

Pose-based and Velocity-based Approaches to Autonomous Inspection of Subsea Structures

Francesco Maurelli, Tom Larkworthy,
David Lane
Ocean Systems Laboratory,
Heriot-Watt University,
EH14 4AS Edinburgh, UK
f.maurelli@ieee.com, d.m.lane@hw.ac.uk

George C. Karras, Charalampos P. Bechlioulis
and Kostas J. Kyriakopoulos,
School of Mechanical Engineering,
National Technical University of Athens,
Athens 15780, Greece
{karrasg, chmpechl, kkyria}@mail.ntua.gr

I. INTRODUCTION

Autonomous Underwater Vehicles (AUVs) are routinely used for surveillance tasks in the oil&gas domain, as well as in the defence domain. Generally those tasks require little or no interaction with the environment, the robot swim freely in the designated area and has no cognition about the structures and the surroundings. An increased interest both from the research community and from the industry is towards more complex tasks, like autonomous inspection of complex subsea structures, with partial, inadequate or missing previous knowledge, in varying environmental conditions. As part of the European project FP7 PANDORA, the research presented in this paper focuses on inspection of subsea structures.

The main underwater sensors, able to function with varying water conditions, low visibility and scattering are acoustic sensors. The incorporation of acoustic imaging data to the motion control of a robotic system [2], [6], [10], [7], [8], [5], is called sonar servoing, similarly to visual servoing when data from visual sensors (e.g cameras) are used to minimise the control error function.

Most of state-of-the-art techniques address the task of autonomous inspection bounded to specific situations, where the inspected structure is known, the vehicle model available and with limited noise and external disturbances. Lapierre *et al.* present a combined path-following and obstacle avoidance technique which is proven reliable for wheeled robots [4]. However, when tested in the water [1], the vehicle dynamics, currents and disturbances made this technique unsuitable. Sonar servoing is successfully incorporated in the wall inspection task of Kazmi *et al.* [3]. The raw sonar data is pre-processed using a low-pass filter to remove the backscatter noise. Trucco *et al.* showed in [9] that the median filter can be approximated using a 7×7 Gaussian filter at a reduced computational cost. In most real time applications the smoothed image is segmented using a threshold algorithm.

Section II will therefore focus on sonar image analysis in order to determine the relative position of the vehicle with respect to the structure. Section III will focus on two different control strategies, one based on velocity control, one based on pose request. Section IV will present experimental results with



Fig. 1. The Autonomous Underwater Vehicle *Nessie*. On the front, a Tritech Gemini 720i is mounted.

the *Nessie*^{AUV} both with and without external disturbances. Finally, conclusions are highlighted.

II. STRUCTURE DETECTION AND POSE ESTIMATION

This section analyses the relative pose estimation of the vehicle from the sonar image. The sonar mounted on *Nessie*^{AUV} (Figure 1) is a Tritech Gemini 720i Multi-beam Imaging Sonar, with a field of view of 120 degrees with a variable range extending between 0.2 and 120 meters. In the raw image data, the field of view is arranged in to 256 beams, while a maximum of 25 meters range at a scale of 120 pixels per meter in to the vertical bins, with a chosen frame rate of 2Hz.

An empirically defined threshold is applied to the raw image to identify pixels corresponding to a strong reflection. The lower range sonar readings are ignored in the subsequent processing since they are a result of the AUV body structure's reflections. The object to inspect is assumed to be the closest object of reflection, as a result only the first bin close to the sonar is considered. We have compared approaches based on RANSAC, on least square algorithm and on Hough transform. RANSAC algorithm performs better. However, its parameters are very problem-dependent and the output is the one best line fit, discarding other points. In complex structures, there is the risk that only a portion of the structure is considered, i.e. the best line approximation in a subset of the image. If we analyse cases of irregular shapes and corners, a RANSAC

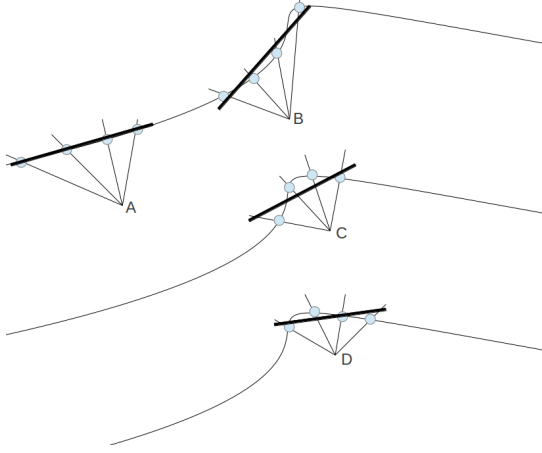


Fig. 2. A least-square approach is able to address non-structured environments and automatically adapt to the changes perceived by the acoustic sensor. The Figure shows how this works in practice, with the vehicle facing the wall at different angles, and the resulting best linear fit. While readjusting its orientation, the vehicle effectively is able to follow complex trajectories.

approach is not able to cope with those, whilst a least square solution considers all the sonar return and is therefore able to take into account a shape change, as soon as it is visible, from the very beginning. Therefore, although RANSAC is to be preferred in case of wall following, with no corners, a least square approach is more general and able to address a wider range of environments, with no specific shape definition, as highlighted in Figure 2.

III. CONTROL SCHEMES

A. Velocity control

Following common practice in the relevant literature, we initially derive a kinematic control scheme considering the actuated velocities u, v, w, r as virtual control inputs (i.e., we design some appropriate desired velocities u_d, v_d, w_d, r_d). Subsequently, the selected velocities are considered as reference velocities in the dynamic model and the actual control inputs X, Y, Z, N are designed.

The analysis will proceed in an Input to State Stability framework, i.e., we shall first study the stability of the actuated degrees of freedom assuming that p, q are absolutely bounded by some constants $\bar{p}, \bar{q}$, that is:

$$ii) |p(t)| \leq \bar{p}, |q(t)| \leq \bar{q}, \forall t \geq 0 \quad (1)$$

and then prove that the overall closed loop system response does not violate the aforementioned bounds.

In this respect, let us first define the position and orientation errors $e_x = x - x_d, e_z = z - z_d$ and $e_\psi = \psi - \psi_d$. Notice, however, that we have not defined a position error in y -axis since: i) we require constant velocity $\dot{y}_d$ in this axis and ii) an accurate estimate of y is almost impossible in the absence of absolute position measurements. To proceed, we select the

following kinematic controller:

$$\begin{bmatrix} u_d \\ v_d \\ w_d \end{bmatrix} = \mathbf{J}_1^{-1}(\eta_2) \begin{bmatrix} -k_x e_x \\ \dot{y}_d \\ -k_z e_z \end{bmatrix} \quad (2)$$

$$r_d = -2k_\psi \frac{c\theta}{c\phi} e_\psi$$

with $k_x, k_z, k_\psi > 0$ and we design the control inputs as

$$\text{follows: } \begin{bmatrix} X \\ Y \\ Z \\ N \end{bmatrix} = \bar{\mathbf{M}} \begin{bmatrix} \dot{u}_d \\ \dot{v}_d \\ \dot{w}_d \\ 0 \\ 0 \\ \dot{r}_d \end{bmatrix} + (\bar{\mathbf{C}}(\mathbf{v}) + \bar{\mathbf{D}}(\mathbf{v})) \begin{bmatrix} u_d \\ v_d \\ w_d \\ 0 \\ 0 \\ r_d \end{bmatrix} + \bar{\mathbf{G}}(\eta) - \begin{bmatrix} k_u e_u \\ k_v e_v \\ k_w e_w \\ k_r e_r \end{bmatrix} - \begin{bmatrix} \mathbf{J}_1^T(\eta_2) \begin{bmatrix} e_x \\ 0 \\ e_z \end{bmatrix} \\ \frac{c\theta}{c\phi} e_\psi \end{bmatrix} \quad (3)$$

where $\bar{\mathbf{M}}, \bar{\mathbf{C}}(\mathbf{v}), \bar{\mathbf{D}}(\mathbf{v})$ and $\bar{\mathbf{G}}(\eta)$ involve the rows of the corresponding dynamic model matrices, concerning only the actuated degrees of freedom (i.e., u, v, w, r). Finally, k_u, k_v, k_w, k_r are positive control gains and $e_u = u - u_d, e_v = v - v_d, e_w = w - w_d, e_r = r - r_d$ denote the velocity errors.

Considering an underwater vehicle and the control scheme (2), (3), there exist positive control gains $k_x, k_z, k_\psi, k_u, k_v, k_w, k_r$ such that the proposed control scheme solves the Structure Inspection task, despite the presence of modeling uncertainties and external disturbances.

B. Pose request

This section presents a control approach based on pose request, rather than on force/velocity. It is useful in cases when the low-level control of the vehicle is not known, or the vehicle model is not available. Therefore it is based on giving pose requests to the pilot system, which will then translate those into force requests. Three cases are considered:

- **angular error:** if the angular error $|\theta_{err}|$ between the desired orientation and the current orientation is greater than a threshold θ_t , the vehicle only requests an angular adjustment. It does not move at the same time, because an angular error might be caused by obstacles at the side of the field of view, thus requiring an immediate rotation, in order to avoid the obstacle and continue to perform the inspection.
- **distance error:** if the vehicle is too close to the structure it is inspecting, the safest behaviour is to ask only for the requested distance from the wall, and adjust any angular error. Being too close to the structure, the field of view is very limited and the safest behaviour is to return to a stable situation, i.e. at the desired distance and desired angle, before re-engage in the dynamic inspection.
- **normal situation:** this happens when $|\theta_{err}| < \theta_t$ and $|dist_{real} - dist_{desired}| < t_{dist}$. In this case, the waypoint is computed and requested in order to complete the inspection.



Fig. 3. (a) The OSL Wave Tank; (b) the CMRE waterfront (sea)

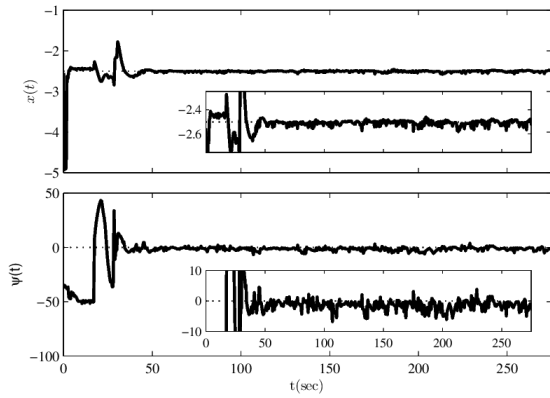


Fig. 4. No disturbances: The distance and orientation with respect to the wall along with the desired values.

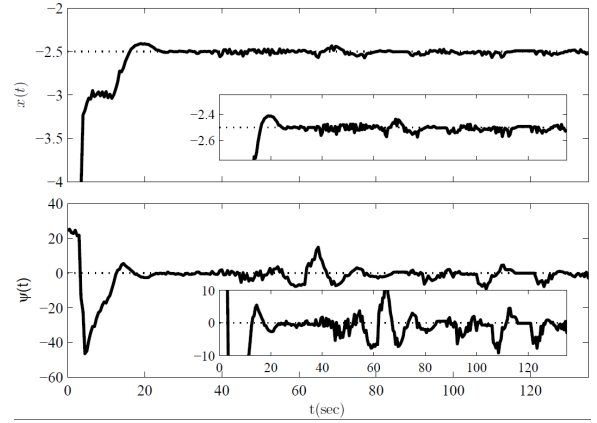


Fig. 5. In the presence of disturbances (medium height waves): The distance and orientation with respect to the wall along with the desired values.

This technique doesn't require for the waypoints to be reached by the vehicle. They can have arbitrary distance, as new waypoints are issued at every sonar frame. Compared to the previous approach, it can handle heterogeneous structures, and it doesn't require any knowledge of the vehicle model. On the other hand, velocity-based control is much smoother in defined situations, where lines are the predominant feature of the structure.

IV. EXPERIMENTAL RESULTS

Experiments took place at the Wave Tank, of the Ocean Systems Lab, Heriot-Watt University and at the waterfront of the NATO Centre for Maritime Research and Experimentation (CMRE), during the SAUC-E competition - sauc-europe.org/ (Figure 3). Being 12x9x2.5 m, the Wave Tank represents an excellent facility to perform experiments in controlled conditions. The wave-making possibility is crucial for testing under varying disturbances. Two sets of experiments were considered: the first one without disturbances, and the second with disturbances (i.e. medium waves). In both cases the vehicle responded very well, as highlighted in Figure 4 and Figure 5. Figure 6 shows the vehicle coping with waves and disturbances.

The condition at the CMRE waterfront were not as controlled as in the Wave Tank, as current sea conditions were depending from several conditions: a fresh water stream, on specific times of the day, waves caused by weather conditions, waves caused by passing ships. The algorithm was tested in various conditions, at different times of the day, and the performances were always very satisfactory. Analytical results show that the error is always bound in between 10 cm for patches of clear wall, even in case of disturbances. Close to corners, the error increases, due to the limited field of view of the sensor. However, as soon as the turn is completed, the error is again bounded. Figure 7 shows the vehicle surveying two walls. The algorithm is general enough to handle corners and not linear surfaces.

Analysing the results of the different trials, it is possible to see that a RANSAC approach is more robust in the case of clear wall, whilst a least square approach allows the vehicle to successfully overcome obstacles and corners. The best structure identification algorithm therefore can be dependent on the type of structure being inspected. A velocity-based approach provides smoother trajectories, mainly in presence of clear walls, and allows to define the desired velocity of the vehicle. A pose-based approach, on the other hand, is more

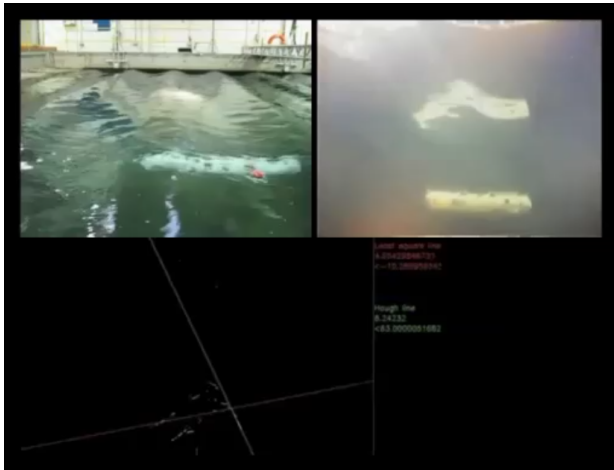


Fig. 6. The vehicle autonomously surveying the wall in presence of waves. The sonar data and first analysis is shown at the bottom of the Figure.

general, and depends on geometric calculation only, leaving all aspects related to the vehicle itself out of the loop. In this case, it is not possible to directly control the velocity, but the pose request does influence the velocity, if the internal control of the vehicle is based on a PID.

V. CONCLUSIONS

This paper has presented approaches towards the problem of underwater autonomous structure inspection. It has analysed several approaches for the acoustic sensor analysis, showing advantages and disadvantages according to the type of environment. Two control strategies have been presented and analysed. One is velocity-based, the second one is pose-based. Finally, experimental results were presented, showing the results of tests at the Wave Tank, in Heriot-Watt University and the CMRE Waterfront. The achieved results showed robustness in presence of disturbances, like waves and currents.

ACKNOWLEDGMENT

The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007-2013 - Challenge 2 - Cognitive Systems, Interaction, Robotics - under grant agreement No 288273 - PANDORA. The authors would like to thank all the other members of the PANDORA project for their support and advice.

REFERENCES

- [1] R. Baxter, J. Cartwright, J. Clay, O. Clert, B. Davis, J. Lopez, F. Maurelli, Y. Petillot, P. Patron, and N. Valeyrie. Nessie v: a new torpedo-shaped hover-capable autonomous underwater vehicle for survey, inspection and intervention. In *AUVSI's Unmanned Systems North America, Denver CO, USA*, August 2010.
- [2] H. Johannsson, M. Kaess, B. Englot, F. Hover, and J. Leonard. Imaging sonar-aided navigation for autonomous underwater harbor surveillance. In *IEEE/RSJ 2010 International Conference on Intelligent Robots and Systems, IROS 2010*, pages 4396–4403, 2010.
- [3] Wajahat Kazmi, Pere Ridao, David Ribas, and Emili Hernández. Dam wall detection and tracking using a mechanically scanned imaging sonar. In *IEEE International Conference on Robotics and Automation*, pages 3228–3233, 2009.

- [4] Lionel Lapierre, Rene Zapata, and Pascal Lepinay. Combined path-following and obstacle avoidance control of a wheeled robot. *Int. Journal of Robotics Research*, page 26:361, 2007.
- [5] P. . Lee, B. . Jun, J. . Li, H. T. Choi, K. Kim, S. . Kim, C. . Lee, S. . Han, B. . Gu, S. . Lee, H. . Chung, and H. S. Choi. Navigation and control system of a deep-sea unmanned underwater vehicle 'hemire'. In *OCEANS 2006 - Asia Pacific*, 2007.
- [6] D. Nad, N. Miskovic, V. Djapic, and Z. Vukic. Sonar aided navigation and control of small uavs. In *2011 19th Mediterranean Conference on Control and Automation, MED 2011*, pages 418–423, 2011.
- [7] M. Pinto, B. Ferreira, A. Matos, and N. Cruz. Using side scan sonar to relative navigation. In *MTS/IEEE Biloxi - Marine Technology for Our Future: Global and Local Challenges, OCEANS 2009*, 2009.
- [8] E. Thurman, J. Riordan, and D. Toal. Integrated control of multiple acoustic sensors for optimal seabed surveying. In *IFAC Proceedings Volumes (IFAC-PapersOnline)*, volume 7, pages 367–372, 2007.
- [9] E. Trucco, YR Petillot, IT Ruiz, K Plakas, and DM Lane. Feature tracking in video and sonar subsea sequences with applications. *Computer Vision and Imaging Understanding*, pages 92–122, 2000.
- [10] Y. Yang and D. Zhu. Research on dynamic path planning of auv based on forward looking sonar and fuzzy control. In *Proceedings of the 2011 Chinese Control and Decision Conference, CCDC 2011*, pages 2425–2430, 2011.

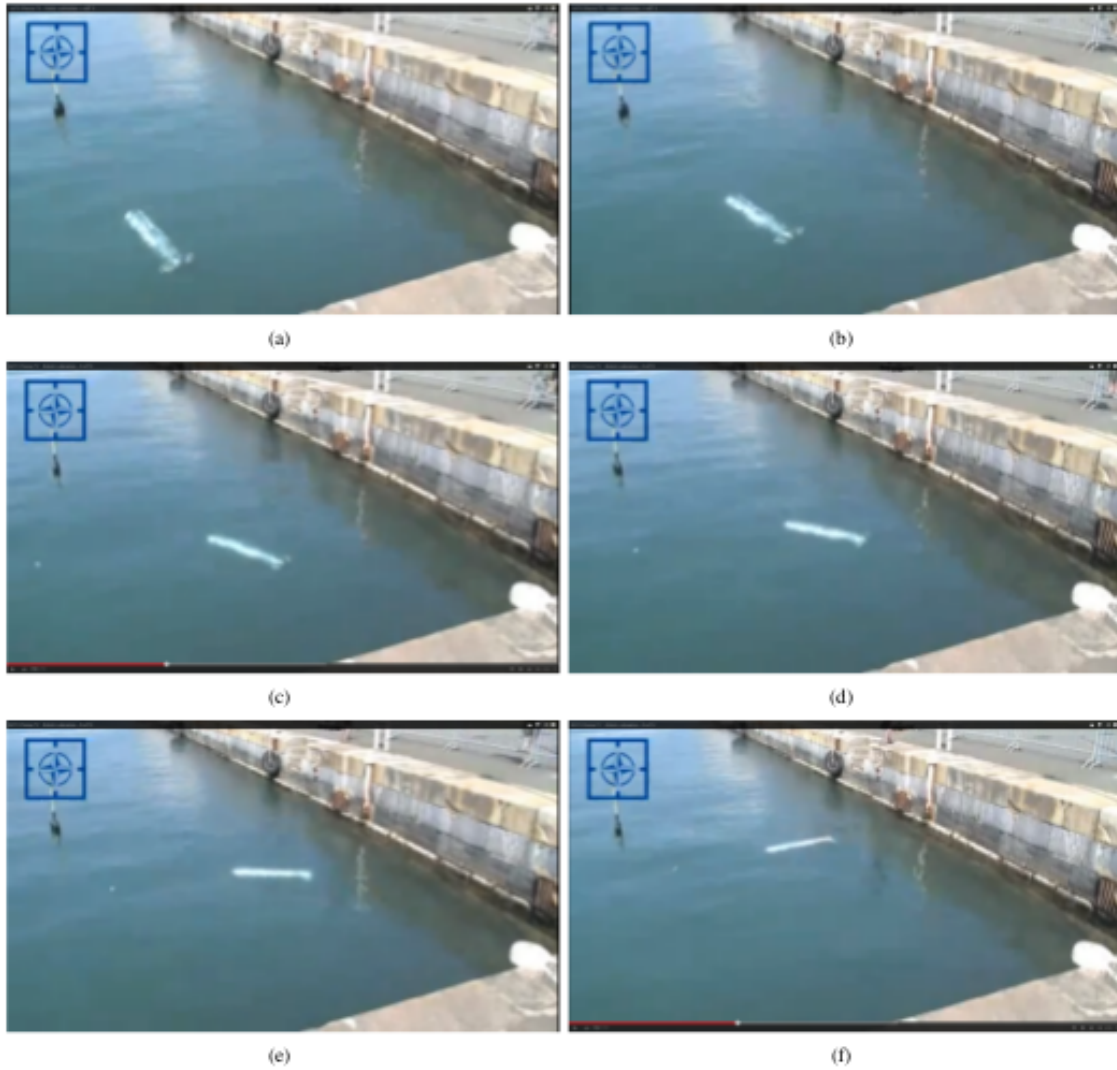


Fig. 7. Wall Inspection at NATO CMRE Waterfront. The envisaged algorithm is able to survey any surface, and overcome angles, as well as unstructured environment. In the Figure, the vehicle is able to turn itself using a very simple and generic approach, not dependent on the specific scenario.