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Autonomous Intervention on an Underwater Panel mockup by using Visually-Guided Manipulation Techniques ⋆

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Abstract: The long term of this ongoing research has to do with increasing the autonomy levels for underwater intervention missions. Bearing in mind that the specific mission to face, has been the intervention on a panel, in this paper some preliminary results in water tank conditions are presented by using the real mechatronics and the panel mockup. Furthermore, some details are highlighted describing the methodology implemented for the required visually-guided manipulation algorithms, and also a roadmap explaining the different testbeds used for experimental validation, in increasing complexity order, are presented. It is worth mentioning that the aforementioned results would be impossible without previous generated know-how for both, the complete developed mechatronics for the autonomous underwater vehicle for intervention, and the required 3D simulation tool. In summary, thanks to the implemented approach, the intervention system is able to control the way in which the gripper approximates and manipulate the two panel devices (i.e. a valve and a connector) in autonomous manner and, preliminary results demonstrate the reliability and feasibility of this autonomous intervention system in water tank conditions.

Keywords: Underwater Intervention, Autonomous Manipulation, I-AUV, Robot Kinematics, 3D Simulation.

1. INTRODUCTION

Looking for higher autonomy levels in underwater intervention missions, a new concept, called I-AUV (Autonomous Underwater Vehicles for Intervention), was born during the 90's. Presently, endowing an I-AUV with the ability to manipulate an underwater panel in a permanent observatory is one of the challenges of the GRASPER project. GRASPER ("Autonomous Manipulation", under responsibility of the Jaume I University, UJI) represents only a sub-project inside a Spanish Coordinated Project, entitled: TRITON, "Multisensory Based Underwater Intervention through Cooperative Marine Robots", which includes two other sub-projects: COMAROB ("Cooperative Robotics", Univ. of Girona, UdG), and VISUAL2 ("Multisensorial Perception", Univ. of Balearic Islands, UIB).

The TRITON marine robotics research project is focused on the development of autonomous intervention technologies really close to the real needs of the final user and, as such, it can facilitate the potential technological transfer of its results. The project proposes two scenarios as a proof of concept to demonstrate the developed capabilities: (1) the search and recovery of an object of interest (e.g. a "black-box mockup" of a crashed airplane), and (2) the intervention on an underwater panel in a permanent observatory. In the area of search and recovery, previous projects like SAUVIM (Marani et al. (2009)), RAUVI (Sanz et al. (2010)) and more recently TRIDENT (Sanz et al. (2013b)), have become milestone projects, progressively decreasing the operational costs and increasing the degree of autonomy. With respect to the intervention on an underwater panel, the ALIVE project (Evans et al. (2003)) demonstrated the capability of an underwater vehicle to dock autonomously with a ROV-friendly panel by using hydraulic grabs. Nevertheless, unlike in TRITON, a very simple automata-based manipulation strategy was used to open/close a valve. Finally, to the best of the author's knowledge, it is worth mentioning that currently another ongoing project, PANDORA, funded by European Commission, has some similarities with TRITON, where a learning solution for autonomous robot valve turning, using Extended Kalman Filtering and Fuzzy Logic to learn manipulation trajectories via kinaesthetic teaching was recently proposed (Carrera et al. (2012)).

In this paper, recent progress towards autonomous underwater manipulation using UWSim (Prats et al. (2012)) as 3D simulation tool, and new algorithms for visually-guiding the manipulation actions are presented and discussed. A different preliminary approach of the same problem but based on 3D reconstruction, by using laser and vision techniques, was presented before (Sanz et al. (2013a)), where only simulation results were presented. The testbed for evaluating the intervention approach has

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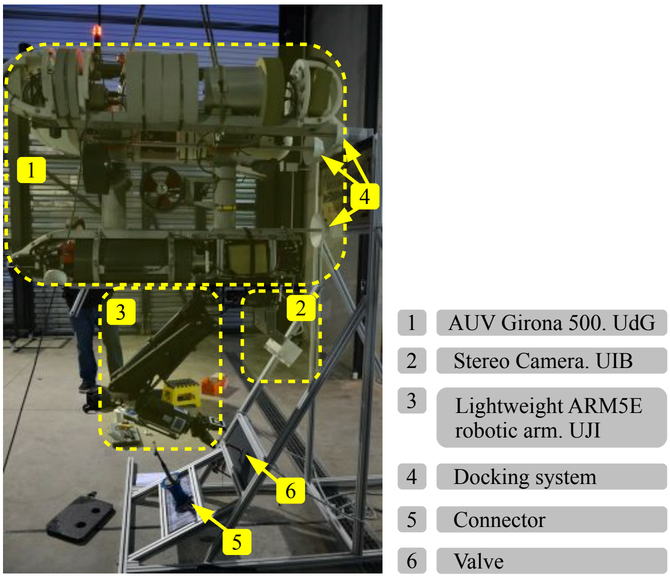
Fig. 1. TRITON hardware system with its components attached to an underwater panel mockup.



been an underwater panel mockup in a permanent observatory, the second scenario proposed by TRITON (Fig. 1).

In the next sections, the methodology followed to perform interventions with the manipulator arm mounted on the AUV is presented. Fist of all, in section 2, a visually-guided algorithm to control the robotic arm is explained and developed. The aim of this algorithm is to increase the robustness of the robotic arm, by preventing calibration joint errors. Secondly, in section 3, the methodology to manipulate a valve and a connector (hot-stab) is detailed.

2. VISUALLY-GUIDED ALGORITHM TO CONTROL A ROBOTIC ARM

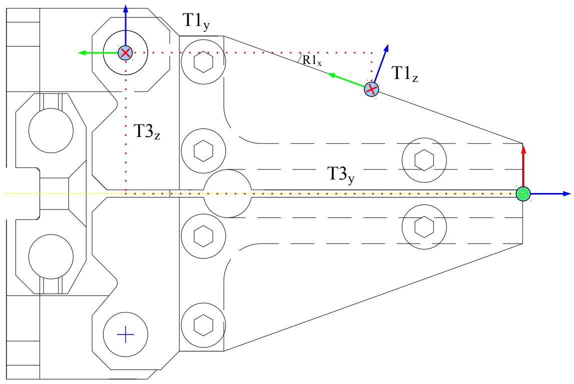
A new algorithm has been developed to control, in an autonomous way, the position and orientation of the end-effector of the Light-Weight ARM5E robotic arm (Fernández et al. (2013)) with respect to its base. This algorithm, updates the values of the each joint of the robotic arm from the detection of a marker (a square that a vision algorithm can recognize and track), placed in a known part of the arm, using a camera. Using this method, some errors such as a bad initialization of the arm or miscalibration of the joints that affect to the kinematics of the arm, can be avoided. Furthermore, the calculation process of the position and orientation of the camera with respect to the base of the arm is not necessary.

2.1 Detection of the marker

As have been said before, a marker with a known size is attached to the robotic arm. This marker is detected using the ARToolkit library [1] . Despite ARToolKit is a software library for building Augmented Reality (AR) applications, the library provides multiple methods for detecting and localizing the position and orientation of a marker.

[1] Available online: `http://www.hitl.washington.edu/artoolkit`

Fig. 2. Static transformations between the marker and the end-effector.



2.2 Transformation between the camera and the end effector

Once the marker has been detected, the library provides the position and orientation of it, with respect of the camera (cMm, which is the homogeneous matrix that represents the relation between two frames, in this cases the camera c and the marker m). So, the next step consists in obtaining the transformation between the camera and the end-effector of the arm (cMe). For this, is just needs to multiply the homogeneous matrix between the camera and the marker (cMm) by the relation between the marker and the end-effector (mMe), which must be known:

$$\mathrm{cMe} = \mathrm{cMm} * \mathrm{mMe}$$

For this experiment, the marker has been placed on the top of the gripper and the end-effector of this arm is in the front of this gripper. So, the relation between the marker and the end-effector, depends, in addition to the static measures (see Fig. 2), on the opening of the gripper at each moment.

Then, the relation between the marker and the end-effector for this gripper, is going to be detailed:

- The first transformation is a rotation around the x axis (R1x) in order to place the marker frame parallel to the palm of the gripper and a translation about the y (T1y) and z (T1z) axis in order to place the frame in the joint of the wrist of the gripper which allows the arm open and close the gripper (mMw).
- The second transformation is a rotation around the x axis, which depends of the opening α of the hand in each detection of the marker.
- The next transformation is translation about the y (T3y) and z (T3z) axis in order to place the frame in the position of the end-effector (wMe).
- Finally, two rotations around the x (R4x) and z (R4z) axis are needed to orientate the frame like the end-effector frame.

2.3 Transformation between the base of the arm and the camera

In order to obtain the relation between the base of the arm and the camera (bMc), the arm is placed in a configuration that allows the camera to see the marker and therefore, calculate the relation between it and the end-effector (cMe) at this moment. On the other hand, the relation between the base of the arm and the end-effector (bMe) is calculated by means of the direct kinematics of the arm at this moment. Once these two matrices (cMe and bMe) have been obtained, in order to calculate the relation between the base of the arm and the camera (bMc), just a product operation is needed:

$$\mathrm{bMc} = \mathrm{bMe} * (\mathrm{cMe})^{-1}$$

This part of the algorithm must be done preferably in a moment when the user is sure that the arm is well calibrated, for example just after the initialization, because the matrix obtained will be used in the next steps and this matrix depends directly on the values of the joints.

2.4 Updating the joints

Once the process of initialization of the algorithm has been done, the camera will be trying to detect the marker all the time, and for each detection, some steps are followed in order to obtain the real value of each joint and update them:

- Calculate the relation between the base of the arm and the end-effector (bMe) at this moment, using the detection of the marker and the values calculated in the initialization of the algorithm:

$$\mathrm{bMe} = \mathrm{bMc} * \mathrm{cMe}$$

- Obtain the real value of the joints q, using the inverse kinematic (IK) of the arm for the frame (bMe) calculated in the previous step:

$$\mathrm{q} = \mathrm{IK}(\mathrm{bMe})$$

- Update the internal values of the arm with the values obtained in the previous step.

2.5 Kinematic control of the arm

Due to the fact that the algorithm updates the internal values of the joints, the user does not need to be careful about whether the marker is detected or not. If during a period of time, the camera cannot detect the marker, the values of the joints are updated depending of its movement, whereupon some errors due to miscalibration can be added, but in the moment that the camera can detect the marker again, these errors are cancelled. And, despite the possible errors during the no detection time, these errors will always be equal or smaller than the errors produced without the algorithm. This is because the errors are produced when the arm is moving, so the movement executed by the arm from the last position without errors is always either equal or smaller.

3. THE METHODOLOGY FOR INTERVENTION

After the vehicle has successfully docked the underwater panel, the intervention begins. Two basic operations have been defined to solve in completely autonomous manner: (1) open/close a valve and (2) plug/unplug a hot-stab connector. The main steps followed for the intervention are summarized hereinafter:

3.1 Initialization of the Visual Kinematic Controller

First of all, the Visual Kinematic Controller must be initialized. For this, the first preferable step is to initialize the robotic arm, to be sure that the values of the joints have not suffered any kind of miscalibration. Then, the arm has to be moved to a predefined initial posture that allows the camera to see clearly the marker. At this moment, the arm waits until the camera estimates the position and orientation of the marker and the algorithm calculates the transformation between the base of the arm and the camera (bMc) following the steps detailed in previous sections. Henceforth, the Visual Kinematic Controller is updating the internal values of each joint for each detection of the marker.

3.2 Detection of the object to Manipulate

Once the Visual Kinematic Controller has been initialized, a service proportionated by the University of Balearic Island is started. This service, using the same camera that detects the marker, estimates the position and orientation of the object to manipulate with respect to the camera (cMo). In order to know the distance between the end-effector and the object to manipulate (eMo), the system uses the relation from the base of the arm to the camera (bMc), and the inverse of the direct kinematics (DK) of the arm at this moment (eMb) (see Fig. 3):

$$\mathrm{eMb} = \mathrm{DK}^{-1}()$$

$$\mathrm{eMo} = \mathrm{eMb} * \mathrm{bMc} * \mathrm{cMo}$$

3.3 Manipulation

After the system has been completely initialized, the manipulation starts (see Fig. 5). In order to reach the positions to manipulate the objects in a correct way, some waypoints respect to the position of the object have been defined (see Fig. 4). To reach each waypoint, the system calculates the Cartesian distance between the end-effector and the waypoint, and using Cartesian velocities, the end-effector tries to reach the position of the waypoint. Due to the arm used, the Light-Weight ARM5E (Fernández et al.

Fig. 3. Complete system frames and transformations.

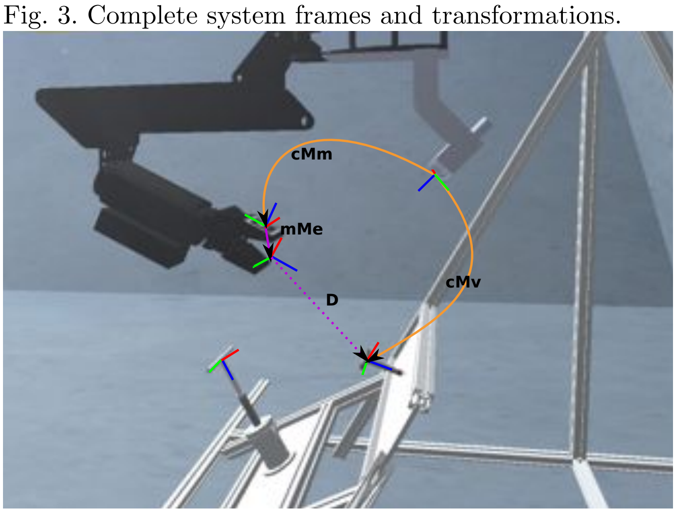


Fig. 4. Waypoints of the interventions.

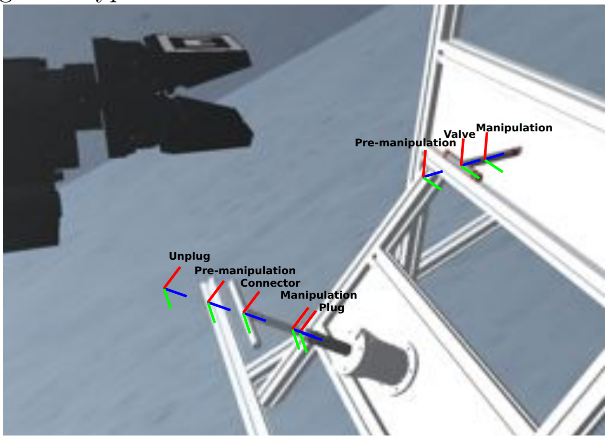
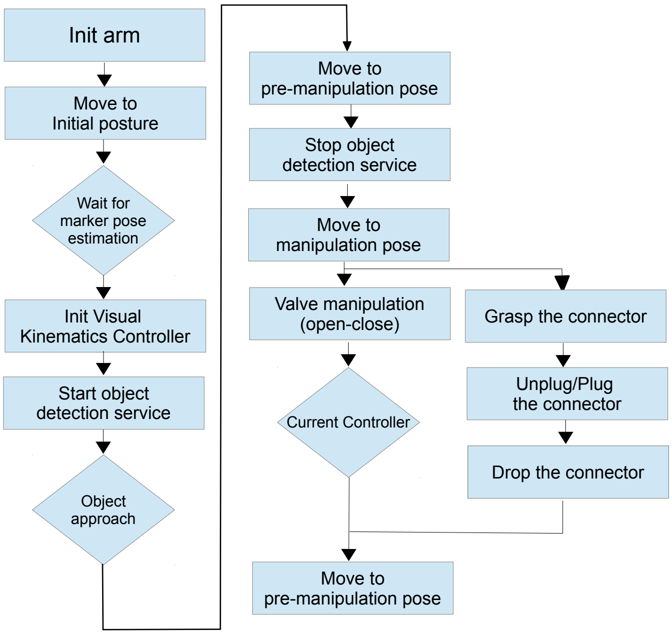


Fig. 5. Flow chart of the intervention.



(2013)), that has just four rotation D.O.F, the orientation with the waypoint is reached is not taken into account. So, both the valve and the connector must be inside a quite wide range of positions reachable for this arm. The process of initialization of the system is similar for the two operations proposed in the paper, but not the process of manipulation.

Open/Close the Valve The next steps are followed to open and close the valve:

- Start the service that provides the position and orientation of the valve.
- Reach the pre-manipulation waypoint. This waypoint is a translation of seven centimeters in the -z axis with respect to the frame of the valve.
- Open the gripper until the opening for manipulation.
- Stop the service to avoid wrong detections when the arm covers the valve.
- Reach the manipulation waypoint. This waypoint is a translation of three centimeters in the z axis respect to the frame of the vale. The translation is just three centimeters because is not necessary to keep the valve completely within the gripper to manipulate it.
- Turn the gripper to the right to open the valve, until the current of the wrist joint exceeds a threshold.
- Turn the gripper to the left to close the valve, until the current of the wrist joint exceeds a threshold.
- Reach the pre-manipulation waypoint.

Plug/Unplug the Hot-Stab Connector The next steps are followed to plug and unplug the connector:

- Start the service that provides the position and orientation of the connector.
- Reach the pre-manipulation waypoint. This waypoint is a translation of seven centimeters in the -z axis with respect to the frame of the connector.
- Fully open the gripper.
- Stop the service to avoid wrong detections when the arm covers the connector.
- Reach the manipulation waypoint. This waypoint is a translation of eight centimeters in the z axis with respect to the frame of the vale. In this case, it is necessary that the valve is completely within the gripper because it has a specific zone that make possible to grasp the connector more robustly.
- Close the gripper completely.
- Reach the unplug waypoint. This waypoint is a translation of eleven centimeters in the –z axis with respect to the frame of the connector. In this waypoint, the connector fully out of the socket.
- Reach the plug waypoint. This waypoint is a translation of nine centimeters in the z axis with respect to the frame of the connector. This waypoint is one centime deeper than the manipulation waypoint, because sometimes is necessary to exert a bit of force to be sure that the connector has entered completely.
- Fully open the gripper.
- Reach the pre-manipulation waypoint.

4. THE ROADMAP FOR EXPERIMENTAL VALIDATION

Following the know-how generated through previous projects (RAUVI, TRIDENT), a roadmap has been developed for experimental validation, independently of the underwater intervention context. So, in Fig. 6 the four basic steps designed for the roadmap are instantiated for a specific intervention mission (i.e. intervention on a panel).

4.1 Simulation

The first step is validating the algorithms and the whole system in simulation. Abstraction from hardware problems allows to think in different solutions. Different approaches were tested in simulation in order to achieve the desired results, such as in Sanz et al. (2013a), where a 3D laser reconstruction was used instead of stereo cameras. The only difference between simulation and real scenario is the physics. Although UWSim simulates physics it is in experimental state so it just simulates collisions. In consequence, manipulation algorithms were slightly modified to work on simulation using position stop instead of current while manipulating the valve. The whole system was successfully tested under UWSim, as can be seen on Fig. 7.

Fig. 6. The four testbeds designed for the experimental roadmap are instantiated for a specific intervention mission (i.e. intervention on a panel).

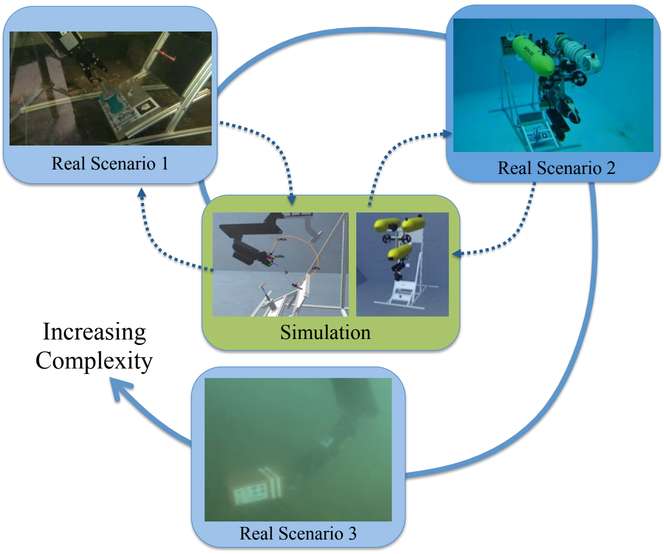
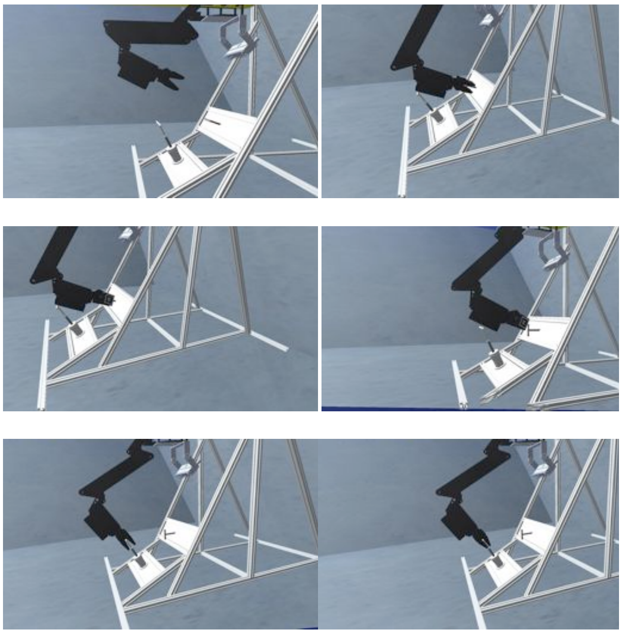


Fig. 7. Intervention simulation in UWSim.



4.2 Real scenario 1: water tank

After the task validation within the UWSim, the system is almost ready to perform the intervention in a real scenario. Thus, once the arm and the camera systems are integrated, the system was tested in a water tank with a panel mockup of an Underwater Observatory. Furthermore, the stereo cameras system, which will be used in the I-AUV, was endowed to the arm. As it has been mention before, the camera attached to the arm identifies the marker placed in the end-effector, meanwhile the stereo camera system is in charge of detecting the marker next to the valve. The validation was tested combining different conditions:

- Attaching the arm to a fixed-base without perturbations: the arm was attached to a fixed-base, which allows the arm to perform the intervention in perfect conditions.
- Adding perturbations to the system: bearing in mind the shallow water intervention in Girona's harbour, some perturbations were added to the system. We assume that in Girona's harbour, the I-AUV will be perturbed due to water currents, so as well as the docking vehicle should be as much stable as possible, the grasping algorithms should be reliable in these conditions. The perturbations were introduced in the system manually, just by moving the arm base.
- The panel is perfectly aligned to the arm: this is the perfect condition for grasping the hot-stab and handle the valve.
- The panel is disaligned.

4.3 Real scenario 2: swimming pool at Girona University

Successful experiments at the swimming pool facilities at Girona University were recently done. Further details of those experiments are out of the scope of this paper.

4.4 Real scenario 3: shallow water

Experiments in shallow water conditions are scheduled for the next months near Girona (Spain). Those experiments will be performed in real harbour conditions.

5. EXPERIMENTAL RESULTS

In this section, the successful experiments of turn the valve and unplug/plug the connector inside the water tank are shown (Fig. 8). The complete sequence can be watched on-line (`http://youtu.be/6pYBL-6Tw4c` and `http://youtu.be/_WkQYtcLsMU`). The Figs. 9 and 10 present the joint evolution during the valve and connector manipulation respectively and the different steps described in the Fig. 5 are also depicted.

6. DISCUSSION AND FUTURE LINES

In this paper, some preliminary results in water tank conditions are presented concerning the GRASPER project. The long term objective is to increase the autonomy levels of an underwater intervention system, through the available I-AUV within the Spanish coordinated project, called TRITON. In particular, some details are highlighted describing the methodology implemented for the visually-guided manipulation algorithms. Furthermore, a roadmap explaining the different testbeds used for experimental validation, in increasing complexity order, has been presented. So, after suitable validation in simulation (UWSim), the real system (hand-arm, and vision) was tested in water tank conditions (UJI), and after succeed there, the integrated system (I-AUV) has been finally tested in water tank conditions again (CIRS, UdG). Only the final sea trials are presently pending for testing. Summarizing, an autonomous intervention has been demonstrated in water tank conditions, under the Spanish coordinated TRITON project, including the docking (out of the scope of this paper) and the intervention on a panel, with two basic operations: 'open and close' a valve, and 'plug and unplug' a connector. As future lines, it is worth

Fig. 8. Intervention in water tank conditions at UJI: valve and connector (hot-stab) manipulation.

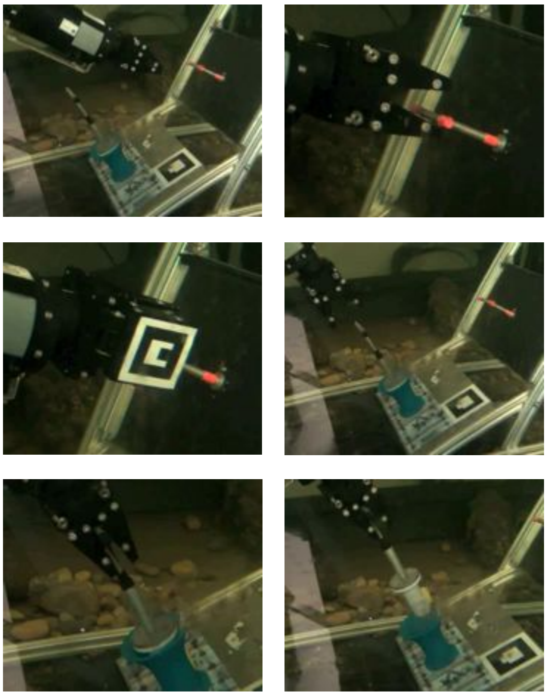
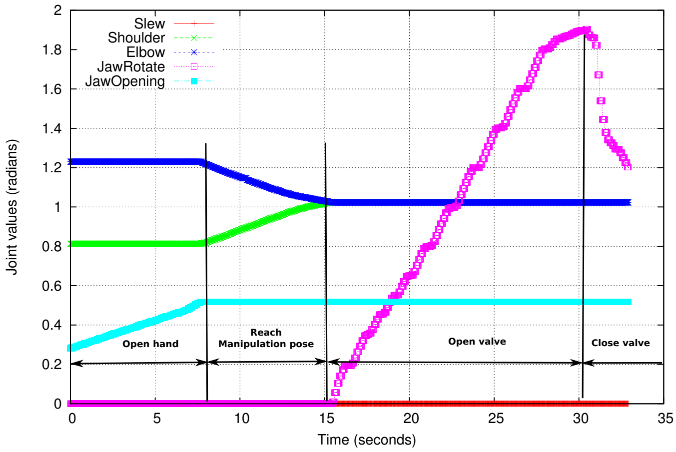


Fig. 9. Joint evolution during valve manipulation.



mentioning that cooperation research actions are now open to explore other paradigms for improvements in manipulation like those based on "learning by demonstration" (Santos et al. (2013)).

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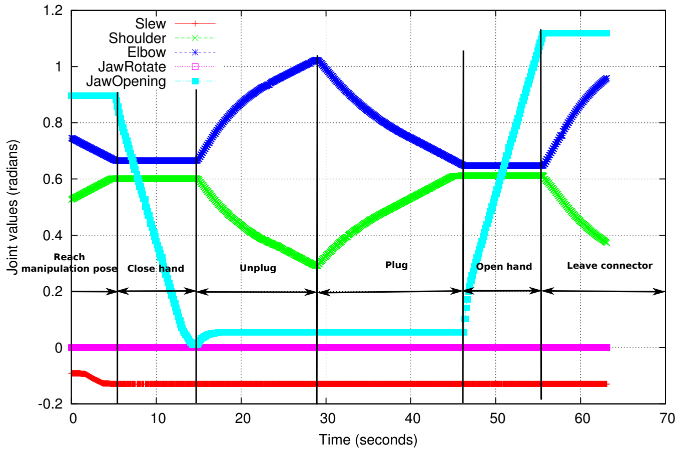
Fig. 10. Joint evolution during connector manipulation.



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