Long-Endurance Green Energy Autonomous Surface Vehicle Control Architecture

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***Abstract*—This paper presents the system design and architecture of a wave-powered Autonomous Surface Vehicle (ASV). The proposed solution complies with the self-powering nature of the vehicle, ensuring long-duration operations in the open ocean. In our field-tested concept, the vehicle is equipped with the instruments and capabilities to deal with the environmental uncertainties, while serving as an in-situ data provider for oceanographers and biologists. Robustness to mission failure and a high degree of redundancy are achieved by allocating computational efforts and responsibilities to independent subsystems. A three-layered system subdivision facilitates the implementation of several capabilities involving solar energy harvesting, storage and distribution, radio communication, autonomous navigation, AIS-based collision avoidance and onboard autonomy to supervise both the mission execution and the scientific payload employment.**

***Index Terms*—Autonomous Surface Vehicle, System Architecture, System Design**

I. INTRODUCTION

This article focuses on the system architecture of a green-energy wave-propelled autonomous surface vehicle (ASV) which relies on solar energy for powering its scientific payload and support both navigation, control and communication. This system is specifically developed for the commercially available AutoNaut [1] (Fig. 1), chosen for its simplicity of operation and innovative propulsion system. Unlike common robotic platforms, this system is less constrained by energy limitation with respect to both propulsion and payload, ensuring long-duration missions without physical human intervention.

This work presents a control system architecture, entirely developed in academic environment, that is designed to meet the requirements of robustness, endurance and redundancy required to successfully accomplish long-duration operations in the open ocean. The architectural choices described revolve around the unique self-powering nature of the vehicle, that is both capable of transforming the energy induced by surface ocean waves into forward propulsion but also of harvesting the energy captured by solar panels. The proposed solution is modular and scalable and relies on off-the-shelf components to target science-driven mission profiles.

II. MOTIVATIONS

With the emphasis on the ocean as the primary sink for greenhouse gases, ocean science has become critical to the understanding of climate changes. Monitoring dynamic environmental changes is of extreme urgency and advancements in autonomous robotic systems can positively impact capabilities of ocean observation systems [2].

The lack of autonomous mobile platforms recording data continuously over long periods of time and in different areas of the globe, suggests the necessity to analyze oceanographic phenomena at spatio-temporal scales that are not approachable with current observation tools and methodologies, which often rely on traditional ship-based methods. These observations cause substantial release of CO_2, disturb the boundary layer significantly, are not continuous and therefore limited in scaling across space and time. Meso-scale variability can be best analyzed with semi-autonomous mobile platforms equipped with a suite of scientific payloads that can sample chlorophyll and biomass concentration, temperature, salinity, vertical current structure, sea surface height, turbulence etc.

To date, oceanic exploration and monitoring of the upper water column, driven by scientific hypothesis and by means of long-endurance robotic platforms, has already been demonstrated, e.g. [3], [4].

Several types of long-endurance, green-energy powered

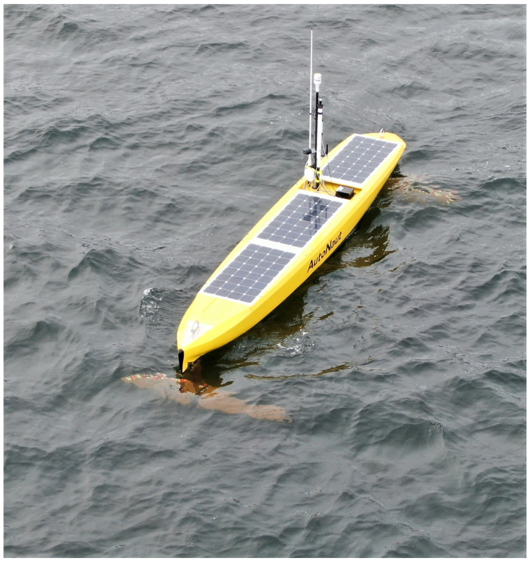


Fig. 1. Vehicle during operations in Trondheimsfjord.

surface vehicles are available on the market, e.g. Liquid Robotics WaveGlider [5], Offshore Sensing SailBuoy [3], AutoNaut [6], or L3 Technologies C-Enduro [7]. All show different architectural approaches, and find utility need in various types of operations. In the case of academic research where configuration of the vehicle to cover a wide range of different tasks is a requirement, an architecture that facilitates easy system customization is of high importance. However, to the authors' best knowledge, current literature lacks details on the design of a long-endurance surface vehicle, that could be easily modified towards research in oceans studies, marine biology, and control engineering.

This paper presents a custom system architecture, suitable for long-endurance green-energy powered surface vehicles. The presented architecture has been designed to cover various criteria of research operations. Moreover, it is implemented and tested onboard the AutoNaut.

The structure of this paper is as follows. Section III defines most important system design criteria. Section IV describes the AutoNaut platform. Section V presents the system architecture, whereas Section VI shows the energy budget. Sections VII, VIII, IX guides through design of the system control logic. Section X discusses the communication solutions that were adopted. The design validation is presented in Section XI. Section XII contains conclusion remarks and future work.

III. MAIN SYSTEM REQUIREMENTS

The proposed system's main focus is research activities conducted both in the Arctic and Atlantic waters and in Norwegian coastal waters. The environmental harshness of these regions and research applications result in a set of requirements that the presented system architecture needs to fulfill.

Research missions in the Arctic waters face different challenges. The use of classic research vessels usually implies significant constraints, such as limited number of onboard researchers, tight schedules due to high cost of operation, or non-negligible travel time to the point of interest. Moreover, human factors can not be neglected. Crew fatigue and seasickness can have a significant impact on missions results. Moreover, vessels powered by combustion engines have a particularly negative impact in the Arctic environment.

Two types of mission profiles are defined for the considered autonomous vehicle.

1) Long-duration polar region research: The vehicle is deployed using a Research Vessel in the polar region, where it should work continuously during polar-day time, and for at least two weeks continuously during polar night. The vehicle needs to be able to collect scientific data with re-configurable intervals, implying that communication is reduced to a global-coverage satellite network. Access to the vehicle is limited, therefore control system robustness is a key feature. Large volumes of sensor data can be accessed only using a local short-range radio, or WiFi, e.g. from a research vessel or Unmanned Aerial Vehicle (UAV).

2) Short-duration fjord operations: The vehicle is deployed from the shore (using a slip or pier crane), and performs multi-day missions in the fjord. This (mission) profile serves coastal research and supports vehicle development and testing. The vehicle is typically within the coverage of a high-speed cellular network. Access to the vehicle is possible, although may require additional assets. Quick access to both vehicle and sensor data is a key characteristics of this type of operation.

Taking these mission profiles into consideration, the design requirements of the vehicle are:

- Deployment and recovery: The vehicle should support deployment from a slip or by crane. Deployment should not require significant effort or put users at risk. The sea-bottom depth during launch should be as low as possible. The vehicle should also be tow-able using a support boat.
- Robustness: The system needs to be robust enough to avoid maintenance for several months. Mechanically that can be achieved by a sturdy design and a limited number of moving parts. Electronically, the system should be based on industrial grade components, including cables and connectors. Control-wise, the system should provide a well defined fallback system with redundant communication channels.
- Energy management: The energy management system should enable to plan and monitor energy consumption, as well as to harvest energy. The low-level system should allow to schedule when selected components are turned on and off.
- Communication: Three categories of communication links need to be covered. An near-real-time, low bandwidth, global coverage link to report vehicle health status of the vehicle and location, and an emergency manual control. A real-time, low bandwidth, long-range control of the vehicle, and detailed vehicle status and telemetry. A real-time, high bandwidth, short-range data link to collect sensors data. The mission scenario should define which links are active. Therefore, faster links with lower range should be able to cover functions of the slower, long-range links.
- Autonomy and control: The vehicle needs to be able to execute maneuvers, and its predicted trajectory needs to be computed taking into account environmental conditions such as sea currents or winds. The system needs to be able to handle current and future developments in control algorithms and autonomy. The control system should be compatible with the fleet of Unmanned Vehicles used at NTNU [8], [9], supporting a fully autonomous tasks allocation and multi-type, multi-vehicle cooperation in the future. The vehicle should also support manual control, especially for launch and recovery.
- Modularity and scalability: The control and sensors systems should not limit each others development and upgrades. The system should be modular, and each segment should support independent upgrades. Finally, the platform should be able to accommodate additional scientific

sensors in the future.

IV. VEHICLE OVERVIEW

In order to accomplish missions with the profiles described, the AutoNaut is equipped with a scientific payload that targets the environmental parameters of interest. The vehicle is provided with a propulsion system that entirely relies on sea surface waves [1]. Two pairs of spring-loaded submerged hydrofoils are connected at the bow and stern by two vertical struts. When a surface wave lifts the bow or the stern of the vehicle, the corresponding strut lifts the foils, which are subsequently pulled back by the spring generating a forward thrust. This self-propelling mechanism limits the speed achieved by the vessel during operations up to 3-4 knots. However, the platform is equipped with a small thruster that can be actuated by the collision avoidance algorithm to enable sharper maneuvers or whenever surface waves are too small to produce acceptable propulsion. The heading of the vessel is controlled by means of a rudder commanded by the navigation control unit, and can turn up to $\pm 45^\circ$ relative to its centered position.

The hull is divided into two main water-tight compartments, where batteries, computers and some sensors are hosted. However, most of the sensors needed for navigation and environmental data collection are placed outside the compartments (Fig. 2).

The scientific payload is described in Table I. Except for the Weather Station (Airmar 120WX) which is connected to the vehicle mast, all other sensors are placed on the submerged keel (Fig. 3).

V. ARCHITECTURE OVERVIEW

The proposed architecture, which is publicly available and documented in [10], equips the vehicle with autonomous communication and navigation control capabilities. This section discusses the design choices that have been made in order to provide the vessel with reliable navigation, control and communication tools. Tables II, III, IV and V list all the sensors and hardware units that support navigation control, communication and power management.

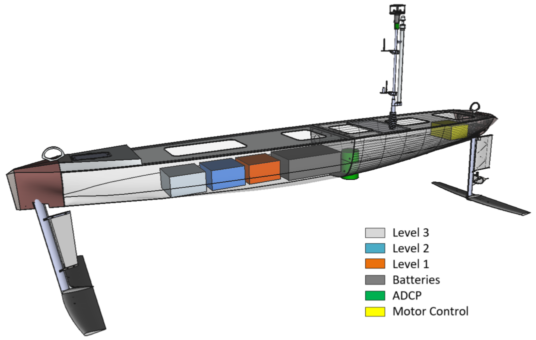


Fig. 2. Vehicle 3D model with hardware placement.

TABLE I
SCIENTIFIC PAYLOAD

Sensor	Information
Nortek Signature500 ADCP	Current profiles at up to 8 Hz sampling frequency.
Seabird CTD SBE49	Conductivity, temperature, and pressure of seawater.
ThelmaBiotel TBR700	Continuos tracking of tagged fishes.
Aanderaa Oxygen Optode 4835	Oxygen saturation and % saturation.
WET Labs ECO Puck Triplet	chlorophyll and FDOM fluorescence and red backscattering.
Airmar 120WX Weather Station	Wind, temperature and pressure.

TABLE II
NAVIGATION SENSORS

Sensor	Information
Vector V104 GPS Smart Antenna	Accurate Time, SOG and COG/heading.
Raymarine AIS650	Tracking information for collision avoidance
Airmar 120WX Weather Station[a]	Wind, temperature and pressure.
ADIS16485 IMU	Triaxial gyroscope and accelerometer data.
HMR3000 Digital Compass	Heading, pitch and roll outputs.
Echomax Radar Reflector	Active Radar Reflector
Navigation Light	Mast Navigation Light

[a] both used for navigation and environment analysis.

TABLE III
COMMUNICATION LINKS

Unit	Purpose
OWL VHF Radio	Long-range, low bandwidth radio transceiver.
MikroTik 4G/LTE Modem	4G/LTE Modem onboard the vehicle.
RockBLOCK+ Iridium	Satellite communication.

In our field-tested control system architecture, a layered subdivision of computation efforts and mission responsibilities provides a high degree of robustness and redundancy (Fig. 4). *Level 1* unit is the lowest-level component of the system, which

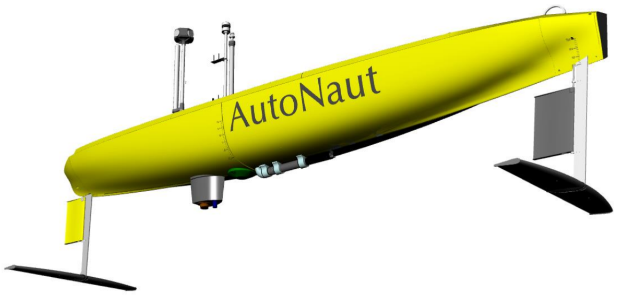


Fig. 3. Scientific Payload: ADCP, CTD, Optode4835 and ECO Puck on the keel; Weather Station on the mast with Navigation Light and Radar Reflector.

TABLE IV
POWER MANAGEMENT

Unit	Purpose
Victron BlueSolar MPPT Controller	Solar Panels - Battery charge controller
DRA1-MPDCD3-B	Solid State Relay
861SSR115-DD	Solid State Relay

TABLE V
COMPUTATIONAL UNITS

Unit	Purpose
Campbell Scientific CR6 Datalogger	Level 1: system monitoring, power distribution, fallback communication and autopilot.
BeagleBone Black	Level 2: advanced navigation, collision avoidance and system monitoring.
TS-7970	Level 3: scientific Payload Control Unit.
SenTiBoard	High-accuracy timing board.

also provides a fallback mechanism in case of failure in the higher-level units. It monitors the hardware and health status of the vehicle, autonomously commands fallback maneuvers, and manages power harvesting, storage and distribution. *Level 2* provides the vessel with advanced navigation capabilities, including a course-keeping autopilot and an AIS-based collision avoidance algorithm. *Level 3* controls the scientific payload depending on the mission profile.

The *Level 3* runs as a slave CPU, controlled by *Level 2*. Because of the slow-moving nature of the vehicle, *Level 3* is mostly in stand-by mode during navigation towards the mission area, saving power consumption. The multi-layered approach decreases the interdependencies of the design and facilitates easy integration of new functionalities. Also, it enables graceful degradation in low energy situations. As the only energy source for the onboard electronics is solar panels, situations where energy must be conserved might arise. In such cases *Level 3* (and *Level 2* in the worst-case scenario) can be turned off without losing safety-critical functions.

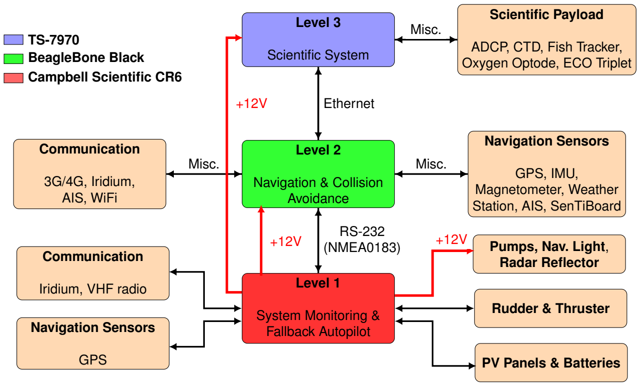


Fig. 4. System Architecture

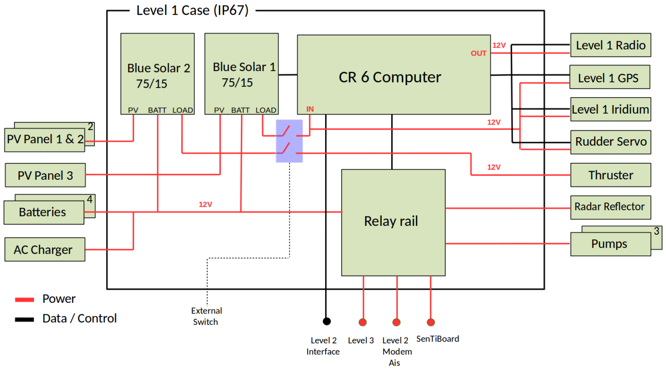


Fig. 5. *Level 1* Hardware Architecture

VI. ENERGY HARVESTING, STORAGE & DISTRIBUTION

The upper surface of the hull is covered with three Solbian SP 104 solar panels, whose maximum output power rating is 104W each. The onboard battery bank is made of four 12V 70Ah Lead Gel batteries, wired in parallel as most of the components require around 12V. In order to control the power produced by the panels, two Maximum Power Point Tracking (MPPT) controllers are chosen. These have built-in inverters and can step the voltage up or down prior to supplying the batteries. This is required as the solar panel output varies with the observed load impedance. Two step-down MPPT controllers is used in the power system. Panel 3, which is furthest from the mast, is connected to one controller because it is unlikely that the internal bypass diodes are activated due to shading, meaning that the panel output always will be higher than the required input voltage for the controller. The panels near the mast which are likely subject to partial shading, are connected in series to another step-down MPPT controller. The chargers input will thus always be higher than the minimum voltage requirement, even if both arrays in one panel are bypassed. The units selected are Victron BlueSolar MPPT 75/15.

Fig. 5 provides an overview of the structural design of the power management system implemented into *Level 1* unit housing. An external toggle switch allows to disconnect the load power line that provides power to all components. This means that when a mission is completed and the user turns off the computers and sensors, the batteries can still be recharged by the solar panels through the controllers. Fig. 5 also shows how the power is distributed to the whole system. The CR6 Campbell Scientific Datalogger, compass GPS, Iridium and Rudder Servo are directly connected to the load port of BlueSolar 1, through the switch. However, they are controlled by the CR6. *Level 2*, *Level 3*, AIS transceiver, 4G/LTE Modem, SentiBoard timing unit, Radar Reflector and Pumps are instead powered through solid state relays that are digitally controlled by CR6 GPIOs. The OWL VHF radio is the only component being directly powered by a 12V output port of the CR6. Historic data for solar radiation during fall in Trondheim

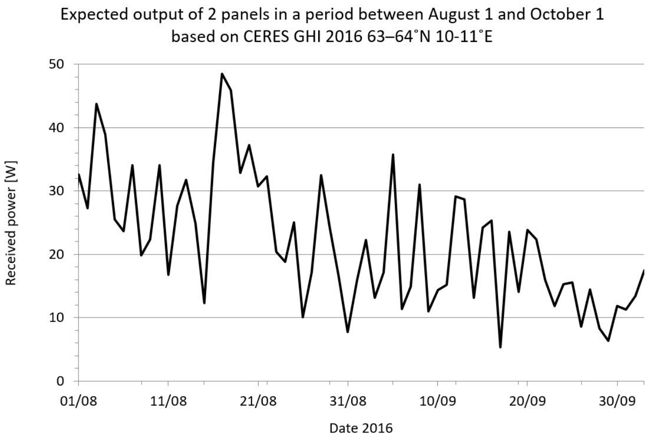


Fig. 6. Expected power on two solar panels through a period between August and September in Trondheim, based on historic data.

(Norway), reduced by the solar panel efficiency factor, gives an insight about the expected amount of energy the panels should produce (Fig. 6). An estimate of the power consumption of the vehicle was defined according to datasheets of onboard, considering the expected time of use for each device mentioned in Tables I, II, III, IV and V. *Level 1* and *Level 2* are estimated to consume approximately 20W, assuming 14V system voltage (fully charged lead-acid batteries). The maximum average current consumption is estimated to be around 1.4A. The consumption of *Level 3* is dependent on sampling frequency of the scientific payload. Based on sampling routine suggested by biologists and oceanographers, the average constant power requirement for *Level 3* is estimated to reach 21W.

VII. SYSTEM MONITORING & FALLBACK AUTOPILOT

Level 1 subsystem is responsible for monitoring the health status of the whole system. This unit observes the operation of all sensors and subsystems and is able to identify anomalies. These can be related to powering issues, e.g. sudden decrease of supplied current or increase of consumed energy, or to communication issues. In case an anomaly is detected, a dedicated routine will try to provide a solution for it (e.g. restarting) and will open a communication link and notify the operators about the failure. During development of the system, it was sought to keep complexity as low as possible while still meeting the system requirements listed in Table VI, as described in [11].

A. Behavioural Design

Level 1 works as a state machine, switching operation mode when a failure is detected or when the operators need to manually control the vehicle (Fig. 7). The transition from *normal* or *fallback* to *manual* only takes place if the operator sends a dedicated command to the system. If the connection is lost between the remote operator and the USV when in manual mode, the USV will enter fallback mode. Also, fallback state will be entered automatically if *Level 1* does not receive commands from *Level 2*. Note that a warning will be sent to the operator, over Iridium, in the event of this transition. The transition from *fallback* to *normal* is also automatic and occurs as soon as *Level 1* receives a valid command from *Level 2*. During *normal* operations, *Level 1* periodically receives rudder (and, if needed, thruster) commands from the heading controller running on *Level 2*. Communication happens according to NMEA0183 protocol at RS-232 voltage levels. The communication standard was chosen because of low power consumption, low bandwidth requirement and human-readable formats. If the CR6 computer does not receive a verified control signal from the *Level 2* computer within a user-defined amount of time, it will assume that *Level 2* has failed and therefore switch to *fallback* state. When the system enters fallback mode, three different operating modes can be selected depending on the circumstances:

TABLE VI
L1 Requirements

System Requirement Description	Subsystem Requirements
Onboard Power	12 ± 2V output Load power monitoring PV panel power monitoring Stored energy estimation Disabling device power In-port charging
Error Handling	Device error monitoring Level 2 failure monitoring Level 3 failure monitoring Sensors failure monitoring Leak detection Bilge pumps control
Control of Operation Mode	Remote Control Interface protocol Manual Control Mode Level 2 Control Mode Fallback Autopilot Mode
Manual Control	Remote Control Interface protocol Rudder Angle Control Thruster Control Disabling of Power for Devices
Remote Data & Communication	Iridium Communication Link VHF Radio Communication Link 4G/LTE Communication Link Output System Energy Parameters Output Position, COG and SOG Output Leak and Error Status

- *Fallback mode 0*: Sets the rudder angle to zero and thruster to 0.
- *Fallback mode 1*: Sets the rudder angle to 45 and the thruster to 0.
- *Fallback mode 2*: Activates a course-keeping autopilot that reads the course over ground (COG) measurement from the GPS and computes the rudder angle that makes the vehicle keep a desired course.

However, *Level 1* periodically checks for messages received from the operators over VHF radio or Iridium. If a message is received by the onboard transceiver, the state machine automatically switches to *manual*, as shown in Fig. 7, prioritizing the operator's directives. Manual control is needed, for

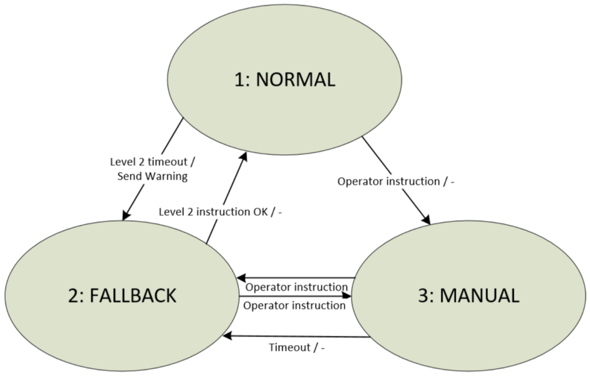


Fig. 7. *Level 1* State Diagram.

example, to directly maneuver the vehicle inside the harbor. As already anticipated, *Level 1* also monitors the battery voltage, solar cell power and load power. It obtains navigation data from GPS and checks for leaks. For leak detection, the onboard bilge pumps are used. Since the motors are inductive loads, the current will change based on their resistance. Pumps are periodically activated, and based on the increase in current, the system is able to detect if water is being pumped.

B. Software Implementation

The choice of Campbell Scientific CR6 computer to fulfill the requirements proposed for *Level 1* is due to its proven reliability in long-term monitoring experiments in harsh environments [12], [13]. The Campbell Scientific CR6 has a Renesas RX63N processor with a clock rate of 100 MHz and has sixteen general I/O pins and dedicated hardware for supporting numerous communication protocols [14]. The CR6 was also chosen due to the need of multiple I/O ports and a fast CPU. All the functionalities of *Level 1* described so far are implemented by means of the PC400 Datalogger Support Software and CR Basic Editor. To support communication over VHF Radio and provide a human-readable GUI for operators on shore, a Java application was developed. Fig. 10 shows how the operator is able of manually command the rudder and thruster of the vessel. Sensors and other units can be manually turned on and off and the fallback behaviour can be chosen and communicated to the vehicle.

VIII. ADVANCED NAVIGATION & COLLISION AVOIDANCE

The *Level 2* subsystem implements advanced navigation and collision avoidance capabilities. It is powered through a dedicated solid state relay in the *Level 1* casing that provides 12V. This voltage is then regulated to match the input requirements for some of the components of *Level 2* that work at 5V (Fig. 8). The embedded computer chosen for this subsystem is a BeagleBone Black, provided with a 1GHz ARM-based CPU and two 46 pin headers that enable communication with a wide range of sensors and other hardware components. During normal operations, *Level 2* acquires navigation data from GPS, magnetometer, IMU and Weather Station. This information is used to determine both the current state of the vehicle (heading, course over ground (COG), speed over ground (SOG), location) and the state of the sea (waves amplitude, frequency and direction, wind speed and direction). A high-level autopilot is implemented in order to govern the course and the speed of the vehicle by observing the waves' direction and height. Plans can be defined by the operator on shore and dispatched over 4G/LTE or Iridium to the onboard unit (Fig. 9). A typical mission plan can be made of a single waypoint or of a more complex sequence of waypoints, e.g. a survey plan of an area. When the vehicle operates in remote areas, communication is sporadic and onshore operators may not have the same situational awareness of the environment as the vehicle. In this case, a mission plan dispatched from shore may be a list of high-level goals including target areas and specific data to be collected and sent to shore. An onboard decision-making system supports the generation of the navigation plan, based on in-situ measurements and sea-state estimation. T-REX is an execution layer designed with goal-driven mission planning in mind [15], [16]. T-REX dictates the execution of plans and supports fast re-planning of the mission, providing a high degree of responsiveness to those environmental changes that may cause the failure of the mission. A sea-state estimator receives environmental data from the weather station (wind intensity and direction, temperature, pressure) and heave acceleration from the IMU and computes an estimation of the current state of the environment. Once the plan is refined onboard the vehicle, the desired course is computed according to the chosen navigation law. *Line-of-sight* is preferred, due to its simple implementation. A PID *course controller* reads the current course provided by the GPS and computes the rudder angle that allows the vehicle to keep the desired course to the target waypoint.

A. Collision Avoidance Algorithm

The collision avoidance algorithm involves a continuous monitoring of the area in which the vehicle is navigating. A monitoring radius around the vessel is defined and navigation data of nearby vehicles equipped with AIS, are provided by the transceiver. For the ASV to obey the rules-of-traffic when encountering other vehicles and execute the correct and pre-

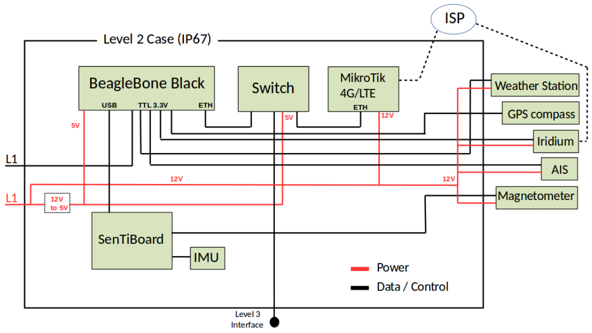


Fig. 8. *Level 2* Hardware Architecture.

dictable actions in hazardous situations, the algorithm needs to be COLREGS compliant. Based on the information provided by the onboard AIS transceiver, the algorithm searches for COLREGS compliant and collision-free trajectories through a series of predictive simulations with a finite set of offsets to the nominal course. The offset associated with the lowest cost, while producing a collision-free and COLREGS compliant trajectory, is selected as the new modified course reference, and is passed on to the autopilot. When the original desired trajectory no longer contains any potential collision, the ASV would return to the desired nominal path and proceed towards the target destination. If no obstacle is present in the vicinity of the vehicle, no deviation is applied to desired course and speed. The algorithm is described in detail in [17], [18] and [19].

B. Software Implementation

The software employed in this subsystem is an open-source toolchain developed by the Underwater System and Technology Laboratory (LSTS). The toolchain supports networked vehicles systems constituted by human operators, heterogeneous autonomous vehicles and sensors [20]. The software toolchain is primarily composed of the onshore mission control software Neptus, the onboard software Dune, and IMC, a communication protocol. The toolchain also uses its own operating system (GLUED), a minimal Linux distribution targeted at embedded systems. Operators on shore have complete control over the mission through Neptus and are able to customize the mission plan visually as shown in Fig. 10.

IX. SCIENTIFIC PAYLOAD

The *Level 3* subsystem is responsible for controlling the scientific payload according to the mission plan. During navigation to the survey site, this unit is meant to be turned off in order to save energy. When the target area is reached, *Level 2* communicates to *Level 1* the need to turn on the scientific unit. A plan that involves commanding the scientific payload is either manually built by the operators and dispatched to *Level 2* over 4G/LTE or Iridium, or autonomously synthesized onboard the vehicle. Plans involving the control of the scientific payload are synthesized in *Level 2*, where decision-making techniques deduce mission plans while reasoning on resources, time constraints, environment changes and operational risk. This functionality will support the mission execution when the vehicle is exploring remote areas and communication to shore happens to be sporadic and expensive.

The master-slave relation between *Level 2* (master) and *Level 3* (slave) further explained with the following routine example.

1) based on the chosen navigation law, the master autopilot computes rudder commands that allow the vessel to reach the area of interest described by the operator plan - the slave unit is turned off.
2) once the target area is reached, the slave is turned on and a plan is communicated by the master to the slave.
3) the slave executes the plan and locally stores data sampled by the sensors.
4) data are then compressed, packed and transferred to the master.
5) the master communicates the outcome of the mission to the operator, sends the data and turns off the scientific subsystem.

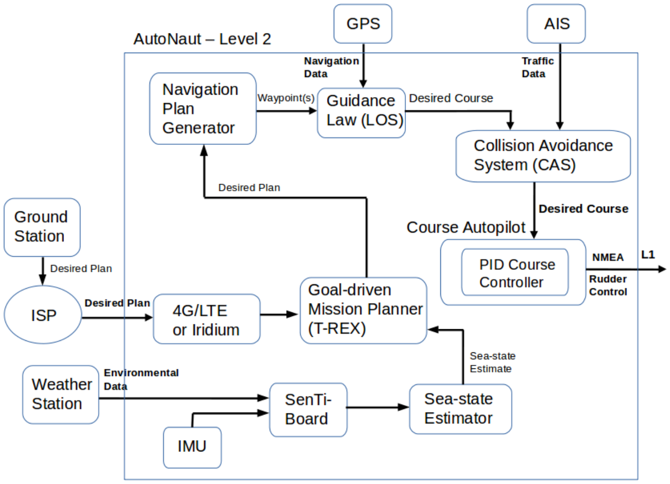
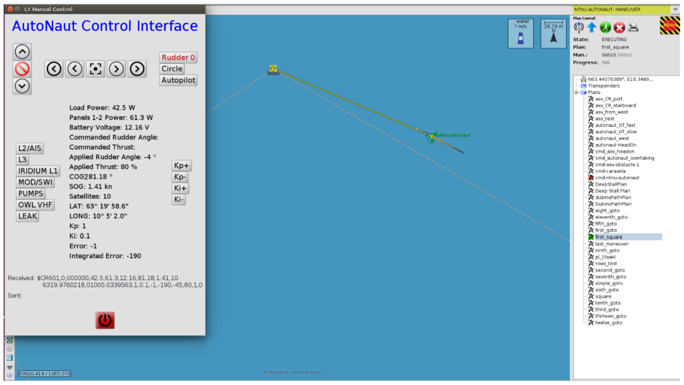


Fig. 9. *Level 2* Software Functionality.



Load Power: 42.5 W
Panels 1-2 Power: 61.3 W
Battery Voltage: 12.16 V
Commanded Rudder Angle:
Commanded Thrust:
Applied Rudder Angle: -4 °
Applied Thrust: 80 %
COG281.18 °
SOG: 1.41 kn
Satellites: 10
LAT: 63° 19' 58.6"
LONG: 10° 5' 2.0"
Kp: 1
Ki: 0.1
Error: -1
Integrated Error: -190

Received: $CR601,0,000000,42.5,61.3,12.16,81.18,1.41,10
6319.9760218,01005.0339563,1,0.1,-1,-190,-45,80,1,0
Sent:

State: EXECUTING
Plan: first_square
Man.: Goto3 (Goto)
Progress: N/A

Fig. 10. Onshore mission control center (Neptus).

X. COMMUNICATION LINKS

The vehicle is provided with four different communication links. Depending on the mission, the operator can communicate with the vehicle over 4G/LTE, Iridium or VHF radio (Fig. 11). Both *Level 1* and *Level 2* have access to separate Iridium transceivers.

A. 4G/LTE Communication

Communication over Internet allows the users on shore to have a full live stream of the mission. Onboard the vehicle a 4G/LTE modem (MikroTik) connects to Internet through a dedicated antenna on the mast. Every five minutes a program internal to the modem reports the modem IP to a dynamic DNS remote service. The modem implements port forwarding and NAT, enabling communication between operators and the BeagleBone Black in both directions, through the router itself. The local network is therefore always accessible via the same URL, no matter the IP provided by the internet service provider. An ethernet switch allows the inclusion of *Level 3* in the local network (Fig. 8). The operators are able to closely observe and control *Level 2* and *Level 3* via the SSH protocol. As discussed in VIII-B, the communication protocol (IMC) allows different nodes to share the same message formatting. In order to enable a full transmission of the messages payload from one node to another (in our case, the operators and the vehicle), a dedicated proxy is used. *IMCProxy* bridges IMC networks over Internet. This is achieved through a centralized proxy server that receives IMC messages and forwards them to other connected nodes (Fig. 12). For missions close to the coast, where signal coverage is strong, this communication link is preferred due to its flexibility.

B. Iridium Communication

The vessel is equipped with two separate Iridium Rockblock+ units that host an Iridium 9602 transceiver, an antenna and a voltage regulator. As shown in Fig. 4, both *Level 1* and *Level 2* can send a receive messages over satellite. This communication link supports the mission when 4G/LTE coverage is absent and involves less mission flexibility and higher costs.

Level 1 periodically sends a message reporting the overall state of the system: time and location, power settings, battery voltage, consumed and produced power. The operator is therefore able to communicate changes in the power settings of the vehicle and restart sensors and components.

The Rockblock+ unit connected to *Level 2* is instead used to communicate new or modified plans to the onboard software (Dune). The vehicle acknowledges the reception of the plan and later its outcome. This solution has a limited bandwidth and is therefore only suitable for simple control monitoring or tracking applications. The maximum package sizes are 340 bytes for sending and 270 bytes for receiving. Although the latency is typically a few seconds, it may increase to up to a minute or more depending on the remoteness of the area and the available satellites.

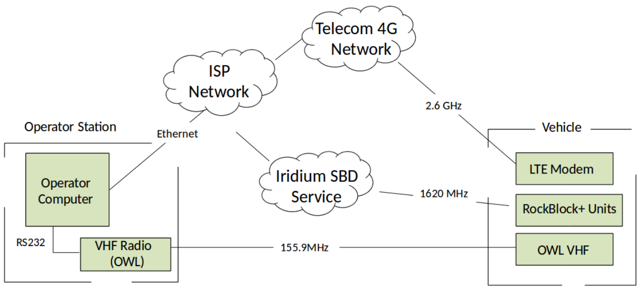


Fig. 11. Communication links.

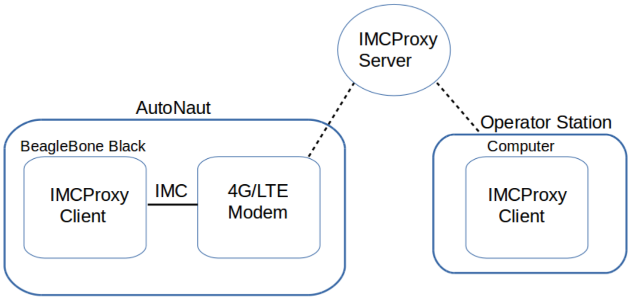


Fig. 12. IMC networks communicating.

C. VHF Radio Communication

Onboard the vehicle, an OWL VHF radio transceiver allows efficient point-to-point communication between the operators and *Level 1*. It supports a large variety of modulation types and encoding, that can be configured through a serial port. A Java GUI (Fig. 10) enables manual control and direct monitoring of the vehicle, over VHF. During a mission, this link is turned off in order to save energy. It is however turned on when manual control of the vehicle is needed. An automatic routine enables the radio whenever a fault is detected. The radio transmits the location and power settings, allowing the operators to find the vehicle and manually control it to shore.

A passive duplexer allows the OWL VHF radio to share one antenna with the AIS. Unlike an active splitter, the duplexer has a notch filter in each port that attenuates the frequency used by the other port. This means that both radios can always transmit without hearing each other and everything is sent out on the antenna. The filters are tuned to specific frequencies, so the radios cannot change frequency. The selected cut-off frequency of the AIS port is 162MHz (center of AIS frequencies 161,975MHz and 162,025MHz) and 155,9MHz for the VHF radio.

XI. ARCHITECTURE VALIDATION

The proposed architecture has been validated through several field trials in the Trondheimsfjord (Trondheim, Norway). The missions conducted so far aimed at testing the correct functioning of *Level 1* and *Level 2* subsystem. This involved monitoring of the onboard energy balance of the vehicle, manual control and autonomous waypoint navigation. Implicitly, all three communication links were successfully tested.

A. Power System Validation

Based on the considerations anticipated in section VI, a 24-hours long dataset was acquired on September 7, 2019 in Trondheim. Figure 13 shows that the power harvested by two solar panels properly fits within the margins defined by historic data (Fig. 6). Figure 14 shows a 24-hours system run. It can be observed that measured current consumption of *Level 1* and *Level 2* is below the estimated value of 1.4A, based on maximum components consumption and mentioned in section VI.

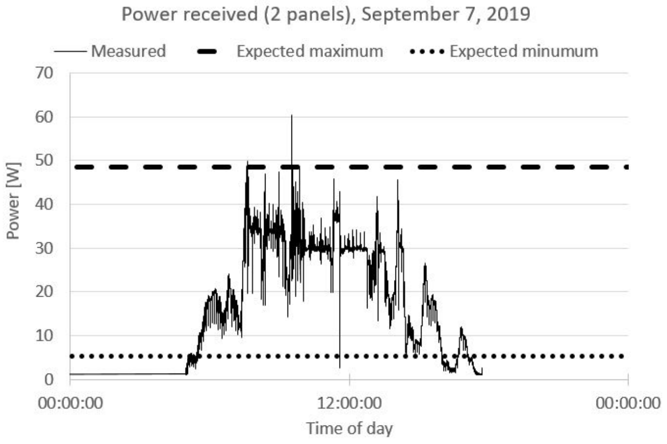


Fig. 13. Power generated by two solar panels on September 7, 2019 in Trondheim.

Graphs showing the expected remaining onboard energy for Trondheim and Svalbard areas, where the vehicle is expected to operate mostly, are presented in Fig. 15 and Fig. 16. Graphs are based on expected power consumption of all three subsystems, and the historic data of solar irradiance in these regions. The graphs give information about the remaining energy stored in the onboard battery bank of the vehicle during a long-term mission. By evaluating both the power produced by solar panels and that consumed by the system, including *Level 1 & 2*, the graphs show a higher energy efficiency than the estimated values.

B. Navigation Control Validation

Once *Level 1* proved to work properly, advanced navigation and collision avoidance were tested. Fig. 17 shows a simple *goto* mission, where the vehicle navigates towards a destination target from the harbor. The line-of-sight navigation law computes the desired course for the course-keeping autopilot. Moreover, Fig. 18 shows a route of consisting of five waypoints executed by the vehicle close to shore. The completion of this mission took around 76 minutes and the vehicle average speed was 0.8m/s. The navigation plans was defined on shore via Neptus GUI and dispatched over Internet to the vehicle. On shore, the mission was observed in Neptus that periodically received real-time navigation and power management data.

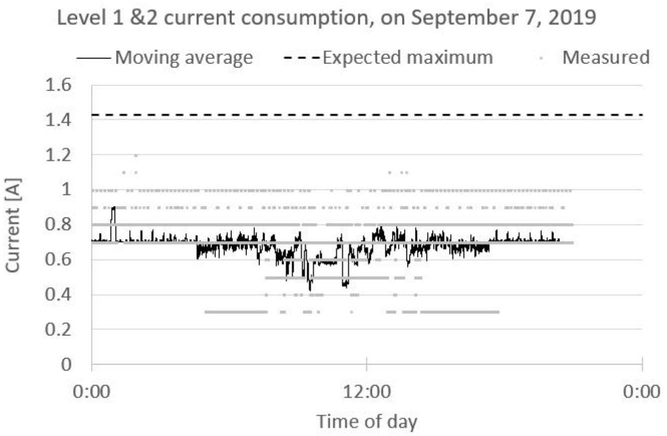


Fig. 14. Current consumption by *Level 1* and *Level 2* on September 7, 2019

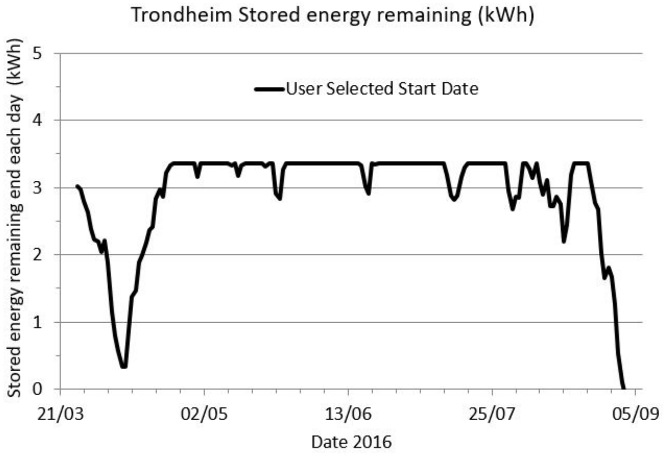


Fig. 15. Expected onboard stored energy based on data from 2016 in Trondheim.

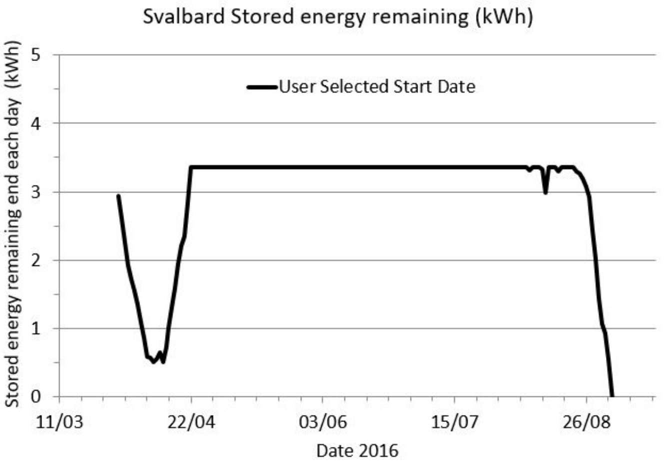


Fig. 16. Expected on-board-stored energy based on data from 2016 on Svalbard

XII. CONCLUSIONS & FUTURE WORK

In this article we presented the system architecture design of an autonomous surface vehicle that targets long-duration missions in the open ocean. The design choices were motivated keeping in mind the concepts of operation and the mission profiles stated in section III standing beyond the choice of the vehicle. Through the validation of the proposed architecture, we aim at providing scientists a tool to further extend the concept of marine observation and monitoring. Our intention is to leverage current technological efforts towards building a persistent observational capability, in order to better observe and understand those environmental oceanic phenomena that evolve at spatio-temporal scales not approachable with current

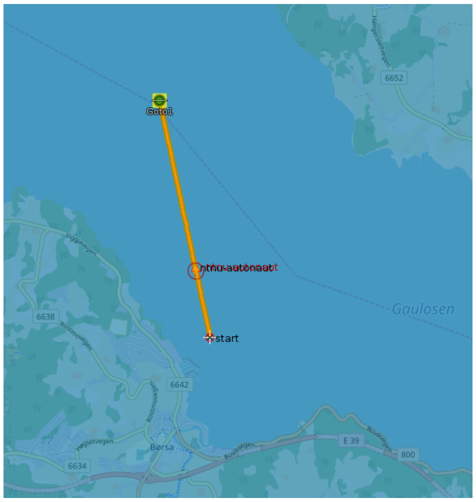


Fig. 17. Autonomous navigation towards a target location.

instrumentation.

Future work point in the direction of onboard, goal-driven mission planning. To date, the literature already presents systems of extensive operational capability with networked heterogeneous assets for upper water-exploration driven by scientific hypotheses. Moreover, the vehicle will need to autonomously synthesize its own short-term mission goals onboard, without relying on support from shore, reasoning on available resources and its perception of the environmental conditions.

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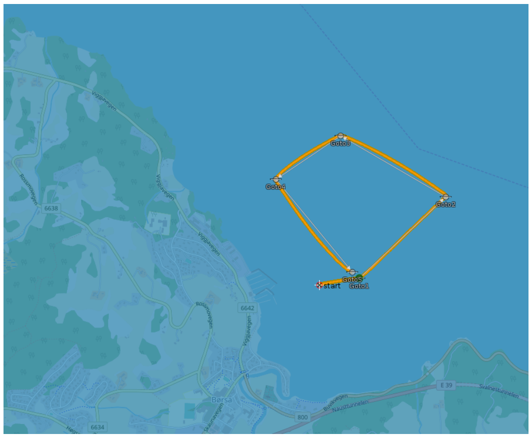

Fig. 18. Autonomous survey of five waypoints.

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