SBE-19plusV2 and SBE-43.

2.3.2 CYBER-PHYSICS SIMULATOR ENVIRONMENT

The prototyping and development of software for underwater robots entail particular challenges in comparison to indoor and ground robotics. The risk of a software failure or unexpected behaviour endangering the hardware or causing the loss of the vehicle is higher underwater. Additionally, the extra effort, time and cost of testing a vehicle in open waters, motivates the use of effective simulation environments while developing an AUV. An essential tool for development of robots and algorithms within SMaRC is therefore a cyber-physical simulator environment connecting software architecture and various simulators with hardware and operational human interfaces. An overview of the cyber-physical simulator environment is depicted in figure 7.

The simulator environment consists of a mission simulator³ using the open-source Stonefish simulation tool⁴ that enables validation of the entire software pipeline so that full missions can be rehearsed in a virtual environment, with support for multi-agent operations. New individual software packages, as well as the entire software system, can be rapidly tested to reduce risks. In addition, specific manoeuvres and control strategies can be verified in a higher fidelity simulator in Simulink, where the AUV dynamics are modelled more accurately (Bhat et al. 2019). Both simulators are designed to offer the same communication interface as the real AUV. This allows seamless switching between the real hardware and the simulation environments. The use of these simulation tools facilitates a streamlined development pipeline, reduces

risks and costs, and ensures tighter system integration.

The core software systems run within the Robot Operating System (ROS⁵). The operator commands mission plans to the AUV through the LSTS Neptus⁶ software's graphical user interface, a distributed command and control infrastructure connecting vehicles and other entities. Open-source and easy-to-use graphical interface and mapping functions were the main reasons for choosing Neptus as a mission planning system. Within SMaRC, we have added to the capability of Neptus by developing an open source communication bridge between Neptus and ROS⁷ that makes data available on both sides (Bhat et al. 2019 and Bhat et al. 2020).

Within the SMaRC simulator environment, a mission-critical behaviour tree has been developed. Although conventionally used, finite-state machines can predictably respond to faults and mission-progression triggers, that are inherently limited to the operator's expectations and inflexible to unexpected observations. Behaviour trees are therefore advantageous, as they enable goal-based and deliberative mission-planning systems. Here, the behaviour tree receives the mission plan and delegates commands (e.g. way-points) to lower-level controllers (e.g. motion planners). A crucial aspect of this implementation is that emergency conditions are checked with the highest priority at every query of the behaviour tree. The reactivity and modularity of the behaviour tree ensures both maintained safety during the course of a mission and easily re-configurable tasks.

Figure 7: Integrated software, hardware, and simulator environment.

³ github.com/smarc-project/sam_stonefish_sim

⁴ github.com/patrykcieslak/stonefish

⁵ ros.org

⁶ lsts.pt/toolchain/neptus

⁷ github.com/smarc-project/imc_ros_bridge

Figure 8: Group photo from Askö 2020.

2.3.3 JOINT WORKSHOP- AND DEMONSTRATION (JWS&D) PERIODS

As a backbone for collaboration within SMaRC, annual Joint Workshop- and Demonstration periods are arranged, during which typically system-level capabilities are tested and demonstrated. The demonstrator periods enable all partners in SMaRC to meet (including top management and scientific advisory board) and thereby ensures relevant feedback to the research projects. The annual workshops are also a possibility for the PhD students to meet, interact and solve mutual problems. During the workshops, presentations are held describing current ongoing work, possibilities for joint workshop activities are arranged, and educational activities are offered. As part of these annual demonstration periods, the detailed plans for the upcoming test periods are typically also discussed with the scientific advisory board, other partners as well as with the SMaRC board.

During the JWS&D periods, the partners have access to state-of-the-art research equipment and facilities from the stakeholders in SMaRC. As an example, three excellent AUV test sites have been identified: Motala (Saab facility), Kristineberg (Gothenburg University), and Askö (Stockholm University). In all these places, the supporting facilities in close vicinity to water are excellent. The JWS&D periods are also open for international collaboration with other research teams. The partners of SMaRC are active in a number of international collaborations with other research groups (e.g. UTAS Australia and U-Laval Canada, University of Zagreb, LSTS Portugal and NTNU Norway) through which these JWS&D periods offer a possibility for broadening the collaboration.

The JWS&D periods have been arranged since the start of the centre. However, their character has changed; the first years' focus on sub-components and status presentations was shifted towards higher maturity and the ability to carry out tests related to the milestones of the sub-projects. In 2019 the vehicles were in a status where integrated sub-project tests could be performed.

The following JWS&D periods were carried out:

- In 2017, the JWS&D period was arranged at **Kristineberg Marine Research Station** (operated by Gothenburg University). This was the first time that the senior staff and PhDs were gathered. The event was focused on the sub-project activities and planning.
- In 2018, the second JWS&D period was arranged at **Saab's test facility in Motala**. Parts of the platforms were on display as well as posters presenting early results.
- In June 2020, a JWS&D was arranged at **Askö Laboratory** (operated by the Baltic Sea Centre of Stockholm University), where all platforms demonstrated new capabilities. Due to Covid-19, it was necessary to restrict the JWS&D to the core team of the project. A movie⁸ to disseminate the results was produced showing the activities.

It should be noted that these events have been highlighted as very beneficial, by both external visitors and the internal SMaRC personnel, being the project group and the doctoral students. The main objective of the JWS&D periods is to test and integrate new tools into the vehicles, but the importance of the social aspect, which constitutes a prerequisite for a highly functional research environment, should not be underestimated.

⁸ smarc.se/askofilm2020

2.4 LIST OF SELECTED PUBLICATIONS

- Bhat S., Stenius I., and Miao T.,** *Real-time Simulation of Hydrobat AUVs over the Full 0-360° Flight Envelope*, Journal paper to be submitted to IEEE Journal of Oceanic Engineering, **2020a.**
- Bhat S., Torroba I., Özkahraman Ö., Bore N., Sprague C. I., Xie Y., Stenius I., Severholt J., Ljung C., Folkesson J., and Ögren P.,** *A Cyber-Physical System for Hydrobat AUVs: System Integration and Field Demonstration*, in IEEE OES AUV2020 Symposium, St. John's, NL, Canada, **2020b.**
- Bore N. and Folkesson J.,** *Modeling and Simulation of Sidescan using Conditional Generative Adversarial Networks*, submitted to IEEE Journal of Oceanic Engineering, **2020.**
- Chiche A., Lagergren C., Lindbergh G., and Stenius I.,** *Sizing the energy system on long-range AUVs*, in 2018 IEEE/OES Autonomous Underwater Vehicles (AUV), **2018.**
- Deutsch C., Kutteneuler J., Melin T., and Heil P.,** *Glider Performance Analysis and Intermediate-Fidelity Modelling of Underwater Vehicles*, Ocean Engineering, volume 210, **2020b.**
- Deutsch C., Thuné S., Söderling F., Moratelli L., and Kutteneuler J.,** *Design of an AUV Research Platform for Demonstration of Novel Technologies*, in 2018 IEEE/OES Autonomous Underwater Vehicles (AUV), IEEE/OES AUV, Porto, **2018.**
- Folkesson J., Chang H., and Bore N.,** *Lambert's Cosine Law and Sidescan Sonar Modeling*, in (submitted to) IEEE OES Autonomous Underwater Vehicle Symposium, **2020.**
- Lidström V., Erstorp E. S., Nordenvaad M. L., Sigra P., and Kutteneuler J.,** *Non-Coherent Acoustic Modulation for Energy Constrained Underwater Platforms*, in OCEANS 2019 - Marseille, pp. 1-7, IEEE, **2019.**
- Torroba I., Sprague C.I., Bore N., and Folkesson J.,** *PointNetKL: Deep Inference for GICP Covariance Estimation in Bathymetric SLAM*, IEEE Robotics and Automation Letters, volume 5(3):pp. 4078-4085, **2020.**
- Wählin A.K., Steiger N., Darelus E., Assmann K.M., Glessmer M.S., Ha H.K., Herraiz-Borreguero L., Heuzé C., Jenkins A., Kim T.W., Mazur A.K., Sommeria J., and Viboud S.,** *Ice front blocking of ocean heat transport to an Antarctic ice shelf*, Nature, volume 578:pp. 568-571, **2020c.**
- Ögren P.,** *Convergence Analysis of Hybrid Control Systems in the Form of Backward Chained Behavior Trees*, Robotics and Automation Letters, IEEE, **2020.**
- Özkahraman Ö. and Ögren P.,** *Underwater Caging and Capture for Autonomous Underwater Vehicles*, in Global OCEANS 2020, **2020b.**

2.5 FUTURE RESEARCH PLANS

Early in the project, fundamental work was done to describe the scenarios encompassing the system boundary for SMaRC's activities (see section 1.2.2). These scenarios were essential for the project and were used as guidance for the first part of SMaRC. Halfway, we now conclude that they are still valid and relevant, and that the future plans will continue to be based on these scenarios. Being at the halfway mark, we now have the advantage of using these scenarios for identifying priorities for the coming period (2021-2024), thus delivering direct linkage between scenarios, capabilities and milestones.. Focus for the second half of the centre's funding period will be on a selection of six out of the ten scenarios (see pages 24–29) as key scenarios to demonstrate our progress. The milestones act as targets to make sure we follow the right track and clearly demonstrate our progress towards the scenarios and benefit areas. The milestones also ensure that key responsibilities within the project are clear to the involved researchers, supervisors and industry partners.

We would like to underline that we have deliberately set very challenging scenarios and goals for ourselves and that the end users in SMaRC are the main architects of these scenarios. The demonstration of a full scenario will be based on the successful development of a number of capabilities set out as milestones for our future work. Notably, some of these milestones and final demonstrations of a full scenario are also dependent on SMaRC being able to secure additional funding in addition to what is currently included in the project budget (these parts are clarified with a footnote). This highlights the strong involvement of the SMaRC end-users and indicates that the industry and defence partners are already looking beyond the timeline of SMaRC and considering additional funding to realise these very ambitious milestones.

During the second half of the project, focus thus shifts towards more intensive integration and demonstration of system-level capabilities (see section 1.2.2). This implies more integration of results into the robots, a tighter collaboration with end users and natural scientists as well as collaboration with industry-partner platforms or other research groups. The scenarios also accentuate the importance of the JWS&D periods (see section 2.3.3), where the integration takes place and where results are tested in the field.

We want to demonstrate the feasibility of small, cost effective, agile, and modular maritime robotics tools as critical components of ocean aquaculture infrastructures. For the final SMaRC demo we aim to demonstrate the fully autonomous collection of high-resolution subsurface data to enable prospecting

and licensing of an ocean production site on the Swedish west coast. Further, the aim is to demonstrate the fully autonomous inspection of an already existing algae-farm (e.g. the SMaRC test-farm at Kristineberg or one of KosterAlgs commercial farms in the Koster Archipelago). Key capabilities are:

improved monitoring of an area using e.g. machine learning and optimisation tools (**SP07**), safe operations in confined spaces with underactuated AUVs (**SP04**), running real-time algorithms such as SLAM, object detection and adaptive data collection on a maritime robot (**SP05-SP08, SP14**).

Milestones 2021:

1. SAM-1 operational with side-scan sonar, CTD and cameras as payloads. SAM-1 can be operated by virtually any operator after a short intro course. SMaRC-DeepVision DVL calibrated and verified. SAM capable of running BT based adaptable missions autonomously with real-time object detection algorithms (**SP14**).
2. Demonstration of optimal control strategies for underactuated and hydrobatic AUV's are implemented and demonstrated on SAM, e.g. demonstrating infrastructure monitoring and line following based on camera feedback (**SP04**).
3. Demonstration of capability to operate in an algae-farm autonomously with an AUV (**SP04-SP08, SP14**).
4. Improved monitoring of an area using machine learning and optimisation tools (**SP07, SP08**).

Milestones 2022:

1. Demonstration of capability to operate in an algae-farm prospecting area (**SP14**).
2. SAM-2 operational with a full payload

sensor suite, i.e. micro multibeam, side-scan sonars, forward- looking sonar, CTD, cameras as well as chemical sensors or a gripper. Simple UW-communication capabilities between SAM-1 and SAM-2 are implemented and demonstrated. High-speed missions are demonstrated while running onboard real-time algorithms such as SLAM, object detection and adaptive data collection (**SP14**).

3. Implementation of multiple optimal control strategies on SAM while demonstrating capability for adaptive selection of most suitable control policy based on mission objectives e.g. long-range vs precision maneuver for docking (**SP04**).
4. Use of payload sensors to aid in mission execution (**SP05, SP06**).
5. Use of payload sensors to improve drift in navigation (**SP05, SP06**).

Milestones 2023:

1. Demonstration of an algae-farm prospecting operation with at least 2 cooperating AUVs (**SP14, SP05-SP08**).
2. Three operational SAMs accessible and

capable of running multi-agent missions (**SP14**).

3. Demonstration of advanced hydrobatic manoeuvres (including manipulation) with underactuated AUV's for optimal cooperation with multiple AUVs (**SP04**).

Milestones 2024:

1. Demonstration of capability for long-term operation in an algae-farm by completing a full operational cycle with an AUV and a dummy docking station (**SP14, SP04-SP08**).
2. SAM capable of safe confined space manoeuvring in an algae-farm including capability to dock into a dummy docking station (**SP14**).
3. Demonstration of the use of reinforcement learning in combination with behaviour trees to improve performance and/or robustness of mission execution, without reducing transparency (**SP07**).
4. Demonstration of advanced hydrobatic manoeuvres with underactuated AUV's in confined spaces for docking and optimal sensor coverage (**SP04**).

OP04 PIPELINE INSPECTION

Main demonstrator platforms:
MMT S-ROV, MMT ROV, Ran, Saab Sabertooth.

This scenario will be performed on an existing pipeline installation in the Baltic Sea or North Sea where a set of targets/objects/observables along the pipe are available. The plan is to make an inspection of a section on the pipeline and then place a target and a simulated gas leak (placed source on the seafloor). The AUV is expected to find the target and detect the leak as well as raise an alarm, document, and produce a report of the anomaly. In a final demo, we aim to demonstrate:

- Finding pipeline
- Inspect 5 km pipeline
- Classify anomalies and adjust mission plan

accordingly

- Combine data for ultra-high accuracy
- Find hydrocarbon leak
- React to leak by transmitting alert message
- Find serious crack or damage and switch to detailed inspection mode.
- Demonstrate capability to detect anomalies with 80 % correct classification, 0 % misses and max 20 % false detections.

Key capabilities are:

- Real-time identification of anomalies and classify them into cracks, damages, growth, movement of pipe or buckling (**SP05, SP06, SP02**).

- Mission planning based on detected anomalies to be reset to inspection mode (**SP07**).
- Cross referencing Side Scan data, Multi-beam, (if possible also Magnetometrics) and/or Photogrammetry to achieve navigation accuracy sufficient to detect movement of pipe (**SP05, SP06**).
- Detect hydrocarbons to identify leakage, change mission to inspect leakage. Raise alarm for major hazards by communicating on surface or via acoustic link (**SP10, SP05**).

Milestones 2021:

1. Classification of anomalies by machine learning on existing library (miss alignments of pipe as well as a set of images for classification) (**SP05, SP02**).
2. Mission-planning adjustments based on anomalies (**SP07**).
3. Demonstration of ability of the sniffer sensor (inc. trained neural network) to detect a selected number of compounds autonomously in a laboratory setting (**SP10, SP05**).
4. Established interface between sniffer and mission planning (**SP07, SP10**).
5. Assembled search patterns based on anomalies found by sniffer (**SP07, SP08**).
6. Reassigned mission plan to document leakage detected by sniffer (**SP07**).

Milestones 2022:

1. Correlated visual data with MBES data sets and resolve size and position. (**SP05, SP06**)
2. Automation algorithm outputting classification of targets (image, position, size) (**SP05, SP06**).
3. Demonstration of ability to successfully refine position accuracy by utilising multibeam echo sounder and camera images, possibly also other sensors (**SP06, SP05**).
4. Demonstration of transmitting request signals for immediate response by surfacing and communicate by satellite link (**SP07**).
5. Organisation of Raman library (**SP10**).
6. Improved monitoring of an area using e.g. machine learning and optimisation tools (**SP07**).

7. Algorithm for sensing of contaminants in real time. The point source can be demonstrated with the release of a water soluble tracer, Rhodamine, that has been shown to be a good Raman scatterer (could for example be the sunken ship Skytteren located on the west coast of Sweden) (**SP10, SP05**).
8. Testing of the fully integrated setup in simulator environment on real data sets from a pipeline with a single fast ROV (SROV or AUV and optionally with a set of AUVs collaborating along a pipeline) (**SP02, SP05-SP08, SP14**).

Milestones 2023-24:

1. Partial demonstration of the final demo on real vehicles.
2. Final demo performed on a real vehicle and in a real setting.

SEC01 LONG-RANGE RECONNAISSANCE

Main demonstrator platforms: **LoLo, Saab AUV62.**

The vision here is to demonstrate a long-range mission (<1000 km or 30 days at optimal speed and >400 km at 5 knots) with the capability of accurate GNSS-free underwater navigation (with launch and recovery from an underwater station). The mission is a security and defence task that requires the AUV to stay submerged without exposing any sensors above water. The AUV (LoLo) should

be able to perform long-range missions and autonomously navigate to a predetermined location, perform data collection and safely return home. Key capabilities are:

- Long-range transit.
- GNSS-free underwater navigation.
- Establishing an ad-hoc uw-communication network for extended communication range.

- Data collection.
- Self-diagnostic and mission re-planning based on actual and predicted situations.
- Rendezvous with another underwater vehicle or station for hard- and soft docking and sharing of relatively large amounts of data.

Milestones 2021:

1. Demonstration of long-range capability beyond state-of-art in power consumption in relation to size of vehicle (e.g. using hybrid propeller/gliders modes) (**SP03**).
2. Demonstration of extended range capability by onboard energy-management strategies and system optimisation. Demonstrate a realistic design of a fuel-cell system/module with at least 2x higher energy density than a comparable secondary Li-ion battery solution (**SP09**, **SP03**).
3. Demonstration of way-point navigation with a ROS-based back-seat driver computer on LoLo (**SP13**).

Milestones 2022:

1. Establishment of an ad-hoc network with underwater communication nodes dropped from an AUV and demonstrate "call-home" capability through the network (**SP13**, **SP11**, **SP12**).
2. Demonstration of bottom navigation beyond current state of art, and capability

of self-positioning using a-priori-defined (and -located) natural bottom references (**SP06**).

3. Demonstration of obstacle avoidance and re-planning for covering of avoided area (if not permanently obstructed) (**SP13**, **SP07**).
4. Demonstration of safe surfacing through detection, prediction of trajectory and avoidance of possible threats (vessels or other unpredicted objects "in the way") (**SP13**, **SP07**).
5. Demonstration of adaptation to new sudden situations through re-planning of tasks and priorities according to a predefined decision matrix. Show software architecture that allows incremental upgrade to the decision matrix when the automated tasks are proven to be reliable enough (**SP13**, **SP07**).

Milestones 2023:

1. Demonstration of a long-range mission (<1000 km or 30 days at optimal speed and >400 km at 5 knots)⁹ with the capability of (**SP13**, **SP03**, **SP01**):

- a. accurate GNSS-free underwater navigation (**SP06**);
 - b. recovering from sudden unpredicted events (**SP13**);
 - c. understanding of current situation, application of recovering measures and mission re-planning in case of: i. ordered change of plans, ii. loss of energy, iii. forced change of course, iv. sensor malfunction, v. vehicle malfunction, vi. collision, vii. dead end (**SP07**).
2. Demonstration of change-detection capability and performing of actions as described in a predefined decision matrix (**SP07**).

Milestones 2024:

1. Demonstrate the full 2023 scenario mission including launch and recovery from an underwater station (**SP13**, **SP03**, **SP01**)¹⁰.

⁹ Reaching the final goal may also require additional funding for batteries, fuel-cells or alike.

¹⁰ Requires additional funding to be secured for a successful demo of this milestone.

SEC02 MULTI-AGENT HOME RECONNAISSANCE

Main demonstrator platforms: **SAM, SubNero nodes, LoLo, Saab nodes, Saab vehicles, and WARA-PS assets.**

In this scenario, we aim to demonstrate collaborations between heterogenous robots in a maritime environment in cooperation with the WASP/WARA-PS research arena. Such a scenario would be a multi-agent area-patrolling scenario with a combina-

tion of moving underwater robots, a fixed network of underwater sensors, as well as moving surface robots, aerial vehicles and database cluster from the WARA-PS teams. Key capabilities are:

- Optimising task performance by utilising

multiple agents.

- Adaptation to sudden changes and re-planning.
- Sharing of data between agents and establishing common strategy to reach goal.

Milestones 2021:

1. Demonstration, in a simulator environment, of collaborative underwater search, taking navigation uncertainty into consideration. Coverage of a bottom area is related to navigation uncertainty (**SP08, SP14**).
2. Demonstration of underwater communication and data exchange between moving and stationary nodes in an area-surveillance system (including command) (**SP12, SP13**).
3. Transfer of gathered information to command unit either via fixed gateway or moving nodes (surfacing or communicating to predefined nodes) (**SP11-SP13**).
4. Demonstration of directive underwater communication between transmit and receiver node (**SP11**).
5. Establishment of common interfaces and demonstrate data-sharing capabilities between SMaRC robots, Saab nodes and WARA-PS database (**SP14, SP11, SP12**).

Milestones 2022:

1. Demonstration of directive underwater communication in archipelago environment employing directive technique

(SP11).

2. Demonstration of multi-agent behaviour through sharing of information and tasks to achieve common goals, e.g. demonstrating sharing of data between moving nodes in order to pursue and predict a possible intruder's trajectory through a surveyed area. (**SP08, SP14**).
3. Demonstration of adaptation to new sudden situations through re-planning of tasks and priorities according to a predefined decision matrix (**SP07, SP08**).
4. Demonstrating the use of two moving nodes sharing tasks to achieve a common strategy to better pursue a moving intruder (**SP08**) as well as use of fixed UV nodes to "close" a passage and patrolling surrounding area with moving nodes (**SP08**).
5. Enhanced data sharing and operational efficiency in a network of heterogenous robots and sensor nodes in collaboration with the WARA-PS team (**SP14, Saab as well as relevant WARA-PS teams**)¹¹.

Milestones 2023:

1. Demonstration of ability to first detect a target and then share the information to other moving agents and use reinforce-

ment learning in combination with behavior trees to improve performance and/or robustness of mission execution, without reducing transparency (**SP07, SP08, SP14**).

2. Demonstration of ability to first collect and then transfer both information and large amounts of data from a patrolling vehicle to a moving node (other vehicle) and/or to a fixed node (sensor node, UV garage, or similar), with the goal of sharing the information to the UV surveillance and control network (**SP11, SP12, SP13**)¹².

Milestones 2024:

1. Demonstration of a full data-sharing scenario from the underwater domain (through moving nodes, fixed nodes, surface vehicles, aerial vehicles and 5G link) to a control central where a decision is taken and then orders are sent back to the robot that changes the behavior or takes an action (**SP14, Saab as well as relevant WARA-PS teams**)¹³.

¹¹ May require additional funding to be secured for a successful demo with all partners involved.

¹² Depending on data transfer link to be used, additional funding may be required here.

¹³ Requires additional funding to be secured for a successful demo of this milestone.

ENV01 GLACIER-FRONT MAPPING

Main demonstrator platform: **SAM**.

Demonstrate an autonomous survey of a glacier front with an underwater robot that navigates (repeatedly) along a dynamic ice front, while localising, mapping and monitoring

it with payload sensors such as multi-beam. Demonstrate capability to autonomously adapt mission to rapid potential change of local environmental conditions (changes

in the shape and position of the ice front caused by the breaking off ("calving") of icebergs) and/or properties of the water-masses in front of it).

Milestones 2021:

1. Drone-based (aerial) inspection of near glacier front sub-surface ice conditions (2020 first trip to Sulitelma and 2021 a second field trip with SMaRC PhDs to Svalbard). Undertake drone-based tests for best-practice guidance for approaching glaciers with AUVs (**SP14, SP04, SP07**).
2. Analysis of the soundscape at a calving glacier front, based on data acquired with in SMaRC in 2020 (or from other project, but available to SMaRC), whether/how calving (cracking) acoustics interfere with UW communication (**SP11, SP12**).
3. Based on data from inspections, development and demonstration of a realistic glacier-front simulator environment (e.g. Stonefish) with ice melange and icebergs, glacier front and bathymetry that mimics realistic conditions as close as possible (**SP14, SP04, SP07, SP08**).

Milestones 2022:

1. Demonstration of safe under-ice operational capabilities. This includes safe

operational protocols as well as the ability to map surface ice cover (on the fly) to identify spots of ice-free areas as a requirement for surfacing, even in emergency mode. Demonstration is planned for a semi-controlled icy environment in e.g. Bay of Bothnia and Luleå archipelago (**SP14**).

2. Demonstration of capabilities to carry payload sensors and retrieve data (e.g. a multi-beam echosounder for mapping) at 180 deg and 90 deg roll angles while using DVL and collision avoidance for navigation (**SP14, SP04**).
3. Demonstration of a simulated glacier-front mapping mission with multi-beam and camera-based collision avoidance (including dynamic conditions in the simulated environment, such as ice-infested waters after calving of ice bergs from ice fronts, and using bathymetry targeted for the Svalbard Demo 2023 (**SP14, SP04-SP08**).

Milestones 2023:

1. Full ENV01 demonstration of autonomous

survey of a glacier front in Svalbard in locations where the seafloor in the fjord, very close to the calving front, is well-mapped. The aim is to perform at least 2 sweeps along the glacier front, to collect monitoring data (with the payload sensor). Target base stations: Longyearbyen or Ny Ålesund, or more remote fjords along Svalbard's coast if cooperation with UNIS ship-based teaching expeditions is possible (**SP14, SP04-SP08**)¹⁴.

Milestones 2024:

1. Backup time for Svalbard expedition taking into account un-expected events (weather, other SMaRC demo events, failures, synchronising with other activities etc.).
2. Possibility for add-on demonstrations such as deployment of sensor nodes with underwater communication to download data¹⁵.

¹⁴ Requires additional funding to be secured for a successful demo of this milestone.

¹⁵ Requires additional funding to be secured for a successful demo of this milestone.

ENV02 BELOW-GLACIER MONITORING

Main demonstrator platform: **Ran.**

In this scenario, SMaRC joins the RV/IB Palmer on a second expedition to the Thwaites

glacier arranged by the ITGC¹⁶ in early 2022 for under-ice missions. Target capabilities are

safe AUV operations under ice, risk assessment, and pre- and post-dive procedures.

Milestones 2021:

1. Under-ice test period 1, in Härnösand: Testing and comparison of different upward looking multibeam solutions. Expected outcome: (i) Three different under-ice sensors will be compared and validated with respect to resolution, detection rates, software capabilities, and noise/disturbance/unwanted interaction with other acoustic sensors. (ii) A recommendation for type of sensor that will be brought to the Thwaites Glacier. (iii) A calibration of the upward-looking DVL will be performed.
2. Under-ice test period 2, in Härnösand, Luleå or the Baltic Sea: Additional tests of the chosen upward-looking multibeam.

Outcome: (i) A data set of ice roughness and draft (ii) A corresponding data set from satellite radar (low resolution) (iii) A corresponding photographic drone data set from above (for cross comparison).

Milestones 2022:

1. Mission workshop at KTH: we will build a bank of 30 missions to be performed in Antarctica. Using the operative system HuginOS, we will construct 30 different missions that can serve as mission base during the cruise. Open for all SMaRC participants, in particular young scientists are encouraged to participate. Update pre- and post dive procedures for under ice missions.

2. Participation in a second expedition to the Thwaites Glacier with the Hugin AUV Ran.
3. Improved monitoring of an area using machine learning and optimisation tools **(SP05, SP06, SP07).**

Milestones 2023-24:

1. Evaluation of the under-ice datasets suitability for use in navigation **(SP05, SP06).**
2. Demonstration (in simulator) of reinforcement learning in combination with behavior trees to improve performance and/or robustness of mission execution, without reducing transparency **(SP07).**

¹⁶ thwaitesglacier.org

3 Strategic Relevance

3.1 SOCIETAL BENEFITS

The societal benefits stem from three important uses of the oceans, which will see disruptive progress in the coming 20 years:

Ocean production – using the oceans for food, energy, and raw materials. Cultivation of marine plants in large farms and mining of the ocean floor are examples. Meeting human development needs and at the same time protecting the earth's life support systems will require a future global economy that is less dependent on fossil resources than today. Biomass is the only sustainable raw material that can provide sufficient fuels and renewable materials at the same time. Hence, a transition to a bio-based economy where raw materials are produced through the sustainable use of ecosystem services from land and water offers an avenue toward energy independence and a "green" economy. Many models for biomass production are based on agriculture on land. Large-scale cultivation of biomass on land has, however, frequently been associated with environmental problems due to extensive use of land (preceded by deforestation), fertilisers and pesticides, and consumption of fresh water. One alternative to terrestrial crops for biomass production is to culture benthic marine algae (seaweeds) in the sea. Seaweeds grow faster than any land plant and are effective at capturing CO₂. Furthermore, the oceans with their extensive coastal regions provide a vast area having a limited conflict with food supply. Seaweeds also function as ocean biofilters, which can be used for nutrient stripping of eutrophicated coastal waters.

Safeguarding society – knowing what is happening on and in our waters. This requires monitoring with sensors and vehicles. More than 90 percent of all trade to and from Sweden is transported by ships. To secure the flow of goods and people, it is of the utmost importance that the sea-lines of communication are safe and secure. The threat can be foreign nations with the intention to disturb the traffic but also criminal activities in the form of smugglers and pirates. A constant and sustained monitoring with large area coverage is required to keep track of sea activities. It must be possible to detect and classify not only ships but also underwater activities. To achieve sustainable monitoring the use of autonomous and robot systems is increasing and will increase even more in the future. The Baltic Sea is a particularly challenging environment to operate in with its heavy sea traffic, complex bathymetric and hydroacoustic conditions and vast archipelagos.

Environmental sensing – measuring physical, biological and chemical parameters to assess the state of the ocean, and to detect man-made and natural variations in concentrations of pollutants and organic material. There is a growing demand for marine environmental monitoring, mapping, prospecting and spatial planning. Sweden has recently decided on new regulations for Swedish areas of the Baltic Sea

and the North Sea under the Marine Strategy Framework Directive (MSFD) issued by the European Union. Environmental quality standards have been defined for pressure and state indicators relevant to describe major environmental stresses impacting the Baltic Sea and the North Sea. Climate change and associated sea-level rise poses severe problems for many of the densely populated coastal areas all over the world. Sea-level rise is due to thermal expansion of the oceans and melting of ice sheets. The fate of the large ice sheets in Antarctica and Greenland is presently the source of the greatest uncertainty for predicting future sea-level rise. We urgently need measurements from the oceans, not only at the surface, but also at depth, and beneath floating glacier tongues. To reach these unexplored areas new safe navigational techniques are required.

All three of these benefit areas are of strategic relevance for society. There is potential for dramatic impact in the natural science community through enabled data availability from inaccessible areas of the oceans at a level we have never seen before. Further, the benefit areas are strategically important from an industrial perspective: any nation with strong, native capabilities to deliver progress within these benefit areas will be in a competitive position on the international market and a sought-after partner for collaboration, create new jobs and export revenues.

3.1.1 INDUSTRIAL BENEFITS

SMaRC has been instrumental in establishing academic maritime robotics research in Sweden. This programme is considered to be the first stepping stone to establish a sustained national maritime robotics and underwater technology research programme in Sweden¹⁷. SMaRC has also supported network development between stakeholders within the maritime robotics and underwater domain including academic research, industry, military and civilian users of underwater technology.

Generally, industrial companies have long product life cycles, thus, the primary interest in collaborating in a research programme, such as SMaRC, is not to get patents or apply results in the short term but rather to safeguard the technological frontline in future products. The centre will ensure the awareness and uptake by industry of cutting-edge technologies from academic and industrial clusters to support the management of product portfolios and to keep up with global market demand over time.

Most research areas in SMaRC are highly relevant for the industry partners in near- to medium-term activities and planning. The following areas are of particular interest: autonomous underwater perception, underwater navigation, air-independent energy storage, and underwater communication. Additionally, industry highly values the networking and, potentially, the recruitment opportunities created by SMaRC. The centre does not only create innovation and technology but also educates and trains skilled people that will have attractive qualifications when transiting to employment by industry.

¹⁷ subtechsweden.se/agenda-nria-u-2019

3.2 CENTRE KPIS

Scientific significance and progress are measured with the help of key performance indicators (KPIs). In this section, we highlight the centre KPIs that were created and submitted to SSF as part of the application process. These criteria are also used to assess the yearly progress of the centre. Naturally, many criteria become more relevant over time, and for some criteria, maximising their values may not be desirable. Note also that no target values were submitted as part of the SMaRC application. The KPIs stated here are a snapshot of current status; in the comments column (tables 8–12), current values are related to what may be realistically expected, given budget and time, where relevant.

■ **Scientific KPIs** Scientific productivity is often measured in terms of number of scientific contributions in journals and successful PhD defences. As it is not realistic that any PhDs will be finished by the mid-term evaluation, number of produced papers and number of started PhDs are more relevant measures. These are listed in table 8.

■ **Implementation KPIs** An important aspect of the centre is the development and testing of real systems at sea in realistic scenarios. A clear-cut KPI on implementation status is difficult to find. Table 9, however, lists a number of KPIs that collectively give an indication of our status with respect to implementation.

■ **Impact KPIs** The impact of the centre is ultimately measured by the commercial applications using our results. It is not realistic to expect any products to be produced after only four years but some commercially relevant KPIs are identified and listed in table 10.

■ **Success KPIs** There are also KPIs associated with our milestones and year-end goals. Table 11 lists some of these success criteria, but other measures may also be added when relevant.

■ **Process KPIs** Finally, for the centre to be successful it is important that the management is handled thoroughly and hence there are KPIs associated with the management and over all progress of the centre activities also, table 12.

Table 8: Scientific KPIs.

KPI	Result	Comment
Number of published/submitted papers	38	On par with what can be expected from a project of this size (given 12 PhDs about 36 papers can be expected in a three-year period).
Number of collaborative papers (of total published)	16	Almost half of all papers are with collaborations outside the own research group and five of these are with external international collaborations. This indicates quite substantial cross coupling of knowledge within SMaRC.
Number and progress of PhDs/Licentiate started	13	Follows the initial plan (two of these are post-doctoral researchers).

Table 9: Implementation KPIs.

KPI	Result	Comment
Number of vehicles built/used	3	Two in-house-developed AUVs (SAM and LoLo) have been tested. One commercial AUV (Ran) has been operated in extreme conditions (Antarctica). This follows the initial plan and is considered a good balance between investment and the benefits these tools provide to the researchers in SMaRC.
Number of sensors built/used	>10	More than ten different payload sensors have been used in different environments. In addition, we have so far been developing five custom sensors as part of SMaRC. This is more than we expected at the outset of this project.
Number of joint tests and demonstrations	8	2017: Kristineberg JWS&D; 2018: Motala JWS&D; 2018–2019 Antarctic exp.; 2019 Bornö Testing with Ran; 2019: Motala measurement campaign; 2020: Härnösand, Under-ice operations; 2020: Askö JWS&D; 2020: SMaRC/WARA-PS demo Västervik. This is in alignment with the original plan.
Longest mission time/distance	13 h/70 km	Ran June 26, 2019: 13 hours/70 km under Thwaites Glacier in Antarctica. The extension and severity of participating in this kind of expedition already halfway through the project is considered a great success.
Total hours/km of submerged missions	54 h	Ran Bornö: 54 h Ran; Antarctica: 13 h under Thwaites.
Total amount of data collected (time x number of sensors)	365 ~100 GB (Motala) 30 GB (Askö & Baggen)	Ran Bornö: 365 GB (54 hours x eight types of data), 6 MB as Raman spectra (four months of collection). There is no point in just maximising the amount of data collected. However, this gives an indication that we are collecting considerable amounts of very useful data for the researchers in SMaRC.
Number of different environment types tested in	6	Antarctica; Swedish east coast; Lake Vättern; Swedish west coast; Svalbard; Swedish arctic glacial lakes (Sulitelma/Tarfala). As with some of the above KPI's there is no point in maximising this value. But this gives an indication of the width of various environments we are working in and the severity of these environments.

Table 10: Impact KPIs.

KPI	Result	Comment
Number of patent applications		– This is not the most important KPI for our industry partners (see also industry comment on long development cycles, (section 3.1.1)). Furthermore, we believe that the impact KPIs will be more relevant during the second half of SMaRC.
Number of algorithms or design ideas being considered for industrial prototypes		– This will be much more relevant during the coming years. We have ongoing discussions, but no concrete deliverables yet.

Table 11: Success KPIs.

KPI	Result	Comment
Number of systems deployed combining N capabilities, for N=1,2,3,...	5	The following systems have been deployed and tested combining capabilities according to the numbering in appendix A: SAM: Combination of capabilities 1, 5, 13-15; Ran: Capabilities 1, 13; LoLo: Capabilities 2, 3, 9-11; Sub-Nero nodes: Capabilities 8.
Number of missions where we successfully deployed navigation/communication nodes autonomously and had the robot utilise them	1	First autonomous deployment of a sensor node was demonstrated from LoLo at Askö Jun 2020. This can be considered in line with plan.
Number of different SLAM systems (different landmarks or sensors) deployed		– Will be more relevant during the years to come.
Size of the largest SLAM map	1 km ²	1 sq km (offline).
Size of our largest 3D reconstruction	10.000 m ²	About 100 x 100 m (offline).
Accuracy of our 3D reconstruction (RMS error using a known structure)	0.7 m	0.7 m (offline).
Distance of our longest underwater communication	3 km	3 km with KTH node2node at Baggensfjärden. 1 km with Ran-cNode.
Success rate for autonomous docking		– Not tested yet.

Table 12: Process KPIs..

KPI	Result	Comment
Number of SAB meetings	4	In alignment with plan.
Number of centre-board meetings	13	In alignment with plan.
Number of applicant meetings	26	In alignment with plan.
Number of joint workshops and experiments/demonstrations	3	In alignment with plan.
Feedback from the co-applicants, SAB and centre board regarding the management of SMaRC.	Yes	2019: SMaRC-SSF programme committee dialog meeting. Project group two-day meeting Hönö (Jun 9-10). The management is also discussed regularly at the board meetings and the management has been strengthened based on feedback from the project group.

4

Graduate Training

4.1 PHD FIELD-TRAINING COURSES

Field training is an essential activity for an Industrial Research Project, since the methods and results developed in the sub-project need to be tested outdoor in the field to reach a level that is useful for the industry. In the field, students get the opportunity to both test results and adapt their methods to fit the tough marine environment. To train the PhD students a number of activities were organised. Training with the AUV Ran was done three times and included all aspects of AUV handling including preparation, programming, launch and recovery of AUV and post-processing of data. These training events have been acknowledged by the students as beneficial in that they were arranged in an early phase of the project and the PhDs were exposed to the special conditions encountered at sea. This experience has positively influenced their work and production as a PhD. These training sessions were also used to collect data for the sub-projects, especially for those investigating different aspects of AI and perception where data is necessary. The following events were arranged employing the AUV Ran:

- 26–30 September 2017: a field course on Skagerrak employing M/S Franklin (belonging to the industrial partner MMT). The students received two ECTS credits for participating. In total, 21 persons participated.
- 23–28 August 2018: Bornö (in Gullmarsfjorden) AUV course. This course was dedicated to working with the Ran AUV. Mission planning and mission execution were parts of the course. The base of operation was M/S Askholmen (belonging to the industrial partner MMT) from which Ran was deployed. The students received three ECTS credits for the course. In total, 18 persons participated.
- In 2019, a field exercise was arranged with Ran to obtain data for test and development of underwater navigation algorithms for SLAM.
- SMaRC PhD student Christopher Sprague participated in an Antarctic expedition. He was trained in running an AUV in polar conditions.
- In 2020, an international workshop was arranged in Härnösand with the subject of AUV operation under ice. Students were invited and participated accordingly.

SMaRC has been continuously in contact with the WASP/WARA-PS project, Wallenberg AI, Autonomous Systems and Software Program

(WASP), which is Sweden's largest research programme¹⁸. This is a multi-billion Wallenberg project investigating different aspects of autonomous systems with focus on AI and 5G, dealing with surface and air applications (excluding the underwater domain). SMaRC was cordially invited to participate in the WARAS-PS demonstration week in 2019. Several of the PhD students gained insight into the research questions that are common to both SMaRC and WASP, and into the benefits to be gained through collaboration and knowledge sharing of robots in the surface and air domains with that of robots in the underwater domain.

A crew consisting of nine participants (PhD students and seniors) visited the Breaking the Surface (BTS) conference in Croatia 2019. This conference also encompassed tests, demonstrations and tutorials with representation from the leading research groups in Europe on underwater robotics. The PhD students not only received training in underwater robotics but also got the opportunity to meet with other students and give their own tutorials. The SMaRC contribution at BTS was highly appreciated by the organisers and we are planning for a succession of participating in the BTS during the coming years also.

4.2 PHD SEMINARS

The cross-disciplinary character of the project means it falls outside the normal research topics represented at KTH. As a result, there is a shortage of important and necessary scientific discussion on underwater robotics that normally enriches a research field and which is fundamental for the professional development of the PhDs. To overcome this problem, SMaRC started the SMaRC Academy, where colloquial seminars and discussions were organised. The speaker list spans external speakers, senior lecturers, PhD students and industrial partners. Since the start of SMaRC, seminars have been arranged on various topics, including:

- Glacial marine science.
- Acoustic beamforming by bottle-nose dolphins.
- Extended Fourier transform to study transients.
- Particle motion – the second component of sound.
- “Speed talks” – rapid PhD research-status presentations.

¹⁸ wasp-sweden.org

5 Collaboration

5.1 NATIONAL COLLABORATIONS

SMaRC has been instrumental in building national collaboration between a unique set of partners, spanning multiple research disciplines and end-user communities. Researchers from engineering sciences, end-using natural sciences and defence research are joining forces. This connects environmental end-user needs with ocean production and strategic national defence interests uniquely in a mutually beneficial constellation spanning all three benefit areas identified in SMaRC. The scientific collaboration between different disciplines and departments (shown in joint sub-projects, publications etc.) is also in coherence with national research agendas such as NRIA-U 2019¹⁹ and NRIA Sjöfart 2020²⁰. The national research agendas also points out the importance of multidisciplinary collaboration and development of demonstrators, which is an essential part of the research programme in SMaRC.

An extension of the national collaboration within SMaRC has been to create close connections with WASP. The research arena within WASP, WARA-PS, is demonstrating research scenarios connected to public safety and SMaRC has been jointly participating in the WARA-PS demonstrations in Västervik²¹. Key future demonstrations are connected to extending this collaboration during the coming years of SMaRC.

Finally, as part of strengthening the national collaboration, SMaRC has participated in national fairs and strategic meetings to increase the visibility of SMaRC and create new networks – for a more detailed list, see the news feed on the SMaRC website²².

5.2 INTERNATIONAL COLLABORATIONS

SMaRC has been involved various international collaborations encompassing joint research proposals (T-NetOcean, ACCROSS, CHRONUS), organisation of workshops (BTS 2019, under-ice 2019&2020, ROS-WHOI), as well as participating in international polar expeditions (Thwaites Glacier expedition in Antarctica and study of glacier front calving events in Svalbard).

Further, joint papers (King et al. 2018, Sprague et al. 2018) and visits²³ have been produced. SMaRC researcher and board member Anna Wåhlin was also invited as keynote speaker at the IEEE OES AUV2020 conference in Canada.

It has become clear that SMaRC in comparison to similar (but larger) institutes/centres has a unique position in our long-term perspective in addressing research questions at lower technology readiness levels (TRL). Common to other centres with close cooperation with end users and natural scientists is a rather short time horizon with respect to the research focus – six to twelve months before a system must be proven and work under severe conditions. By comparison, SMaRC has a longer-term vision and research focus at lower TRLs, and as such, SMaRC is an attractive collaboration partner for larger, centres with budgets several times larger than the one of SMaRC.

5.3 TRIPLE-HELIX COLLABORATIONS

There has been strong interaction between all parties in SMaRC, within the entire triple helix: academic, industry and government bodies. Saab has two industrial PhDs working in the project, one from Saab Kockums and one from Saab Dynamics, and SMaRC participation forms a key cluster of research and development activities concerning machine learning and related technologies in the underwater domain. During the period covered in this half-time report, one person from Saab has been affiliated to the faculty at KTH-AVE which has strengthened the interaction between Saab and SMaRC including management and supervision support.

Saab, FOI, and MMT have provided valuable support and input concerning design and development of AUV demonstrators and sensors. The parties have collaborated closely in collecting data and running equipment tests, where e.g. MMT underwater systems have been used for data gathering which has been very important in the research. Furthermore, Saab's testing facilities in Linköping and Motala have been used for data collection and equipment testing, and the FOI water tank in Kista has been utilised for underwater sensor testing.

A number of parallel projects have been initiated during the period. For instance, FMV has initiated a joint project for "intelligent navigation" and underwater communication, a feasibility study on fuel-cell integration on LoLo, and an add-on study on SAM for manipulator capacity. Saab, with support from FMV, is also in the process of supplying SMaRC with a number of underwater sensor nodes.

5.4 LESSONS LEARNED – FEEDBACK FOR FUTURE CALLS

Some of the important lessons learned from the project so far are:

- The SSF funding has been instrumental in building a much-needed centre in Sweden on maritime robotics. Despite the strategic importance, the large industries and the many (fragmented) research groups, such a centre has not previously existed. We conclude that funding the IRC programmes has had a sparking effect on research that is of strategic importance for Sweden and can have long-lasting effects.
- SSF's key requirements for the call stated that each organisation could only participate in one application. While this has secured support for the selected call in the top management of each partner it has also become clear how this plays out very differently for large and small organisations. Saab, being a very big organisation, has two business units (Saab Kockums and Saab Dynamics) as partners in SMaRC. Each of these units are large enough to be a separate company with dedicated shares in the board but are treated as one. Further, these business units have different management structures, thus the involvement and possibility of collaborations can be challenging. Perhaps, in future similar calls, some governance documents could be prepared by SSF to facilitate structuring complex collaborations with many and different partners.

¹⁹ subtechsweden.se/agenda-nria-u-2019

²⁰ smarc.se/nriasjofart2020

²¹ smarc.se/warapsdemo

²² smarc.se

²³ SMaRC-NOC visit 2018, UNHAN visit to KTH/SMaRC 2018

6

Continued Work After the Project is Finished

After expiration of the SFF funding, the goal for SMaRC is to continue its operation and transform into a national centre for maritime robotics and underwater technology. The scope of the centre may be broadened and additional partners will be invited to participate, from both academia, industry and governmental bodies. The industry in Sweden has indicated a willingness to continue and already today, we note interest from our industrial partners that has resulted in financed projects that are spin-offs from SMaRC. Further, there is a huge potential for added leverage of a centre similar to SMaRC in future international collaborations such as Antarctic expeditions where investments can be scaled up tenfolds by joining forces. However, this requires a substantial long term commitment in a centre such as SMaRC so that it can be a reliable, attractive and trustworthy partner in such large scale projects.

The rationale for the continuation of a SMaRC-like centre can also be found in the National Research and Innovation Agenda for Underwater Technology (NRIA-U) published in 2019²⁴ which clearly states that there is a need for a national underwater centre in Sweden with long-term financing. The national centre will have the vision to become a key player globally in research on maritime robotics and underwater technology to make a concrete contribution to not only the existing SMaRC benefit areas (ocean production, safeguarding society, and environmental monitoring) but also to strengthen the collaborations with natural sciences. One activity of the national centre will be to arrange bi-annual national joint workshop and demonstrations, where operators, scientists, and governmental bodies actively contribute to provide regular test- and innovation events in the Swedish arena.

Sources of funding such as the Horizon Europe and the European Defence Fund offer new opportunities to collaborate with international partners. However, a prerequisite for being an attractive partner is the existence of high-profile research programmes on a national level. We believe that SMaRC can meet all the criteria to fill this role, and

for this, long-term financing has to be secured.

In SMaRC, strategic planning has started for beyond 2024. A strong link to WASP has been established. Contacts have been taken with Swedish financing authorities to inform about the need for future efforts. However, there are no firm signals today indicating this kind of continuation. In the coming years, efforts will be made to secure funding, partners and the organisation of such a centre. Important activities will be to form working groups and to organise workshops with the board and SMaRC's current project group, as well as to engage in outreach activities to invite new partners and to acquire attention from research-funding organisations such as e.g. Knut and Alice Wallenberg foundation (the financer of WASP), Swedish Foundation for Strategic Research (SSF), Swedish Innovation Agency (Vinnova), Defence Authorities, as well as industries.

The ambition is to expand and include a broader set of partners in Sweden as well as to identify and create close strategic partnerships with international key players. This expansion is a critical factor for maintaining and developing the knowledge, experience, capabilities, and personnel required for Sweden to:

- contribute extensively to the work within the UN Decade of Ocean Science for Global Sustainability²⁵;
- help fulfill relevant UN Sustainability Development Goals and the societal benefits stated within the SMaRC scope;
- ensure that maritime robotics and underwater technology competences match the corresponding "Vital Security Interest" stated by the Swedish Government.

With secured financing, SMaRC can continue to be an attractive partner in international collaborations in ocean sciences, and to be an important international player developing cutting-edge technology that will support industries to be market leaders and natural science to perform novel research.

²⁴ subtechsweden.se/agenda-nria-u-2019

²⁵ oceandecade.org

7

Budget

A summary of the economic reports for the first years (2017–2019) is presented in figures 9 and 10. Available funding each year is approximately 20 MSEK cash and 10 MSEK in-kind. As shown in figure 8 the costs during the start-up period the first year were less than planned. After the second year, the costs were in parity and slightly

above budget showing that SMaRC was fully operational. We can see that although the costs during 2018 and 2019 are slightly above budget the accumulated costs do not exceed the available funds as there was balance left from the first year. The accumulated balance is 5.3 MSEK in cash and we are on balance regarding in-kind.

Figure 9: Cash and in-kind financial outcome 2017-2019 (costs, budget and accumulated balance).

Figure 10 shows the total accrued funds and remaining available funds for the first three years. We see that during the first three years

the accumulated costs are 54 MSEK and that we have about 90 MSEK left for the remaining years.

Figure 10: The total accrued funds and remaining available funds for the first three years.

Figure 11 summarises the above presented financial outcome with a prognosis for the costs the remaining years until 2024. The figure shows accumulated available funds (given that SMaRC gets the remaining 25 MSEK after the mid-term review) and accumulated costs (both accrued and prognosis,). We see that with this budget, we will never exceed available funds and we will have a small margin for corrections and possible final investments 2024.

SMaRC is eligible for three per cent utilisation funds (so called

“nyttiggörandedel”). So far, none of this funding has been used. However, this is part of our strategic plan as the first years have been a build-up period and we expect that the results achieved so far will now be mature for integration and transfer to the industry partners and thereby we also expect to utilise these funds during the remaining period of the project. This also enables larger investments into the parts of utilisation that we consider most relevant.

Figure 11: Summary of the financial outcome with a prognosis for the costs the remaining years.

8

External Information and Other Activities

2017 SSF revealed the birth of SMaRC in an advertisement in Framtidens Forskning. An article about the centre was run in the Swedish technology journal Ny Teknik. In FMV's Framtidsspaning, an infographic explained the centre's setup.

2018 The SMaRC website (smarc.se) was launched in March 2018. For the premiere, a short intro movie for advertising SMaRC was created. SMaRC was in focus in a number of interviews and news stories, for instance Lighthouse, FMV, and WARA-PS.

2019 During 2019, the website had 10 507 page views (4 609 in 2018) and was regularly updated with news, publications, media coverage, a revisited brochure and new technical illustrations. The SMaRC Newsletter came out with three issues to 75+ subscribers. The SMaRC Day 2019 on January 17 gathered some thirty representatives from academy, government, military and industry. Helen Ågren, Sweden's Ambassador for the Ocean at the Ministry of Foreign Affairs, visited SMaRC on April 2. SMaRC had an exhibition stand or participated at Saab's annual meeting on April 11, the UDT conference in Stockholm on May 13-15, Donsö Shipping Meet on September 3-4, Sweden's Environmental Monitoring Days on September 24-25, and the conference Digitalize in Stockholm on November 26-27. Further, SMaRC was presented in eight media journals (paper and digital), for example the Rolling Stone, New York Times and Jane's International Defence Review, and in articles from Linköping University and the trade union Swedish Association of Professional Scientists.

2020 SMaRC Day 2020 on February 5 at the KTH Campus gathered about 80 representatives from industry, agencies, universities and others. During the poster and mingle session, the SMaRC research teams presented their work within underwater perception, autonomy, endurance and communication, and the research demonstrator robots SAM and LoLo were put on display. Rear Admiral Ewa Skoog Haslum, Chief of the Swedish Navy, visited SMaRC on April 23, 2020. A film about SMaRC was published by The Swedish Foundation for Strategic Research, SSF, and can be found on their and SMaRC's websites. SMaRC was presented in web articles on Kristineberg centre's and University of Gothenburg's web sites, and in media such as Nature News Paper as well as in Ångermanland, a local newspaper. Further, a movie made by Baltic Sea Centre was made at the Askö joint workshop and demonstration period 2020 (JWS&D).

9

SWOT Analysis

INTERNAL

STRENGTHS

- SMaRC combines a multitude of competencies and brings together large parts of Swedish expertise. The triple-helix cooperation is strong, which enables a unique opportunity to quickly and powerfully combine academic research and theory with practical applications.
- SMaRC gathers researchers developing the technical systems and sensors (KTH, FOI, GU) with researchers who use these systems and sensors (GU, SU) in some of the world's most inaccessible areas (e.g. Antarctica). Furthermore, SMaRC brings together competencies from industry and authorities with long experience of design, manufacturing and use of these systems in the field (Saab, MMT, FMV, FM).
- Through SMaRC's partners and their in-kind contributions, SMaRC has access to very advanced and expensive equipment as well as unique test facilities. This implies a great advantage for academia to directly collaborate and gain access to world-leading competence, resources and platforms such as Saab Dynamics, Saab Kockums, MMT, and FMV.
- SMaRC is currently Sweden's largest investment in research in maritime robotics and underwater technology.

WEAKNESSES

- Time and resources were initially spent on building up an organisation (management team) to establish SMaRC. The lack of organisation and established routines for cooperation between the parties have naturally meant that SMaRC has had to devote time and resources to building this from the start, which has been a weakness during the first three years. As of 2020, however, several parts of the organisation and governance of SMaRC (as also described in section 1) have been strengthened and we have now ensured management-support services at the level required to deliver the full potential of SMaRC.
- Even though there is a strong collaboration with the industry partners, the knowledge transfer from academia to industry and vice versa can be further improved.
- SMaRC addresses a large number of research challenges, which can be a weakness as this may not provide sufficient depth in the research to achieve ground-breaking research results. However, we deem the likelihood of this to be low.

POSITIVE

OPPORTUNITIES

- SMaRC sees great opportunities to continue development of research results into a commercialisation phase that already has a concrete use and benefit for the industry.
- The centre can contribute to creating priceworthy and robust underwater robots within the new areas of use-case such as environmental analysis, energy recovery and food production at sea.
- We have the opportunities to inform, educate and tell media and other external stakeholders what potential the oceans have together with autonomous underwater robots.
- We also see a great interest in collaborations with other partners. Through collaboration with external parties, there are great opportunities to also strengthen SMaRC financially through new applications.

THREATS

- Balancing openness and publications of research results against intellectual property interests and defence interests is a challenge that we deal with continuously in SMaRC.
- Demonstrations and experiments that we do in the field are often associated with risk. Partly in the form of high economic values in equipment and vessels and partly for involved personnel who may be exposed to situations they are not used to (e.g. doctoral students who are not used to being at sea may need to handle research equipment from a large ship).
- The global Covid-19 pandemic is also posing a threat due to high potential for extended lock-down periods, but will most likely affect the entire world for years to come. This will naturally also affect SMaRC and our possibilities for international collaborations, participation and organisation of workshops and conferences, as well as conducting the demonstrations of our milestones. We will continue to investigate virtual remedies where feasible, to reduce the long-term impact of such events.

NEGATIVE

EXTERNAL

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Appendix A: Capabilities

	Scenario								
	OP01	OP02	OP03	SEC01	SEC02	SEC03	ENV01	ENV02	ENV03
1. Navigation Capability to navigate safely in unknown and dynamically changing environments without access to surface while retaining a total navigation accuracy better than 10m.							•	•	
2. Payload deployment/retrieval Capability to deploy (and preferably retrieve) payloads to well defined positions and in typical ambient conditions from "Mother AUV".				•				•	•
3. AUV deployment/retrieval Capability to deploy and retrieve small AUVs from underwater garage, "Mother AUV" (preferably moving), ships, submarines, and piers (including park on the bottom).				•					
4. Swarm intelligence Capability to use collective swarm behaviour to, for instance, localise the source of pollutants, map the extension of a polluted area, create perimeter around an object of interest.					•				•
5. Precision manoeuvring Capability to manoeuvre safely, with precision, without entanglement, in an underwater environment with obstacles such as pillars, anchors, rigs, and similar.		•	•						
6. Mission adaptation/re-planning Capability to adapt and re-plan a mission for instance if an anomaly is detected, if mission profile and tasks are modified, or in case of emergency.		•	•		•	•	•	•	
7. Surveillance Capability to survey, pursue and gather data from fixed and moving targets with minimised risk of losing object.				•	•	•			
8. Communication Capability to perform optimised underwater communication and data transfer with for instance seafloor nodes, "Mother-AUV", and networks of other moving or static nodes/vehicles.				•	•	•	•	•	•
9. Operation in severe conditions Capability to robustly and with minimised risk operate in extremely dynamic and challenging environments with an underwater robot for close-range mapping.	•						•		
10. Long-range operation Capability to perform missions with a range of >1.000 km or 30 days at optimal speed and >400km at 5kn.				•				•	
11. Long-term operation Capability to perform long-term continuous operations in a predefined area and perform multiple missions: docking, transferring data, recharging and repeating mission.		•	•			•			
12. Pollutant detection Capability to detect pollutants on molecular level in the water column with an advanced sensor suite.									•
13. Accurate localisation Capability to accurately localise surrounding objects for operating in dynamic ocean conditions without GPS.	•			•			•		
14. Identification/classification Capability to autonomously, in real-time, accurately identify features and classify objects, both natural and made-made.	•	•				•			
15. Anomaly detection Capability to autonomously, in real-time, identify a deviation from a "normal state" and monitor and detect variations from a "normal state" in the underwater domain.		•			•	•			

Sub-project												Robot		
SP01	SP02	SP03	SP04	SP05	SP06	SP07	SP08	SP09	SP10	SP11	SP12	LoLo (SP13)	SAM (SP14)	Ran (SP15)
	•	•	•	•	•	•						•	•	•
•	•		•	•	•	•	•			•	•	•		
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Appendix B: SAB Governance Document

SMaRC Scientific Advisory Board (SAB) – Governing Document

Members

In the current mandate period (20170301 - 20200301) the SMaRC scientific advisory board (SAB) consists of Pr. João Sousa (chair of the SAB), head of LSTS at the Porto University¹, Pr. Martin Ludvigsen, NTNU Institutt for marin teknikk², Dr. Louise Newman University of Tasmania³, and Pr. Gia Destouni, Head of the Department of Physical Geography at Stockholm University⁴.

Motivation

Central to SMaRC is close cooperation with industry partners, international cooperation and excellent research. To succeed it is important to receive external evaluations giving feedback and suggestions for improvements. The SMaRC steering board appoints an external science advisory group comprised of leading national and international scientists with expertise to advise SMaRC on a wide range of aspects of maritime robotics research and impact areas thereof. The composition of the SAB is proposed to the SMaRC steering board by SMaRC's Management, after consultation with the SMaRC Project Group. The SMaRC steering board can also terminate an appointment as SAB member at any time if necessary. The mandate period for members of the external science advisory group is three years. Members can however serve more than one mandate period. This document is to ensure that the SAB can continue to fulfil its function as observing and advising body to SMaRC, as well as to ensure that SMaRC provides the best-possible conditions for the SAB to carry out this very important task.

History

In Feb 2017 SMaRC was granted funding from the Swedish Foundation for Strategic Research (SSF). The total funds granted from SSF were 75MSEK over an 8-year period with an opportunity for an additional 25MSEK provided that the half time evaluation (in 2020) is successful. SMaRC is further also funded by the partners (industry, government and academia) to a total amount exceeding 100MSEK of which about 40MSEK is cash and 60MSEK is in-kind support. The first SAB meeting was held as part of the SMaRC kick-off at the Sven Lovén Centre for Marine Sciences in Sept 2017. The first SAB report was received in Nov 2017 (Appendix A).

¹ <http://lsts.pt>

² <https://www.ntnu.no/ansatte/martin.ludvigsen>

³ <http://www.utas.edu.au/profiles/staff/imas/louise-newman>

⁴ <https://www.su.se/english/profiles/gdest-1.182913>

Central task

The external science advisory board's main tasks are:

- (i) To review strategic plans and directions, to inform SMaRC of its strengths and weaknesses, and to recommend future possibilities for development,
- (ii) To help increase SMaRC's contacts to international networks and research groups within the maritime robotics area, including academia, government, sponsors and the public when such opportunities arise,
- (iii) To increase the quality and international visibility of science and impact of SMaRC by providing constructive feedback to scientists, students and industry partners on the research.

Accomplishment of these tasks is suggested to be achieved through the following activities:

- March: The Management sends a status report (e.g. the SMaRC Annual report) documenting the annual progress of each research area and projects to the SAB, and responding to the recommendations made by the SAB in the previous annual report.
- May/June: SMaRC JWS&D days: It is suggested that each year, the SAB would attend the SMaRC Joint Workshop & Demonstration (JWS&D) days in May/June, and report on tasks (i) - (iii) described above directed to the Board and the Management of SMaRC. At the JWS&D
 - SAB participates and interacts with all SMaRC members.
 - Time is reserved for meetings between the SAB and SMaRC Steering Board, Management, Project Group, and PhD's during the SMaRC JWS&D days, to share advice and impressions orally.
- August: The SAB sends its written report to the SMaRC Management.

In order to fulfil their mandate, members of the SAB may obtain more information from the SMaRC Board or Management, and may – in agreement with them – visit SMaRC at times other than the SMaRC JWS&D days. Relevant additional information sent out at the beginning of each mandate period to the SAB includes the Strategic Plan of SMaRC and the SMaRC Communication Strategy. If updated revisions become available, these will be sent to the SAB immediately.

Annual SAB report

The SMaRC Management will send a template for the SAB report to the SAB along with the status report (in March), giving the SAB sufficient time to prepare for answers, reflection and discussion at the SMaRC JWS&D days (in May/June). The SAB chair person is responsible for ensuring its timely and proper completion, and for sending it to the SMaRC Management, who will share it with the SMaRC Board and with the Project Group, and finally make it publicly available on the SMaRC homepage. Therefore, sensitive recommendations or information should be discussed separately from the annual SAB report, e.g. in a confidential letter to the SMaRC Board and/or Management.

Appendix C: IPR Management Plan

Outline/first version of IPR management plan.

Phase/component	Description/Objective
1. Initiation -of projects, results, IPR and cooperations for commercial	<ul style="list-style-type: none"> - Enable needs driven generation of 'disruptive' knowledge and IP. - Decide on the best and prioritized research activities to launch to ensure relevance, potential for impact, feasibility etc.
Key activities <ul style="list-style-type: none"> - Project planning and proposals- templates to include components on need, novelty, value/impact, possible forms of IPR that could generated etc (responsible centre management) - Evaluation- decisions on projects to involve partners and include assessment of need/relevance and feasibility (responsible centre management) - Set-up of project organisations- inclusion of partners in projects, focus on demonstrators to facilitate cross-fertilization, integration of disciplines and partners (responsible centre management) 	
2. Capture and identification -of IPR in generated results.	<ul style="list-style-type: none"> - Identify potentially important and valuable IP assets
Key activities <ul style="list-style-type: none"> - Establishing simple process for results pre- publication screening (responsible centre management supported by KTH Innovation) - Regular structured IP reviews of project results- e.g. yearly intellectual asset inventories of projects to scan, find, describe and define IP assets (workshops facilitated by KTH Innovation or other support organization) - Training of researchers- basic training workshops on "basics of IPR", "how to spot ideas and your valuable IP assets" or similar (supported by KTH Innovation or other support organization) - Regular workshops and testing periods with industry to in structured way present results, enable early-on jointly identifying interesting results. 	
3. Evaluation - of identified IPR/results	<ul style="list-style-type: none"> - Initial evaluation of interesting results to determine if they have potential value and determine how to initially handle them.
Key activities <ul style="list-style-type: none"> - Initial feasibility analysis e.g. ownership/legal aspects, novelty/patentability and commercial potential (supported by KTH Innovation and use of SSF 3% funds for external experts) - Establishing simple process for results communication to industry to assess their input/interest. (responsible centre management) 	
4. Verification / Validation -of defined IPR with potential	<ul style="list-style-type: none"> - Ensure that there are market/industrial needs for and potential value in a specific result/technology and how it could be further developed and protected
Key activities <ul style="list-style-type: none"> - Planning and launch of stepwise verification to assess key aspects (facilitated by KTH Innovation, SFF funds for use of external experts) - Inclusion of results in demonstrators, involvement of partners and others in validation of value and plan e.g. through an innovation council/board. 	
5. Creation – of formal IPR	<ul style="list-style-type: none"> - Secure and protecting results/concepts/technologies through different forms of IPR e.g. patenting.
Key activities <ul style="list-style-type: none"> - Defining possible and suitable protection strategy (first IPR strategy) and possibly securing in the form of patents etc. (facilitated by KTH Innovation and use of external experts) 	
6. Commercialization /Monetization – of secured IPR	<ul style="list-style-type: none"> - Planning and development of business concepts to create business value and impact.
Key activities <ul style="list-style-type: none"> - Defining plan for commercial development and strategies (facilitated by KTH Innovation) - Financing – work to plan and actively secure for funding securing IPR over time and development of concept (outside centre) (facilitated by KTH Innovation) 	
Supporting IPR management	
7. Management / Governance –for management of IPR	<ul style="list-style-type: none"> - Determine the organization, policies, procedures, decision making, incentives etc that is needed for IPR management
Key activities <ul style="list-style-type: none"> - Defining organization and team for IPR- clear structure. - Draft basic processes and internal responsibilities, decision making in centre 	
8 Implementation of Agreement – for IPR relevant parts.	<ul style="list-style-type: none"> - Make sure to adhere to parts connected to the IPR management e.g. ownership, decisions on joint ownership, licenses etc..

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