Proceedings of the ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering
OMAE 2015
May 31-June 5, 2015, St. John's, Newfoundland, Canada

OMAE 2015-41620

APPLICABILITY OF CURRENT REMOTELY OPERATED VEHICLE STANDARDS AND GUIDELINES TO AUTONOMOUS SUBSEA IMR OPERATIONS

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ABSTRACT

This paper employs a combination of literature review and case study methodology to assess the gap between current remotely operated vehicle (ROV) standards and future autonomous IMR operation requirements. With advent of autonomous subsea and underwater vehicle systems, current ROV standards and guidelines may not offer the same benefit in designing and setting guidelines for safe autonomous operations. The reasons for this claim are two-fold. Firstly, the literature review shows that existing requirements in the ROV standards lack specifications related to autonomous subsea interventions. Secondly, the results from the case study demonstrates existence of knowledge and technology gaps, which pose challenges in development of future autonomous IMR operations.

INTRODUCTION

In recent years, the amount of subsea oil and gas installations have increased rapidly. Industry estimates state existence of over 4000 functional subsea oil and gas installations worldwide [1]. Maintaining production from these installation is the key goal of subsea operators around the world. However, similar to other man-made systems, subsea systems are susceptible to failure during their useful-life. Failures in such systems can result in production losses, which add on to field operating costs. The way to restore a faulty or failed susbea system is by intervening i.e. through subsea intervention. With the increase in number of subsea installations, demand for subsea interventions are also estimated to increase [1]. Subsea intervention, maintenance, and repair (IMR) operations can potentially provide cost benefits if carried out safely and efficiently.

Remotely operated vehicles (ROVs) are key enablers to install, operate, and maintain oil and gas, fisheries, and marine infrastructures. In the subsea oil and gas industry, applications of ROVs range from simple observational diving assistance

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to complicated heavy subsea interventions. With advances in technology, operational capabilities of different ROV classes have increased in the last decade [2]. Standards and guidelines such as EN ISO 13628-part 8, ISO 13628-part 9, API 17H, NORSOK U-102, IMCA R 004, IMCA R 005, and IMCA R 018 have spearheaded application of safe design and operational principles of ROVs for subsea interventions [3–9].

The Norwegian oil and gas industry continues to focus on optimizing subsea IMR activities. The industry together with the scientific community currently envision a prospective solution of developing underwater vehicles capable of autonomous operations with limited or no operator control. Subsea factories in the future will also create need for autonomous IMR operations. Intervention systems operating in subsea factories need capabilities to maintain and repair subsea systems autonomously thereby maintaining production uptime and reducing cost of intervention.

Demonstrations of underwater vehicles capable of performing autonomous IMR operations are steadily increasing with added functionalities [10–18]. Research projects are experimenting with manipulator arms installed on AUVs to perform IMR operations and have been successful in their early trials [19, 20]. *DeepStar project* is a joint industry project in Houston, which is currently working on standardizing AUV interfaces [21]. [22] highlights that hazards associated with use of autonomous systems vary depending on different environmental scenarios. Similarly, functional requirements differ when autonomy is introduced into existing technical systems, as suggested by [23]. It is vital to get an overview of current standards specifying functional and operational requirements of ROVs to determine to which extent autonomous functionality already is covered. This will contribute to highlighting any knowledge gap that may hinder the development and adoption of autonomous IMR operations in the industry.

The main objective of this paper is to provide an overview of existing ROV standards and perform a gap analysis related to autonomous IMR operation capability. A subsea intervention operation is used as a case study to demonstrate the gaps.

This paper is organized as follows: the next section provides a review of international ROV standards/codes and standards describing autonomy in underwater vehicles. A subsea intervention case study is presented in the succeeding section. A discussion on the observations from the review and case study is followed by conclusion and scope for future work.

ROV STANDARDS

Fig. 1 illustrates the collection of international ROV standards reviewed in this paper. Tab. 1 provides overview of the requirements in current international standards. Symbol ✓ signifies the requirements are specified in the respective standard/code while, symbol ✕ signifies absence of corresponding requirements.

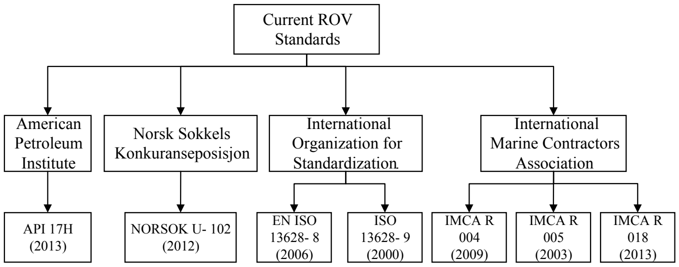

FIGURE 1. OVERVIEW OF CURRENT ROV STANDARDS

EN ISO 13628-8: 2002 (E)

The International Organization for Standardization (ISO) is the author of ROV specific standard ISO 13628- part 8. The European Committee for Standardization (CEN) adopted the standard in 2006 and designated EN ISO 13628-8 as a national standard. Currently, the standard is applicable in twenty-nine countries within Europe [3].

Guidelines on intervention philosophy and functional requirements for ROV application in the petroleum industry are described in the standard. Five standard ROV intervention configurations are explained; ROV intervention with manipulators, a manipulator arm, tool deployment unit, dual down line method, and tool skids or frames. For each configuration, the standard highlights general design and operational considerations. The standard provides guidelines towards subsea facility design in relation to fail-safe design, damage potential of subsea structures, load reaction of subsea structure, interface minimization between the ROV and subsea structures, position control of the ROV, and ROV access requirements.

The ROV access requirements are further divided into externally located interfaces, external boundary penetration, and internally located interfaces. The internally located ROV interfaces on subsea structures are required to consider width of access, height of access, and vertical access limits. Conceptual design considerations address assessment of requirements, failure mode identification, method of intervention, frequency of intervention, and use of standard tools. Loading forces exerted on the subsea system and the ROV are also required to be considered namely, the design for loading, forces exerted by tools, sea water currents, and collision with unprotected subsea facilities.

ROV design involves developing desired features related to visual aids on the ROV, recommendations on color codes on structures, requirements on anti-fouling, parking locations of the ROV, use of guide cones and guideposts, orientation of the subsea structure, and protection of valve steps against excessive torquing. In contrast, snagging of umbilicals with subsea struc-

TABLE 1. OVERVIEW OF ASPECTS IN INDUSTRY ROV STANDARDS

Aspects	**ISO 13628-8**	**ISO 13628-9**	**API 17H**	**NORSOK U-102**	**IMCA R 004**	**IMCA R 005**	**IMCA R 018**
Design	✓	✓	✓	✓	×	×	×
Materials	✓	✓	✓	×	×	×	×
ROV classification	×	×	×	✓	✓	×	✓
Type of vessel	×	✓	✓	×	✓	×	✓
Life cycle cost	×	✓	✓	×	×	×	×
Type of intervention	✓	×	✓	×	✓	×	×
Launch and recovery system (LARS)	×	✓	✓	✓	✓	×	✓
Tether management system	×	✓	×	✓	✓	×	✓
ROV parking	✓	×	×	✓	✓	×	✓
ROV control room	×	×	×	✓	✓	×	✓
Subsea interfaces	✓	✓	✓	✓	×	×	×
Subsea equipment marking	✓	×	✓	×	×	×	×
Operations	✓	✓	✓	✓	✓	✓	×
ROV access	✓	×	✓	×	×	×	×
ROV docking (for stabilization)	✓	×	✓	×	×	×	×
Power (electric and hydraulic)	×	✓	✓	✓	×	×	✓
Handling systems	×	✓	✓	✓	✓	×	✓
Human machine interface	✓	×	×	✓	✓	×	×
Intervention crew	×	×	×	✓	✓	✓	×
Personnel communication	×	×	×	✓	✓	×	✓
Crew training	×	×	×	✓	✓	✓	×
Organization responsibilities	×	×	×	✓	✓	✓	×
ROV tooling	✓	✓	✓	×	✓	×	×
Risk assessment	✓	✓	×	✓	✓	✓	✓
Emergency recovery	×	×	×	×	×	×	✓
Environment	×	✓	✓	×	✓	×	✓
Working temperatures	×	✓	×	×	✓	×	×
Seabed characteristics	✓	✓	×	×	✓	×	×
Documentation	✓	✓	✓	✓	✓	×	×
Navigation	×	×	×	×	✓	×	×
Communication (ICT)	×	×	×	×	×	×	✓
Umbilicals	×	×	×	✓	✓	×	×
Certification	×	✓	×	✓	✓	×	×
Testing	×	✓	✓	✓	✓	✓	×
Condition monitoring	×	×	×	✓	×	×	×
Maintenance	×	×	×	✓	✓	✓	×
Spare part strategy	×	×	×	✓	✓	×	×

tures, size of the subsea valve, orientation of levers, hidden indicators from ROV point of view and low operating heights are undesirable ROV design features. To ensure safe ROV interfaces with the subsea systems, EN ISO 13628-8 provides a comprehensive checklist on ROV interface requirements for the subsea structures. Design of structures, such as subsea trees, manifolds, subsea valves and chokes, control modules, multiphase meters, high integrity pressure protection systems (HIPPS), and umbilical jumpers should satisfy the requirements. Operational limitations, such as access requirements for certain operations need consideration. The human machine interface provides visual cues to the ROV operator. Requirements to design indicator systems, which help the operator to easily process the information, are provided in the standard.

Material selection of the subsea interface is specified in relation to the yield stress, ultimate tensile strength, fatigue, internal wear and tear due to frequent use, corrosion of interface, and marine fouling of the material. Documentation requirements on equipment design, testing and information feedback in design, testing and installation phases are recommended to be maintained. The standard concludes with set of ROV interfaces, as shown in Tab. 2.

ISO 13628-9: 2000 (E)

Part 9 of the ISO 13628 standard describes functional requirements and recommendations for remotely operated tool (ROT) systems interfacing with subsea structures. This standard is limited to ROT systems and does not cover ROV intervention systems, such as manned intervention systems, replacement of subsea modules and internal wellbore tools. [4] defines ROT system as *dedicated, unmanned, subsea tools used for remote installation or module replacement tasks that require lift capacity beyond that of free swimming ROV systems*. The ROT systems consists of systems dedicated to certain intervention tasks, deck handling systems, intervention control system, deployment or landing equipment, and ROV spread interfaced with ROT systems. Examples of ROT systems are component change-out tool (CCO), equipment running tools, connection actuation tool (CAT).

ROT systems are utilized in all phases of a subsea field and are required to consider intervention operations performed in all phases. The link between ROT intervention systems and the Life-Cycle-Cost (LCC) of the field is highlighted in the standard. Improper planning of ROT systems can increase the LCC of the whole subsea field. Deck handling equipment, such as skid systems, winches, vessel cranes, mobile A-frames and heave-compensated systems, influence the choice of intervention vessel. Since some ROT systems are controlled from topside facilities, requirements on control and monitoring of ROT during topside function test, running of tool during and in between interventions are specified. Possible deployment and landing of tools through guideposts, funnels and connectors, side entry, variable buoyancy of ROT and haul-down require consideration during ROT design and operations.

Tools for primary intervention during tie-in operations need to specify sealine, type of intervention vessel, and environmental attributes (e.g., water depth, sea current), and production system layout. While tools for primary intervention during module replacement need to specify operational issues, environmental attributes, access to subsea facility, frequency of intervention, and physical limits of the module to be replaced (e.g., mass, dimensions). Functional requirements and recommendations with respect to deployment and landing, surface equipment, control system, tie-in operations, and module replacement are extensively listed [4][page 8-18].

Testing requirements consist of re-qualification due to change in fit form and function, evaluation for qualification and wet testing, verification of contingency functions, surface testing prior to deployment, verification of entry access angles, verification of electrical and hydraulic interfaces, verification of masses and dimensions, verification of ROT torque output, calibration of sensors, switches etc., and verification of ROV access for monitoring inspection of ROT systems. The standard concludes with a set of internal and external interface requirements on the vessel/rig, subsea structures and the ROV systems.

API 17H

The latest version of API 17H (2013) standard is drafted by the American Petroleum Institute (API). However, the current API 17H standard is a combination of EN ISO 13628-8 and ISO 13628-9 standards. Tab. 2 shows the difference in requirements for ROV tooling interfaces in EN ISO 13628-9 and API 17H.

In addition to the contents of ISO 13628- part 8 and part 9, API 17H describes component and module intervention by illustrating two different types of ROT system philosophies: ROT with self-contained control system and ROV supplied hydraulic/electric power ROT systems. The major difference in the ISO 13628-8, 9 and API 17H is that API 17H is a recommended practice guideline, whereas ISO 13628-8 and 9 are normative standards in design of ROV and ROT systems. This is evident in the language used while drafting requirements. The API 17H describes requirements in *should* (recommendation), whereas ISO standards uses *shall* (mandatory) while specifying requirements. Since the API 17H standard is a combination of ISO 13628- part 8 and part 9 and to avoid duplication of content, further detail of requirements in API 17H are not described here (refer to two previous subsections).

NORSOK U-102

The NORSOK U-102 standard is developed by the Norwegian petroleum industry to ensure safe and efficient ROV operations. The standard is published with support of Norwegian Oil Industry Association (OLF), Federation of Norwegian Industry, Norwegian Shipowners' Association and the Petroleum Safety Authority of Norway (PSA) [6].

NORSOK U-102 classifies ROVs into three major classes; Class I-Pure observational class, Class II- Observation with payload options, and Class III- work class vehicles. Class II ROVs are further classified into Class II A-Observation class with payload and Class II B-Observation class vehicles with light intervention, survey and construction capabilities. Class III ROVs are further classified into Class III A- work class vehicles < 100 kW and Class III B- work class vehicles > 100 kW. NORSOK U-102 is one of the standards in this review, which is also applicable to autonomous underwater vehicles (AUVs).

The standard specifies set of administrative requirements, such as documentation of quality management systems, contractors responsibilities, maintenance systems and reporting. Personnel qualification requirements with respect to manning level, crew qualification, ROV pilot requirement are extensively listed. Requirements related to interface between the ROV and intervention vessel, such as deck loads, sufficient electric power, noise levels, installation outlets, safe access between control and launch sites, launch positions, vessel motion characteristics, protected area for maintenance, hoses and cable routings, and safe launch distances from the vessel are described in the standard.

Technical requirements for all three classes of ROVs are extensively specified in [6][page 15]. These technical requirements are specified for operational depth of the ROV, buoyancy, maneuverability, choice of cameras and lights, type of instrumentation, automatic functions (depth and heading readings) and choice of transponders/responders on the ROV. For Class II and Class III vehicles, additional requirements on type of sonars (obstacle avoidance and measuring sonars), plug in connection points, manipulator arms (outreach, lift capacity, grip capacity) and hydraulic power packs are specified.

Operational requirements are addressed in relation to risk assessment, operational management, mobilization plan, function testing of equipment, work procedures, personnel familiarization and experience transfer. Requirements to comply with safe working loads and length of the tether management system (TMS) are specified and are subject to the scope of the work. While, umbilical and tether are required to be designed as to limit mechanical damage during normal operations. Requirements on handling system, such as safe working load, launching criteria and umbilical winch speed are specified. The standard concludes with set of requirements on ROV control room facil-

TABLE 2. TOOLING INTERFACES ISO 13628-9 VS. API 17H

ROV Tooling Interfaces	ISO 13628-8, 9	API 17H
Stabilization	✓	✓
Handles for use with manipulators	✓	✓
Handles for use with tool deployment unit	✓	×
Rotary docking	✓	✓
Rotary interface low torque	✓	✓
Rotary interface high torque	✓	×
Linear interface type A and C	✓	✓
Linear interface type B	✓	✓
Hot Stab connection A	✓	✓
Hot Stab connection B	✓	✓
Hot Stab connection C & D	×	✓
Rotary fluid coupling	✓	✓
Component Change Out interface	✓	✓
Lifting mandrels	✓	✓
Electrical and hydraulic jumpers	✓	✓

ities. The ROV control room shall be designed to reduce noise level, maintain ergonomic working conditions with video feeds and provide communication channels with the bridge and launch areas while, operator stations shall be designed to reduce physical stress. Condition monitoring capabilities shall be provided in the ROV control room to monitor ROV status.

IMCA R 004

IMCA R 004 ROV (Rev.3 2009) code of practice is authored by International Marine Contractors Association (IMCA). Previous versions of this code of practice date to the year 1997 and 2003. The earliest version of this code dates to the year 1988 [24].

The code classifies ROVs into five categories, such as observation, observation with payload, work-class, towed and bottom crawlers and prototype vehicles. The classification is followed by brief description of ROV tasks, such as observation, survey, inspection, construction, intervention, burial and trenching. ROV tools used during ROV operations, such as video cameras, non-destructive testing (NDT) sensors, acoustic and tracking sensors, cleaning devices, vehicle station keeping devices, and work tools are briefly explained. However, no detail requirements or recommendations are provided on operating these ROV tools.

Requirements on environmental considerations, ROV operations, equipment certification and maintenance, and personnel are addressed extensively in IMCA R 004. Environmental conditions, which influence safe ROV operations are divided into weather, sea state and swell, sea currents, water depth, seabed characteristics, and pilot experience of unfavorable conditions. Weather characteristics, such as wind speed, rain and fog, combinations of wind, rain and snow, hot and humid weather effect on ROV electronics are recommended to be considered during ROV operations. Sea state due to rough seas, and their effects on handling systems, and personnel on board is described and use of heave-compensated deployment systems is recommended. Hazards due to varied sea current are highlighted, and simulations of sea current is recommended to obtain better sea current predictions. Factors affecting ROV maneuverability underwater, such as length of umbilical, propulsion system, flying depth and orientation, vehicle hydrodynamics, non-uniform current profiles, and umbilical spinning in deep water are explained. Consideration of working depth with respect to umbilical length and drag, transit time, visibility, temperature, salinity, pollutants, and water movements are described. Seabed characteristics, such as rocky outcrops and soft seabed bottom need consideration during ROV operations phase.

The code recommends performing a risk assessment to identify and mitigate site-specific hazards before every ROV operation. Description and measure to mitigate physical hazards within handling systems, water intakes and discharge, ROVs near diving operations (operations along with human divers), electricity, and high-pressure water jetting operations are mentioned. The ROV contractors are recommended to maintain documentation of operations manual, HSE management system, technical manuals for equipment, daily logs/reports, planned maintenance schedules, maintenance and spare parts records, and pre/post-dive checklists. ROV location and integrity on the intervention vessel with respect to factors, such as vessel size, handling systems, mobilization plans, permit-to-work system, hazardous areas, and ships center of gravity are discussed.

[7] provides requirements on equipment certification and maintenance. The certification requirements encompass vehicle, electronic control, vehicle power-on checks, ancillary tools, and handling systems certifications. The maintenance requirements encompass equipment register, planned maintenance schedules, and spare part planning. Handling systems consisting of ROV lifting cables, sheaves, rings, shackles and pins are required to be examined and certified every six months. The code concludes with requirements on personnel (crew) and associated responsibilities of the different stakeholders during ROV operations. Support functions, safe working practice, minimum crewing levels, and tooling setup dictate the team size required for every operation. Maximum working period of 12 hours for personnel is recommended to limit exhaustion and safety incidents due to low concentration levels. Personnel training requirements consist of survival, first aid, fire fighting, and hazard awareness.

IMCA R 005

IMCA R 005 is a guidance document developed to ensure electrical safety while handling high voltage equipment (voltage exceeding 1kV) such as ROVs [8]. The document describes responsibilities of ROV crew towards familiarization of electrical hazards at work-site and recommends a syllabus for training personnel designated to work in high voltage and electrical hazardous areas. IMCA R 005 recommends maintaining work safety systems such as safety procedures by contractors, presence of at least two personnel while handling high voltage equipment, control of permit to work system, mechanical isolation of work-sites, familiarization with the equipment, and risk assessment before start of operations.

Procedures to area isolation and access for maintenance include safe isolation of work-site and certified proved dead (no voltage) areas by voltage tester. The code also provides checklists to prepare for maintenance work and fire extinguishing activities. The code concludes with testing requirements on instruments, testing equipment and proving dead areas [8].

IMCA R 018

IMCA R 018 is not normative, but provides general outline requirements for installation of ROV systems on offshore vessels and platforms [9]. Sub-systems of ROV are ROV, LARS, TMS, control cabin, umbilical winches and workshop cabin. The documents classifies ROVs into five classes as classified by [7]. Two generally used ROV deployment methods are explained, i.e., over the side and moonpool deployment. Over the side deployment is mostly used in offshore vessels while, the moonpool deployment is used on fixed or floating platforms. Platform inlets or outlets and simultaneous operations are recommended to be considered prior to installation of LARS. Working area near or directly behind the handling systems and the umbilical winch need to be cleared before launch and recovery to ensure minimum restrictions in umbilical movement. [9] provides guidance checklists for installation of A-frames, hydraulic power units (HPUs), ROV control room, ROV workshop area, deck space (for ROV parking and handling), head room (overhead clearance), skid handling systems, oil reclamation and water drainage system, control stations of handling systems, access and exit paths and emergency recovery of ROV (e.g., isolation of vessel thrusters, capable and available crane coverage and prior risk assessments).

Furthermore, the document describes in detail the electrical power requirements for both support vessel main supply and the ROV. Two-way communication between ROV control room and positioning sensors on the ROV along with continuous videolinks (camera feeds) are recommended to be established. Fresh water availability for washing ROV after recovery, fire alarm integration to all outdoor sections of the vessel, close circuit camera television (CCTV) and survey sensor requirements are recommended. The document concludes with operational requirements concerning sea state, total load path of the ROV (load of ROV, winch, umbilical and handling system), deck loading and relevant regulations are recommended to be followed.

STANDARDS ADDRESSING AUTONOMY

In addition to the traditional industry ROV standards, the American Society for Testing and Materials (ASTM) is the author of four standards applicable to autonomous unmanned undersea vehicles (UUVs). Fig. 2 provides an overview of these standards [25–28]. These standards provide general guideline to develop autonomous UUVs by addressing requirements for each sub-system making the UUV. The four standards address aspects related to general autonomy and control, payloads and interfaces, recommendations for communication networks, and collection and processing of sensor data by autonomous UUVs. However, these four standards do not provide detailed requirements on functional safety aspects of UUVs. Tab. 3 provides an overview of the high level aspects mentioned in these standards.

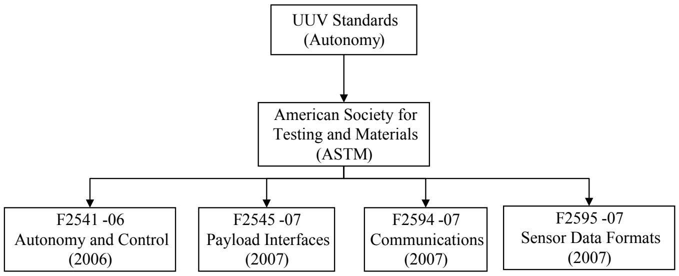

FIGURE 2. STANDARDS CONSIDERING UUV AUTONOMY

F2541- 06

This standard addresses requirements, which can enable UUV systems to operate autonomously for extended period of time without human intervention [25]. The standard defines terminologies used in describing autonomy and control of UUVs extensively. The standard describes UUV functional susbsystems and interfaces namely, vehicle control, payload control, autonomous control, on-board safety systems, and communications. An extensive list of UUV capabilities is listed in the standard, for example, levels of situational awareness of the UUVs are categorized. Levels of autonomy, system capabilities, system architecture and design, operator interaction, sensor input, application of autonomy levels, system performance, and collaboration requirements are specified.

F2545- 07

This standard addresses key interface aspects for autonomous UUV systems interfacing with dedicated mission payloads. Requirements related to the physical payload, such as physical characteristics (size, buoyancy and trim, hull, mechanical/electrical connections and vent plugs), functional characteristics, and signal interface are addressed in the standard [26]. Quantitative requirements for each of the above mentioned high level requirements are addressed in the standard. For example, size requirements of the physical payload are divided into subrequirements of acceptable payload volume (5 cubic ft), payload diameter (20.940 inches), and payload weight (400 pounds) .

TABLE 3. OVERVIEW OF ASTM UUV AUTONOMY STANDARDS

Aspects	F2541- 06	F2545- 07	F2594- 07	F2595- 07
Design	✓	✓	✓	✓
Autonomy	✓	✓	✓	✓
Physical payload	✓	✓	×	×
UUV classification	✓	×	×	×
Functional safety	✓	×	×	×
External/Internal interfaces	✓	✓	×	✓
Electrical power	×	✓	×	×
Sensor integration	✓	×	×	✓
Communication (ICT)	×	×	×	✓
Navigation	✓	×	×	×
Environmental data	✓	×	×	×
Situation awareness	✓	×	×	×

F2594- 07

This standard addresses communication requirements for autonomous UUV systems. The document is categorized as an informative guideline and not a normative standard [27]. The guideline adopts the nomenclature used by the telecommunications industry of Seven Layer Open System Interconnection (OSI) and specifies requirements for each of the seven layers, i.e., physical, data link, network, transport, session, presentation, and application layer. Optical communication requirements with respect to laser communications is specified. Underwater acoustic communication constraints, such as information exchange rates, adverse transmission channel, asynchronous networking, efficiency and endurance of underwater batteries, and information transfer, are discussed. Radio frequency (RF) communications requirements for light of sight, tactical common data link (TCDL), and beyond line of sight techniques are specified. UUV network and communication security requirements are also described. Challenges in communication related to seven layers of OSI are discussed in the document.

F2595- 07

This standard describes various methods and techniques to setup and integrate sensor networks to enable UUV operations [28]. The main requirements addressed in this standard are derived from U.S. Navy's Mission Reconfigurable UUV systems. The main requirements for sensor data formats are described in 11 sub sections namely, general water column and ocean bottom guidelines, low volume data versus high volume data, governing U.S. Military specifications, specific water column guidelines, specific ocean bottom guidelines, imagery data, unified sonar image procession system (UNISIPS), side looking sonar (SLS), ambient noise, other geophysical data, and above-waterline sensor data. Specification of mission data formats are described, i.e., mission timing, vehicle mission data, external interface data formats, joint architecture for unmanned systems (JAUS), and security. The standard data storage media and metadata format requirements are followed by recommendations of sensor formats for UUVs.

CASE STUDY

To demonstrate the gap in current requirements for ROV design and operation, a case study method is hereby employed. Replacement of a subsea control module (SCM) is chosen as the subsea intervention operation, which will be evaluated against two ROV system scenarios. SCM is a metal canister, which houses redundant subsea electronic modules (SEM) providing two-way communication between topside and subsea facilities. The SCM also houses hydraulic directional control valves (DCVs) used to operate subsea valves either autonomously or by emergency push-buttons installed topside. The choice of this particular intervention operation is based on inputs from the partners in the NextGenIMR project at AMOS centre.

This paper provides a high level definition of autonomous ROVs in-line with the definition of autonomous underwater vehicles (AUV) is described in [6] and associated intervention philosophy. *Autonomous ROV is equipment used in water with an ability to position itself and operate ROT systems on subsea systems without interference from surface (i.e, without cables to surface)*. The autonomous ROVs can be classified into two distinctive subsea intervention philosophies:

Type 1 semi-autonomous ROVs (SAROV) can operate with existing offshore infrastructure, launch and recovery systems, subsea systems, subsea interfaces and umbilical systems, but are able to fly, control the manipulator arms, and perform subsea IMR operations with limited operator control.

Type 2 autonomous ROVs (AROV) are able to function autonomously and reside in designated subsea docking areas, are able to independently control manipulator functions, can navigate autonomously, perform self diagnostics, and are equipped with automatic ROT systems. The case study considers both *Type 1* and *Type 2* ROVs as work-class vehicles, as defined by [6].

Based on the set of autonomous functions required in the future, the intervention operation of replacement of SCM will be evaluated against existing requirements in the following subsections. A brief operational sequence of the intervention is listed in Tab.4.

Replacement of SCM- current scenario

Definition of task is replacement of subsea control module. Specification for this task consists of technical information on the subsea system and ROV contractors. Intervention philosophy is use of IMR vessel with combination with ROT and ROV systems to replace the SCM. Subsea and ROV interfaces are defined to develop the torque tool, manipulator arms, jumper parking zones with reference to standards [4, 5]. ROV access requirements are also referred from [3, 5]. The subsea equipment is designed to interface smoothly with the ROT systems. ROT systems such as

TABLE 4. SEQUENCE OF SCM REPLACEMENT

Step	Description of SCM replacement operation
Step 1	The ROV is launched through the LARS from an IMR vessel.
Step 2	The ROV is flown by two human ROV operators (one controlling the flight path and other controlling the manipulator arms) to the vicinity of the X-mass tree.
Step 3	The ROV manipulator arms remove the electrical and hydraulic jumpers connected from the X-mas tree to the SCM connector ports (electric/hydraulic/optical connectors).
Step 4	The ROV parks the jumpers in the slot provided in the X-mas tree.
Step 5	The ROV is flown above the SCM and the SCM protection cap is removed.
Step 6	The SCM lock down mode is disengaged by the ROV manipulator arms.
Step 7	The torque tool is lowered down in an ROV tool basket.
Step 8	The torque tool is picked up by the ROV and placed in the slot provided on top of the SCM. (with correct orientation)
Step 9	The torque tool is engaged and is turned to a predetermined revolution.
Step 10	The SCM running tool is run subsea from a different location of the IMR vessel.
Step 11	The ROV steers the SCM running tool and guides it to the SCM slot on the X-mas tree.
Step 12	The SCM running tool is mechanically locked in position by use of a lock mechanism by the ROV manipulator arms.
Step 13	The SCM is connected to the running tool and the topside winch lifts the SCM while the ROV guides the operation subsea.
Step 14	The spare SCM is lowered on the SCM running tool and the *sequence is reversed to replace the SCM*.

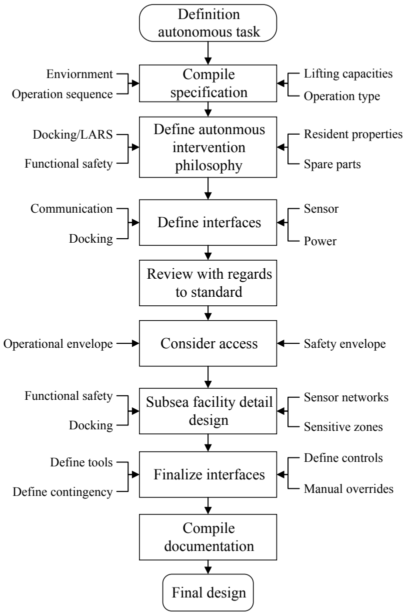

FIGURE 3. DESIGN PROCESS FOR ROV/ROT ADAPTED FROM [3]

SCM running tool, manipulator arms, torque tool, SCM protection cap and parking leads are defined, finalized, and document before final design. Sequence of operations is as described in Tab. 4.

Requirements for semi-autonomous ROV (SAROV) systems

ASROV systems will be able to carry out predefined autonomous functions. Since such systems can utilize current offshore infrastructures, adoption of these systems by the petroleum industry will be earlier than the fully autonomous ROV systems (*Type 2 ROV systems*).
For this case study, the following assumptions have been made: a) SAROV can operate with existing LARS, ROT, subsea interfaces and umbilicals. b) SAROVs can fly along their planned flight path and operate manipulator arms without human intervention. c) Autonomous functions of SAROVs can be overridden by human interference from ROV control room. The SAROV operational sequence is suggested as follows- Step 1, and step 3 to step 14 are identical to SCM replacement in current scenario as described in Tab. 4. Step 2 will require monitoring from the ROV operators topside.

Gap in requirements With reference to Tab. 4, SAROV systems can perform steps 1, 7, 9, 10, 13, and 14 using existing offshore/subsea infrastructure. However, steps 2, 3, 4, 5, 6, 8, 11, 12, and 13 require further development in functional requirements related to navigation, localization and guidance. In addition, sensor fusion requirements are necessary for the SAROVs perception of the surroundings. Functional safety requirements related to asset and subsea equipment safety are also key requirements, which need development. Requirements concerning manipulator arms capabilities (e.g., lifting capacities, reach), fault tolerance capability (e.g., accuracy levels with sensor degradation), control and monitoring from topside (e.g., personnel requirement and competence), manual overrides (e.g., scenarios triggering manual override), and contingency plans (emergency SAROV recovery) are other key areas for development.

Tab. 5 indicates the gap in requirements for *Type 1* ROVs (SAROVs). Symbol ✓ signifies existence of gap in current requirements while symbol ✕ signifies relevant requirements are currently existing in standards/codes.

Requirements for autonomous ROV (AROV) systems

AROV systems are aimed at performing functions with full operational autonomy. Previous studies with similar intervention philosophy using AUVs have been demonstrated by [17,19,20]. The intervention philosophy of the systems in these studies is derived from AUVs with manipulator capabilities. Nevertheless, the philosophy in this case study as compared to [17,19,20] is the same, i.e., subsea intervention by use of underwater vehicles and manipulators. In this paper underwater vehicle refers to ROVs.

Gap in requirements If the requirements for AROV systems were derived from current ROV standards, AROVs would not be able to perform any steps described in Tab. 4. The reason for this claim is- autonomous operations are not defined in the current ROV design or operational standards/codes. Furthermore, previous studies [17, 19, 20], do not cite to any standards including [25–28], meaning that the functional requirement of AUV demonstrated in past studies were developed on a case-by-case basis.

In addition to the requirements mentioned in Tab.3, Tab.5 identifies additional requirements, such as safe state of the AROV, fault tolerance, maximum sensor degradation, and functional safety. These requirements are critical to safe autonomous operations, but need further development.

TABLE 5. GAPS IN AUTONOMOUS IMR OPERATIONS

Aspects	**Type 1 SAROV**	**Type 2 AROV**
Autonomy	✓	✓
Subsea facility design	×	✓
Navigation	✓	✓
Path-planning	✓	✓
Localization	✓	✓
Guidance	✓	✓
Functional safety	✓	✓
Sensor fusion	✓	✓
Fault tolerance	✓	✓
Resident properties	×	✓
Launch and recovery	×	✓
Manipulator arms	✓	✓
Lifting capacities	×	✓
Qualification	✓	✓
ROT systems	×	✓
Spare parts	×	✓
ROT control system (topside)	×	✓
ROT control system (self-contained)	×	✓
Subsea docking (for charging and parking)	×	✓
Environmental conditions	×	✓
Power	×	✓
Communication	×	✓
Control and monitoring	✓	✓
Manual override and monitoring	✓	✓
Contingency planning	✓	✓

DISCUSSION

The case study approach shows that autonomous IMR operations using ROV systems need to consider a variety of technical requirements in addition to the requirements specified in existing ROV standards. The sequence of operations mentioned in the case study highlights key challenges and gaps in realizing autonomous subsea IMR operations. Studying IMR operations, such as installation of pig-loop, installation of subsea connectors etc. may reveal more gaps, which the SCM replacement case study did not uncover.

The terminology and classification of types of underwater vehicle systems vary in the standards. Standards have introduced many nomenclatures for underwater vehicles for example, ROVs, AUVs, UUVs, which post challenges in defining assumptions for the case studies. Some gaps identified from this study are applicable to AUVs. For example, aspects, such as sensor fusion, manipulator arms, manual override and monitoring, resident properties, subsea docking, navigation, localization etc. are applicable to underwater vehicles other than the ROVs.

The existing ROV tooling design process described in EN ISO 13628-8 is a robust process, which can be adapted to develop autonomous ROV/ROT systems as illustrated in Fig. 3. The figure illustrates the additional inputs required to design ROV/ROT systems for autonomous IMR operations as identified in Tab. 5.

SAROVs defined in this paper can utilize existing infrastructure and can potentially decrease the duration of intervention activities. They also require less development work when compared to the development work scope of fully autonomous ROV systems.

CONCLUSION AND FURTHER WORK

This paper provides an overview and a detailed review of existing ROV standards and standards considering underwater vehicle autonomy. The study shows that a combination of current ROV standards provides a basis for further development of requirements for both autonomous IMR operations, and associated ROV systems. However, with introduction of autonomous functions, the paper demonstrates that there is a need for additional requirements at various sub-system levels, for example, functional safety, sensor fusion, subsea facility design etc.

This paper describes the SCM running and retrieval sequence carried out during SCM replacement subsea intervention. The study highlights the importance of a semi-autonomous systems, which can operate on existing infrastructure. Due to technology and knowledge gaps, the study concludes that current ROV standards are only partly applicable to future subsea autonomous IMR operations. However, the ASTM standards reviewed in this paper provide a starting point for developing detailed functional requirements.

Measures to fill the gaps highlighted in this study require further research by multi-disciplinary research teams. For example, developing functional safety requirements for AROV systems and defining safe states of AROVs need combination of control theory and reliability analysis. Investigation of reliability assessment of safety critical systems of autonomous ROVs and development of safety functions is one of the key future work prospects. Replicating the method used in this paper to study other subsea intervention operations can lead to identification of additional technology and knowledge gaps.

ACKNOWLEDGMENT

This work is supported by the Research Council of Norway, Statoil and FMC Technologies through the project Next Generation Subsea Inspection, Maintenance and Repair Operations, 234108/E30. The work is associated with AMOS, 223254.

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