COPPE UFRJ
Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia

MASTER THESIS PROPOSAL

UNDERWATER 6 DOF LOCALIZATION USING IMAGING SONARS

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Proposta de tema de tese a ser desenvolvido no LEAD/COPPE/UFRJ para o Mestrado do Programa de Engenharia Elétrica da COPPE/UFRJ

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Chapter 1

Introduction

The development of underwater systems has grown in the last past years, due the increase in the complexity and risk of the tasks to be executed. The inspection, installation and maintenance of undwater structures is usually performed by diver and this tasks are a slow, expensive and dangerous work. In addiction, due the hidrostatic pressure, a diver is recommend to go only until 100 meters deep. Thus, in subsea exploration there are several applications, which the utilization of a diver is simply not possible. To fullfil the crescent needs of the oil and gas, hidreletric industries, as well the subsea floor and life mapping and research, the academic and industrial community is focusing in the development of unmmaned underwater vehicles and systems capable of execute generic tasks. In this context, the GSCAR group, including the participation of the LABCON and LEAD laboratories, COPPE/UFRJ, has given a special attention to submarine robotics.

In a patnership with the company Energia Sustentável do Brasil (ESBR), the Laboratório de Controle e Automação, Engenharia de Aplicação e Desenvolvimento (LEAD/PEE/COPPE) has signed a project, named ROSA, to develop a monitoring and 3D mapping system to work in Stoplog operations at the hidreletric power plant of Jirau. The system is responsible to monitor the operation of insertion and withdrawl of Stoplogs, metal blocks used to seal the inlets and outlets of the turbines, and also to map the bottom of the tubine inlets, looking for debris and acumulated silt.

The ROSA Robot consists in a system with a ground eletronic and a underwater embbeded eletronic. The latter has four inductive sensors, a pressure sensor, a inclination sensor, a pan-tilt unit and the possibility to connect either a profilling sonar, the *Tritech Seaking*, or a Mechanically Scanned Imaging Sonar (MSIS) sonar, the *Tritech Micron*.

The ROSA robot is going to be the central piece of development of the proposed thesis and localization algorithm.

Chapter 2

Motivation

In the ROSA robot, the mapping is performed by the sonar, where each echo received is processed and taken into account to generate a map of the underwater environment. However, if the location of the system isn't known, it is not possible to align all the data received from different positions and orientations and construct a 3D model of the environment. There are several techniques to map and localize a underwater system in respect to the environment, however the Jirau power plant is located in the Madeira River and its turbid waters forbids the application of vision. Besides, there is many regulations and constraints that make any modification to the dam structure virtually not possible. For that reasons, the most suitable sensor to map the underwater environment is a sonar device.

The ROSA robot is attached to the Lifiting Beam and is submerged following a rail in the dam concrete wall. The whole system can only move in the vertical direction and the head of the sonar can be oriented in almost any particular desired direction, because ofs the presence of the pan-tilt unit. Without a localization algorithm is not possible to position the echo received in a three dimensional map.

The intention of the project is to allow a person to assemble and disassemble the system as many time as desired. That means mounting differences in each assembly, in every operation there are going to be unkwown parameters. The estimation of theses parameters are also relevant to the localization algorithm, because the transformation between the coordinate frame of the body of the robot and the head of the sonar, i.e. the orientation of the beam emitted, has an unknown bias. This biases can make a error of several centimeters with the increase of the distance of an obstacle measured.

In the literature, the localization of underwater systems with the support of active sonars is little explored, specially taking into account the 6 DoF of the vehicle. In general, the localization techiques aim in a plane based localization and mostly uses the range finder theory to perform the evaluation of the sonar beams. The incorporation of the wave propagation caracteristics and beam shape are still very little explored. The implementation of Underwater 6 DoF Localization using Imaging Sonars would be a contribution of great value to the academic field, specially if the algorithm succeed with inexpensive sonars.

Chapter 3

Objectives

The main objective of the proposed master thesis is to research the state of the art of undewater localization and the utilization of sonars to perform this task. The techniques are going to be compared and its pros and cons listed.

In addition, it is proposed a implementation of a 6 DoF localization algorithm using a Mechanically Scanned Imaging Sonar, the *Tritech Micron*. The algorithm is going to be based on a Rao-Blackwellized Particle Filter and be responsible to estimate the position of the ROSA robot and also the unknown parameters caused by the manual assembly..

The sonar sensor model will receive special attention and is intended to incorporate underwater acoustics theory and intrinsec caracteristics of the sonar, as an example its beam shape, to use the most of information provided by the sensor as possible and not only a distance measurement.

Chapter 4

Metodology and Expected Results

The metodology of work will consist in a detailed study of the state of the art in the field of underwater localization of mobile systems, incorporating classic techniques and implementing in a actual system.

The techniques proposed in the literature will be evaluated in terms of cost, praticallity and viability of implementation in the Jirau Powerplant. The Stoplogs holes are a unfriendly environment and the system is exposed to the weather, to debris present in the water and, in addition, there are several constraints in the permanent alterations that can be made in the current structure.

The ressources needed during the development of the master thesis, human and computacional, are going to be provided by the Laboratório de Controle e Automação, Engenharia de Aplicação e Desenvolvimento (LEAD/PEE/COPPE) and Laboratório de Controle (LABCON/PEE/COPPE).

The test setups are going to be realized in a partnership with the Laboratório de Ensaios Não Destrutivos (LNDC/PEMM/COPPE), where there is a water tank with the dimensions of 12 meters long, 6 meters wide and 7 meters deep. There is, also, going to be gathered a real dataset in the field trips to the hidreletric power plant of Jirau.

Chapter 5

Research Topics

This section describes the topics to be studied in order to accomplish the fullfilment of the requirements of a master thesis and the implementation of the desired localization algorithm.

- Underwater Locazlization techniques - study of the state of the art in the field of underwater localization, analysis of the techniques applied in the literature and evaluation in respect of cost, processing power requirement, sensors used and robustness.

- Particle Filtering study - Study of the Particle Filter approach as a pratical implementation of a Bayesian Filter. Due the strong non linear caracteritics of the problem and also from the sonar sensor, this particular type of filter was chosen to be the main technique to be explored as a possible solution of a low cost underwater localization problem.

- State Space Modelling - the number of dimensions to be sampled in the particle filter has a direct effect in the number of particles necessary to sufficently cover the state space. In consequence, a special attention must be given reduce as much as possible the number of state sampled.

- *A priori* map construction - Study of the state of the art of spacial data representation and the construction of a map model from the actual environment.

- Sonar Sensor Modelling - Study of underwater acoustics and wave propagation, sensor modelling and likelihood functions fitting. A sonar sensor model will be derived and evaluated within the algorithm.

5.1 Underwater Localization techniques

Study of the state of the art in localization techiques for underwater systems. This study has the objective to point, evaluate the possible approaches and all the pro and cons associated with each one. And finally, justify, formally, the use of a sonar as main sensor.

Underwater localization can be performed with the utilization of one or more transponders. The baseline techniques can differ in the number of trasnponders required and the maximum coverage area. However, all of these techniques require the implementation of an additional infraestructure, what requires authorization and represents costs and maintenance.

Video aided localizationis also possible underwater, but it has hard requirements of luminosity and transparency of the water. This requirements makes this approach impraticable for most apllication, speacially in the Madeira River water, that has zero visibility. On the other side, due the caractheristics of sound wave propagation in water, the acoustic sensors are the most suitable sensors to perform underwater localization and mapping, being able to measure long ranges without signficant signal energy loss. In the industry, there are many types of sonars avaiable. The Profiling sonars behave almost like a laser scan, with a pencil like beam shape, but with a much bigger aperture. Imaging sonars, on the other hand,provides more information about the echo received and produce an image of the insonificated area.

In the scope of the proposed thesis, the sensor that is going to be explored is the Tritech Micron, a Mechanically Scanned Imaging Sonar (MSIS). This sensor is an inexpensive sonar is going to perform a main role in the development of the particule filter and sensor model explained in more details in the section 5.2 and 5.4.

5.2 Particle Filtering Study

The localization algorithm must be able to handle all the uncertainties related to the process of gathering data, processing it using different models and with the support of computacional systems. All this steps have their own kinds of uncertainty and noise. The sensors are imprecise and affected by external noise; the movement of the robot is subject to mechanical clearances and vibrations and the model used to describe either the robot and the environment that surrounds it can never be considered trully accurate.

Uncertainties are going to be present in every real system and, therefore, to handle this kind of problem, one strategy is to incorporate the errors intrinsec of the process inside the models and represent the uncertainty explicitly.

To properly estimate the state of the system from the sensor data avaiable, the most general technique used to approach this kind of problem is to solve it recuservely, with a practical implementation of the Bayes Filter. There are several bayesian filtering techniques, with different assumptions, pros and cons. For example, the Kalman Filter assumes that the dynamic of the system is linear and it is possible to represent the variables to be estimated and the errors related to the process as multivariate normal distributions. The Kalman filter is the most utilized filter and considered an optimal estimator. However, it has its limitations and cannot, for example, represent non-linear dynamics or multimodal distributions.

This document proposes that, during the development of the master thesis, the state of the art in Bayesian Filtering is going to be deeply studied, showing the techniques well explored in the literature and the reasons for choosing a Particle Filter as the recursive state estimation filter to be applied and implemented.

Considering that the pressure sensor and the inclinometer are absolute sensors, a Rao-backwellized Particle Filter is going to be proposed to solve the localization problem. The utilization of absolute sensors allows the filter to marginalize dimensions measured by this sensors and to sample only some of the variables, reducing the number of particles needed and the computational power needed. A Kalman filter, a alpha-beta filter or any other optimal filter can be applied, then, in the marginalized variables.

5.3 State Space Modeling

As mentioned in section 5.2, a special attention must be given to the analisys of the state vector of the system. The number of variables sampled by the particle filter has a direct effect in the number of particles needed, because a bigger state space requires more particle to be well covered.

The physycal caracteristics of the Stoplog rail limits the dynamic of movement of the whole system. Therefore, the system can move, basically, in the vertical direction. The position in the xy plane can be considered fixed, but with a precise initial position unknown. The orientation of the body is also very constrained due the rail, the pitch angle can be considered negligibe, as well the yaw. The roll angle is measured by the inclination sample, however its actual position is drifted by an offset due the manual installation of the system.

The depth sensor gives the water column height above the sensor, now called h_s, but the a position in respect a fixed reference is not provided by the sensor, once the total water column height h_w, from the bottom to the water surface, is variable. To be able to calculate the measurement of the vertical position z, the filter need to sample the offset between the information given by the sensor and the height of the system in respect a fixed reference. In other words, the filter needs to sample the water column height and calculate the vertical position z as $z = h_w - h_s$.

Given the configuration of the setup assembled to gather data of the ROSA robot in the LNDC lab, with the yaw orientation being free, the filter needs to be able to sample the yaws orientation and alternate to sample around a initial position in this dimension when desired, as well.

Additional parameteres to be sampled are all the biases in the transformation between the coordinate frame from the body and the head of the sonar, the system was hand-assembled in each test made, so the errors of mouting need to be taken into account.

5.4 Sonar Sensor Modeling

The utilization of laserscan and range finder sensors to perform localization of terrestrian mobile systems is well explored in the literature. A laserscan returns a time of flight measurement and the distance to the obstacle can be easily calculated. The hit of the laser is considered pontual and the likelihood function of the given point been full or not can be modelled much more easily than in the sonar case. If compared to a laserscan, the sonar sensor,which has a much broader beam, can be considered a very noisy range finder.

Although, in underwater environments, the use of laserscanners to sensor the environment is almost impractical due the caracteristics of ligth propagation in water, with high attetuation and dispersion. The sound wave propagation in water, with a lower attenuation, makes sonar the most suitable underwater sensor.

Profilling sonars return a time of flight measurement and have a pencilar beam shape and, therefore, can be used as a usual range finder sensor. However, it produces sparse data and have a very poor angular precision. A Mechanically Scanned Imaging sonar, on the other hand, emits a fan shape beam and returns an array of intensities of acoustic signal backscattered form the environment. Each intensity correponds to a particular section of the beam, discretized in the radius direction. The transducer is mechanically rotated and a full 360^o sector scan can be perfomed, but with a slow refresh rate cost. Even being a imaging sonar, the MSIS can be acquired with a relatively low cost.

In the literature, this kind of sonar is explored, in the context of underwater localization, with a range finder approach, however there is a lot of loss of information and introduction of unecessary noise if one applies the range finder theory to a MSIS device, extracting the most intense echo and converting it to a distance measurement. Therefore, its proposed to study the underwater acoustics and wave propagation and apply this theory in a low cost sensor, the Tritech Micron. The information of the fan shaped beam, with its horizontal and vertical apertures, and also all the intensities contained, if incorporated into the sensor model, allows the proposal of a likelihood function that is much more close to the real behavior of the sensor.

5.5 A priori map construction

To be able to localize the system, one needs to represent the environment that surrounds it. The more suitable environment model for a underwater vehicles, as well aerial systems, is a volumetric 3D model. The deegres of freedom of the system allows the system to explore the map in all three cartesian dimensions.

There are several techniques and data structures to represent, probabilistically, the posistion of the robot and the environment. The model must fullfill the requirements of dimensions derised and also be efficient computational wise.

In the literature, it is possible to cite the use of grid of cubics volumes of equal size, with the drawback of a big memory consumption. Other possibility is to store directly the measurements and generate a point cloud, which is not that more efficent in terms of memory consumption. A more efficient approach is to use 2.5D grid maps, elevation maps or Multi-Level-Surface Maps. This kind of maps discretizes the vertical dimension and, therefore, can optimize the computacional consumption. However, they cannot fully represent the actual 3D environment, what for a underwater system can forbid a good position estimation.

The mapping approach proposed to be studied more deeply and used in the construction of the localization algorithm is the Octomap framework [48], which is based in octrees, a hierarchical data structure for spatial subdivision in 3D. The octree based mapping framework allows a volumetric 3D representation of the environment with a low memory cost, has the capability to distinguish free and unmapped areas and it is open source.

The *a priori* maps, to be used with the datasets gathered detailed in the section 5.6, also need to be modelled. The LNDC map can be handmade, beacause of it's simple configuration. The Stoplog hole, at the Jirau Dam, must be modelled with the support of a 3D CAD model. The octomap framework also allows the conversion from the industrial standards 3D model files to an octree.

5.6 Case Study

The proposed algorithm is going to be evaluated in respect of two different scenarios. The first one is the a test setup in the LNDC (Laboratório de Ensaios Não Destrutivos), which the system is going to be tested standing still, with different heigths and free Yaw orientation. The water tank of the LNDC lab is a square shaped tank with 12 meters long, 6 meters wide and 7 meters deep, which provides a good initial evaluation environment, due the simple structure geometry.

The final evaluation of the proposed localization technique is going to be perform with a real dataset, aquired during the field trips to the Jirau Dam, in a real Stoplog hole. This setup provides a much more complex data, with noise provenient from mechanical vibrations, water turbulence and also a more complex *a priori* map.

Chapter 6

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Chapter 7

Workplan

- Particle description - 1 week
- Implement Kalman filter for the depth and inclinometer (alpha beta filter) incl. Wave removal + testing - 1 month
- Build apriori map - 1 month
- Full review particle filter algorithm + mock test - 1 month
- (Implement state of the art - 1 month)
- Write down a full sensor model - 6 months
- Postprocess LNDC logs - 2 week
- Postprocess Jirau logs - 2 week

Chapter 8

Conclusion

In this master thesis proposal, it was described all the relevant aspects to reach the state of the art in underwater localization and implement a localization algortihm in an actual system. The main topics to be explored in this work are the current underwater localization techniques, the bayesian filtering techniques and particle filtering, construction of a priori 3D environment occupancy models, underwater acoustic theory and sensor modelling theory.

Finally, the main contribution of the proposed master thesis will be the implementation of a Rao-Blackwellized Particle Filter with 6 DoF using a inexpensive sonar and the derivation of it sensor model.