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A guidance and control system proposal for autonomous pipeline inspections

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Abstract This paper describes a guidance and control method, used to guide an autonomous underwater vehicle (AUV) in the task of locating and tracking underwater pipeline and cables. The article also gives details about the simulation and experimental results of the AUV's navigation when searching for simulated pipelines on the seabed in shallow waters.

Sonar based pipeline detection and tracking starts by the acquisition of the sonar image and further realtime processing to distinguish the pipeline from the seabed. Depending on the success of detection, an artificial intelligence (AI) based dynamic path planner must decide the next actions: a search, a skip, an obstacle avoidance or a track process. For instance, pipeline searching involves a series of zig zag explorations of the area where the pipeline is presumably located. Pipeline tracking involves keeping the navigation at fixed distance from the pipe. The path following method proposed in this article is based on a combination of a Lyapunov technique and a PI controller acting over two horizontal thrusters dual torpedo AUV.

The article finally reports some of the stages involved in the detection of the pipeline using a sonar, the guidance and control method used for the generation of a smooth path following trajectory, the main aspects of dynamic mission re-planning, and the results, both in computer simulation as well as sea trial experiments for a search process of a simulated pipeline in shallow waters.

Keywords: Autonomous underwater vehicles, Acoustic imagery, Pipeline inspections, Guidance and control system.

1. Introduction

Tracking pipelines and cables with an AUV consists of detecting the pipeline and recognizing some of its features, like its direction, and then feeding that information directly into the vehicle's mission replanning system, that feeds the guidance and control system, which drives the vehicle along the pipeline without user intervention. Whereas the term "tracking" is sometimes used for pure image analysis, the meaning in this context involves everything that happens from the moment the AUV is launched until it returns with a raw image (e.g. bathymetry) of the pipe. Reacquiring may be necessary if the detection stage fails after many attempts. A representation of such a system is shown in Fig. 1

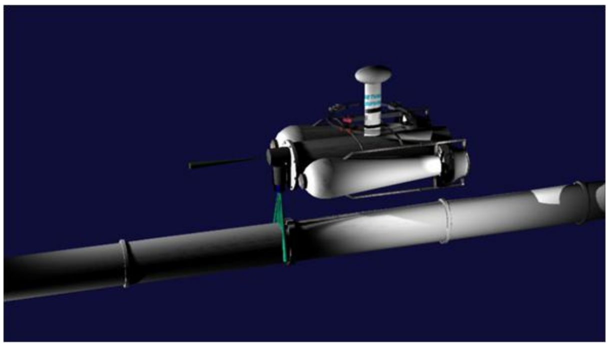

Fig. 1. Sonar based pipeline tracking

Pipeline tracking with an AUV implies the following actions: the pipeline detection and recognition itself, and the guidance and control of the vehicle through a series of waypoints. These waypoints should guide the AUV along the pipe at a predefined offset , without human intervention. If the AUV stops acquiring reliable good quality data, that is, its sensors acquires data below a predefined certainty, it is necessary to correct the trajectory or asses a new running hypothesis (i.e., the target is buried or there is an obstacle in the pipelines trajectory). Such a system requires a dynamic and adaptive path planner to determine the trajectory to follow and a control system capable of taking the robot to the desired waypoints rejecting any possible perturbations.

An AUV tracking system called AUTOTRACKER (2002-2006) [7], funded by the EU under the 5th Framework Programme, was developed with the coordination of the Heriot Watt University (HWU), and designed by a team of universities and companies (the University of Balearic Islands (UIB), the National Technical University of Athens (NTUA) and the companies Subsea and Innovatum). The end users of the project: BP, Alcatel Submarine Networks and SEAS Distribution, provided the necessary inputs for the project to make it useful to them. The system was tested successfully in the North Sea and the results have just been published in [4] and [5]. The authors participated in the design of the path planning strategy of the AUTOTRACKER [4] project using the commercial AUV (Geosub) owned by Subsea7. The search process was implemented with an expert system described in [5] and [6]. Within the framework of a Spanish funded project a new AUV was designed with the goals of testing different search strategies, when complex pipe configurations in an inexpensive and quick way. In an autonomous pipeline/cable inspection system the AUV is sent initially to the survey area and would automatically start a search phase within a corridor specified by the survey in the legacy data. This search is usually performed using a sidescan sonar with the vehicle describing a lawnmower pattern until the target is found or the search is abandoned, to look in a different area of the seabed. The dynamic planner system determines the waypoints of this desired trajectory and the guidance and control system should outcome a smooth trajectory that the AUV has to follow, even in the presence of perturbations and model uncertainties. This paper describes this guidance and control modules for generating the trajectory of the AUV when searching or tracking a pipeline.

The paper is organized as follows: Section II presents the characteristics of the pipeline detection, as a main input to the expert system for waypoint proposal. Section III shows the Lyapunov based guidance strategy applied to the AUV and the simulation results for pipeline searches following a sinusoidal path. Section IV accounts for the design objectives of this AUV. In section V, some conclusions are given. Finally in Section VI, future work about experimental trials of path following and dynamical path re-planning, is presented.

2. Pipeline detection and tracking

Tracking pipelines with an AUV is the process of detecting and recognizing it, and feeding this information directly into the dynamic mission planner, providing the trajectory constructed by four waypoints. These waypoints are fed to the vehicle's guidance and control system, which drives the vehicle along the pipeline without user intervention. The term "tracking" is sometimes used for pure image analysis, although the meaning in this context comprises everything that happens since the AUV is launched untill it returns with raw image (e.g. bathymetry) data covering the pipe. Reacquiring, which may be necessary if the detection ceases for too long is also included.

Today, external pipeline inspections are carried out with towed platforms. ROTV-based acoustic (sidescan sonar) inspection has limited resolution and is used for the rapid, low-cost inspection of many kilometers of pipeline. ROV-based visual survey (with additional sensors) provides a highly detailed, but expensive picture of the pipeline condition. Both inspection techniques become exponentially more expensive as the depth increases. ROTV inspection of pipelines becomes non-viable in water depths greater than 300m due to the long laybacks involved, which increases turnaround times. The speed of ROV inspection is limited by the dynamics of the vessel / umbilical / ROV system which becomes increasingly unwieldy as water depth increases. These features give strong reasons for an automatic pipeline data acquisition with an AUV.

Two tracking methods are often implemented in AUV's, depending on if the pipeline is exposed or buried: (a) Acoustic tracking based on a multibeam echosounder and/or a sidescan sonar and (b) Magnetic tracking based on a magnetic sensor system. The acoustic tracking involves the image analysis of acoustic data and the validation and pipeline's position and direction estimation. The magnetic tracking system can be used for buried pipelines and cables. It also gives information on the burial depth. Then, a sensor fusion system fuses acoustic and magnetic data along with a priori knowledge of the pipeline position and provides tracking data directly to the AUV dynamic mission planner system. Using a sensor fusion system that takes advantage of a priori knowledge of the target to inspect is a very important concept, which inserts a level of intelligence between the detection system and the control system thereby creating a robust system, which works well with strong variation in sensor data quality, like the one existing in the underwater world. Because of the low altitude (less than 5 m) required for inspections, and because fishing nets and rocks are not rare in some areas, there is a need for an obstacle avoidance system (OAS) to be included within the dynamic mission planner. This system usually relies on data coming from two forward- looking mechanical scanning sonars: (a) Profiler with resolution on the vertical plane or (b) Fan-viewer with resolution in the horizontal plane.

This dynamic mission planner controlling the tracking process was built with and expert system shell called COOL, an object oriented version of the CLIPS. A typical inspection mission will start as a normal AUV survey, executing a diving procedure, a search to determine the initial inspection point, positioning at the desired depth, and then starting the target's following. Once the AUV is close to the pipeline, the dynamic mission planner module will keep on performing the tasks involved in tracking: acquiring, following and reacquiring. The cable/pipe information is not used on the guidance and control (autopilot) level, but at the higher level of the dynamic mission planner. This fact has an advantage from a system design point of view, because it decouples the attributes of the detection system from the guidance and control system and thereby allows a relatively static guidance string.

2.1 Pipe detection by signal processing of sonar images

The sonar image is obtained from a set of echoes from the underwater objects and the shadow areas. Both are very important in the image processing because they facilitate the processing and the object recognition.

In Fig. 2, it is shown how these pieces of information, echoes and shadow areas, permit the recognition of many parts of the object in the image. Figure 2 shows a sunken ship sitting on the seabed.

The geometric relationship between echoes and shadow zones introduces an important factor to estimate three dimensionality in a bidimensional image record. In Fig. 3, this relationship can be observed. The object's height can be estimated by the length of the shadow, the altitude of the sonar and its distance to the shadow final point. However, the image quality acquisition depends on some factors, assuming that such sonar has a satisfactory quality in the process of image acquisition, the sensor movement in pitch and yaw should be avoided, because this affect the geometry formation of the image.

The speed of sonar in reference to the seabed should be constant too. This fact include another paradigm analysis in sonar image processing, which is the motion analysis problem. Generally, the motion-analysis problem has two possible solutions: methods based on optical flow and those using feature tracking. The detection of a pipeline with acoustic MBE or sidescan sonar involves steps that are known to the vision pro-

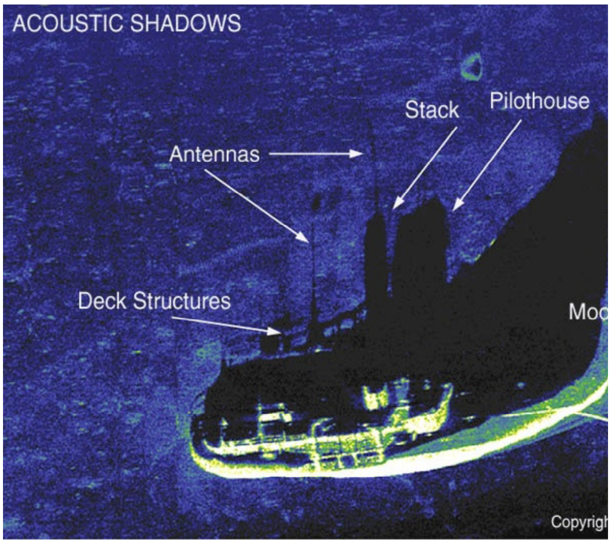

Fig. 2. Sidescan sonar image of sunken ship with shadows

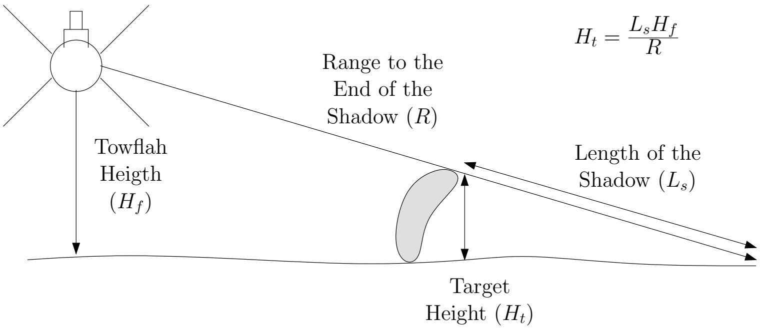

Fig. 3. Sonar signal geometry

cessing community. In Fig. 4, we can see a basic steps involved during image processing.

2.2 Image processing

The extraction of parameters from an image is the basic objective in the image processing, however for an efficient extraction next the acquisition of image from sonar, we need to execute the pre-processing of the input image because the image in the most types of sonar have some noise. The key issue in the pre-processing is to improve the image in order to increase the success of the following procedures. In this example, the pre-processing typically involves techniques for the enhancement of contrasts and removal of noise, isolation of regions by identification of abrupt change in the neighboring pixels. In most of the cases this process occurs by using the Gaussian Filter Mask to make a convolution of the image in grey-scale. The Gaussian convolution mask is circularly symmetrical. The effect of this operation mask can be seen in Fig. 5.

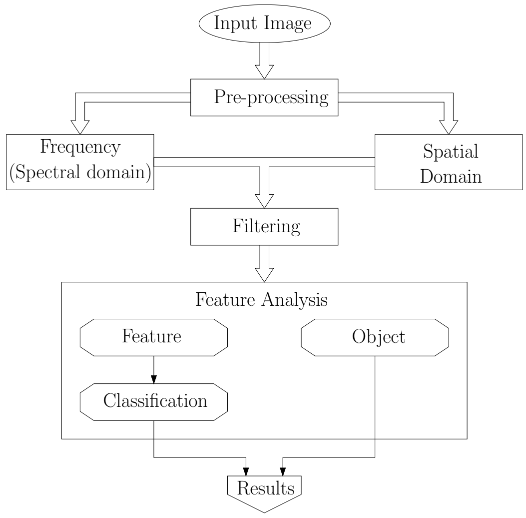

Fig. 4. Basic steps in image processing

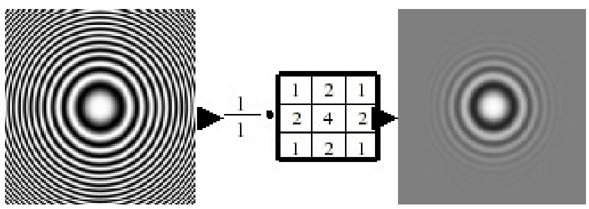

Fig. 5. Smoothing by gaussian mask

2.3 Canny edge detect algorithm

As an example of pre-processing, the Canny edge detection algorithm is applied in Fig. 6. This algorithm is based on gradient intensity in the image by computing a first directional derivative of the whole image in the x and y directions.

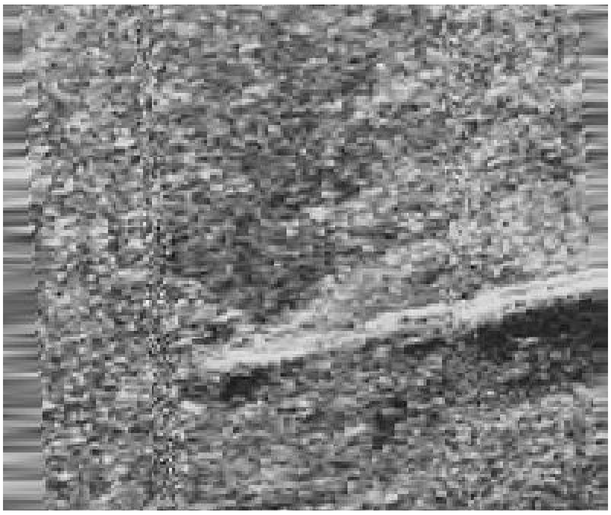

Fig. 6. Pipe on the seabed

This algorithm is based on gradient intensity g_x and g_y in the image by computing a first directional derivative G_x and G_y of the whole image in x and y directions over all pixel into the image $I(x, y)$ This operation over an image is given by the following mathematical expressions:

$$g_x = G_x \star I(i, j) , \quad g_y = G_y \star I(i, j) \tag{1}$$

where: g_x and g_y are gradient intensities on x and y directions, respectively, and G_x and G_y are directional derivative function on x and y directions, respectively. Then the module of both resultant images is calculated:

$$E(i, j) = \sqrt{[g_x(i, j)]^2 + [g_y(i, j)]^2} \tag{2}$$

Hence the edges are detected applying a threshold to that gradient and the result can be seen in Fig. 7.

After this pre-processing an algorithm is needed to evaluate and to detect a model of the object shape in the image. One of the most accepted algorithm is the Hough transform.

2.4 Hough transform

Hough transform is the most accepted method for detecting the shape of an object. It uses the parameter of the object desired for its recognition of straight lines, circles and ellipses. Hough proposed to detect a straight line in the image. For this reason, a point and the slop-intercept equation should be considered. Hence, through this equation, the start point and the end point of a line segment can be recognized. Then, by mean of the threshold compensation, the estimate of the full line structure is reconstructed. A set of parameters for the image of Fig. 6 can be seen in Fig. 8.

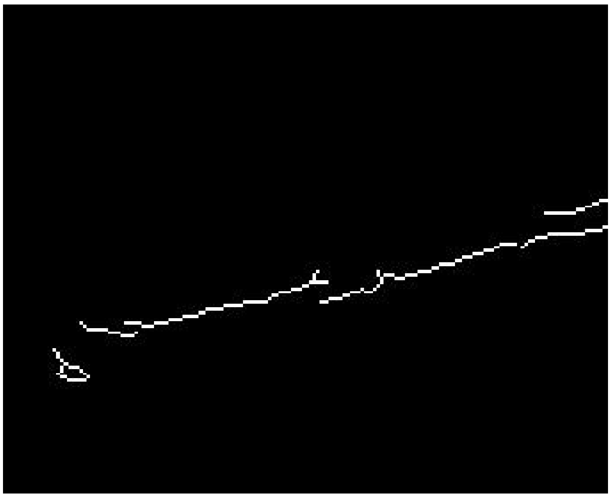

Fig. 7. Image after pre-processing

The original image, Fig. 6, after “line detected” applied in the Target object by a Hough parameters can be seen in Fig. 9.

2.5 Segmentation

For some application, it is necessary to resource to the segmentation stage which divides an entry image into constituent parts or objects.

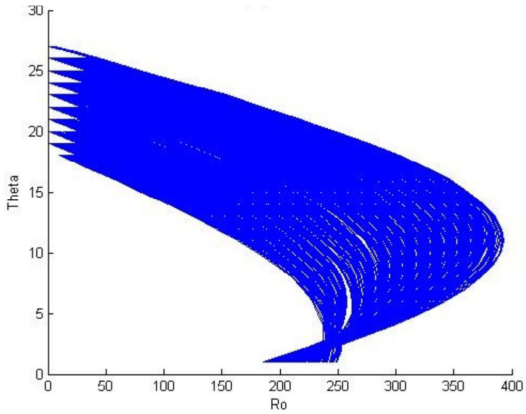

Fig. 8. Hough parameters

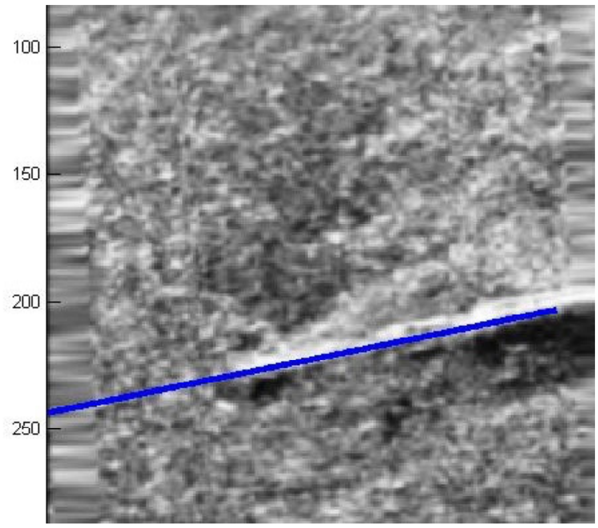

Fig. 9. Original image with line pattern detected

The output of the stage of segmentation is typically formed by data in the form of pixels. After segmentation we divided the image in regions with well defined borders. At first it must be decided whether a set of data should be represented as borders or as complete regions. The border is the appropriate representation when the interest focuses on the characteristics of the external form, such as corners or points of inflection.

2.6 Feature extraction

The process of description, called features extraction, searches to extract features that result in some quantitative information of interest or that are basic to discriminate between classes of objects. It seems that reducing the dimensionality of the data will not improve the performance of the classifier since it does not increase the information content of the input data.

2.7 Recognition and interpretation

The final stage involves recognition and interpretation. Recognition is the process in which a label is assigned to an object, based on information provided by its descriptor, in a clear classification process. The interpretation involves the further allocation of significance to a number of previously recognized objects.

2.8 Neural network

The artificial neural network (ANN) is a computational model inspired by brain human capacity with the purchase and maintenance of knowledge. The ANN has proven high efficiency in recognition of patterns, whith simple architectures like Perceptrons and multilayer Perceptrons (MLP), trained with a backpropagation algorithm. The MLP can do any mapping between sets of variables. The layers of neurons are designed as follows: an input layer in charge of receiving spectral values for each pixel in entire image. Next layers perform the representation of the data to be put into the classifier, conforming what is called a feature space, and are used to make the feature extraction, recognition and the interpretation of objects in the image.

The image processing carried out in this way gives a prioritary input to the dynamic mission planner to know the estimate of the target (pipeline or cable) direction. Hence, with this important information, the planner will generate the four waypoints of the trajectory which will be the reference for the autopilot. This last system will be described in the sequel and an implementation tested in the AUVI prototype will be reported with some preliminary results.

3. Lyapunov based guidance module applied to a pipeline tracker AUV

In order to keep on researching in AI-based dynamic mission planer, guidance and control systems, pattern recognition with sonars for pipeline detection and AUV's navigation, it was decided to construct a low cost and easy to deploy AUV. It should be software compatible with the previous platform used in the Autotracker project, where most of the pipe tracker was developed and run under the OceanShell environment developed jointly with the researchers from Heriot Watt University[7]. The same software that runs on the vehicle can run on a real time simulator previously developed by UIB [4, 5]. Several algorithms mentioned in this article were tested in the Geosub AUV, owned by SubSea7, partner of the Autotracker project. However, even when that vehicle was capable of diving at great depths with accuracy and fairly good autonomy, the operational costs of the trials were too expensive for a university budget. Then, the idea of having a shallow water AUV to test all the algorithms seemed to be very appealing, minimizing costs of each sea trial. A light AUV capable of porting necessary sensors for specific missions with a plug and play feature would be more than enough to validate the new algorithms. This was fully achieved with the AUVI prototype shown in Fig. 10. AUVI stands for Autonomous Underwater Vehicle for Inspections [6]. It has a dual torpedo shape, with two propellers, mounted in an aluminum frame and equipped with a Tritech SuperSeaKing imaging sonar.

Fig. 10. Photograph of the AUVI

A photograph of the prototype can be observed on Fig. 10. AUVI was designed to operate predominantly near the water surface, travelling at low speeds, where the wave resistance is negligibly small. Considering this operational feature, the general model can be reduced to only six equations that represents the AUV's movements on a plane of constant depth [1].

The principal control objective proposed for the AUVI is to closely track a predefined constant depth path $\mathbf{p}^* = [x^*, y^*]^T$, even in the presence of disturbances and model uncertainties. To fulfill this requirement, a method based on a combination of a Lyapunov controller and a standard PI was employed. The method was applied to a vehicle designed for other oceanography purposes [3]. The technique was reformulated for the AUVI's autopilot with a new problem in mind: zig-zag path following for pipeline searching with acoustic sonar. This autopilot approach is based on the scheme shown in Fig. 11. It includes two main blocks, called the Guidance module and the PI Control module. The former generates on-line the necessary references of speed and orientation that would allow to converge towards the desired path and follow it. This references are fed to the Control module, which is composed of a PI controller that regulates the dynamic behavior of the AUVI in the reaching and tracking phases.

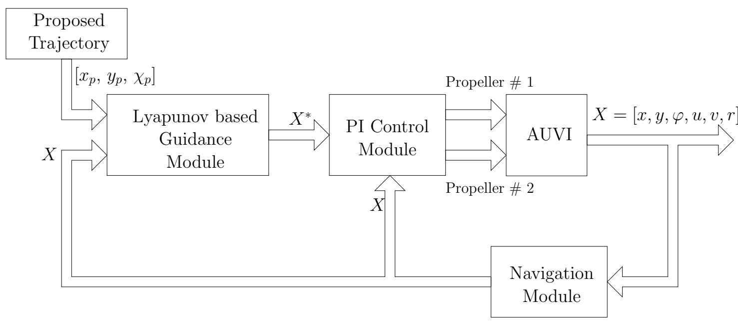

Fig. 11. Guidance and Control System Design

3.1 Guidance module description

A key element for the efficient operation of the whole control system is the on-line generation of appropriate references for it. With this aim, a path following Lyapunov-based algorithm, adapted from [2], has been developed for the AUVI. The algorithm is based on the postulation of two fictitious particles, one of them belonging to the prescribed path and the other corresponding to a particle within the AUV. In particular it can be generally associated with the AUV's center of buoyancy). Then, considering the relative positions of these particles the method determines: a) the velocity and orientation that the AUV's particle must follow in order to approach the path particle, and b) the path particle position refreshment in order not to be reached by the AUV's particle. A detailed description of the method is given in the following paragraphs.

Consider an ideal particle p without dynamics, whose position and speed in a plane of constant depth are respectively described in the N-frame by the vectors $\mathbf{p} = [x, y]^T$ and $\dot{\mathbf{p}} = [\dot{x}, \dot{y}]^T$. The speed vector can also be characterized by its magnitude and orientation (see Fig. 12):

$$U_d = \|\dot{\mathbf{p}}\|_2 \quad (3)$$

$$\chi_d = \arctan\left(\frac{\dot{y}}{\dot{x}}\right) \quad (4)$$

In the following paragraphs they will be determined the expressions corresponding to these variables, in order to ensure the convergence of the hypothetical ideal particle towards a desired path (on the same constant depth plane) and follow it. The desired path geometric locus is continuously parameterized by a time dependant scalar variable (ϖ).

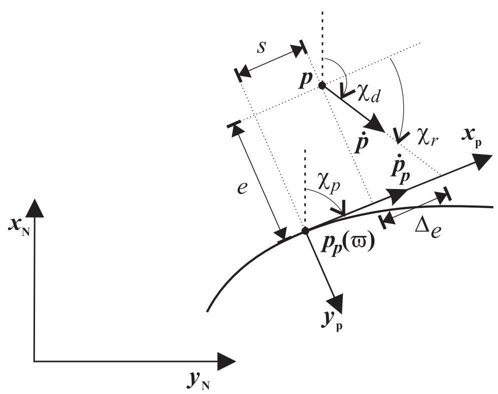

Fig. 12. Navigation Scheme

The path particle (p_p) of this geometric locus whose instantaneous position in the N-frame is denoted as $\mathbf{p}_p(\varpi) = [x_p(\varpi), y_p(\varpi)]$.

With the purposes of developing a search of a pipeline, a sinusoidal trajectory was chosen. In this case the desired path $\mathbf{p}_p$ is defined by choosing:

$$y_p = \varpi \tag{5}$$
$$x_p = A \sin(\varpi) \tag{6}$$

where A is the width of the corridor where the search is performed.

The orientation of this particle is defined by its evolution on the desired path:

$$\chi_p = \arctan \left[\frac{\frac{dy_p(\varpi)}{d\varpi} \times \frac{d\varpi}{dt}}{\frac{dx_p(\varpi)}{d\varpi} \times \frac{d\varpi}{dt}} \right] = \arctan \left[\frac{y_p'(\varpi)}{x_p'(\varpi)} \right] \tag{7}$$
$$\frac{dy_p(\varpi)}{d\varpi} = 1 \tag{8}$$
$$\frac{dx_p(\varpi)}{d\varpi} = A \cos \varpi \tag{9}$$

At this point it is useful to define an auxiliary frame attached to p_p and aligned with the path particle orientation (P-frame). The angle χ_p, determine the transformation matrix from the N-frame to this local reference frame:

$$\mathbf{R_p} = \begin{bmatrix} \cos \chi_p & -\sin \chi_p \\ \sin \chi_p & \cos \chi_p \end{bmatrix} \tag{10}$$

It should be noted that this rotation matrix preserves the vector magnitudes, which means that $\mathbf{R}_p^{-1} = \mathbf{R}_p^T$.

The new local frame, allows to easily define a positional error vector composed by the along-track error and the cross-track error: $\boldsymbol{\varepsilon} = [s, e]^T$. Then, in the N-frame this error vector can be expressed as:

$$\boldsymbol{\varepsilon} = \mathbf{R}_p^T \left[\mathbf{p} - \mathbf{p}_p(\varpi) \right] \tag{11}$$

Once the expression of the error vector on the N-frame is obtained, it is straightforward to define the following Positive Definite Lyapunov Function:

$$V_\varepsilon = \frac{1}{2} \, \boldsymbol{\varepsilon} \, \boldsymbol{\varepsilon}^T \tag{12}$$

Then, differentiating (12) with respect to time along the trajectories of $\boldsymbol{\varepsilon}$:

$$\dot{V}_\varepsilon = \boldsymbol{\varepsilon}^T \dot{\boldsymbol{\varepsilon}} = \boldsymbol{\varepsilon}^T \left[\dot{\mathbf{R}}_p^T (\mathbf{p} - \mathbf{p}_p) + \mathbf{R}_p^T (\dot{\mathbf{p}} - \dot{\mathbf{p}}_p) \right] \tag{13}$$

It can be computed:

$$\dot{V}_\varepsilon = s \left[U_d \ \cos(\chi_d - \chi_p) - U_p \right] + e U_d \ \sin(\chi_d - \chi_p) \tag{14}$$

Firstly, to ensure (14) to be negative, its first term would be considered. It is straightforward to see that this term would be always negative choosing:

$$U_p = U_d \ \cos(\chi_d - \chi_p) + \gamma s \tag{15}$$

with γ an arbitrary positive gain constant. We can write:

$$\dot{\varpi} = \frac{U_p}{\sqrt{{x'}_p^2 + {y'}_p^2}} = \frac{U_d \ \cos\chi_r + \gamma s}{\sqrt{{x'}_p^2 + {y'}_p^2}} \tag{16}$$

On the other hand, looking for a negative definite expression for $\dot{V}_\varepsilon$, one of the possible options for the selection of χ_r may be:

$$\chi_r = -\arctan\left(\frac{e}{\Delta_e}\right) \tag{17}$$

where Δ_e is an upper-bounded positive time-varying variable called lookahead distance, used to shape the convergence of s to zero [2].

Choosing the velocity of the ideal particle as:

$$U_d = \mu \ \sqrt{e^2 + \Delta_e^2} \tag{18}$$

with $\mu > 0$, determines that:

$$\dot{V}_\varepsilon = -\gamma \ s^2 - \mu \ e^2 < 0 \tag{19}$$

Therefore, the error vector $\boldsymbol{\varepsilon}$ converges uniformly globally and exponentially to zero when the positions of the ideal and the path particle are governed by equations (16), (17) and (18) [2]. The necessary references that this Guidance Module must produce can be readily obtained from (17) and (18). According to Fig. 12 it is straightforward to determine:

$$u^* = U_d \cos(\chi_p + \chi_r - \psi) = -\mu\sqrt{e^2 + \Delta_e^2} \ \cos(\chi_d - \psi) \tag{20}$$

$$v^* = U_d \sin(\chi_p + \chi_r - \psi) = -\mu\sqrt{e^2 + \Delta_e^2} \ \sin(\chi_d - \psi) \tag{21}$$

$$\varphi^* = \chi_p + \chi_r \tag{22}$$

3.2 PI control module description

The PI Control Block receives two input vectors. On the one hand, the state-space vector X (positions and velocities) from the AUVI's Navigation Module. On the other, a vector of desired variables $\boldsymbol{X}^* = [x^* \ y^* \ \varphi^* \ u^* \ v^* \ r^*]^T$ from the Guidance Module: x^* and y^* are the desired trajectory coordinates, φ^*, u^* and v^* are the reference signals generated by the Guidance Module (in accordance with 20 and 22) and, considering that yawing is undesired, the desired value of r is set equal to zero ($r^* = 0$).

Then, in the first and main stage of the Control Module, the aforementioned input vectors are processed by two PI controllers providing proportional and integral action. The proportional gains $\boldsymbol{K}_{pi}$ and integral gains $\boldsymbol{K}_{ii}$ have been tuned resorting to an optimal transient response.

4. Simulation results

Exhaustive computer simulations were carried out to assess the performance of the proposed guidance and control strategy.

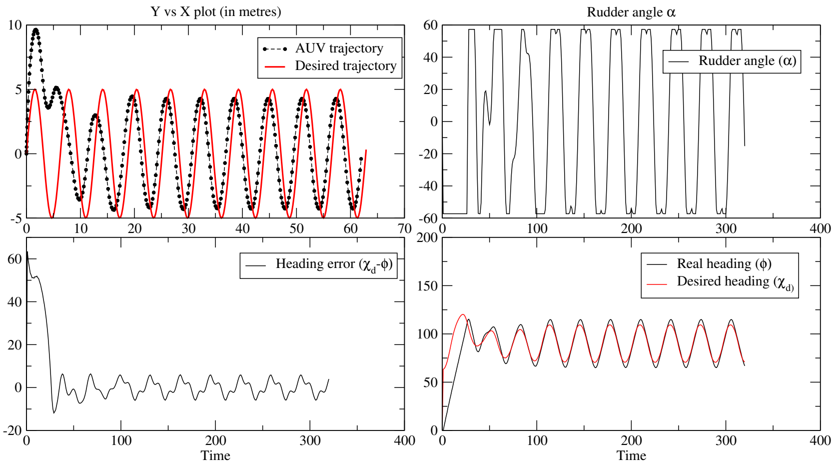

Fig. 13. Lyapunov based path following control

In order to test the performance of the control system for pipeline search, a sinusoidal trajectory was chosen for the ideal particle. In Fig. 13 the AUVI and the planned trajectories are displayed and can be compared. The desired path is depicted in continuous line, while the AUVI trajectory is the dotted line. They both start at [0 0] but with different speeds. After the initial overshoot the AUVI tracks the desired trajectory. The same picture shows in the upper right panel the "equivalent" rudder angle, which is the difference between the speeds of propeller 1 and propeller 2 of the AUVI, assimilated to a rudder angle. In the bottom panel, the desired and actual headings (right) and the heading errors $\chi_d - \phi$ (left) are displayed. It can be clearly appreciated in the evolution of x and y the moment when the AUV follows closely the desired path. By proper adjustment of the controllers and relaxing the constrains imposed by the turning radius and stretching the sinewave along the X axis, the performance would improve considerably.

5. Preliminary experimental results and future work

The performance of the AUVI pipeline tracking, was tested in sea trials using a line of sight (LOS) guidance method and a proportional controller. With this simple scheme the AUV was able to follow a series of waypoints minimizing the angle computed as the difference between the actual heading and the angle of the line that joins the AUV with the target (next waypoint). A corrective signal proportional to the heading error is applied to the thrusters as a differential speed, adjusting the heading continuously to minimize this heading error. Experimental results of this approach are shown in Fig. 14. The AUVI was programmed to go through a series of eight waypoints inscribed in a circle with a radius of around 45m. The vehicle follow the waypoints correctly though some oscillations were observed when passing over waypoints 2 and 4. It should be noted that an error tolerance was given to the control since the experimental area was small and turning radius was limited by software to avoid oscillations. Since the aim of the test was to determine the maneuvering of the vehicle in water a proportional controller was used at this stage. Better results should be expected with a PI or PID controller. Trials were made in a shallow bay called Cala Estancia, near Palma de Mallorca, at the Balearic Islands. The vehicle navigated just below surface.

Figure 15 displays the different variables involved in controlling the AUV such as desired heading (LOS angle), real heading ϕ, heading error and correction applied to the thrusters as a differential thruster force. If movement on the horizontal plane and in vertical plane are decoupled, thrusters will have effect in surge, heave and yaw motions.

Once the AUVI's onboard electronics and software architecture was verified in water as explained earlier, the experimental tests for the Lyapunov based guidance system and the PI controller, as showed feasible in computer simulation, must be done. It will be interesting to contrast both approaches for the guidance system (Lyapunov and LOS), and different kind of linear and nonlinear controllers. This is the current undergoing research regarding this topic that the authors are working in.

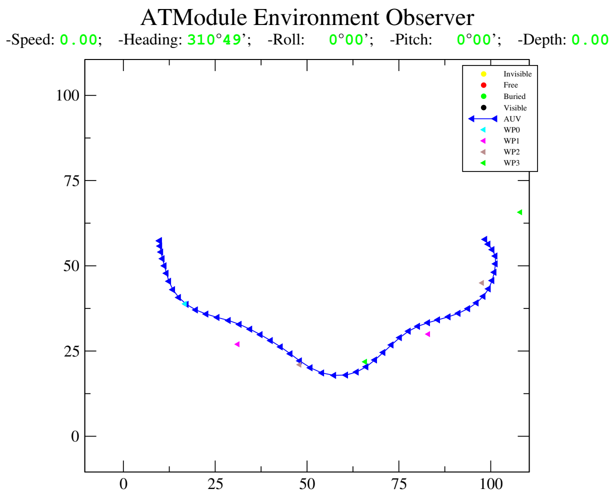

Fig. 14. Experimental results of the LOS method. The AUV passes trough a series of waypoints

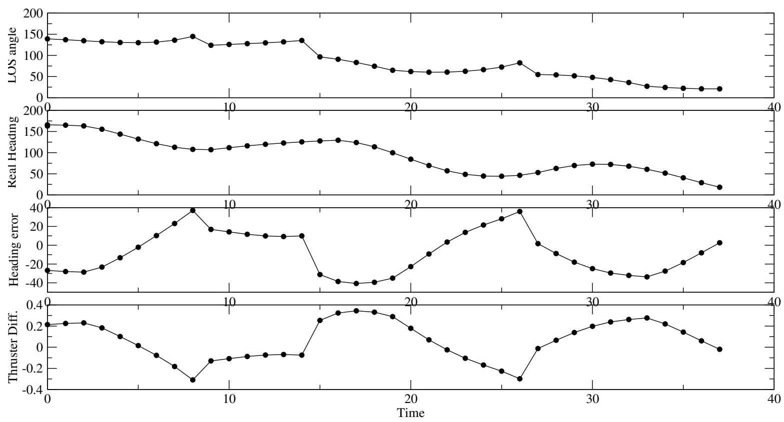

Fig. 15. Experimental trajectory of AUV using Line of Sight (LOS) algorithm

6. Conclusion

The paper presented a guidance and control method for governing an AUV to perform lawnower searches of pipelines and cables. This method is based on the approximation of two virtual particles, minimizing a distance error through a Lyapunov function to achieve better performance with guaranteed convergence, combined with a PI controller. These two modules allow to reach and track a pre-specified trajectory in real time, even in the presence of perturbations. The guidance module creates robust references in order to guide the vehicle towards the desired trajectory. The control module uses the aforementioned references to control the dynamic behavior of the system. The overall performance of the proposed control design is analyzed through representative simulations where common perturbations have been considered. The results are expected to be applied to cable and pipeline trackers, where the requisites of the path planner are tighter, since detoring from the pipe trajectory could imply loosing the pipe and starting a costly searching process. The inexpensive AUV prototype AUVI was developed to test the algorithms that allow the detection and tracking of the pipe with acoustic sensor, and was also successfully tested in sea trials. Work is in progress to mount the MBE and Sidescan sonar and test the image recognition algorithms in real time, as a specialized input for the dynamic mission planner. The new designed vehicle will perform full 3D navigation so the control algorithms will have to be redesigned accordingly.

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Biographies

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Gerardo Gabriel Acosta has graduated as Engineer in Electronics at the National University of La Plata, Argentina (1988), and as Ph.D. in Computer Science, at the University of Valladolid, Spain (1995). He is currently Associated Professor in Control Systems (Electronic Area) in the Engineering Faculty at the National Buenos Aires Province Centre University (UNCPBA), Argentina. He is also a researcher of the Argentinean National Research Council (CONICET), since 1997 and Director of the Research & Development Group "INTELYMEC", at the Engineering Faculty - UNCPBA. His working interests comprise the use of computational intelligence in automatic control, particularly intelligent control techniques in terrestrial and underwater robotics. He has more than one hundred publications and two copyrights in this and related fields. He is Senior Member of the IEEE since 2001, and Chairman of the IEEE Computational Intelligence Society Argentinean Chapter (2007-2008), receiving the 2010 Outstanding Chapter Award from CIS. Also he is a member of the Hispanic-American Fuzzy Systems Association-HAFSA (local branch of IFSA) and AADECA (local branch of IFAC). He has been the research leader of more than ten R+D projects, funded by the Argentinean Government and the European Union. He has been invited as a professor of Ph.D programs in Argentina and Spain, and serve as reviewer and member of the scientific committee of several national and international journals and conferences. More details in:
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Oscar Calvo was born in Necochea, Argentina, in June 12th of 1954, and passed away in Pamplona, Spain, in November 20th of 2009. He received his BSEE in electrical engineering, as a Telecommunication Engineer, from the National University of La Plata – UNLP (Argentina) in 1979, his MSEE in computer and electrical engineering from the Illinois Institute of Technology, (Chicago, IL, USA) in 1988 and his PhD in Electrical Engineering from the Politechnical University of Cataluña, (UPC Barcelona, Spain) in 2004. Dr. Calvo's research career began as with a fellowship in 1981 in the area of microprocessor based control systems, applied to power systems and mobile robotics, under the supervision of Prof. José María Caltalfo. He then started as Professor of Electronics Devices, in the Faculty of Engineering, UNLP, and Researcher of the Committee on Scientific Research of the Buenos Aires Province, both positions in Argentina. He has taught also at the National Technical University (1982), the Instituto Tecnológico of Buenos Aires (ITBA) and the Balearic Islands University (1994). He has also taught courses on Fuzzy Control at UNLP. He was Secretary of Science and Technology of the Engineering Faculty at UNLP. His last position was in the University of the Balearic Islands, Spain, where he was Professor belonging the permanent staff since 2001. His areas of interest were the automatic control, robotics and power electronics.