AN ARCHITECTURE FOR SUPERVISING THE TELEMANIPULATION OF AN IAUV-MOUNTED ROBOTIC ARM

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Abstract: A challenging topic in the research of underwater robotics is the development of Intervention Autonomous Underwater Vehicles (IAUVs) that are controlled through an acoustic link. IAUVs should be capable to perform missions using a manipulator arm on deep-sea structures. Such missions require special capabilities like operating in a roughly known environment, which imply a certain degree of autonomy in performing the robotic tasks. A solution is to use the visual servoing at the execution level. Also, due to limitations of the acoustic link, a real video feedback is unrealistic, and thus, a direct telemanipulation (TM) from surface is excluded. Instead, a supervisory control for communicating high level goals from surface to the execution level is used. In this paper the architecture of such a supervision system and its numerical simulation are presented.

Keywords: Supervision, Visual Servoing, Telemanipulation

1. Introduction

The history of the exploration of the seas has started in the late 19th century with the first manned submarines. Since then, man has steadily increased the depth of deep-sea intervention and research. Oil exploitation reaches depth down to 3000 meters while the exploration of the seabed reached the deepest grounds on earth. Human divers were replaced by remote operated vehicles (ROV), sub-sea robots that are linked to the surface by an umbilical. The latest development goes to Autonomous Underwater Vehicles (AUV). These systems feature onboard autonomy and are not controlled and supplied in energy by the surface through a physical link. The control of the vehicle is generally done by an acoustic modem between the vehicle and the surface which only allows a limited communication [1]. AUVs can be divided into three different classes:

- **AUVs for survey**: AUVs for surveying are already widely used for the exploration of the oceans, cartography of the seafloor and probe sampling. These torpedo-like vehicles turn the disadvantage of the missing physical link into an advantage by executing missions over great distances in autonomous mode without the necessity of a support vessel on its side.
- **Hybrid ROVs/AUVs**: This is an intermediate solution between the ROV and an autonomous vehicle. In fact the proposed solution is to use an autonomous carrier vehicle (an AUV) to transport a ROV to the sea-bed. Once arrived there it docks automatically to a docking station which is linked to the surface with to supply energy and communication links. At this stage the ROV can be launched from the carrier by using the energy and the real-time control from the surface. This concept was successfully tested on the SWIMMER vehicle of Cybernetix [2].
- **IAUVs**: This third class of vehicle can be seen as the successor of the classical ROVs. The last ones have found a vast field of application especially in the offshore oil industry. Typical missions are the activation of valves, the deployment of components or the inspection during the installation and maintenance of sub-sea wellheads. Since umbilicals are practicable for depth of more than 3000 meters. IAUVs can be used to replace ROVs in deep sea applications. As the first European IAUV, the ALIVE vehicle can be stated which saw its successful sea trials in October 2003 [3].

The development of key technologies for IAUVs is the subject of the Research Training Network *FREESUB* which consists of seven leading European organisations in the research and development of sub-sea robots.

The supervision of the intervention executed by a manipulator arm onboard of the IAUV plays a critical role in the global control system for such a vehicle due to the limited bandwidth of the acoustic communication. The research in FREESUB concentrated therefore on the architecture of an adequate supervision system able to overcome these limits and enabling such a vehicle to perform tasks autonomously on the seabed.

2. Architecture Overview

The architecture consists in three sub-systems which are inter-connected via a limited rate communication channel.

- *The TM Supervisor* is the graphical supervisory module situated at surface which permit to operator to program the tasks, to simulate and to supervise their execution.
- *The IAUV Simulator* reproduces the operation of the robotic part of the IAUV by simulating its kinematics and geometry.
- *The TM Controller* represents the control module of the robotic arm. It contains also the software interfaces between TM supervisor and IAUV simulator.

2.1. TM Supervisor

The TM Supervisor is based on *Magritte*, a graphical supervision software for the robotic and/or tele-operated system developed by the CEA, France. It is implemented in C++, under Ms Windows or Unix operating systems with a user interface based on OpenInventor and Qt. This interface provides means for the graphic programming of the robots, based on a 3D virtual model of the environment surrounding the robot in order to facilitate the man-machine communication.

Using *Magritte* [13], the operator simulates the task controlling a virtual arm in manual or robotic mode. The key configuration of the arm are then captured as "target images", i.e. images seen by the manipulator camera when in the correct position with respect to environment objects. Practically, the target is defined in terms of a cloud of 3D points $\mathbf{s}_{des,i}$ (see Figure 1) in affine camera space. In this way, the operator may specify the task even if the model he uses is slightly different from the real environment.

During execution, the cloud of 3D points is sent to the controller to parameterize the control law. Furthermore, beside the cloud of 3D points, the coordinates of at least four points in the object frame are sent for pose reconstruction (see 3.2.).

2.2. IAUV Simulator

The simulation environment of the IAUV considering its kinematics is based on *VirtualRobot*[1], a graphic simulator developed by DISA-UPV Robotics group for research and educational purposes. It is implemented in C++, under Ms Windows operating system, with a user interface based on OpenGL. *VirtualRobot* is composed by three modules [8]:

- *VirtualRobot Modeller* (*VRM*): A basic geometric modeler for creating and editing the structures to be used in the simulator.
- *VirtualRobot Translator* (*VRT*): A converter for importing geometric data from common format files as DXF, VRML or 3DS.
- *VirtualRobot Simulator* (*VRS*): The main application for robot simulation and programming.

The most powerful tool of *VRS* is the *VirtualRobot External Access Library* (*VREAL*). This library offers a wide and flexible interface between the simulator and client applications which allows to users to define and manage elements in *VRS* (robots, sensors, maps, environment entities or traces).

VirtualRobot has been used successfully in several projects and applications, as the generation of 3D maps from the data of ultrasonic or laser range sensors [44], haptic device development and testing [6], underwater tele-manipulation [5], 3D devices for robot programming [7], underwater vehicle dynamics simulation and many others.

2.3. TM Controller & Software Interfaces

The TM controller is a server application able to request, to receive, to monitor the commands and to generate the joint and cartesian trajectory references for the controlled mechanisms using a look-ahead interpolation technique. Furthermore, it contains also the

[1] *VirtualRobot* is freeware and can be downloaded from http://www.isa.upv.es/~vrs.

visual servoing loops, and a mechanism to parameterize the above-mentioned control loops using the “target images”.

The interface between TM supervisor and TM controller is based on a message communication protocol (*MCP*) developed by CEA, France for teleoperation applications [14]. *MCP* is based on TCP/IP and UDP/IP network protocols and allows creation of communication channels able to handle entities like *Commands, Events*, and *Status*.

The interface TM controller - IAUV simulator is based on *VREAL* (see 2.2.).

3. Visual Servoing

The visual servoing is implemented for a 6 DOF Samm manipulator arm manufactured by Cybernetix, France. The camera is mounted on the end-effector of the arm, an eye-in-hand configuration.

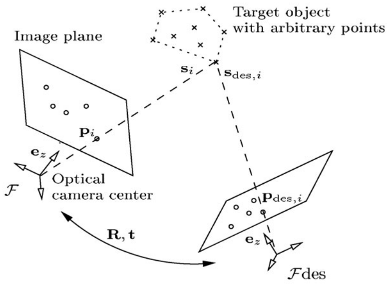

Fig. 1. The control problem

3.1. Camera Model

Usually, it is safe to use the linear perspective model of the camera when the focal length is large. Furthermore, in practice, the simplest model of distorsion it is radial, directed directly or towards from the centre of the image. In order to simulate the camera such a model was used.

3.2. Control Algorithm

Basic visual servoing schemes [9] like *image based* or *pose based* approaches inhibit an analytic analysis with respect to uncertainties on intrinsic camera parameters or pixel measurement errors, due to image treatment algorithms in the control loop (pose based approaches), or due to known rank deficiency and local minima (image based approaches). Recently hybrid approaches [10] provide analytical robustness, but require a noise sensitive partial reconstruction.

In the sequel a novel visual servoing control law is presented, which fulfils the most general *FREESUB* mission (geometric model not available) and which requires the same a priori information as a usual 2D image based approaches (see Figure 1), i.e. perfectly matched image point pairs $\mathbf{p}_i$, $\mathbf{p}_{des,i}$ from an initial and final view of the target, as well as depth information z_i to build up the image Jacobian. Following the linear camera model, 3D points $\mathbf{s}_i$ are reconstructed from image points $\mathbf{p}_i$ by $\mathbf{s}_i = z_i \mathbf{A}^{-1}\mathbf{p}_i$. Several algorithms allow to recover depth up to a common scale factor [10]. Then, the error vector to be controlled incorporates all points[2], $\mathbf{e} = \mathbf{s} - \mathbf{s}_{des}$. Velocity of points s_i in affine camera space are related to the velocity screw of the camera center $\mathbf{u} = \begin{bmatrix} V^T & \Omega^T \end{bmatrix}^T$ through the image Jacobian by $\dot{\mathbf{s}}_i = \mathbf{J}_i \mathbf{u}$ where: $\mathbf{J}_i = \begin{bmatrix} -\mathbf{I}_3 & [\mathbf{s}_i]_\times^T \end{bmatrix}$.

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[2] $\mathbf{s}^T = \begin{bmatrix} s_1^T & \dots & s_n^T \end{bmatrix}$, $\mathbf{e}^T = \begin{bmatrix} e_1^T & \dots & e_n^T \end{bmatrix}$

Then a linearizing control law based on a pseudo-inverse with $\mathbf{u}$ as the usual velocity control can be stated as

$$\mathbf{u} = -\lambda\left(\mathbf{J}^T\mathbf{J}\right)^{-1}\mathbf{J}^T\mathbf{e} \tag{1}$$

with: $\mathbf{J}^T = \left[\mathbf{J}_1^T \quad \mathbf{J}_2^T \quad \ldots \quad \mathbf{J}_n^T\right]$.

In [11], the control law based on a transposed has been proofed to be globally asymptotically stable regardless the camera calibration. This is mainly due to the incorporation of (relative) depth in the error vector. Trajectories are compact due to the image based error, but visibility is not ensured in a formal manner.

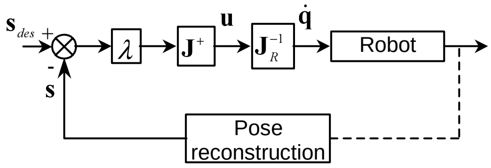

Fig. 2. Visual servoing overall scheme

Figure 2 represent the visual servoing scheme for joint control where $\mathbf{J}_R$ is the robot Jacobian. This was symbolically computed using the *Symoro+* software [12].

If a geometric model of the target is available (at least four points in the object frame, see 2.1), we use DeMenthon's method [15] for performing complete pose reconstruction instead of depth recovery up to a common scale factor. The pose is calculated using an iterative approximation between perspective and scaled orthographic camera models.

4. Results

In case of approach to an object (valve), firstly, graphic programming is used to get the object in the camera field of view, and then approaching is performed by task programming and visual servoing. Figure 3 shows the path described by the end-effector arm. Even using slightly different models on TM supervisor and IAUV simulator the results are promising. By adding new extensions on our simulator, finally, we will be able to accurate measure the performances of our approach.

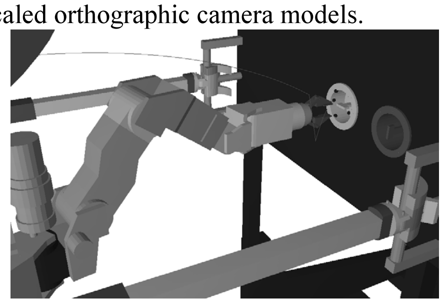

Fig. 3. Screenshot of IAUV simulator

5. Conclusion

The present paper described a simulation architecture of a supervision system for the telemanipulation of an IAUV-mounted robotic arm. The system includes a visual servoing loop and a task programming mechanism based on target definition using synthetic images.

Further work will concentrate on adding feature for image processing and tracking. Finally, the control and supervisory modules of this architecture will be integrated in an real tele-robotic system.

6. Acknowledgements

The authors of this paper want to thank the members of the FREESUB Network. FREESUB is a Research Training Network financed by the European Commission under the Human Potential Programme. Its objective is the development of key technologies for Intervention AUVs and the training of Young Researcher. Four of the authors are, or have been Young Researchers of FREESUB, therefore we want to express our thankfulness to the European Commission for making this research possible. The authors are furthermore much indebted to the DISA Robotics group of the Universidad Politécnica de Valencia for developing the *VirtualRobot* and making this tool accessible to the scientific community.

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