Cognitive Processes: Final Project

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Abstract

This project focuses on the cognitive decision-making processes of an underwater Remotely Operated Vehicle (ROV) executing a Search and Rescue (SAR) mission. The objective is the recovery of an underwater black box. The ROV explains its decisions using a cognitive map, an explanation protocol, and a "thinking-aloud" textual communication framework designed for human operators.

1 Introduction

The field of human-robot interaction increasingly demands autonomous systems capable of not only performing complex tasks but also communicating their internal reasoning to human operators. In this project, we investigate the cognitive decision-making processes of an underwater Remotely Operated Vehicle (ROV) during a Search and Rescue (SAR) mission, specifically focusing on the recovery of an underwater black box.

The ROV operates in a structured environment equipped with visual landmarks (ARUCO markers) and defined operational boundaries, enabling the construction of a cognitive map that supports both navigation and task execution. Beyond autonomous action, the system is designed to generate clear, human-understandable explanations of its decisions through a dedicated Explanation Protocol and a "thinking-aloud" textual communication framework. These explanations provide real-time feedback to the human operator, enhancing transparency, situational awareness, and trust in the robotic system.

This work combines three core components: (i) the cognitive map, which models the environment, task goals, and feasible robot actions; (ii) an explanation protocol that structures the robot's perception, goals, decisions, justifications, and outcomes; and (iii) a user interface that integrates textual and visual feedback, allowing operators to monitor, confirm, or adjust robot actions during mission execution. By systematically integrating these elements, the system demonstrates how cognitive reasoning and communication can improve operator understanding and confidence, particularly in time-critical and safety-sensitive underwater operations.

The remainder of this report details the design and implementation of the cognitive map, the explanation protocol, mission execution, recorded logs, and a critical evaluation of the system's performance and usability.

2 Cognitive Map

This section describes the cognitive map used by the ROV. The map has been updated from the first deliverable to reflect the final mission parameters, environment, and robot specifications.

2.1 Nodes and Landmarks

The ROV operates inside a rectangular water tank measuring approximately $12\,\mathrm{m} \times 8\,\mathrm{m}$, with a depth of approximately $5\,\mathrm{m}$. The following landmarks are used:

- Nine ARUCO markers arranged in an evenly spaced grid
- Water tank boundaries: four walls, one bottom surface, and one open top surface
- Deployment and recovery coordinates
- The black box node as the mission target

ARUCO markers serve as localization landmarks. Tank boundaries define the operational space. The deployment/recovery point and the black box are considered goal-type nodes.

The following Figure1 depicts the landmarks of the water tank:

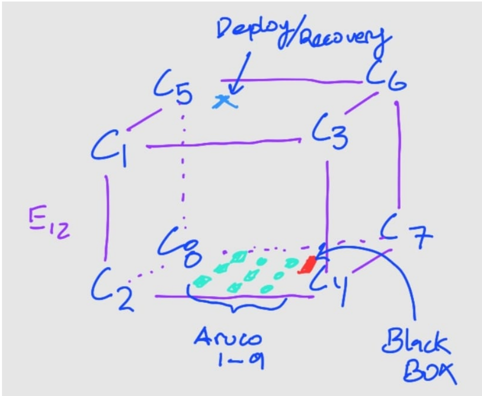

Figure 1: Landmarks diagram

Please note that although corners (C1-C9) and edges(E12, numbers are the corners they connect) are shown in diagrams to define walls, the robot cannot directly detect these elements visually. Instead, proximity is inferred through localization data.

2.2 Connection Edges

Connections between landmarks define the robot's action space, based on energy consumption and operational risk:

- **Navigation paths:** High energy cost, low risk
- **Boundaries and hazards:** High risk, negligible energy cost
- **Recovery waypoints:** Medium energy and medium risk
- **Target interaction:** High energy and high risk due to manipulation tasks

The following diagram in Figure2 a top view of the water tank with the said spaces:

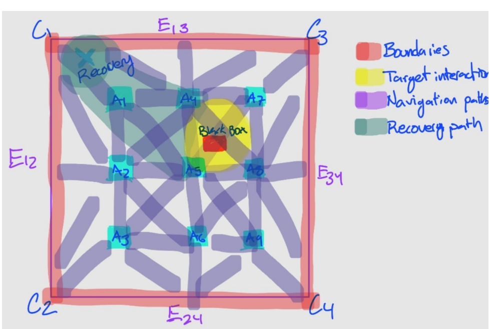

Figure 2: Connections diagram

2.3 Weights and Costs

Weights were designed to allow the robot to evaluate alternative actions based on energy consumption and operational risk. However, during the mission, most navigation decisions were made by a human pilot operating the ROV in teleoperation mode.

The weights consist of a combination of energy cost and risk level, as defined in the connection edges described in the previous subsection. These weights are multiplied by the distance or angular displacement associated with each specific motion. Table 1 summarizes the assigned weights for different operational areas and motion types.

Table 1: Risk and Energy Assessment of ROV Areas and Motions

Area / Motion	**Risk Level**	**Energy Cost**
Operational Areas		
Near boundaries	High	–
Navigation space	Low	–
Target interaction	High	High
Recovery operations	Medium	Medium
Robot Motions		
Roll	High	High
Pitch	High	High
Yaw	Medium	Medium
Heave	Low	High
Sway	Low	High
Surge	Low	Low
Control / stabilization mode	Low	High

As shown in Table 1, qualitative risk and energy levels are categorized as *High*, *Medium*, and *Low*. These levels are mapped to numerical values as follows: High = 3, Medium = 2, and Low = 1.

To compute the total cost of an action, the robot decomposes the overall maneuver into a sequence of motion subsets performed in specific operational areas. For each subset, the risk and energy values are summed and multiplied by the distance or angular displacement. The total action cost is obtained by summing the costs of all subsets:

$$\text{Total Cost} = \sum \left[(\text{Risk} + \text{Energy}) \times \text{Distance or Angle}\right]$$

Example: Cost Evaluation After Deployment Option 1: Move from the deployment point to the center of the pool.

- **Yaw** 20° to align with the target direction (near boundary):
$$(3 + 2) \times 20 = 100$$
- **Surge** for 6 m in the navigation space:
$$(1 + 1) \times 6 = 12$$

Total cost: $100 + 12 = 112$

Option 2: Descend to 1.5 m depth and approach ARUCO marker 1.

- **Heave** 1.5 m near a boundary:
$$(3 + 3) \times 1.5 = 9$$
- **Yaw** 10° toward ARUCO marker 1 (near boundary):
$$(3 + 2) \times 10 = 50$$
- **Surge** 3 m toward the marker (navigation space, with stabilization control active):
$$(1 + 3) \times 3 = 12$$

Total cost: $9 + 50 + 12 = 73$

Option 2 is selected because it results in a lower total cost. This outcome aligns with the intended behavior of the cost function, which favors shorter and more controlled motions that improve stability and situational awareness.

Autonomous decision-making was primarily used during the carabiner attachment task, which followed a predefined finite-state machine. As a result, these weights were not actively used during mission execution.

2.4 Incorporating Memory

Initially, the tank was divided into sectors based on ARUCO markers. Due to improved detection performance, the environment was instead divided into four large quadrants.

The system recorded the following information over time:

- Updated robot position
- Black box detection and confidence level
- Orientation of the black box
- Handle detection and orientation
- User commands and confirmations
- Mission phase

2.5 Update Rules

To avoid unnecessary logging, the following rules were implemented:

- Logging occurs at a fixed rate for continuous processes
- Logged variables depend on the mission phase
- User confirmations trigger explicit log entries
- Detection confidence is averaged over time and stored in short-term memory; once a threshold is reached, detections are permanently recorded

For example, during the mission the ROV may experience multiple brief misdetections occurring over time due to changes in environmental lighting or the presence of similarly shaped objects in the background. These effects can produce false detections in single frames, which should not be recorded. Therefore, a detection is only recorded and updated if it is sustained with sufficient confidence over a defined period of time.

2.6 Route Planning and Decision-Making

Mission execution followed predefined flowcharts used by both the robot and the pilot to determine phase transitions and actions. To create the flowcharts the mission was splitted in 3 steps:

1. Deployment and initialization
2. Search
3. Rescue

The first step "Deployment and initialization" flowchart is the following:

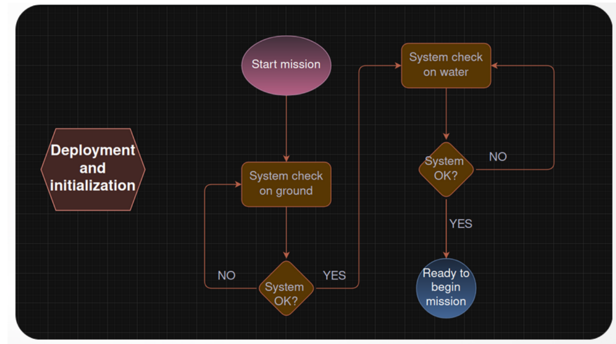

Figure 3: Deployment and Initialization flowchart

The second step "search" flowchart is the following:

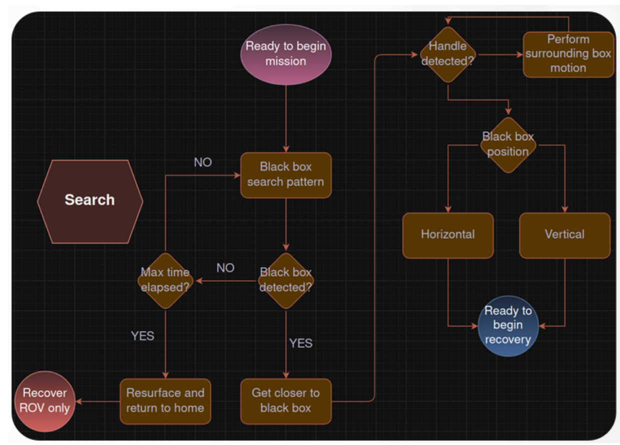

Figure 4: Search step flowcahrt

The third step "Rescue" flowchart is the following:

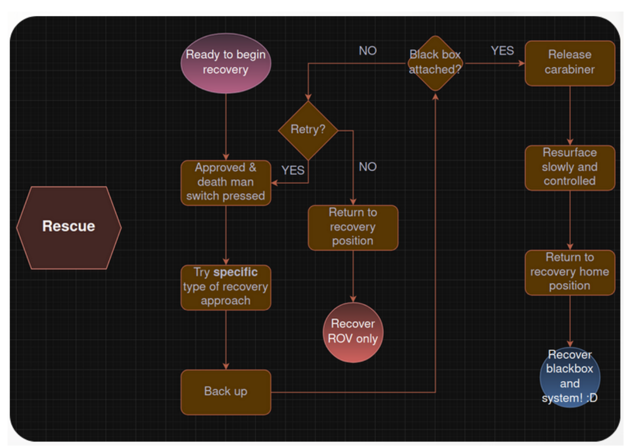

Figure 5: Rescue step general flowchart

Finally, for the specific autonomous approach of the robot to the black box a detailed flowchart for this step was done:

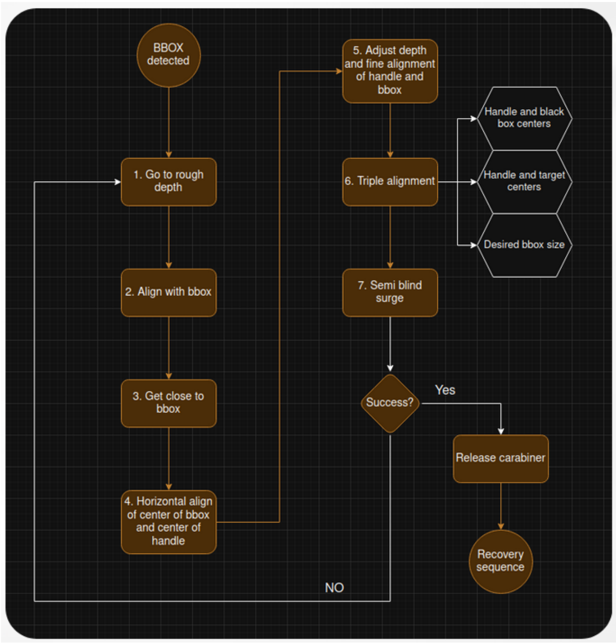

Figure 6: Detailed approach flowchart

3 Explanation Protocol and Evaluation

3.1 Explanation Protocol

Introduction

This Explanation Protocol describes how the underwater robot transforms its internal cognitive map (created in Activity 1) into clear, human-understandable reasoning. The robot's cognitive map consists of:

I) ARUCO markers used as underwater landmarks for localization,

II) The black box as the primary target object,

III) The handle as the final manipulation target.

IV) The purpose of this protocol is to define how the robot verbalizes its perception, goals, decisions, justifications, and outcomes while performing the underwater task.

Explanation Framework

The robot's explanations follow a consistent five-step structure: Perception, Goal, Decision, Justification, and Outcome. This enables transparent communication of both the robot's internal state and the reasoning behind each action.

Perception

This describes what the robot detects through sensors. It includes:

I) ARUCO marker ID and distance

II) Estimated robot position

III) Black box presence

IV) Handle visibility

V) Detection confidence

VI) Visibility or disturbances

Format:

I detect black box at 10m. Confidence: high. Visibility: low.

Goal

This describes what the robot intends to achieve at the current moment.

Format:

"My goal is to recovery the blackbox. My overall objective is to attach the carabiner to the handle."

Decision

This explains which action the robot chooses.

Format:

I decide to move forward because foudn the blackbbox.

Justification

This describes the reasoning behind the chosen action. It may depend on:

Localization accuracy

Best visibility

Lower risk

Highest detection confidence

The shortest or safest path

Format:

I chose this action because I found this is shortest path to reach blackbox.

Outcomes / Feedback

This communicates what happened after executing the action and whether re-planning is needed.

Format:

The result is black box found. I will continue / re-plan because to move towards to desired location.

Template of the Final Explanation Protocol

For each robot step, communication follows this structure:

Perception:

Goal:

Decision:

Justification:

Outcome:

This structured approach ensures consistency and clarity for human operators.

Explanation Protocol Applied to the Underwater Recovery Task

Below are the explanation templates adapted specifically for our case.

Step Type 0 – Mission Start and System Verification

Perception: "I am powered on. Running diagnostic checks: sensors (camera, sonar), thrusters, IMU. No critical errors detected."

Goal: "My goal is to ensure that the system is stable before entering the water."

Decision: "I will perform a water-entry calibration check."

Justification: "Validating system performance before diving prevents mission failure underwater."

Outcome: "All systems nominal. Ready to begin the mission."

Step Type 1 – ARUCO Marker Localization **Perception:** "I detect ARUCO marker ID 12 at 1.3 meters. Confidence: 0.82."

Goal: "My goal is to localize my position before searching for the black box."

Decision: "I will move closer to refine my pose estimation."

Justification: "Approaching the marker increases localization accuracy and reduces drift."

Outcome: "My position estimate is updated. Localization error is reduced."

Step Type 2 – Black Box Search **Perception:** "I detect a dark rectangular object ahead. Confidence: 0.71."

Goal: "My goal is to identify whether this object is the black box."

Decision: "I will approach the object from the front."

Justification: "A frontal viewpoint provides better visibility of the handle area."

Outcome: "The object is confirmed to be the black box."

Step Type 3 – Handle Identification **Perception:** "I detect a handle-shaped structure. Confidence: 0.64."

Goal: "My goal is to confirm that this is the correct handle."

Decision: "I will rotate 12 degrees and lower altitude slightly."

Justification: "This position improves the view of the handle and increases detection confidence."

Outcome: "The handle is confirmed."

Step Type 4 – Carabiner Attachment **Perception:** "The handle is centered and stable in my gripper's viewpoint."

Goal: "My goal is to attach the carabiner to the handle."

Decision: "I will move the gripper forward slowly."

Justification: "A slow approach reduces turbulence and increases the precision of the attachment."

Outcome: "The carabiner is successfully attached. The task is complete."

3.2 Thinking Aloud Simulation Transcript

System Start and Health Check

Operator: ROV-1, confirm startup.

Robot: System online. Performing initial diagnostics.

Internal Reasoning: CPU load 21 percent. Thruster calibration deviation 0.3 percent. IMU drift acceptable.

Robot: All systems nominal. Ready for deployment.

Entry Into Water

Operator: Proceed to water deployment.

Robot: Entering water. Buoyancy stable. Starting localization routine.

Internal Reasoning: Water turbidity medium. Visual sensors adjusting exposure.

ARUCO Marker Search

Robot: Scanning for ARUCO markers to establish starting position.

Operator: Marker detected?

Robot: ARUCO ID 12 detected at distance 1.3 meters. Confidence 0.82. Pose estimation updating.

Internal Reasoning: Localization error reduced from 0.42 m to 0.17 m.

Unexpected Occulusion

Robot: Warning. Visual occlusion detected. Tracking lost.

Operator: Compensating?

Robot: Yes. Switching to inertial prediction and maintaining heading.

Internal Reasoning: Confidence decay rate 0.16 per second. Reacquisition routine activated.

Black Box Search

Robot: Beginning search pattern near pool boundary.

Operator: Did you find Any detections?

Robot: Dark rectangular object detected. Confidence 0.71. Approaching for verification.

Internal Reasoning: Path cost equals distance 4 plus risk 1. Total cost acceptable.

Object Verification

Robot: Distance to object is 0.6 meters. Shape consistent with black box.

Operator: Confirm identity.

Robot: Object confirmed as black box.

Handle Detection

Robot: Scanning for handle.

Internal Reasoning: Image contrast low. Adjusting gain. Rotating 12 degrees.

Robot: Handle detected. Confidence 0.64.

Operator: Increase certainty.

Robot: Lowering altitude. Handle confirmed.

Carabiner Attachment

Operator: Can you Proceed to recovery action.

Robot: Centering handle in gripper view. Stabilizing and reducing thrust.

Internal Reasoning: Motion speed reduced to 0.05 meters per second. Drift correction active.

Robot: Advancing to attach carabiner.

Micro Disturbance

Robot: Lateral drift detected. Correcting alignment.

Internal Reasoning: Disturbance amplitude estimated at 3 to 4 cm.

Task Completion

Robot: Carabiner secured.

Operator: heyyy fiesta Confirm final status.

Robot: Attachment confirmed. Task complete. Ready for extraction.

3.3 Comparison of Explanation Styles

Technical Log Style

- **ARUCO Marker Localization:** Detected marker ID 12 at 1.3 m, confidence 0.82. Pose refined by moving closer. Localization error reduced.
- **Black Box Search:** Detected dark object, confidence 0.71. Approached frontally. Black box confirmed.
- **Handle Identification:** Detected handle-shaped structure, confidence 0.64. Rotated 12 degrees and lowered altitude. Handle confirmed.
- **Carabiner Attachment:** Handle centered in gripper view. Gripper moved forward slowly. Carabiner successfully attached.

Cognitive Narrative Style

- **ARUCO Marker Localization:** "I begin by scanning for markers to understand my position. I see marker 12 ahead, so I move closer to refine my pose, ensuring I start the search accurately."
- **Black Box Search:** "I spot a dark object with moderate confidence. To maximize visibility of the handle, I approach from the front, confirming it is indeed the black box."
- **Handle Identification:** "I detect a handle-like shape. By adjusting my orientation slightly, I increase my confidence and verify it is the correct handle."
- **Carabiner Attachment:** "With the handle centered, I carefully extend my gripper to attach the carabiner, minimizing risk and completing the task successfully."

Analysis of Styles

The **Technical Log Style** is precise and concise, making it ideal for debugging or reviewing data post-mission. However, it may be harder for human operators to intuitively understand the robot's intentions. The **Cognitive Narrative Style** communicates both what the robot does and why, improving transparency and building trust. For real-time human-robot interaction, the cognitive narrative style is more effective.

3.4 Reflection and Conclusion

Key Points on Clear and Trustworthy Explanations

- **Transparency:** Explaining why each action is taken makes the robot's decision-making understandable.
- **Intentions:** Including goals and reasoning helps operators anticipate future actions.
- **Trust:** Human operators trust robots that can articulate both their decisions and the trade-offs considered.

Role of Reasoning

Providing the *why* behind decisions bridges the gap between raw sensor data and meaningful actions. Operators can better interpret uncertainties, risks, and priorities, which is essential for safe and efficient underwater operations.

Integration with Final Communication Design

The Explanation Protocol can be implemented as:

- Real-time textual output on the operator interface.
- Audio or visual "think-aloud" messages in future robotic systems.
- Adaptable format for both technical log review and cognitive narrative communication, depending on the operator's need.

Overall, combining structured technical logs with cognitive narratives ensures both *accuracy* and *explainability*, forming the foundation for trustworthy human-robot interaction.

4 Real life results

THe ROV was deployed and controlled and supervised by a pilot during the mission. Sadly the localization was to heavy to be ran at the same time as the detection and motion alogrithms. Therefore the code had to be adapated to only use the localizatin as position updates but no logic/decision change in actions.

4.1 Cognitive map and mission progress/decisions

The cognitive map was used to define the stages of the mission, specifying the best approach method and coding the steps into the robot. THe pilot knows the mission flow and the robot knows it as well. key parts of the mission are properly defined to know if the robot should continue or not. Finally this cognitive map was used to code a mission controller supervisor node that overviews the whole mission and logs the events.

4.2 Explanation protocol and mission progress/decisions

A user interface was developed to aid the pilot during the mission. IN this user interface several visual aids were added t show the user what the robot is being able to see. But in torder to make things better a proper text communication is needed. The mission ocontrol supervisor prints the explanations of the robot to the user so that it can reply and interact with the robot in real time, confirm or discard events and in general now the current and next phases of the mission.

4.3 recorded logs

A fragment of the logs is displayed bellow. These logs were recorded from an actual real life mission taking place succesfully.

First we can see the initialization and deployment part:

```
MISSION REPORT - START: 2025-12-13
    13:39:22.886053
----------------------------------------------------
[13:39:23] [INFO] Sensors Connected.
    Starting Ground Checks.
[13:39:23] [INFO] >>> GROUND CHECKS PASSED.
    <<<
[13:39:23] [INFO] Waiting for Deployment.
    PRESS 'B' WHEN READY TO START.
[13:39:58] [INFO] >>> MISSION START (User
    Button B). SEARCHING FOR BOX. <<<
```

Second we can see the Search part, where the robot only records the position in long term after being confirmed a good correct detection over time:

```
[13:39:58] [INFO] >>> MISSION START (User Button B). SEARCHING FOR BOX. <<<
[13:40:21] [INFO] BOX DETECTED (Stable). Determining Orientation...
[13:40:25] [INFO] >>> ORIENTATION LOCKED: Horizontal <<<
[13:40:25] [INFO] Target Found. PRESS 'B' TO CONFIRM AND START APPROACH.
[13:40:31] [INFO] USER CONFIRMED (Horizontal). Switching to Approach Mode.
[13:40:31] [INFO] Phase 1: Going to approximate depth to initiate approach...
[13:40:31] [INFO] Please HOLD BUTTON A to engage thrusters for Visual Servoing.
```

Third we can see the Rescue approach part:

```
[13:40:31] [INFO] Please HOLD BUTTON A to engage thrusters for Visual Servoing.
[13:40:54] [INFO] SERVOING UPDATE: Phase 1: Going to approximate depth -4.65m (Curr: -4.00)
[13:40:54] [INFO] SERVOING UPDATE: Phase 1: Going to approximate depth -4.65m (Curr: -3.99)
[13:40:56] [INFO] SERVOING UPDATE: Phase 1: Going to approximate depth -4.65m (Curr: -4.49)
[13:40:56] [INFO] SERVOING UPDATE: Phase 2: Aligning with BBox horizontally (Err: -101)
[13:40:57] [INFO] SERVOING UPDATE: Phase 2: Aligning with BBox horizontally (Err: -124)
[13:40:57] [INFO] SERVOING UPDATE: Phase 2: Aligning with BBox horizontally (Err: -128)
[13:41:12] [INFO] SERVOING UPDATE: Phase 3: Approaching BBox to detect handle (Size: 161/200)
[13:41:13] [INFO] SERVOING UPDATE: Phase 3: Approaching BBox to detect handle (Size: 164/200)
[13:41:13] [INFO] SERVOING UPDATE: Phase 3: Approaching BBox to detect handle (Size: 169/200)
[13:41:13] [INFO] SERVOING UPDATE: Phase 4: Coarse alignment BBox-Handle (Diff: -118)
[13:41:13] [INFO] SERVOING UPDATE: Phase 4: Coarse alignment BBox-Handle (Diff: -109)
[13:41:24] [INFO] SERVOING UPDATE: Phase 5: Descending to -4.885m & Aligning (D_Err: -0.04 | A_Err: -3)
[13:41:24] [INFO] SERVOING UPDATE: Phase 5: Descending to -4.885m & Aligning (D_Err: -0.04 | A_Err: 4)
[13:41:24] [INFO] SERVOING UPDATE: Phase 6: Final 3-Point Station Keeping (P:True C:False Sz:False)
[13:41:25] [INFO] SERVOING UPDATE: Phase 6: Final 3-Point Station Keeping (P:False C:False Sz:False)
[13:42:05] [INFO] SERVOING UPDATE: Phase 6: Final 3-Point Station Keeping (P:False C:True Sz:False)
[13:42:05] [INFO] SERVOING UPDATE: Phase 7: GOING >:) (Blind Surge: 5.0s)
[13:42:05] [INFO] >>> APPROACH SEQUENCE FINISHED (Blind Surge Started). <<<
[13:42:05] [INFO] Did the robot grab the box?
[13:42:05] [INFO] PRESS 'B' to CONFIRM Grasp.
[13:42:09] [INFO] PRESS 'B' to CONFIRM Grasp.
[13:42:09] [INFO] PRESS 'A' to REJECT and RETRY approach.
```

Fourth we can see what happens if the user denies the correct attachment of the carabiner, retrying until confirmation of proper attachment by the user:

```
[13:42:08] [INFO] Did the robot grab the box?
[13:42:08] [INFO] PRESS 'B' to CONFIRM Grasp.
[13:42:08] [INFO] PRESS 'A' to REJECT and RETRY approach.
[13:42:08] [INFO] USER: Grasp Failed / Rejected.
[13:42:08] [INFO] ACTION: Moving to start approach position. Please manually reposition.
[13:42:08] [INFO] Press 'A' again when ready to RETRY APPROACH.
[13:42:09] [INFO] USER: Ready to Retry.
[13:42:09] [INFO] Restarting Visual Approach Sequence...
[13:42:09] [INFO] SERVOING UPDATE: Phase 7: GOING >:) (Blind Surge: 1.8s)
[13:42:09] [INFO] >>> APPROACH SEQUENCE FINISHED (Blind Surge Started). <<<
[13:42:09] [INFO] Did the robot grab the box?
[13:42:09] [INFO] PRESS 'B' to CONFIRM Grasp.
[13:42:09] [INFO] PRESS 'A' to REJECT and RETRY approach.
[13:42:11] [INFO] USER: Grasp Confirmed.
```

Lastly, we can see the end of rescue and return to the recovery point ending the mission:

```
[13:42:11] [INFO] USER: Grasp Confirmed.
[13:42:11] [INFO] ACTION: Please release carabiner and return to recovery point.
[13:42:54] [INFO] Surface Reached (Depth: -0.58m).
[13:42:54] [INFO] ACTION: Recover bbox.
[13:42:54] [INFO] PRESS 'B' for Final Confirmation.
[13:42:59] [INFO] USER: Final Confirmation Received (It is good).
[13:42:59] [INFO] Final Battery Level: 15.35V
[13:42:59] [INFO] End of mission log ready: /home/pablo/ros2_ws/src/bbox/bbox/mission_logs/mission_report_20251213_133922.txt
[13:42:59] [INFO] >>> MISSION COMPLETE <<<
```

4.4 Evaluation of the system

The explanations provided by the robot are generally **clear**, even for non-expert users. Nevertheless, since this project is a prototype and the system still requires a debugging phase, additional information was included in the logs. Especially during the approach and rescue phases, this information may become unclear or distracting for non-expert users. For example, in Phase 6 the system explains the phase goal, but the only indication of the active motions is given through the information shown in parentheses (P:False, C:True, Sz:False). For an expert user familiar with the approach flowchart (shown in previous sections), this notation represents the triple alignment requirements: goal Position, goal Centering, and goal Size.

In terms of **transparency**, the system accurately reflects the true decision-making process. When the debugging information is paired with the user interface (which displays the motion selected by the robot in real time), the operator can fully understand the actions being executed by the robot. These logs are generated automatically during the mission and represent the actual internal process of the robot. For more information regarding the user interface and videos of the robot performing the approach, please refer to the presentation available on Canva.

Regarding **trust**, the human operator can reasonably rely on the robot and feel confident that it is attempting to perform the correct approach to safely retrieve the black box. However, the system can be improved in terms of clarity to allow operators to develop a deeper level of trust in the robot's motions. During the demonstration, it was observed that the robot required additional time to achieve correct alignment. During this period, non-expert observers began to express distrust, as the explanations provided were not sufficiently clear to justify the robot's behavior.

4.5 Reflection and future work

At the beginning of this section, it was explained how the cognitive map supported the generation of explanations. It is important to add that this foundational understanding of how the task should be executed made it possible to clearly identify the key steps and phases that needed to be communicated to the user during the mission. This structured understanding originated directly from the cognitive map and enabled the system to highlight the most relevant information at each stage of execution.

Enabling the robot to communicate its internal state and decisions increased the human pilot's trust in the mission execution. While the robot was performing actions autonomously, only general supervision was required. A deadman switch was implemented to allow the pilot to immediately regain control during autonomous phases if necessary. During the experiments, it was observed that as communication improved, the operator trusted the system more and held the deadman switch for longer periods, allowing the robot to autonomously perform actions for extended durations. This behavior directly reflected the increased confidence resulting from clearer communication.

Although the communication strategy was effective, it can be further improved in future stages. Potential enhancements include adding clearer textual prompts during specific phases, displaying an overall mission flow diagram within the user interface, and enabling more adaptive forms of communication. The integration of a large language model (LLM) to generate more human-like explanations from logs could further improve interpretability. Additionally, enabling two-way interaction—allowing the operator to discuss and modify aspects of the autonomous approach rather than only confirming or rejecting actions—would be a valuable extension. Such interaction would be especially useful in situations where human reasoning is required to improve mission outcomes.

Overall, the use of a communication protocol to explain the ROV's decisions and internal processes during the mission produced positive outcomes across multiple dimensions. It increased the operator's trust in the robot, provided a clearer understanding of the mission state, and improved confidence in the robot's ability to successfully complete the task. The communication protocol also served as a valuable form of long-term memory, allowing the pilot to review mission events afterward and analyze key decision points.

Furthermore, pairing these explanations with a user interface significantly improved the pilot's situational awareness throughout the mission. For example, during the final recovery phase, two people were required to retrieve the robot. Since the pilot could not visually assess the robot's depth beyond the camera view, the system's indication of a safe retrieval depth provided critical information. This feedback allowed the pilot to stop the thrusters at the appropriate moment and ensured safe handling by the assisting partner. Additionally, visual displays of AI-based detections, including bounding boxes and confidence values, increased the credibility of the robot's perception. Requiring user confirmation of these detections further strengthened trust and reinforced effective human–robot collaboration.