# Intervention Payload for Valve Turning with an AUV

Marc Carreras(✉), Arnau Carrera, Narcís Palomeras, David Ribas, Natàlia Hurtós, Quim Salvi, and Pere Ridao

Computer Vision and Robotics Institute, University of Girona, 17071 Girona, Spain
marc.carreras@udg.edu
http://cirs.udg.edu

**Abstract.** This paper presents an intervention payload for an AUV working in a valve turning operation in free-floating control mode. The payload consists of a stereo camera for panel detection, a 4 degrees of freedom electrical manipulator and a specifically designed end-effector, which contains a force and torque sensor, an in-hand camera and a passive effector for valve operation. This payload was designed to be integrated in Girona 500 AUV in the context of an oil application, in which a valve panel must be operated by turning some of the T-bar handles. The paper describes the design of the payload and its interaction with AUV. It also describes the perception systems that have been developed to detect and operate the valves. Experiments in a water tank show the performance of the AUV and the suitability of the payload.

**Keywords:** Autonomous underwater vehicle · Intervention AUV

## 1 Introduction

Intervention-AUVs (I-AUVs) will substitute in the future some of the repetitive tasks that nowadays are being done by ROVs in Oil & Gas infrastructures and other domains. Simple touching applications, such as galvanic measurement at different junction points of long pipes, will be automated by using I-AUVs. Also, intervention applications such as valve turning in a ROV panel, will be done by I-AUVs, which will be in charge of operating underwater infrastructures.

In order to achieve these extended capabilities, several research projects have already done the first steps towards this future technology. ALIVE project [2] developed an I-AUV which was able to dock using an hydraulic gripper to an underwater panel and perform a simple manipulation. The SAUVIM project [5] performed the manipulation of an underwater object using an I-AUV in free-floating mode. TRIDENT project [7] developed a system to search and recover known objects from the seabed using an I-AUV. TRITON project [6] demonstrated the manipulation of valves and connectors while being docked in a sub-sea station. Finally, Pandora [4] project worked in the operation of valves in free-floating control mode. This paper presents the intervention payload that was


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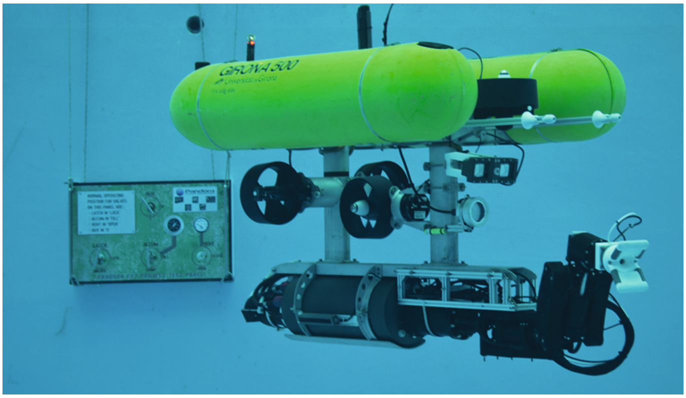



**Fig. 1.** Girona 500 AUV in the water tank, equipped with a stereo camera, a manipulator and a customized end-effector. At the background there is a mock-up of a valve panel.

developed in the Pandora project [4] for valve turning (see Fig. 1). The payload consist of: (1) a stereo camera with lighting for accurate panel detection and positioning with respect to it; (2) a 4 Degrees Of Freedom (DOF) electrical manipulator with position feedback from each joint; and (3) a specifically designed end-effector mounted at the end of the manipulator, which also contains a passive V-shape for T-bar handle turning, a video camera in the middle of the V-shape for handle detection and a Force/Torque (F/T) sensor for detecting the contact between the end-effector and the panel.

The paper describes how the payload was designed and integrated in Girona 500 AUV. It describes the video processing system done for panel and valve detection, and the F/T sensor processing for contact estimation. The paper is structured as follows. After the introduction in Sect. 1, Sect. 2 will present the design of the payload and the integration of all systems: manipulator, end-effector and stereo camera. Section 3 will detail all perception systems required for the valve turning application: manipulator-AUV calibration, panel and valve detection and F/T contact detection. Section 4 will show some results, pointing out the suitability of the intervention payload for I-AUV applications, and it will also conclude the paper.

## 2 Payload Design

### 2.1 Manipulator

Girona 500 can operate as an I-AUV when a manipulator is integrated in the payload area. For the panel intervention task, a 4 rotational DOFs commercial manipulator (ECA ARM 5E Micro) has been used, shown in Fig. 2a. The manipulator can control the Cartesian position ($X$,$Y$,$Z$) and the *roll* ($\Phi$) of the end-effector. Since the manipulator is under-actuated, *pitch* and *yaw* depend on

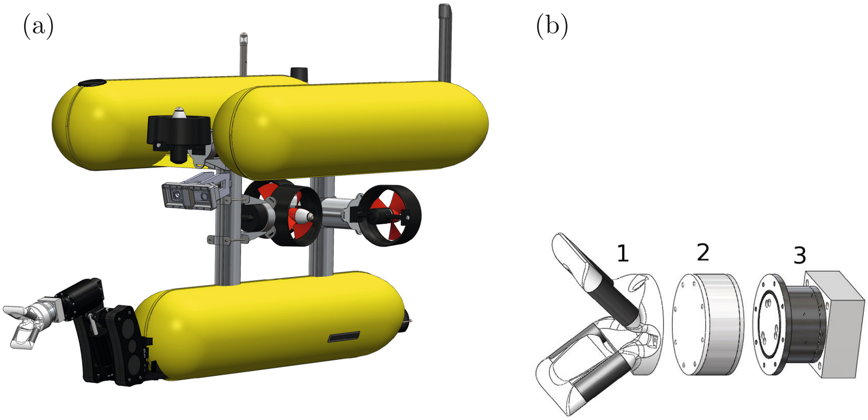



**Fig. 2.** (a) Girona 500 AUV with the 4 DOFs ECA manipulator equipped with a custom end-effector. (b) 3D model of the disassembled customized end-effector, in which three blocks can be distinguished: (1) passive gripper, (2) camera in-hand and (3) F/T sensor.

the reached Cartesian position. The manipulator is rated for 300 meters and is one of the few commercial electrical manipulators available today. It maintains the typical mechanical configuration of ROV manipulators, which is useful when tele-operating with visual feedback. However, for autonomous intervention, the manipulator has a reduced workspace and low speed, which requires the control of the AUV in combination with the manipulator to compensate previous drawbacks. Also, internal joint sensors do not provide absolute orientation, and forward kinematics must be done with an accurate calibration. Improved manipulators in the future will allow more advanced underwater intervention applications.

### 2.2 Custom End-Effector

In order to correctly detect and operate T-bar handles of panel valves with the 4 DOFs manipulator, a custom end-effector was designed and built, as shown in Fig. 2b. The main goal of the end-effector is to compensate the small misalignments in *pitch* and *yaw* that cannot be compensated from the manipulator side, due to the reduced DOFs commented in the previous section. These misalignments depend on the position and orientation of the AUV, which sustains the manipulator, and cannot be corrected at a centimeter scale, unlike the manipulator. Also, there are always some detection and calibration errors which generate some inherent error in the position of the end-effector. Therefore, the external part of the end-effector is a flexible V-shape part which passively corrects the end-effector position and orientation errors, driving the handle of the T-bar valve to its center. The shape of this passive gripper allows the connection of the end-effector and the T-bar handle for rotating the valve, when the manipulator *roll* DOF is actuated.

The second goal of the end-effector is to integrate some sensors to perceive at the intervention point. A first module contains a small analog camera, in the center of the passive gripper, to provide visual feedback during the manipulation. The camera is fixed with respect to the V-shape part and, therefore, it is used to directly measure the orientation error between the end-effector and the valve. After the camera module, a F/T sensor measures the contact forces and torques between the manipulator and the valve. This sensor is used to detect that the contact with the valve handle has been established, by measuring an axial force, and to measure the torque done when rotating the valve. The forces measured by the sensor must take into account the depth of the end-effector, to discount the force generated by the water pressure in the F/T housing. Finally, the complete custom end-effector is mounted in the 4 DOFs manipulator, and will rotate according to the manipulator *roll* DOF.

### 2.3 Stereo Camera

In order to detect the panel and valve handles, a stereo camera (Point Grey Bumblebee 2) was integrated in the front top side of the vehicle (see Fig. 2a), with a specifically designed underwater aluminium housing for a maximum depth of 500 meters (see Fig. 3a).

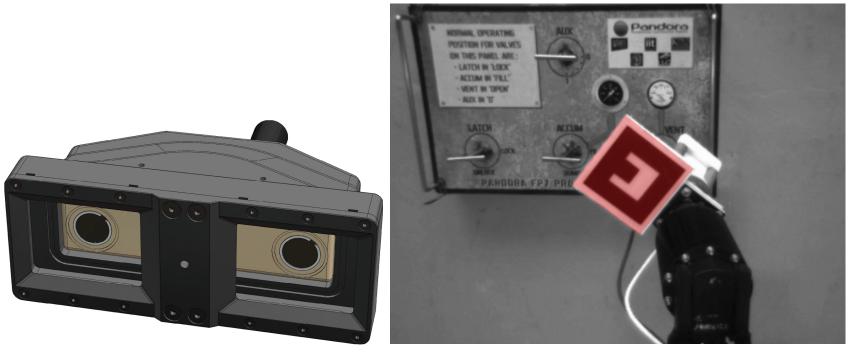
## 3 Perception Systems

### 3.1 Manipulator-AUV Calibration

The manipulator needs an accurate calibration procedure, since it has no absolute encoders to determine an exact position. The authors have proposed a complete procedure to find the state of all joints.

A visual and mechanical calibration method has been designed. To do so, a visual landmark has been integrated at the last joint (wrist), which connects the end-effector with the manipulator. Then, the manipulator is moved to a predefined position where, if the manipulator is approximately calibrated, the marker will be visible by the stereo camera of the vehicle. The wrist will start rotating slowly the end-effector, first 180° and then −360°. During this process, if the marker is detected in a suitable position and orientation (to avoid false positive detections), the inverse kinematic is computed and the arm is calibrated with the values obtained by the visual feedback. Otherwise, the manipulator is moved to the limit of all joints and calibrated using these known positions. The visual landmark provides a more accurate calibration, and it can be regularly applied whenever the user wants a precise calibration.

The algorithm used to compute the position of the landmark with respect the AUV camera relies on the ARToolkit software library [3] to identify, detect and track marks using a monocular camera (see Fig. 3b).




(a) (b)

**Fig. 3.** (a) Stereo camera with housing. (b) ARToolkit algorithm detecting landmark mounted on the wrist of the manipulator.

### 3.2 Panel and Valve Detection

To compute the position of a known landmark, without having to add extra markers, the images gathered by the on-board camera can be compared against an *a priori* known template. In order to extract key-points in the current camera image we use the oriented FAST and rotated BRIEF (ORB) feature extractor that relies on features from accelerated segment test (FAST) corner detection and a binary descriptor vector based on binary robust independent elementary features (BRIEF). These kind of features are present on man-made structures like a valve panel and can be quickly detected.

With these markers, differences between descriptors can be calculated rapidly, allowing real-time matching of key-points at high image frame-rates when compared to other commonly used feature extractors such as scale invariant feature transform (SIFT) and speeded-up robust features (SURF).

Figure 4 illustrates the matching procedure between the *a priori* known template and an image received by the camera. A minimum number of key-points (i.e., 25–40) must be matched between the template and the camera image to satisfy the landmark detection requirement. The detected correspondences are used to compute the transform that relates the template image to the detected landmark. Then, using the camera parameters and the known dimensions of the landmark (i.e., the panel), the landmark's pose can be determined in the camera frame and therefore also in the vehicle frame.

Additionally, since the geometry of the panel is known, the centres of valves on the panel is known in relation to the panel centre. Taking advantage of this, we search a small bounded region of the image for the orientation of the valve. The Hough line transform provides a straightforward method for detecting the orientation of the valves. Outliers are limited by constraining the length of lines and permissible orientations. For more information, please refer to [6].

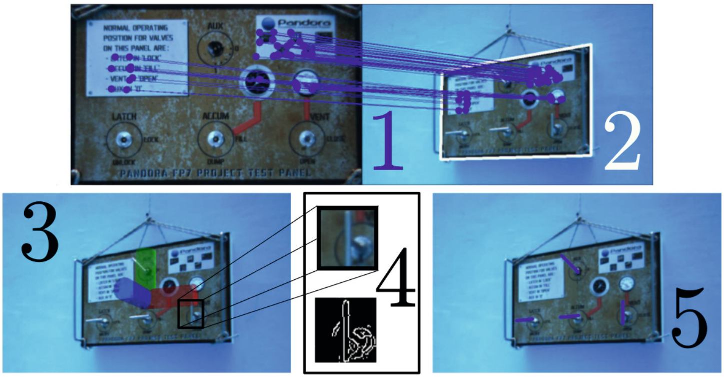



**Fig. 4.** Steps of the landmark detection: (1) Matching of keypoints between the template and camera image. (2) Estimation of the panel corners in the camera image. (3) Estimation of the template's position and rotation in the image by using the camera parameters and the known geometry of the landmark. (4) Extraction of regions of interest and edges. (5) Estimation of valve orientation using Hough transform to detect lines from the edges.

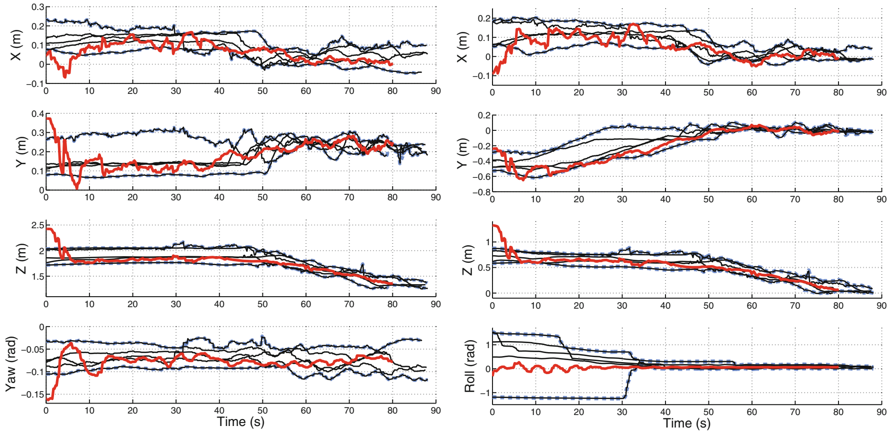
### 3.3 F/T Contact Detection

The F/T sensor is used to detect the contact between the end-effector and the valve handle. In order to correctly use this sensor, several corrections must be done:

**Depth compensation:** The F/T sensor measures the forces and torques that pass through the underwater housing containing the sensor, which resists the water pressure. Therefore, the sensor must discount the force that the water pressure is exerting. In order to do this, the vehicle depth and arm kinematics are used to compute the depth of the end-effector. The pressure of the water generates a force according to the housing area that is compressed, and this force is sustained by the F/T sensor. This force is computed and subtracted from the axial F/T reading.

**Drift compensation:** F/T sensors use strain gauges to determine applied forces and torques. The output signal of strain gauges drift over time even if there is no applied stimulus. Drift compensation is commonly used in industrial and academic applications of strain gauge based sensors. We use the force/torque data just before a contact to calculate a bias point. The bias point is subtracted from the force/torque output.

**Filtering:** F/T data are sampled at 250 Hz. The signals are oversampled to avoid aliasing. The F/T data is filtered using a digital filter with a 3 dB point of 2 Hz. After application of the digital filters, the data is down sampled by a factor of 25.




(a) AUV (b) End-effector

**Fig. 5.** Tele-operated trajectories (black) for the valve turning task, the upper and lower limit is depicted in dashed-blue and an autonomous trajectory is depicted in red. All trajectories are represented in the frame of the target valve. Each plot shows a single DoF for the AUV and the end-effector (Color figure online).

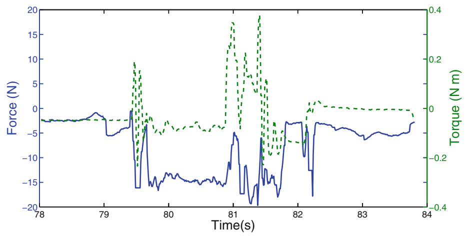



**Fig. 6.** Force and torque in Z axis measured in the end-effector during grasping and turning. It can be appreciated how a negative force was detected when touching the valve, and how the torque increased when operating the roll DOF (at second 81).

## 4 Results and Conclusions

The intervention payload has been extensively used in the context of the Pandora EU project, in a valve turning scenario, in which Girona 500 AUV performs autonomous valve turning operations. Figure 5 shows several trajectories in which the 4 DOFs from the AUV and the 4 DOFs from the manipulator were controlled to approach the valve panel and move the end-effector to the valve handle. The coordinates of the trajectories are relative to the valve handle, so it can be appreciated how the trajectories converged to the correct distance for performing the intervention. From these trajectories, 4 of them (in black) were done in teleoperation mode, and one of them (in red) was done in autonomous mode after a learning process, based on Learning by Demontration [1]. Figure 6 shows the force and the torque applied during the action of turning the valve

90 degrees. It can be appreciated how a contact is sensed with the axial force and how the torque increases when turning the valve. From 24 valve turning attempts, a success of 87.5 % was obtained. The error can be attributed either to a bad detection of the target's pose (i.e. valve pose), that displaces the whole trajectory causing the vehicle to miss the valve, or to a problem in the manipulator's calibration. To diminish the problems caused by the later, a re-calibration procedure was scheduled every two valve turning attempts.

Experiments with water currents perturbations were also performed, being able to succeed with small currents. For better success rates in more challenging and real conditions it will be necessary to integrate better manipulators, with more DOFs, bigger ranges and faster movements. This paper has pointed out the suitability of an intervention payload for an I-AUV in preliminary research experiments. Future developments will continue this work making, step by step, I-AUVs a reality.

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