Human-System Concurrent Task Analysis: An Application to Autonomous Remotely Operated Vehicle Operations

Marilia A. Ramos

The B. John Garrick Institute for the Risk Sciences, University of California Los Angeles, United States. E-mail: marilia.ramos@ucla.edu

Christoph A. Thieme

Department of Marine Technology, Norwegian University of Science and Technology, Norway. E-mail: Christoph.thieme@ntnu.no

Xue Yang

Safetec, Norway. E-mail: xue.yang@safetec.no

Autonomous systems may operate with different Levels of Autonomy (LoA), from remote control to fully autonomous. The latter is not expected in the near or intermediate future for most systems. Thus, operation relies on the interaction between human and system. The Human-System Interaction in Autonomy (H-SIA) method aims to analyse autonomous systems including their interaction with operators in a monitoring or controlling role. The Concurrent Task analysis (CoTA) is a success-oriented method introduced in H-SIA. It models the interactions between tasks performed by different agents (e.g., humans and autonomous system). The CoTA allows for analysing the system as whole and to model an operation with dynamic LoA. These aspects make the CoTA a suitable tool to analyse Autonomous Remotely Operated Vehicle (ROV) operation. ROVs have been recently gaining more autonomous capabilities, allowing for part of their operation to be autonomous with human monitoring. This article applies the CoTA method to autonomous ROV operations for subsea installations inspection. It further discusses how the CoTA can be used to develop operating procedures. These procedures are expected to improve current operations, making them safer with respect to human and environmental safety.

Keywords: Autonomous Systems, Concurrent Task Analysis, Remotely Operated Vehicles (ROVs), Safety, Procedures, Human-system interaction

1. Introduction

Autonomous capabilities have been increasingly introduced to a variety of systems and for different applications. These capabilities give systems the abilities of decision-making that is independent from an external agent, and adaptability to a dynamic environment. Decision-making is, i.e., a supervisor, or a central planning computer.

The degree of independent decision-making and interaction with other agents is defined through the level of autonomy (LoA). Different concepts and scales of LoA have been proposed, and a review can be seen in (Vagia et al., 2016). Generally, lower LoAs correspond to designs in which the human is responsible for decision-making and control (possibly remotely) of the system. Higher LoAs, on their turn, correspond to designs in which the human has a supervisory role. In the highest LoA, systems would operate with no human supervision.

Currently, most systems are equipped with a degree of autonomy ranging from remote control to supervision modes. Some systems may also be designed for operating under human supervision during parts of the operation and remote control in other parts. A system in which the LoA may change is referred to as operating with a dynamic or adaptable LoA.

Examples of recent developments and applications of autonomy can be found especially in transportation, with autonomous cars, drones, and ships on the horizon (Ramos et al., 2019) Higher degrees of autonomy are also found in underwater exploration and work operations. The advantages of a higher degree of autonomy go beyond potentially reducing costs and improving efficiency. They are also related to reducing human's exposure to potentially hazardous environment and human's involvement in repetitive and tedious tasks.

The introduction of autonomy to Remotely Operated Vehicles (ROVs) exemplifies the abovementioned advantages. ROVs are used for subsea operations, such as inspections, installation and maintenance of subsea oil and gas facilities (Mai et al., 2017) and marine aquaculture farms (Bjelland et al., 2016). Some of these operations are performed by divers, which is a hazardous job in a hostile environment. The use of ROVs allows for reducing human exposure

Proceedings of the 30th European Safety and Reliability Conference and the 15th Probabilistic Safety Assessment and Management Conference
Edited by Piero Baraldi, Francesco Di Maio and Enrico Zio
Copyright © ESREL2020-PSAM15 Organizers.*Published by* Research Publishing, Singapore.
ISBN: 978-981-14-8593-0; doi:10.3850/978-981-14-8593-0

to these environments. However, ROVs with a low LoA still depend on remote motion control by humans, in addition to tasks such as image analysis. Depending on the duration of the operation, these tasks can be tedious and highly susceptible to human error.

Autonomous remotely operated vehicles (AROV[a]) are emerging as a cost-efficient solution to regular ROV. AROV have more automated and autonomous capabilities, requiring less human supervision. Consequently, the ROV operators will be able to use time for other tasks during parts of the mission with low supervision needs.

A mix of different operational modes, with high and low LoAs, can assist in reducing work load on operators, reduce human errors in operations and increase efficiency (Schjølberg et al., 2016). Current efforts are undertaken to use AROV in the offshore oil and gas industry and in the marine aquaculture industry.

AROVs have been introduced recently. Today, a majority of ROV operations are carried out manually, i.e., through manual operator input. Despite the advantages brought with higher LoAs, the increase of autonomous capabilities must be designed with care, to assure safe operation. Procedures must be developed for the operators to reliably intervene when necessary. These procedures must include an analysis of the ROV's possible actions and needs and how the operators should respond to them. Procedure development can thus benefit of a holistic view of the system, comprehending human and technical system interactions.

A method named Human-System Interaction in Autonomy (H-SIA) was recently proposed for analysis of autonomous ships operation by (Ramos et al., 2020). H-SIA aims to analyse the system as whole including human operators, software, and hardware, their interaction, and dynamically changing LoAs. H-SIA makes use of Event Sequence Diagrams (ESDs) and Concurrent Task Analysis (CoTA). The ESD models the system operation in a high level, containing events from the technical system and from the human. The CoTA is a success-oriented method introduced by H-SIA that models the tasks from humans and from technical system in a concurrent manner.

The CoTA can be used for multiple purposes, such as development of procedures, identification of specific subsystems and components that are necessary for a successful task, identification of failure sources of the human operator or the autonomous system, of tasks that need to be accomplished for a certain outcome, of interface tasks, and analysis of failure propagation.

This paper aims to illustrate the potential use of the H-SIA method, particularly the CoTA, for informing procedure development. This is achieved through the application of H-SIA to AROV operation for subsea structures inspection. The importance of this case study resides on the increasing use of subsea installations compared to surface installations, and the consequent increased need for inspections and work to be performed (Mai et al., 2017). This development process may be adapted to other systems and application, such as autonomous cars, drones, ships, or trains.

The next section will present the background on AROV, followed by an overview of HSIA and the CoTA in Section 3. Section 4 will present the case study on the AROV operation and describe the CoTA and procedure development for the case study. Section 5 concludes this paper with a discussion, highlighting the key value of the presented approach and providing an outlook for further work.

2. Remotely Operated Vehicles

A ROV is a tethered underwater vehicle which is highly manoeuvrable and operated by either a person or a ROV crew. The crew consists of a supervisor and two or more members, depending the class and size of the ROV. ROVs are increasingly used within the subsea oil and gas industry over the last decades. This can be attributed in particular to the increase of exploration and production in deep waters, where it is impossible for divers to operate. Recent advances in subsea inspection include also the use of Autonomous Underwater Vehicles (AUVs), which differentiate from ROVs by not possessing a tether. The use of AUVs face challenges related to underwater wireless communication, battery and propulsion capacity, refuelling and recharging, and other aspects. (Mai et al., 2017). For example, to support live video for remote inspection tasks, full tele-operation is possible only through a high-bandwidth datalink with current mature technology (Johnson et al., 2014). A recent study by (Mai et al., 2017) concluded that semi-autonomous upgrades to existing ROV technology is a realistic first step towards the adaption of AUVs for sub-sea infrastructure inspection.

2.1 Levels of Autonomy in ROVs

This paper adopts the LoAs by (Henriksen, 2018), presented in Table 1. The author differentiates *Haptic Control* and *Shared Control*, where the

[a] Autonomous ROVs are a category of ROVs and are often simply referred to as "ROVs". Despite not being necessary, this paper will use AROV when necessary to emphasize autonomous capabilities .

first is a special case of the latter. In Haptic Control the automated controller is connected to a haptic control interface. The output of the controller moves the ROV corresponding to the haptic control input. An example of the haptic control mode is an actuated steering wheel on a car. For the purpose of this paper this differentiation is not necessary and haptic control is simply referred to as Shared Control.

Table 1 Levels of Autonomy for ROVs (adapted from Henriksen, 2018)

LoA		**Description**
1	Direct Control	The human directly controls each actuator on the controlled vehicle.
2 and 3	Shared Control (haptic control as a special case)	A computer augments the operator input before it is sent to each actuator. For example, the operator may use a joystick to specify a desired force output in the ROV reference frame, and a controller allocates the desired force to set points for each thruster.
4	Supervisory control	The human delegates and supervises the execution of the tasks. During operation the operator may intervene and alter input parameters.
5	Full Automation	Similar to supervisory control, but without possibilities of interference by the operator.

Main application areas of AROV are oil and gas exploration, pipeline and cable maintenance, marine aquaculture and exploration of the oceans. Typical subsea operations with AROV are IMR (Inspection, maintenance, and repair) operations of underwater structures and facilities and exploration of the sea floor. The AROVs currently adopted in the industry are mainly of a low LoA - remote controlled by the operators. Commercial ROVs are equipped with automatic control features that can be classified as LoA 2 functionality, which are typically Auto-heading, Auto depth and Auto altitude to keep position or heading within certain excursion limits.

AROVs operation could benefit from more autonomous functionalities (Ludvigsen and Sørensen, 2016) for improving efficiency and operation costs. Today's ROVs require special vessels and thereby are constrained by the associated expensive cost and availability of these vessels. Moreover, ROVs operations in low LOAs require highly skilled and trained operators. Finally, less dependency on the vessel will also reduce the surface weather constraints for operations such as launch and recovery.

3. Concurrent Task Analysis

The CoTA was introduced as part of the H-SIA method for analysing how human operators and technical system interact in autonomous ships operations. CoTA is a success-oriented method, and it translates the events of the ESD into tasks to be performed by the systems' agents (Figure 1). This section presents an overview of the CoTA principles and rules for development. For a complete description the reader is referred to (Ramos et al., 2020).

The CoTA is based on Task Analysis (TA) theory and methods. TA was developed in the 1960s (Shepherd, 2001) and had the initial focus of analysing human performance. Task analysis is "the collective noun used in the field of ergonomics, which includes HCI, for all the methods of collecting, classifying, and interpreting data on the performance of systems that include at least one person as a system component" (Annett and Stanton, 2000).

Through a TA complex tasks (goals) are analysed and decomposed into sub-goals. This process is named re-description. A plan indicates how the sub-goals are organized and in which order they should be accomplished to achieve the main goal.

The CoTA consists of TAs of the system's agents that are developed concurrently. The tasks are initially re-described using the IDA model, and further breaking down is executed when necessary to clearly represent the interactions between the agents.

The CoTA includes a new type of task named "parallel task". Parallel tasks are supporting tasks, i.e., they are necessary for the execution of the other tasks and the interaction between the agents but not explicitly included in the ESD. Parallel tasks are related to the normal operation of the system. They are executed continuously, not following a specific order in a plan, i.e., they are

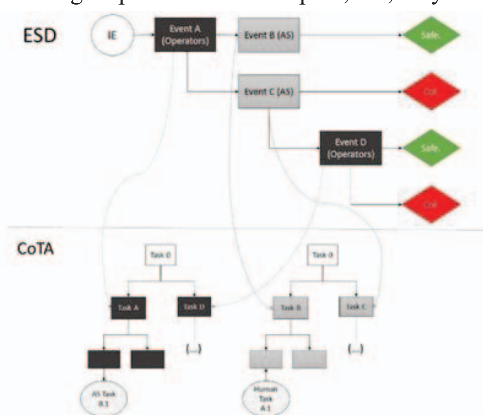

Figure 1: Human-System Interaction in Autonomy (H-SIA) method – ESD and CoTA (Based on Ramos et al., 2020)

executed at the same time as the other tasks. The parallel tasks are normally the ones related to data gathering, monitoring, or communication between the agents.

The process of re-description can be carried out indefinitely without the use of a stop rule. CoTA introduces a stop rule based on a cognitive model; the Information, Decision and Action (IDA) framework. The IDA model was initially developed as a human behavior model for the operation of nuclear powerplants (Smidts et al., 1997). It consists of the cognitive phases I (Information collection and pre-processing); D (decision-making and situation assessment); and A (action taking). The IDA model has been further developed and extended in recent years (Chang and Mosleh, 2007). H-SIA extends IDA, applying it to the autonomous system in a similar manner than to human operators. Indeed, in a high level, an autonomous system's operation also comprises information gathering (e.g. through sensors), situation assessment and decision making (through algorithms), and action. Thus, the sop-rule of re-describing the tasks until they represent one of the IDA phases is applicable for both humans and other technical parts of the system. Furthermore, since the H-SIA method analyzes the interaction between two or more agents, it is beneficial to use a similar model that allows for decomposing functions into the same low-level unit of analysis.

The CoTA can be developed from the ESD or an operational flow chart following the steps below:

1. Definition of agents to be analyzed;
2. Definition of Task 0: the main task to be accomplished by the system's agents. This may be to recover successfully from a disturbing initiating event or to perform normal operation;
3. Definition of high-level tasks: each event of the ESD translates into a high-level task in each of the respective TAs;
4. Identification of parallel tasks;
5. Re-description of tasks until stop rules are satisfied:
   i) The sub-task is associated with only one of the IDA phases;
   ii) If the accomplishment of the task is dependent on another agent, or if the output of the task is an information or command to be sent to another agent, the task is re-described until this interaction can be clearly characterized.

These general guidelines are applied to AROVs operation in the following section.

4. Concurrent Task Analysis of ROVs for Subsea Operation

4.1 Operation Description

The case study for the CoTA application comprises the use of an AROV for IMR operations. The scope of the analysis is the inspection phase of the mission, in which the ROV detects potential damages or defective components. This is vital for the offshore oil and gas industry to ensure safety of underwater wells and continuous operation. Examples of subsea structures include blowout preventers, or underwater valve arrays, so-called X-mas trees.

ROVs used for the task depicted in this case study are generally of a work class or heavy-duty work class. Those are typically heavy and large, requiring a manning level that can reach 4 people per shift. These are comprised within the term crew used throughout the case study.

Figure 2 summarizes the operation of this case study. The ROV crew is located on board an offshore supply vessel and has access to a haptic control interface, i.e., a joystick, for the ROV. The ROV travels to the subsea facility supervised, meaning that the ROV pilot gives several waypoints to the ROV, which it will follow to the last way point. The operator has a supervisory role, monitoring mission progress and the environmental conditions.

The mission tasks of this case study are summarized in the task flow diagram in Figure 3. The control modes are related to the LoAs presented in Table 1: During *subsea inspection* the AROV operates on supervisory control mode, and during *shared control* it operates on shared control mode. When changing from supervisory control to shared control, the ROV may stop and wait for the crew's commands: this is referred to as station keeping, and marked with *SK* in Figure 3.

On arrival at the subsea facility the operator starts the inspection of the subsea structure. The AROV will follow a pre-planned path around the structure filming and scanning the structure. If damages or anomalies are detected through detection algorithms, the ROV enters on Shared Control mode, and stops for waiting commands from the operator (SK). The operator receives an alarm indicating that intervention may be needed. The supervising crew must assess the anomaly and decide if it needs further investigation. If this is the case, the crew controls the ROV closer in a shared control mode around the anomaly for detailed inspection. Input from the joysticks is allocated by the ROV and it compensates for currents and other forces and keeps depth. In case the crew decides investigation is not necessary, they re-activate the subsea inspection mode and the ROV continues operation in supervisory

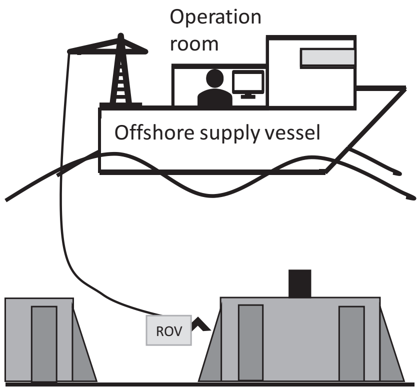

Figure 2: Illustration of a Remotely Operated Vehicle (ROV) inspection operation of a subsea oil and gas structure.

mode. If the ROV for some reason encounters an unexpected obstacle or is stuck, it stops and warns the operators, who need to remotely control the ROV. When the ROV is in a safe position, the crew re-activates subsea inspection mode.
During the mission the crew's tasks are to monitor the video and intervene when alerted. They can execute tasks such as further mission planning during times of low workload. It should be noted that situations other than the ones described above are possible and would need crew's intervention. For instance, the ROV may operate in an abnormal manner, due to failures in software or hardware, or fail to correctly identify an anomaly. However, considering the scope of this application and due to space restrictions, these scenarios are not analyzed. Only the two scenarios described above are examined: encounter of unexpected object and identification of anomaly by the ROV.
At the end of the mission the ROV alerts the crew that it has concluded its tasks. If needed, the crew can decide to further inspect the structure using the joysticks before commanding the ROV to return to the vessel. When the inspection is finished the ROV returns to the ship in a supervisory control mode.

4.2 CoTA Application

The CoTA for the ROV was developed following the guidelines summarized in Section 2.2 and detailed in Ramos et al. (2020). It reflects the tasks to be executed by the ROV and operators, as summarized in Figure 3. For this simplified application, the task flowchart substitutes the ESD: the tasks depicted in Figure 3 are high-level tasks for the CoTA.
Figure 4 and 5 present the resulting CoTAs for the ROV and the crew, respectively. The tasks the crew must perform depend on the reason for the alarm: *anomaly detected*, *unexpected object*, or *end of mission*, as described by the Plan 0. The operators' CoTA contains one parallel task: *Monitoring*. The crew should monitor the screens and assess the safety of the ROV and the progress of the mission. Despite being a parallel task that supports the other tasks, in this case study the crew does not need to monitor the screen at all times, as is common in supervising tasks. Instead, they must monitor it with a certain frequency. This frequency must be defined when planning the mission.
The ROV's CoTA contains two parallel tasks: *Collection of position and environmental data*, and *Communication of data with the operator*. These tasks are carried out independently of the operation mode and hence are parallel to the inspection mission.
The CoTA for the crew can be used to inform the development of procedures, as presented and discussed in the following Section.

3.3 Using CoTA for informing operational procedures

Standard Operating Procedure (SOP) can be defined as a "set of written instructions that document a routine or repetitive activity followed by an organization" (United States Environmental Protection Agency (EPA), 2007). Having complete, correct and comprehensive SOPs are crucial for the successful operation of any system. Procedure writing is an established topic within the field of Human Factors Engineering. Due to space limitation, this paper does not intent to provide a complete background on this topic and its guidelines. Rather, the aim is to provide and initial assessment on how the CoTA can inform procedures development.
Operating procedures should describe the operators' tasks for a successful mission in concise and direct language and should be in an easy to read format. TA is thus an ideal method to be applied before the development of the procedures. The use of the CoTA introduce several elements for informing procedures development compared to regular TA.
Firstly, procedures may over or under specify task steps. This is a similar challenge as in TA with the re-description of tasks. The re-description of the tasks in the CoTA using the IDA model imposes a finite level of detailing of the tasks, such that the steps are clear and concise for the operator. For instance, the CoTA forces the breaking down of the task "*Assess and investigate anomaly*" to the information gathering related task "*Identify type of anomaly*", situation assessment related task "*Assess if anomaly should be investigated*" and action-related task "*control ROV to assess details of anomaly*".

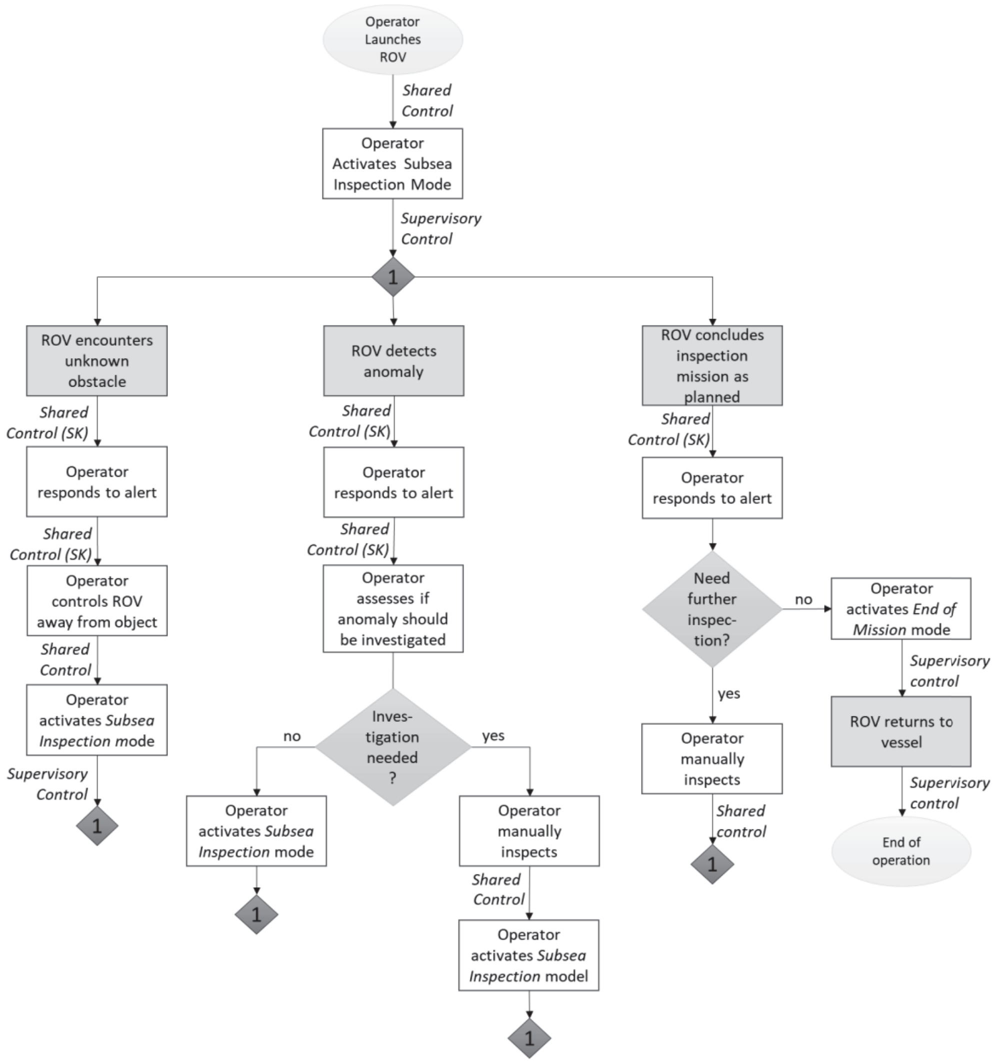

Figure 3: Flowchart of the case study mission tasks

Secondly, the interface tasks specify the systems' output that is necessary for the accomplishment of a task. These can be added to the associated procedures' steps. Thus, the operators are guided to the specific information they need to check. This can become particularly important during complex missions, in which the operators may receive a large amount of information through the human system interface.

Thirdly, the interface tasks can provide a guide for situations during which it is necessary to have troubleshooting procedures, and entry points to those. Because some operators' tasks are dependent on receiving an input from the system, they cannot be performed in case this input is not received. Likewise, they cannot be successfully performed if the input received from the system is incorrect. When describing steps that are related to interface tasks, the procedures can then advise the operator to change to a different procedure in case the information from the system is not (correctly) received. "*Identify cause and source of the alert*", for example, is dependent on the parallel tasks of the ROV concerning data collection and communication. It is necessary to have troubleshooting procedures for the cases in which the ROV fails in performing these parallel tasks, and to provide an entry point to those in the SOPs.

Finally, the use of the CoTA may aid in ensuring that the SOP covers all the necessary steps for mission accomplishment, and that the system is

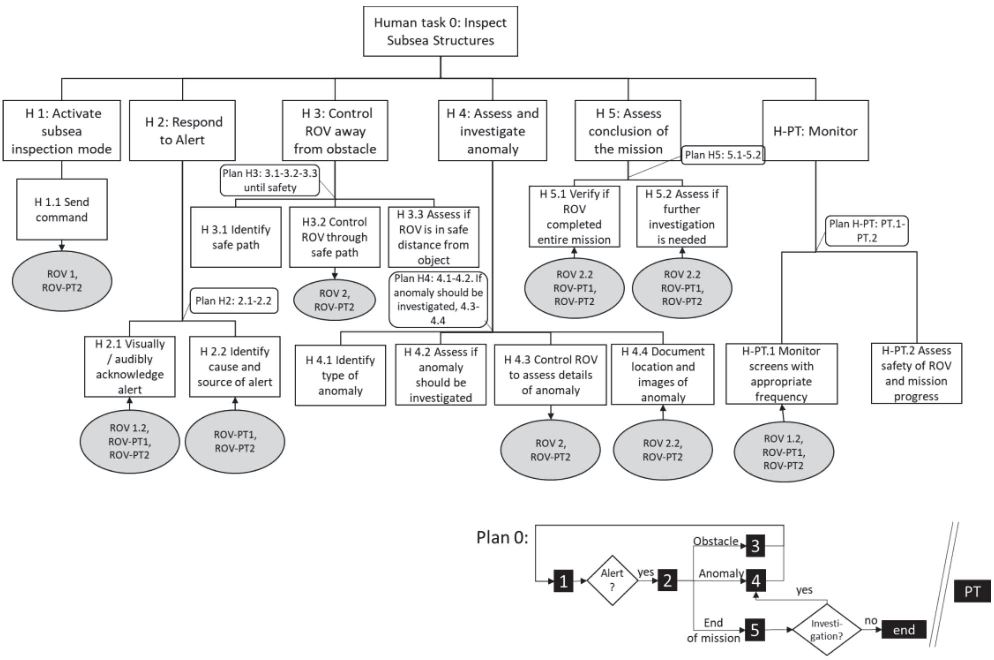

Figure 5: CoTA for the ROV's crew

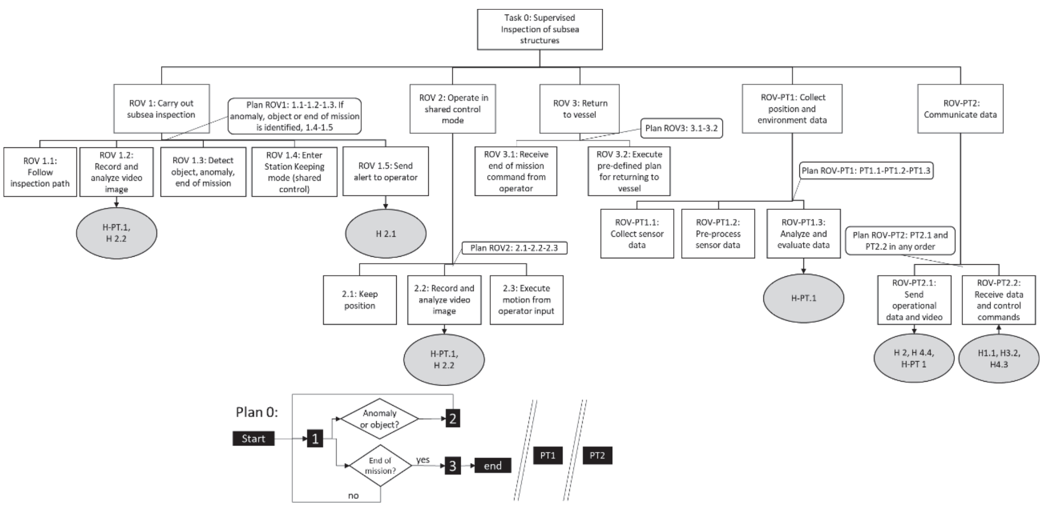

Figure 4: CoTA for the ROV

designed to provide the operators with all necessary information for their tasks.

5. Discussion and concluding thoughts

The increasing level of autonomy in ROVs is a desirable path towards more efficient operations, for example in subsea inspection. To guarantee a safe and successful mission, it is important to analyze the interaction between the ROV and the operators. Above all, it is crucial to ensure that the system design is such that the operators will receive the necessary information for accomplishing their tasks. The SOPs must reflect this interaction between system and crew. The use of the CoTA can aid procedure development, by informing the necessary level of detail of each step in the procedure, the need and location of

entry points to troubleshooting procedures and ensuring that the SOPs steps are complete for the mission accomplishment.
Procedure development, as well the human-system interface design, should also follow state of the art Human Factors Engineering principles. Rather than performing the complete application of the H-SIA method, the case study in the paper was shortened to emphasize the capabilities of using the CoTA for procedures development. The application of the complete method is recommended. In addition to informing SOPs, the method can aid identifying failure propagation, failures modes, and provide a foundation for a complete risk assessment of high LOAs ROV operations. The application of the complete H-SIA method and development of procedures for ROV inspection operations is subject to ongoing work.

Acknowledgement

Dr. Thieme acknowledges the support through the project Unlocking the potential of autonomous systems and operations through supervisory risk control (UNLOCK) funded by the Norwegian Research Council with the project number 274441.

References

Annett, J., Stanton, N., 2000. Tasks Analysis. Taylor & Francis.

Bjelland, H. V., Fore, M., Lader, P., Kristiansen, D., Holmen, I.M., Fredheim, A., Grotli, E.I., Fathi, D.E., Oppedal, F., Utne, I.B., Schjolberg, I., 2016. Exposed Aquaculture in Norway. Ocean. 2015 - MTS/IEEE Washingt. https://doi.org/10.23919/oceans.2015.7404486

Chang, Y.H.J., Mosleh, A., 2007. Cognitive modeling and dynamic probabilistic simulation of operating crew response to complex system accidents. Part 4: IDAC causal model of operator problem-solving response. Reliab. Eng. Syst. Saf. 92, 1061–1075. https://doi.org/10.1016/j.ress.2006.05.011

Henriksen, E.H., 2018. System Design for the Next Generation Subsea IMR Vehicles. Norwegian University of Science and Technology.

Johnson, J., Whitworth, M., Murrie, A., Dodd, S., Teague, J., Gibson, C., 2014. The ROV Manual: A User Guide to Remotely Operated Vehicles, 2nd ed. Elsevier. https://doi.org/10.1016/B978-0-08-098288-5.00031-2

Ludvigsen, M., Sørensen, A.J., 2016. Towards integrated autonomous underwater operations for ocean mapping and monitoring. Annu. Rev. Control 42, 145–157. https://doi.org/10.1016/j.arcontrol.2016.09.013

Mai, C., Pedersen, S., Hansen, L., Jepsen, K.L., Yang, Z., 2017. Subsea infrastructure inspection: A review study. USYS 2016 - 2016 IEEE 6th Int. Conf. Underw. Syst. Technol. Theory Appl. 71–76. https://doi.org/10.1109/USYS.2016.7893928

Ramos, M., Thieme, C., Utne, I.B., Mosleh, A. (Eds.), 2019. Proceedings of the 1st International Workshop on Autonomous Systems Safety, Proceedings of the 1st International Workshop on Autonomous Systems Safety. NTNU, Trondheim.

Ramos, M.A., Thieme, C.A., Utne, I.B., Mosleh, A., 2020. Human-System Concurrent Task Analysis for Maritime Autonomous Surface Ship Operation and Safety. Reliab. Eng. Syst. Saf. 195. https://doi.org/https://doi.org/10.1016/j.ress.2019.106697

Schjølberg, I., Gjersvik, T.B., Transeth, A.A., Utne, I.B., 2016. Next Generation Subsea Inspection, Maintenance and Repair Operations. IFAC-PapersOnLine 49, 434–439. https://doi.org/10.1016/j.ifacol.2016.10.443

Shepherd, A., 2001. Hierarchical Task Analysis. Taylor & Francis, London.

Smidts, C., Shen, S.H., Mosleh, A., 1997. The IDA cognitive model for the analysis of nuclear power plant operator response under accident conditions. Part I: problem solving and decision making model. Reliab. Eng. Syst. Saf. 55, 51–71. https://doi.org/http://dx.doi.org/10.1016/S0951-8320(96)00104-4

United States Environmental Protection Agency (EPA), 2007. Guidance for Preparing Standard Operating Procedures (SOPs), EPA QA/G-6. Washington. https://doi.org/10.31819/9783865278661-007

Vagia, M., Transeth, A.A., Fjerdingen, S.A., 2016. A literature review on the levels of automation during the years. What are the different taxonomies that have been proposed? Appl. Ergon. 53, 190–202. https://doi.org/10.1016/j.apergo.2015.09.013