Shape estimate of a streamer of hydrophones towed by an Autonomous Underwater Vehicle *

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Abstract: The paper deals with the problem of estimating the shape of a streamer of hydrophones for acoustic geoseismic survey when towed by an Autonomous Underwater Vehicle (AUV). The considered problem arises in the framework of a H2020 European Project, named WiMUST, aimed at using a team of AUVs, each one towing a streamer of hydrophones, to perform geoseismic survey missions that are traditionally performed using streamers towed by a single manned surface vessel. The replacement of the towing system of the vessel with a team of AUVs introduces several issues in the localization of the hydrophones, needed to allow the processing of the acoustic data, since they are no more on the sea surface. In this paper we want to study the solvability of the streamer shape estimation problem depending on the possibly available measurements and information that can be collected via the hydrophones, the AUV’s on board sensors, and relying on acoustic communication.

Keywords: Geoseismic survey with AUVs, underwater robotics applications

1. INTRODUCTION

Seismic acoustic surveys at sea are methods for the exploration of the sea bottom and sea subsurface for applications that span from the geophysical domain (e.g. oil&gas) to the geotechnical domain (e.g. civil and commercial applications, underwater constructions). The survey is traditionally performed using a surface vessel carrying one or two powerful acoustic sources (as sparkers) and towing a set of surface streamers equipped with several hydrophones to record acoustic signals. The sparkers generate seismic waves by intermittently releasing electric pulses that produce low frequency sound waves. Such waves travel towards the sea floor and are reflected back to the streamer hydrophones. The speed with which waves return to the surface, registered with the hydrophones, provides valuable information about the properties of the Earth’s subsurface.

Among the possible underwater acoustic data processing approaches, the Matched-Field Processing (MFP) approach was introduced about two decades ago for source localization (see Tolstoy (1993); Baggeroer et al. (1993)). The advantage of MFP over conventional time-of-arrival-based techniques is that bottom sampling and coring is not required since acoustic array data is directly matched with modeled data adjusted for the bottom parameters being estimated. Enlarging the search space of MFP from source localization to geoacoustic parameters was first proposed by Collins et al. (1992), and then used in a variety of setups including in many cases fixed vertical arrays Siderius et al. (2001), towed arrays Jesus and Caiti (1996), drifting arrays using surface noise Harrison and Baldacci (2002) and more recently using vector sensors Santos et al. (2010).

The processing of the acoustic data requires that the position of the hydrophones, forming an array of acoustic sensors, must be known with a required precision at all times. Indeed, the localization accuracy of the hydrophones, their geometric displacement and the acoustic devices detection capabilities are in direct relation with the performance of the spatial coverage mission execution. Traditional survey operations are performed making the surface vessels move along straight paths so that the streamers shapes can be assumed as nominal, i.e. straight lines; in this way the hydrophones are assumed localized in known rigid positions with respect to the surface vessels. Moreover, in practical applications, the positions of vessel, sparkers and buoys attached to the streamer’s tail are known through GPS devices. Such GPS position measurements, together with data about the vessel advancing direction, can be used to estimate the orientation of the streamer and to evaluate possible offset with respect to the nominal configuration. A simple threshold-based policy is commonly used to monitor the proper alignment of the streamer, and in the case it is considered excessive (e.g. larger than 8°) then the acquired data are discharged since the knowledge of the positions of the hydrophones is considered not enough accurate.
The H2020 European Project named WiMUST (Widely scalable Mobile Underwater Sonar Technology) aims at expanding and improving the functionalities of current cooperative marine robotic systems, effectively enabling distributed acoustic array technologies for seismic surveying. The general idea of using autonomous marine robots to carry hydrophones for oceanographic sampling has been considered in the scientific literature and for industrial applications. An interesting example is given by the US patent Schmidt et al. (1999) that considers an oceanographic sampling system composed of multiple underwater vehicles. The interest in the area of marine robotics based acoustic seafloor characterization is also confirmed by recent studies as, for example, in Chotiros and Pallayil (2013), where sediment classification was demonstrated using the self-noise of a single autonomous underwater vehicle (AUV) received on a short towed array.

The WiMUST system can be envisioned as an adaptive variable geometry acoustic array where the streamers are towed by Autonomous Underwater Vehicles (AUVs) as in fig. 1. The loss of the towing system from the surface vessel introduces flexibility to the system in the sense of allowing to modify the horizontal and vertical displacement of the AUVs (an thus of the streamers) to adjust according to specific needs. On the other size, the loss of the towing system introduces high complexity due to the needs of ad-hoc cooperative navigation and control architecture of the AUVs and of acoustic communication among the nodes. Moreover, the hydrophone’s positions can not be easily computed as in the case of surface surveys since AUVs can not rely on GPS, the hydrophones are not constrained to remain on a horizontal plane at the sea surface, there is no GPS equipped surface buoy on the tail’s (since the streamer should operate underwater). Thus, in this work we want to analyze the localization issues of the the hydrophones depending on the kind of available measurements concerning AUVs, sparkers, hydrophones and streamers’ tail.

2. SYSTEM MODELING AND ASSUMPTIONS

Let us focus on the case of a single AUV towing a streamer of hydrophones the receive acoustic signals emitted from one or two surface sparkers. For the problem at hand we make the following assumptions

- one or two sparkers, towed by a surface vessels, periodically emit acoustic signals and communicate their position, gathered via GPS, through an underwater acoustic communication network;
- the acoustic communication network is based on time multiplexing and all the nodes are synchronized;

Let us define \( p_0 \in \mathbb{R}^3 \) the AUV position with respect to an inertial frame, \( p_i = [p_{i,x},p_{i,y},p_{i,z}]^T \in \mathbb{R}^3 \) the position of the \( n \) hydrophones, and \( \alpha = [\theta_1, \phi_2, \ldots, \theta_n, \phi_n]^T \in \mathbb{R}^{2n} \) the vector collecting all the angles. It holds (see fig. 3):

\[
p_i = p_{i-1} + \Delta p_i = p_{i-1} + l_i \begin{bmatrix} \sin(\theta_i) \cos(\phi_i) \\ \sin(\theta_i) \sin(\phi_i) \\ \cos(\theta_i) \end{bmatrix}.
\]
2.1 Range measurements

Denoting as $m_{i,j}$ the range measurement from $p_i$ to the sparker $j$, then the range from the first sparker $s_1$ to the first hydrophone $p_1$ can be computed as

$$m_{1,1} = \sqrt{\left(p_0 - s_1 + \Delta p_1\right)^T \cdot \left(p_0 - s_1 + \Delta p_1\right)}.$$  \hspace{1cm} (2)

The range from $s_1$ to the generic hydrophone $p_i$ is

$$m_{i,1} = \sqrt{\left(p_0 - s_1 + \sum_{j=1}^{i} \Delta p_j\right)^T \cdot \left(p_0 - s_1 + \sum_{j=1}^{i} \Delta p_j\right)} = \sqrt{\left(p_0 - s_1 + \sum_{j=1}^{i} \left[ S \theta_i C \phi_j \right] / \left[S \theta_i C \phi_j \right]\right)^T \cdot \left(p_0 - s_1 + \sum_{j=1}^{i} \left[ S \theta_i C \phi_j \right] / \left[S \theta_i C \phi_j \right]\right)},$$ \hspace{1cm} (3)

where $S \theta_i = \sin(\theta_i)$, $C \theta_i = \cos(\theta_i)$, $S \phi_j = \sin(\phi_j)$, and $C \phi_j = \cos(\phi_j)$. It can be noticed that $m_{i,1} = m_{i,1}((\theta_1, \phi_1)$ and $m_{i,1} = m_{i,1}((\theta_1, \phi_1, \ldots, \theta_i, \phi_i)$. The range measurement can be also expressed in a recursive formulation more convenient for software implementation as reported in eq. 4. The ranges to the second sparker can be computed accordingly to eq. (3)-(4) by replacing $s_1$ with $s_2$.

2.2 Tail buoy measurements

For traditional surveys at the sea surface, the position of a buoy equipped with GPS placed at the tail of the streamers is usually available. In the WiMUST system, the tail buoy can be possibly substituted by equipping the tail of the streamer with an appendix with an acoustic modem; in this case, the tail position can be estimated using localization devices as USBL. In case the tail positioning is available, the tail node is denoted as $p_{n+1}$. Its range to last hydrophone, denoted as $l_{n+1}$, can be computed as

$$l_{n+1} = \left\| p_0 - p_{n+1} \right\| = \sqrt{\left(p_0 - p_{n+1} + \sum_{j=1}^{n} \Delta p_j\right)^T \cdot \left(p_0 - p_{n+1} + \sum_{j=1}^{n} \Delta p_j\right)}.$$ \hspace{1cm} (5)

3. THE LOCALIZATION PROBLEM

The streamer localization algorithm consists of an estimator of the elements of the vector $\alpha$: in particular, we formulate the localization problem as an optimization problem to be solved on the base of an instantaneous set of measurements. We denote the computed estimate as $\hat{\alpha} = [\hat{\theta}_1, \hat{\phi}_1, \ldots, \hat{\theta}_n, \hat{\phi}_n] \in \mathbb{R}^{2n}$ and the expected range measurement from the hydrophone $i$ to sparker $j$, computed on the base of $\hat{\alpha}$ as in eq. 6, as $\hat{m}_{i,j}$. Moreover, in case the position of a tail node is available, we denote as $\hat{l}_{n+1}$ the estimated range between the tail and the last hydrophone that can be computed as in eq. 7.

The localization problem is the formulated referring to a suitable quadratic scalar quadratic function $V(\hat{\alpha})$ of the available measurements and the estimation parameters, that should be properly minimized. In the case no assumption is performed on the streamer shape, the estimation results in the unconstrained minimization problem:

$$\min_{\hat{\alpha}} V(\hat{\alpha}).$$ \hspace{1cm} (8)

Such problem can be solved referring to classical optimization techniques as, e.g., a gradient based approach.

Providing hypotheses on the streamer shape, as, for example, on the maximum twist of the streamer cable, the optimization problem can be also formulated as a constrained optimization problem. The latter constrains can be expressed, for example, in term of maximum values of $|\phi_k - \phi_{k-1}| < \Delta \phi_{\max}$ and $|\theta_k - \theta_{k-1}| < \Delta \theta_{\max}$ that give rise to a set of linear inequality constraints. In this case, the optimization problem assumes the form

$$\min_{\hat{\alpha}} V(\hat{\alpha}) \quad \text{such that} \quad \forall k = 2, \ldots, n \quad \begin{cases} \phi_k - \phi_{k-1} < \Delta \phi_{\max} \\ \phi_k - \phi_{k-1} > -\Delta \phi_{\max} \\ \theta_k - \theta_{k-1} < \Delta \theta_{\max} \\ \theta_k - \theta_{k-1} > -\Delta \theta_{\max} \end{cases}. \hspace{1cm} (9)$$

Moreover, if the streamer is constrained to move in an horizontal plane (e.g. for maneuver on the sea surface with streamers with positive buoyancy), then the optimization problem also includes equality constraints:

$$\min_{\hat{\alpha}} V(\hat{\alpha}) \quad \text{such that} \quad \forall k = 2, \ldots, n \quad \begin{cases} \phi_k - \phi_{k-1} < \Delta \phi_{\max} \\ \phi_k - \phi_{k-1} > -\Delta \phi_{\max} \\ \theta_k - \theta_{k-1} < \Delta \theta_{\max} \\ \theta_k - \theta_{k-1} > -\Delta \theta_{\max} \end{cases} \quad \forall i.$$ \hspace{1cm} (10)

Depending on the specific set of available measurements and hypothesis, it may happen that to same (minimal) value of $V(\hat{\alpha})$ correspond multiple (even infinite) streamer configurations. Thus, in the following we want to evaluate for the possible scenarios of interest for the WiMUST system how/if the localization problem can be solved. In particular, we will consider the case of available range measurements from one/two sparkers, considering the presence/absence of a localized tail, considering the case of 2D/3D streamer configuration. We performed numerical simulations assuming that: the streamer length is of the order of 15 – 25 meters long carrying 8-16 hydrophones equally distanced; the AUV distance from the sparker may range from 5 to 100 meters; the two sparkers are separated by few meters; $\Delta \theta_{\max} = \Delta \phi_{\max} = 50^\circ$. All the previous numbers are coherent with standard set-up for seismic survey application at geotechnical scale level.

3.1 Case I: one sparker, no tail

In case the available measurements are the ranges to a single sparker, then the scalar function $V$ is defined as

$$V(\hat{\alpha}) = \frac{1}{2} \sum_{i=1}^{n} \left(m_{i,1} - \hat{m}_{i,1}\right)^2.$$ \hspace{1cm} (11)

In this case the optimization problem presents multiple local minima and, in case the initial values of the estimated parameters are not very close to the real values, the identified solution can be very far from the real one. Investigating the configurations associated to the same local minima, it can be noticed that there are infinite parameters configuration that give rise to the same set of measurements. As a case of example, let us focus on
where the localization of the first hydrophone of the streamer. Given the range from the sparker, the position of the AUV
and the length of the first link $l_1$, all the positions on the
circle given from the intersection of the sphere centered
in the sparker with radius equal to $m_{1,1}$ with the sphere
centered in the AUV and with radius $l_1$ (see fig. 4) generate
the same range measurements; thus the real hydrophone
position results indistinguishable form any of the points of
the intersection circle. Such consideration can be extended
to the successive hydrophones showing that the streamer
localization can not be solved properly in this case.

In case the streamer is assumed at a known depth, as for
the survey at the sea surface, then the indistinguishable
configurations of the first hydrophone are two (i.e. the two
points on the previous circle at the assigned depth), see
fig. 5. Considering all the $n$ hydrophones, then the number
of indistinguishable configurations is up to $2^n$. The number
of indistinguishable configurations may decrease in case of

specific configurations; e.g. when the streamer is aligned
with the sparker-AUV direction, then the intersection
among the spheres degenerate from circles to points, and
the only indistinguishable configuration is the reale one.

3.2 Case II: one sparker, one tail

In case, beyond the ranges to a single sparker, the position
of a tail node is available, then the scalar function for the
optimization problem can be defined as

$$V(\hat{\alpha}) = \frac{1}{2} \sum_{i=1}^{n} (m_{i,1} - \hat{m}_{i,1})^2 + \frac{1}{2} \left( \hat{l}_{n+1} - \hat{l}_{n+1} \right)^2. \quad (12)$$

The presence of the tail node in a known position helps
in keeping the estimated positions of the hydrophones
closer to the real one (at least for the terminal of the
streamer) as can be seen in the case of fig. 6; however
in this configuration the number of indistinguishable
configurations is still non unique and, depending on the

\[ m_{1,1} = \sqrt{(p_{0,x} - s_{1,x})^2 + 2(p_{0,x} - s_{1,x}) \sum_{j=1}^{l_j} l_j S\theta_j C\phi_j + \left( \sum_{j=1}^{l_j} l_j S\theta_j C\phi_j \right)^2} + (p_{0,y} - s_{1,y})^2 + 2(p_{0,y} - s_{1,y}) \sum_{j=1}^{l_j} l_j S\theta_j S\phi_j + \left( \sum_{j=1}^{l_j} l_j S\theta_j S\phi_j \right)^2 \]

\[ m_{i,1} = \sqrt{(p_{0,x} - s_{1,x})^2 + 2(p_{0,x} - s_{1,x}) \sum_{j=1}^{l_j} l_j S\theta_j C\phi_j + \left( \sum_{j=1}^{l_j} l_j S\theta_j C\phi_j \right)^2} + (p_{0,y} - s_{1,y})^2 + 2(p_{0,y} - s_{1,y}) \sum_{j=1}^{l_j} l_j S\theta_j S\phi_j + \left( \sum_{j=1}^{l_j} l_j S\theta_j S\phi_j \right)^2 \]

\[ l_{n+1} = \sqrt{(p_{0,x} - p_{n+1,x})^2 + 2(p_{0,x} - p_{n+1,x}) \sum_{j=1}^{l_j} l_j S\theta_j C\phi_j + \left( \sum_{j=1}^{l_j} l_j S\theta_j C\phi_j \right)^2} + (p_{0,y} - p_{n+1,y})^2 + 2(p_{0,y} - p_{n+1,y}) \sum_{j=1}^{l_j} l_j S\theta_j S\phi_j + \left( \sum_{j=1}^{l_j} l_j S\theta_j S\phi_j \right)^2 \]
Fig. 6. Real (solid blue) and estimated (dashed green) shape of the streamer in case of ranges from one sparker and known position of the tail.

Fig. 7. Real (solid blue) and estimated (dashed green) shape of the streamer in case of ranges from one sparker and known position of the tail.

Initialization of the optimization problem, can generate large estimation errors as in fig. 7.

### 3.3 Case III: two sparkers, no tail

In the case are available range measurements to two sparkers, then the scalar function may be defined as

$$V(\hat{\alpha}) = \frac{1}{2} \sum_{i=1}^{n} (m_{i,1} - \hat{m}_{i,1})^2 + \frac{1}{2} \sum_{i=1}^{n} (m_{i,2} - \hat{m}_{i,2})^2$$  \hspace{1cm} (13)

Even in this case, there exist multiple indistinguishable streamer configurations. As an example, fig. 8 shows the possible indistinguishable configurations for an assigned displacement of the streamer in the 3D; the figure is built considering the plane passing through \(s_1, s_2\) and the AUV position \(p_0\). The red line show the real configuration of the streamer (from the top and lateral views), while the green lines shows alternative configurations that would generate the same range measurements. As a particular case, fig. 8 shows the indistinguishable configurations in case of an horizontal and straight line configuration of the streamer, that is the nominal configuration of the streamers during the survey.

Fig. 10 and fig. 11 respectively show the real configuration (solid blue) and the estimated configuration (dashed green) of the streamer respectively for the 3D case and planar. It can be noticed that, for the 3D case, the estimation error may increase along the streamer.

Fig. 8. Indistinguishable configurations in case of range measurements from two sparkers. Generic streamer configuration.

Fig. 9. Indistinguishable configurations in case of range measurements from two sparkers. Horizontal straight streamer configuration.

### 3.4 Case IV: two sparkers, one tail

In case the available measurements are the ranges from two sparkers and the position of the tail node, then the
Fig. 11. Real (solid blue) and estimated (dashed green) shape of the streamer in case of range measurements from two sparkers and planar assumption.

Fig. 12. Real (solid blue) and estimated (dashed green) shape of the streamer in case in case of range measurements from two sparkers and position of the tail.

Fig. 13. Real (solid blue) and estimated (dashed green) shape of the streamer in case of range measurements from two sparkers, position of the tail and planar assumption.

The scalar function may be defined as

$$V(\hat{\alpha}) = \frac{1}{2} \sum_{j=1}^{2} \sum_{i=1}^{n} (m_{i,j} - \hat{m}_{i,j})^2 + \frac{1}{2} \left( l_{n+1} - \hat{l}_{n+1} \right)^2$$  \hspace{1cm} (14)$$

Fig. 12 and fig. 13 respectively show the estimated configuration of the streamer for the 3D case and for the 2D case (i.e. assuming that the streamer is in a horizontal plane). In this case it can be noticed that the estimation can be performed quite precisely in both the cases.

4. CONCLUSIONS AND FUTURE WORK

In this paper we analyzed the localization problem of a streamer of hydrophones for geoseismic survey towed by an AUV. We formulated the problem considering different possible configurations in term of available measurements, and evaluated the solvability of the localization problem in the different contexts. Such analysis represent a preliminary step toward the realization of a on-line estimation algorithm to use in real application. Limitations of the performed study and future line of investigation are reported in the following:

- The reported analysis is limited to the case of using an instantaneous set of measurements. Future activity will focus on the integration of the dynamic model of the overall system (i.e. of the towing AUV and of the streamer) in order to provide a continuous-time localization.
- In the performed analysis we assumed that the range measurements form two sparkers are synchronous. However, in real applications, the sparkers emit acoustic signals according to a time multiplexing schedule, and the time distance among the two signals can be of the order of seconds. Thus, we will investigate how to manage the asynchronous measurements integrating motion prediction.
- We want to validate the approach testing the algorithm with data from real operations thus considering the presence of noisy measurements and outliers.
- From the first wet tests performed for the project purposes, it resulted that also depth measurements can be somehow reconstructed from the acoustic signal. Thus, we will integrate the study including also depth sensors.
- We will investigate the combination of the streamer estimation algorithm with the AUV navigation strategy in order to use range measurers from the hydrophone also to improve the AUV localization.

REFERENCES


