AJA method and AJA Canvas as a Design Tool for marine Autonomous Operations with a test case scenario: the detection, inspection and tracking of a waste-water plume.

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Abstract. Autonomous marine operations are difficult to plan, design and perform. Additionally, the complexity of these operations is increasing as they often include more than one vehicle. The AJA (Autonomous Job Analysis) method is a structured approach to gathering the necessary information from experts in order to plan and design an autonomous marine operation and document these facts to make the scope of the operation understood by all stakeholders. This paper presents additional methods that enhance AJA. First, the AJA canvas: a visual tool for organising the information obtained by AJA in a concise way. Secondly, a structured format for writing measurable requirements extracted from the AJA process to help in the design of the operation. Lastly, the tools are demonstrated on a test case scenario where several vehicles will collaborate in order to detect and map a plume of contaminated water from a wastewater facility outlet.

1. Introduction
Autonomous mobile systems are capable of reasoning about and solving unstructured problems without the direct control of humans and are central to future exploration of the ocean space. Although there have been several definitions of the word autonomy throughout the years, we will be following the one presented in [1]: the ability of an engineering system to make decisions about its own actions while performing a task, without the direct involvement of an exogenous system or operator. We have to emphasize that autonomy is not all or none, but can vary across a continuum of intermediate levels, between fully manual and fully autonomous at the two extremes [1]. Particularly well known examples of projects with a high Level of Autonomy (LOA) [2] include the Mars space missions [3] and self-driving cars [4]. The possibility of increasing the usage of autonomy in maritime industries is considered crucial especially in industries like oil and gas, waterborne transport [5], and fisheries and aquaculture. Futuristic visions of those industries include trans-oceanic unmanned cargo ships [5]; Inspection, Maintenance and Repair (IMR) of subsea oil- and gas infrastructure carried out by permanently residing autonomous underwater vehicles [6], [7]; unmanned airplanes surveying the oceans for ice-bergs threatening oil- and gas installations [8]; IMR of aquaculture fish farms at exposed locations using autonomous underwater vehicles [9].

By itself, the design of such types of autonomous operations and systems is a complex task. Any type of method that could offer the users a guideline regarding the autonomous functionalities that they have to organize would be of a great help. Under these assumptions, we developed a method called Autonomous Job Analysis (AJA) [10] that is a structured approach for the design of autonomous operations. AJA is based on principles used in Hierarchical Task Analysis (HTA) [11], [12], [13] and has the underlying principle of breaking down a task into individual elements and studying them one by one. Among the different problems one must face in the task analysis procedures, is deciding what to describe and to what level of detail. This can be challenging enough since it is not always obvious how
to break down an operation in order to accomplish a representative analysis. AJA is one of the suggested methods in the SEATONY methodology [14], which provides a structured approach for design, development and validation of mobile autonomous maritime operations and systems. An analytical and descriptive overview of the SEATONY methodology can be found in [14].

In order to further facilitate and enforce AJA, we are in addition proposing a single page AJA canvas. The canvas idea is based on the business model canvas [15], [16], [17] approach and the scope is to gather the essential information needed for the design of an autonomous operation into a single page document. This facilitates the applicability of the method, provides better grounds for a common understanding among the different stakeholders in the operation, and gives the users the possibility to carefully design and analyse the operation in a structured manner.

In order to ease the understanding of the presented method, we have illustrated it through application on a test case study referred to as "storyboard" which concerns the detection of an underwater waste plume with the usage of a swarms of Autonomous Underwater Vehicles (AUVs).

In addition to AJA, we present a tool called the "requirements table", that can help further with the design of autonomous operations. This table gathers the functional requirements of the operation to be analysed and gives the designers an extra tool in the organization phase. AJA and requirements table are complementary to each other and can give different type of information.

The outline of the current paper is as follows: In Section 2 we will describe AJA, the AJA canvas will be presented in Section 3, and the Requirements table background is presented in Section 4. The results of the test case scenario are presented in Section 5, while the conclusions are drawn in Section 6.

2. The AJA method

2.1. Requirements and advice to be followed

The AJA method is based on principles used in HTA which is considered as the "best known task analysis technique". The authors recommend and encourage the usage of AJA instead of other methods proposed in the past since AJA is designed especially for autonomous marine operations. Therefore, it has a big advantage over the existing methods, which are more extensive and address different kinds of applications.

The past years have seen many developments in ergonomics research and different task analysis methods have been developed, however HTA has remained a central approach. When using a task analysis technique as a method for breaking down an operation, “there is a tendency to fall into the trap of writing down the series of steps a human takes” [11]. The correct way to analyse a task according to Sheridan [2] is to “specify the information required, the decisions to be made, the control actions to be taken”. The task analysis elements include task description, behaviour modelling, risk assessment, hypothesis generation and cost-benefit analysis. In the AJA method, we have chosen an iterative manner to keep the analysis to a manageable size, at the cost of perhaps having to perform the analysis over several iterations, including iterations where additional information from other methods are considered.

Guidelines to be followed

When performing the analysis, a meeting is required which is called the AJA meeting. The form of the meeting is motivated by the form of meetings used for HAZard and OPerability studies (HAZOP), which is “a structured and systematic examination of a planned or existing process or operation in order to identify and evaluate problems that may represent risks to personnel or equipment, or prevent efficient operation”[13]. The main goal of the AJA meeting is to gather and share all available information concerning the operation in question through cooperation between stakeholders. This information is then structured and gathered in a detailed list for sharing. The information can include, but is not limited to, constraints, limitations, restrictions regarding the software/hardware, money, human resources, and any kind of available information that can affect the design or the implementation of the operation. A proposed agenda for the meeting can be as follows:

- Introduction and presentation of participants.
- Presentation of the main goal(s) of the operation.
Presentation of the AJA method.
Recapitulate the context definition and operation concepts.
Perform AJA (as far as possible).
Agree on further actions.

The meeting is driven by the moderator who is responsible for:
- Introducing the method to the client.
- Leading the discussion.
- Ensure completeness of the analysis.

The moderator could be from the team designing the operation or hired from an external company specializing in leading these kinds of meetings. It can for instance be desirable to use an independent third party which does not favour either of the stakeholders.

The secretary is responsible for:
- Preparation of the AJA Table
- Recording the discussion.
- Version control of the AJA table/flow chart.

The AJA table consist of a series of questions to be answered and is described in detail in Section 2.3. The meeting participants should be experts within various aspects of the operation. Meetings including a large number of participants tend to become inefficient and hard to manage. If it is likely that the total number of participants needed exceeds 8-10, then dividing into smaller meetings should be considered.

The responsibilities of the participants are the same as for participants as HAZOP meetings, as described in [17]:
- Be active! Everybody’s contribution is important.
- Be to the point. Avoid endless discussion of details.
- Be critical in a positive way. Not negative, but constructive.
- Be responsible. The person who knows should let others know.

It is unlikely that all questions can be answered during a single AJA meeting even if the total number of participants is kept low. ’Further actions’ could therefore be to choose one or more responsible to actively seek out the relevant or missing information through experts or written material. The AJA table should be updated with this new information, or at least with reference to documentation available elsewhere, before it is distributed among the stakeholders. The person(s) responsible can be chosen from the operation design team, or from the client’s team. The client may have relevant experts in his/her company, even if these experts did not attend the AJA meeting. If a large operation is to be analysed, it may be necessary to perform AJA over several meetings. This gives the opportunity to include new or additional experts to add different perspectives of the operations. It is important that new participants are brought up to date before the meeting in order not to waste time. In the beginning of the meeting the requirements/context specification should be agreed on.

The Autonomous Job Analysis consists of the following steps:
1) Describe the main goal of the operation
2) Divide into sub-operations based on e.g. sequence, parallel behaviour or choices
3) Answer the list of AJA questions described in Table 1.
4) For each sub-operation, go to step 2) and repeat until the sub-operations become trivial tasks.

The following steps are required during post processing:
- The details from the AJA meeting should be processed and distributed among the stakeholders.
- The stakeholders give feedback for possible subsequent iterations.

Another fact that needs to be considered is the presentation of AJA by the moderator. Describing an operation in a clear and informative way is challenging. Different authors prefer different template representations when describing operations. A variation between tables, lists, flowcharts have been proposed and the most common templates are presented in [11]. In [10], the table representation was proposed, together with a flowchart representing the interconnections between sub-operations. That’s the approach we are going to use in our paper as well.
Figure 1: The AJA canvas
Table 1: AJA Table formulation

| ID | Name                                           | Description                                                                 |
|----|------------------------------------------------|-----------------------------------------------------------------------------|
| 1  | Description of sub-operation and corresponding goal | Give a short description of the sub-operation, focusing on the goal without too much technical detail. Achievement of this goal should contribute to the achievement of a goal at a higher level, and eventually the main goal of the operation. |
| 2  | Communication                                   | Communication flow: What key information should be communicated? Communication restrictions: What are the limitations? |
| 3  | Perception                                      | Which information about the environment and the system itself must be available? |
| 4  | Success Criteria                                | List the success criteria for the sub-operation. This can for instance be performance specifications related to accuracy or time. |
| 5  | What can go wrong?                              | Is there anything that can prevent the sub-operation from being successfully accomplished? Be specific about what characterizes abnormal behaviour. |
| 6  | What is the operational safe state?             | Define what state or mode the system should enter when errors occur in order to maintain safety. |
| 7  | Human-Machine Interaction                       | Describe the human-machine interaction and include the required Level of Autonomy |
| 8  | Other premises or requirements                  | Describe other relevant premises for successful execution of the sub-operation, e.g. necessary infrastructure. |
| 9  | Notes and comments                              | Add comments that are relevant for the sub-operation but are not captured by the previous questions in the table. |

2.2. AJA Table formulation
The AJA table consists of rows representing goals and sub-goals, as well as the questions to facilitate a detailed analysis of the operation under evaluation. Each row corresponds to the categories “Communication”, “Perception”, “Success Criteria”, “What can go wrong”, “What is the operational safe state”, “Human-Machine Interaction”, “Other premises or requirements” and “Notes and comments”. The last two rows are to allow for additional information, which do not fit into the other categories. We have carefully chosen the categories based on our experiences on autonomous systems and operations, as well as tested and evaluated AJA together with actual users in multidisciplinary teams to further improve the method. Communication restrictions such as long delay or limited data transmission bandwidth could for instance mean that remote control is no longer possible, and a higher level of autonomy is required.

2.3. Output
The output is a structured description and breakdown of the operation where each sub-operation is individually analysed based on technological and operational constraints revealed by the AJA meeting.

3. The AJA canvas
The AJA canvas (Figure 1) is a tool that we have created in order to ease the application of AJA. It is a graphical representation of the AJA table on a single page. Each block of the canvas is a category of the AJA table and it is aided by questions to ask during the design as well as example answers to
these questions. The idea of the canvas comes from the Business Model Canvas (BMC) [16], [17] that is used as a strategic management and lean start-up template for developing new or documenting existing business models. The way the blocks of the AJA canvas are separated is based on the same philosophy the BMC is using. The first block to be described is the one in the middle. This one is the one that attracts the immediate attention of the reader, so it is important that crucial information is included in that block. Therefore, we decided to dedicate this block to the "Sub-Operation Description". This block in practice divides the canvas in two sides, the left and the right. On the left, we have the blocks that refer to "Communication", "Human Machine Interaction", and "Perception" whereas in the right the blocks of "Success Criteria", "Operational Safe State" and "What can go wrong". Finally, at the bottom we have "Other Possible Inputs" and "Notes/Comments". The placement of the blocks is strategically decided in order to keep similar categories on the same side of the canvas (left or right). At the bottom, the users can also note the number of the sub-operation the canvas is representing in order to relate sub-operations and their corresponding canvases. In order to fill out the canvas the user should print out one copy for each sub-operation to be treated, and use it in meetings between customers, operation designers and field experts (e.g. experts in the area of risk management, robotics, autonomy, instrumentation etc.). This way they can jointly start sketching and discussing the autonomous operation. These meetings are referred to as AJA meetings [10].

4. Requirements Table
After AJA the authors propose the creation of a table referred to as the "Requirements table" that can be used as an extra input to the next development stage. The Requirements table can be made by carefully analyzing the AJA-tables and write these requirements in an agreed upon format.

AT an early stage it is best to focus on functional requirements. For example, one requirement can be that a vehicle shall be able to measure its own position, instead of specifying that it should be equipped with a certain type of sensor that would make it possible to measure this. One challenge is to decide what level of abstraction to choose. In order to avoid endless discussions and at the same time gather useful inputs, one can use comments: A good requirement at an early stage could be:

The vehicle shall measure its own horizontal position with an accuracy of TBD meters (radius). Comment: GPS and inertial navigation might be used. A couple of meters accuracy was discussed. In the requirements table the use of the word “shall” denotes requirements that must be met. Use of the word “should” denotes requirements that are desirable and must be met unless justification is provided for an alternative. Use bold for "shall" and "should". Each requirement shall only contain one "shall" or "should".

Use TBC (To Be Completed) or TBD (To Be Defined) in order to write precise requirements even though all details are not in place. For example: "Accuracy shall be TBD”. Text in italic is used to separate comments, design issues and reasoning from requirements. This helps writing requirements short and precise and still the reader gets the context.

The requirements can be grouped according to the following definitions:

VEH Vehicle requirements. That is AUVs, ROVs and ASVs.
HMI User interface and control station requirements.
COM Communication requirements.
INT Distributed intelligence, typically mapping, cooperation algorithms etc.
GEN General requirements that does not fit into any of the other categories.

Requirements shall be given an identifying number. Requirement numbers should start with the group followed by a unique number. Derived requirements (if any) should have an additional number. For example: GEN-1-1 is the first derived requirement to requirement GEN-1. Requirements can be gathered, and traced to code and tests, by using specialized tools or just a simple spreadsheet for smaller projects.
5. Use-case
The selected use-case to demonstrate AJA, is underwater vehicles used for detection, inspection and tracking of a wastewater plume. During dredging both area surveillance and tracking of plumes are relevant. For oil spills, other strategies can be used in order to detect the source of the oil spill.

For the wastewater plume use-case, the following number of vehicles have been used: AUV: 3, ASV:1, Support vessel:1.

What is the role of each kind of vehicle?
**AUV**: The AUVs will track the plume in order to locate and quantify the scope of the pollution. The more AUVs that are used, the better the resolution of the plume measurements will be. This is especially true when chemical sensors are used instead of cameras, as they can only detect the pollution level in a single point. An additional benefit of having multiple AUVs is that each AUV will have to be less mobile in order to cover the entire plume in satisfactory detail. This will in turn reduce the battery drain and allow for a longer operational time.

**ASV**: The ASV is a relay in order to ease all underwater to surface communications.

**Support Vessel**: The support vessel will transport all the required equipment, robotic vehicles and will supervise all the vehicles that take part in the operation.

**Stage 0: Mission planning**
Actors: Command and Control Centre
Actions to be done: Planning and conditions for re-planning.

**Stage 1: Deployment of AUV’s and ASV’s**
Actors: Support vessel, AUVs
Actions to be done: The AUVs are deployed as near the plume, or potentially the outlet as possible. If necessary one or more ASVs are used for communication between the support ship (or onshore) and the AUVs.

**Stage 2: Detecting and tracking the plume**
Actors: Support vessel, AUVs
Actions to be done: Some or all AUVs are able to detect the plume by using appropriate sensors. The AUVs could swim in and out of the plume and cooperate with each other’s in order to follow and measure the plume. If a vulnerable area needs to be surveyed, for example during dredging, a simplified strategy could be used.

**Stage 3: Share information between AUVs**
Actors: Support vessel, AUVs
Actions to be done: Each AUV reports position and concentration to other AUVs in order to autonomously spread themselves around the plume and also to retransmit information to the surface (see stage 4).

**Stage 4: Share information to the surface**
Actors: Support vessel, AUVs, ASV
Actions to be done: Each (or some) AUV(s) send data to the ASV via a high bandwidth communication link. By retransmitting data between AUVs, it is more likely that all information can be transmitted to the surface vehicle.

**Stage 5: Send information to the Support vessel**
Actors: Support vessel, AUVs
Actions to be done: Data is sent from the ASV to the Support vessel or onshore via RF-link. The possibility of local data storage on AUVs or ASVs and the possibility to ask for retransmission of data, will have to be decided upon.
5.1. AJA Table formulation

Table 2 presents a snapshot example of the AJA-table for the sub-operation number 5 of the plume detection story board.

|   | Description of sub-operation | Detect the plume |
|---|--------------------------------|-------------------|
| 5 | Communication                  | AUV communicates its new position and the sensor data measurements at regular intervals so the operator is able to supervise the movement. |
|   | Perception                     | Beneficial information about sea-current in order to compensate for the forces acting on the AUV. Beneficial information of other AUVs that have detected the plume is critical in that case. |
| Success criteria                  | The sensor detects whether the AUV is inside the plume or not. |
|----------------------------------|---------------------------------------------------------------|
| What can go wrong?               | The sea current is too strong for the AUV to follow its     |
|                                  | trajectory.                                                  |
|                                  | The plume is heading in a different direction compared to     |
|                                  | initial expectations.                                         |
|                                  | The AUV is lost. AUVs are not able to transmit/receive data.  |
|                                  | The sensor fails to detect the plume.                        |
| What is the operational safe state? | If there is a communication problem try to inform the       |
|                                  | operator and other vehicles, otherwise autonomously go to    |
|                                  | the surface and wait for new commands.                       |
| HMI                              | Operator should be able to monitor the AUVs all the time,    |
|                                  | position and status. Operator should have the ability to     |
|                                  | intervene at any time (abort or change mode).                |
| Other premises/requirements       | What is the battery capacity of the AUV?                     |
| Notes/comments                    | This sub-operation runs in parallel with sub-operation 4.    |

5.2. Canvas formulation for the presented storyboard
As far as the AJA canvas example for the presented storyboard is concerned, because of page restrictions we present a canvas for sub-operation 5 only. The others can be generated in a similar manner.

![Canvas Formulation for the Plume Detection Storyboard](image-url)
5.3. Requirements table formulation for the presented storyboard
The communication requirements are used as an example.

Table 3: Snapshot of the requirements table for the presented storyboard sub-operation 5

| COMMUNICATION (COM) | |
|----------------------|-----------------|
| COM-1 | One common communication stack shall be used for the underwater network, which preferably should consist of standardized protocols. |
| COM-2 | Specific vehicles shall be able to relay messages. Comment: Rationale: To increase the range. Comment: Like a dynamic mesh network. Several possible implementation solutions exist. Be aware of bandwidth limitations as well as network latency, on top of the propagation delay. |
| COM-3 | The vehicles shall be able to send time critical messages directly to each other. Comment: E.g. collision avoidance planning |
| COM-4 | Cyclic data periods shall be configurable for different types of data. Comment: Rationale: mission type (e.g. data sampling, scanning, pollution monitoring, repairs in limited spaces), relative distances between vehicles and obstacles, vehicles speeds. Cyclic data periods may overwhelm the communication network. |
| COM-5 | There should be a possibility to detect and cope with bandwidth problems. Comment: This might for example imply to turn off camera live streaming. |
| COM-6 | Underwater modem performances should be adaptable depending on local environmental conditions Comment: Rationale: Bandwidth may vary from location to location. |
| COM-7 | AUVs/ROVs/ASVs shall as a minimum be able to transmit the following data: - Ego localization results (typically own position) - Sensor data - Self-test results (including battery status) - Actual Mode (see INT-1 and INT-2) - Speed - Heading Comment: Sensor data (including camera) may vary between different vehicles. Comment: Ego-monitoring includes useful information from communication modems. Comment: Some of this information could be sent as a short ACK to an external command. |
| COM-8 | AUVs/ROVs/ASVs should as a minimum receive the following data: - Mode selection - Trajectory to be followed or area to be surveyed - Timing requirements - Manual control commands (in manual mode) - List of commands/info from mission planner |
| COM-9 | Underwater protocols should allow robot localization Comment: EVOL modems integrate USBL function. |
| COM-10 | The AUVs shall be able to send data about the chemical concentration and position to each other and the ASV/buoy vessel. |

6. Conclusions
In the current paper AJA are presented. AJA is a method tailored for the design of autonomous marine operations. AJA has been tested and evaluated in real use-cases together with end customers operators and system designers and implementers. By analysing and breaking down an operation, design challenges, needs and limitations regarding autonomous behaviour are revealed. AJA facilitates communication and enhances the understanding between the stakeholders. The AJA canvas contains the categories of the AJA in a single page format, supporting each category with questions to be asked during the design procedure as well as example answers. AJA is demonstrated in a use case scenario which has the goal of detecting, inspecting, and tracking of wastewater plumes. Snapshot examples of
the utilization of the AJA table, the AJA canvas and resulting requirements for the use case scenario are presented in the paper.

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