# Dynamic placement of a constellation of surface buoys for enhanced underwater positioning

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***Abstract*—This paper addresses the challenge of dynamically adapting the location of the nodes in an acoustic network to optimise the localisation performance of Autonomous Underwater Vehicles (AUVs) operating in the area. A dynamic placement algorithm is presented to minimise the Cramer-Rao Lower Bound associated to the connected subset of network nodes. Algorithm performance is shown in simulation and as obtained during the REP14-Atlantic sea trial. REP14-Atlantic took place in July 2014 in front of the coast of Sesimbra, Portugal, and deployed a network composed of four nodes: one AUV of Folaga class, one fixed buoy, and two Wavegliders.**

***Keywords*—Dynamic Optimisation, Acoustic Communication Networks, AUV Navigation and Localisation, Sensor Networks, Acoustic Positioning***

## I. Introduction

This contribution addresses the challenge of using a communication infrastructure as a source of navigational information for Autonomous Underwater Vehicles (AUVs). In some applications [7] the vehicles are part of an underwater sensor network which is used to provide extended communication range and command and control interfaces. Figure 1 shows the typical deployment of the NATO CMRE wide area network. This includes submerged assets, namely AUVs monitoring and surveying an area of interest, mobile and static surface nodes that can be used as relay/gateways towards more distant nodes and/or command and control stations. Additionally, as a desirable by-product of the communication these surface mobile nodes (the constellation) can be used to further support AUV positioning through trilateration.

An example of a communication network able to produce range measurements is provided in [12] and [11]. In this case the range is calculated with acknowledgements at the physical level. A solution for measuring range between nodes on top of an existing communication infrastructure is presented in [4]. In this solution, the range information is obtained by exchanging message timing information within the payload of acoustic messages. References [2] and [13] present results of range based AUV positioning relying on existing acoustic networks using respectively a probabilistic and interval method based approach.

This paper focuses on the dynamic placement of the mobile surface nodes to optimise the localisation capability of possibly multiple target AUVs.

The literature on optimal placement of constellation nodes shows a variety of approaches. Path planning methods have been reported in [15]. In this case, the optimal trajectory of the constellation nodes is calculated based on an a priori knowledge of the trajectory of the survey nodes. In scenarios where the AUVs must react in real-time to sensor measurements (e.g. [5]) this approach might not be applicable. Alternatives include the prediction of the vehicle trajectories in the future to be fed to the constellation planner. These are usually computational expensive algorithms that might not be readily deployable in operational networks with nodes with limited computation power. The usage of a single constellation node as navigational aid is investigated in [10], [1]. In this case, the constellation vehicle has to be faster and more manoeuvrable than the target AUV. In scenarios where the navigational aids are slow moving and not very manoeuvrable (e.g. Wavegliders [14]) the presence of multiple nodes can hence represent an added value. The problem of determining the optimal geometric configuration of a sensor network for multiple target positioning using range-only measurements is tackled in [9]. The Fisher Information Matrix is used to determine a static sensor configuration that yields the minimum localisation uncertainty.

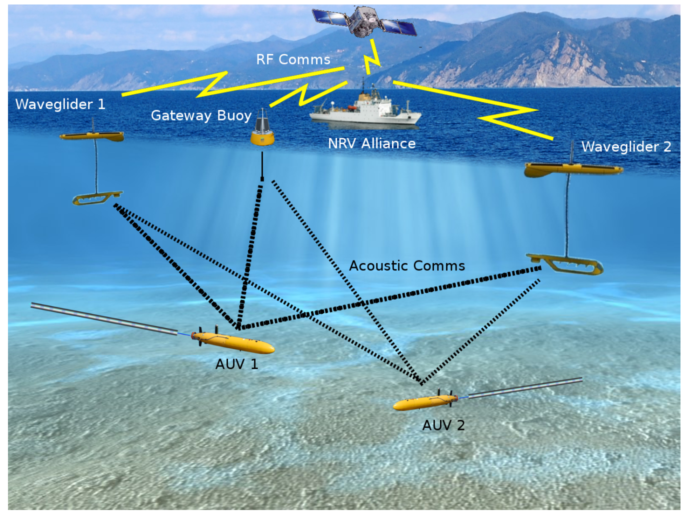


Figure 1. NATO CMRE wide area network

This work moves along this research line. It presents an algorithm for dynamically optimising the position of the constellation vehicles so to maximise the range-related information that is available for target positioning. The optimal placement solution - i.e. the geometry of the constellation with respect to the vehicle - is a function of the actual measurement setup, the measurement model, and the actual position of the target, and naturally has a big impact on the achievable accuracy of the positioning system [3]. To tackle these issues, the algorithm proposed in this work (applied by each node of the constellation at every time frame) performs the following steps every control cycle:

1. receives positioning data from each one of the nodes, including target node (e.g. estimated position);
2. sample the localisation objective function, which is based on the Cramer-Rao Lower Bound (CRLB), on a circle surrounding the constellation node
3. set the course towards the point with the smallest objective function value

The dynamic constellation optimisation algorithm was deployed and tested within the activities of the REP14-Atlantic sea trial. The sea trial took place in July 2014 of the coast of Sesimbra, Portugal, with constellation optimisation activities concentrated between July 22 and July 24. During the REP14-Atlantic activities the dynamic placement algorithm was tested within a network composed of four nodes: one AUV of Folaga class, one static buoy, and two Wavegliders. The Waveglider vehicle was modified by the CMRE to be used as an autonomous vehicle guided by a backseat computer mimicking the commands that would (in the normal configuration) be sent from the Liquid Robotics servers. Results show how the algorithm was effective in calculating the next waypoint as a function of the other constellation nodes and of the target position decreasing the overall uncertainty (CRLB) of the target localisation.

The remainder of the paper is organised as follows: Section II describes the general problem setting. Section III describes the optimisation algorithm. Results are shown in simulation in Section IV, and as obtained from the REP14-Atlantic sea trial in Section V. Finally, Section VI offers concluding remarks and discussions.

## II. System model

In this work, the acoustic network is considered to be composed of two types of nodes: constellation nodes and survey or target AUVs. The first ones are network nodes, static and mobile, that can be used to support the localisation of some target vehicles. Targets are AUVs that are active in a certain marine area. Their position is only driven by their own mission requirements. Let $\mathbf{p}_k \in R^3$ be the position of one target AUV at step $k$, and $\mathbf{c}_k^i \in R^2$ the location on the sea surface of constellation node $i$ at step $k$. Each constellation vehicle is modelled through a simple kinematic motion model which takes into account the presence of water current:

$$\mathbf{c}_{k+1}^i = \mathbf{c}_k^i + \delta t_k \begin{bmatrix} cos(\psi_k^i)v_k^i + sin(\theta)v_c \\ sin(\psi_k^i)v_k^i + cos(\theta)v_c \end{bmatrix} = \mathbf{c}_k^i + \delta t_k \mathbf{u}_k^i \quad (1)$$

$$\mathbf{u}_k^i = \begin{bmatrix} cos(\gamma_k^i) \\ sin(\gamma_k^i) \end{bmatrix} u_k^i(\gamma_k^i, \theta, v_c) \quad (2)$$

where $\delta t_k$ is the sampling step, $v_k^i$ is the forward speed of node $i$, $\psi_k^i$ is the heading and $\gamma_k^i$ is the course. The water current is characterised by the speed $v_c$ and the direction $\theta$. The constellation node is assumed to be able to navigate while compensating for the current (e.g. using the GPS when on surface or using a DVL underwater). $\mathbf{u}_k^i$ is the resulting speed vector in the earth frame of reference. $u_k^i$ is the norm of $\mathbf{u}_k^i$. The forward speed $v_k^i$ is either set to be constant or is not controllable (e.g. in the case of a Waveglider where the forward speed is function of wave height and frequency). In this respect, the only control input for node $i$ is its course $\gamma_k^i$. Note also, that we restrict our analysis to the case in which $v_k^i > v_c, \forall k$ (the node can fight against the current). Figure 2 shows the relation between the final forward speed of the node $\mathbf{u}_k^i$, the course of the node and the water current. Denote by $\mathbb{C}_k^i$ all the points on the circumference of the circle are those points reachable by the constellation vehicle $i$ in one sampling time (vehicle control cycle).

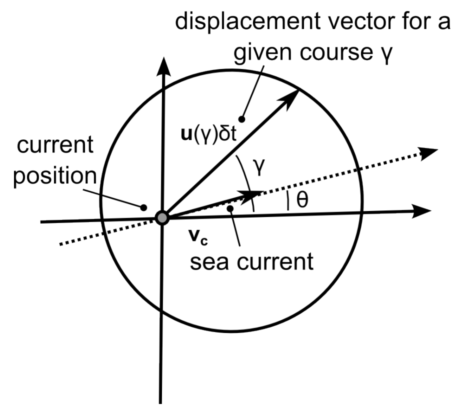


Figure 2. Possible values for the displacement vector.

## III. Algorithm description

To calculate the node's control inputs, this work follows the approach presented in [9]. The Fisher Information Matrix (FIM) is used to calculate the information associated with a specific geometric configuration of the network when all the nodes use a range-only localisation scheme. The resulting network configuration yields the minimum possible covariance of any unbiased target estimator by maximising the logarithm of the determinant of the FIM.

This paper uses an equivalent approach by considering the Cramer-Rao Lower Bound (CRLB) which is the inverse of the FIM. In fact, maximising the information about the position of the target in the case of the FIM corresponds to minimising the positioning uncertainty in case of the CRLB.

The expression of the FIM can be calculated as [9]:

$$FIM_i = C_i^T * R^{-1} * C_i, \quad (3)$$

where $R = diag(\sigma^2)$ is of size $n \times n$, $\sigma$ is the standard deviation on range measurements, and

$$C_i(s_{ix}, s_{iy}, c_{1x}, c_{1y}, ..., c_{nx}, c_{ny}) = \begin{bmatrix} \frac{s_{ix}-c_{1x}}{\sqrt{(s_{ix}-c_{1x})^2+(s_{iy}-c_{1y})^2}} & \frac{s_{iy}-c_{1y}}{\sqrt{(s_{ix}-c_{1x})^2+(s_{iy}-c_{1y})^2}} \\ \vdots & \vdots \\ \frac{s_{ix}-c_{nx}}{\sqrt{(s_{ix}-c_{nx})^2+(s_{iy}-c_{ny})^2}} & \frac{s_{iy}-c_{ny}}{\sqrt{(s_{ix}-c_{nx})^2+(s_{iy}-c_{ny})^2}} \end{bmatrix} \quad (4)$$

where $(s_{ix}, s_{iy})$ is the two-dimensional position of the $i^{th}$ target AUV and $(c_{px}, c_{py}), p \in \{1..n\}$ are the positions of the constellation nodes. The CRLB is hence the inverse of (3).

Given a specific constellation configuration, the CRLB provides a lower bound for the localisation uncertainty of the target AUVs (it is a function of the position of the target AUVs and of the constellation nodes). Figure 3 shows the CRLB associated to one target vehicle within a desired squared area when using two constellation nodes. Figure 3 hence shows what the most convenient position for the target AUV given static positions of constellation nodes. The standard deviation on range measurements $\sigma$ was set to 25m.
When the CRLB is plotted from the perspective of one of the constellation nodes Figure 4 is obtained. In this case, the minimum of the CRLB also gives the optimal position of the constellation vehicle to minimise the localisation uncertainty of the target. Note that in this case, to obtain the minimum lower bound, the second node should be placed on the dotted line perpendicular to the segment connecting the target and the other constellation node.

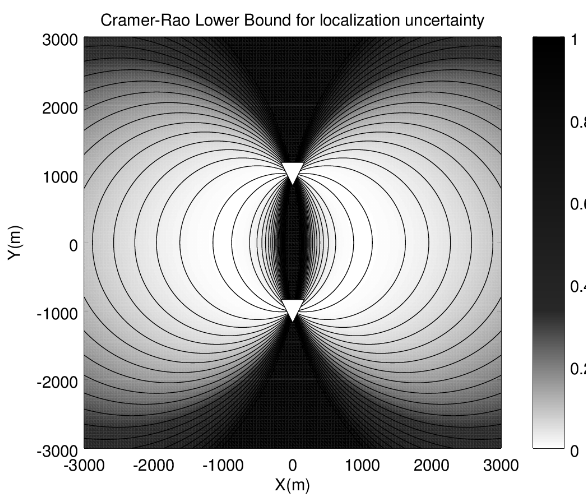


Figure 3. Cramer Rao Lower Bound associated to one target AUV in a 3km $\times$ 3km area when using two static constellation nodes (white triangles). Continuous lines represent the CRLB iso-levels.

Since the CRLB bounds the localisation uncertainty, this information can be used to drive the constellation vehicle. Formally, a constellation node $i$, at step $k$, calculates its control input $\mathbf{u}_k^i$ to minimise the trace of the $CRLB^i$ matrix:

$$\min_{\mathbf{u}_k^i} Tr(CRLB^i(\mathbf{c}_k^i + \delta t_k \mathbf{u}_k^i)). \quad (5)$$

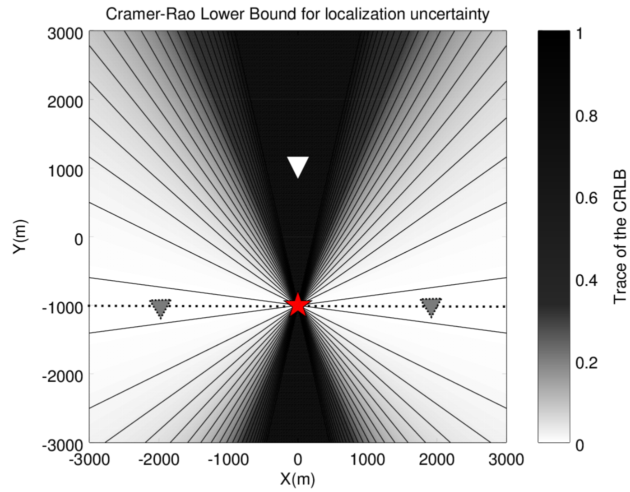


Figure 4. CRLB of localisation uncertainty from the perspective of one constellation node. The target AUV is shown as a red star, the static and already present constellation node is shown as a white triangle. In this case, to obtain the minimum lower bound, the second node should be placed on the dotted line perpendicular to the segment connecting the target and the other constellation node. Continuous lines represent the CRLB iso-levels.

Table I. ADAPTATION ALGORITHM AS APPLIED BY EVERY CONSTELLATION NODE.

| |
|---|
| 1. receive positioning data from each one of the nodes, including target nodes |
| 2. sample the localisation objective function $f$ using (6) on the circle $\mathbb{C}_k^i$ surrounding the constellation node. (See section II for the definition of the circle) |
| 3. set the course towards the point with the smallest objective function value |

When multiple target nodes are present, the previous formulation can be extended to include them all. The objective function in this case is obtained taking the weighted sum of the objective functions associated to each single target [8]. Let $N$ be the number of target vehicles. The final objective function $f$ is:

$$f = \sum_{i \in \{1..N\}} \alpha_i \times Tr(CRLB^i(\mathbf{c}_k^i + \delta t_k \mathbf{u}_k^i)), \quad (6)$$

where $\alpha_i, i \in \{1..N\}$ are tuning parameters that can be used to give more importance to some of the targets. When all targets are considered to be equally important:

$$\alpha_i = 1/N, \forall i \in 1..N.$$

The details of the algorithm applied by every constellation node at each time step are shown in Table I. Figure 5 shows one step of the algorithm.

Note that, the node placement algorithm needs the position of all the nodes of the network, including the target node. For this reason, the localisation is done in an iterative fashion [3]: first a possibly "rough" estimate of the target position is

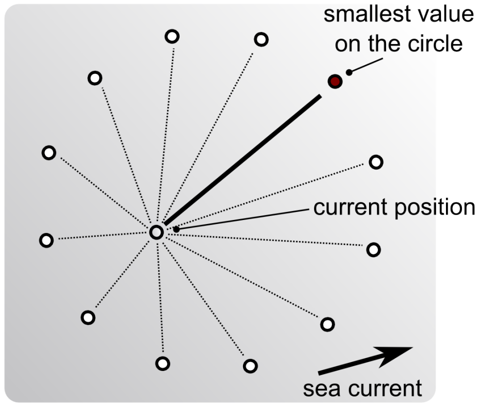


Figure 5. Sampling the objective function on the circle $\mathbb{C}_k^i$ surrounding the current position of the constellation vehicle then set the course towards the point with the smallest objective function value.

received, and then this is used to compute the optimal position of the supporting constellation. Once the sensors are placed in a new optimal configuration, the position of the target can be re-computed and the positioning/estimation cycle continues.

## IV. Simulation results

This section shows simulative results of the proposed approach in two scenarios. From previous experiments [2], the standard deviation on the range measurements has been set to 25m. The first scenario is a simulated version of an experiment performed during REP14-Atlantic experimental campaign in Portugal. Details of the trial are reported in the next section. Only one target node is present (Waveglider 2). The constellation is composed of three nodes, two static, and one mobile (Folaga). The configuration starts in a very unfavourable condition, with all the nodes aligned. To improve the localisation condition of the target vehicle, the mobile constellation node quickly moves to the new position. The final configuration reached is shown in Figure 6. The constellation nodes are represented with triangular markers. The target nodes are represented by a red star marker. The trajectories of the constellation nodes are represented in green. The objective function for the mobile node (green coloured triangle) has been plotted on the background for a grid of points belonging to the area. The objective function has been scaled to a [0,1] interval for better visibility.

The second scenario (see Figure 7) is more complex, and it includes two target vehicles moving along predefined trajectories represented using black lines. Again, all nodes start in an unfavourable position. The targets are initially static. The constellation nodes adapt to improve the localisation of the targets as shown in Figure 8. After 3000s, the target nodes starts moving along the trajectories. The constellation has to dynamically adapt to the ever changing situation. This is shown in Figure 9. Note that the constellation node (green triangle) whose objective function is showed in the Figure can't reach the optimal position fast enough since its speed is lower than the speed of the target node.

In the simulations, the targets were moving at a speed of 1m/s. The speed of the moving constellation nodes was 0.5m/s. The assets were subject to a current of 0.1m/s coming from the South.

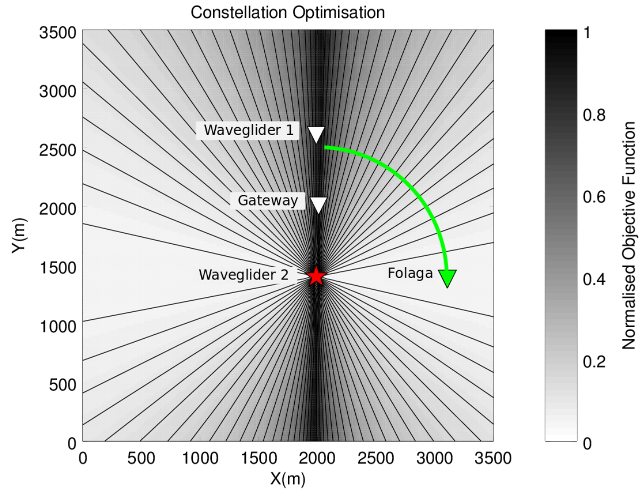


Figure 6. Optimal formation of the constellation nodes.

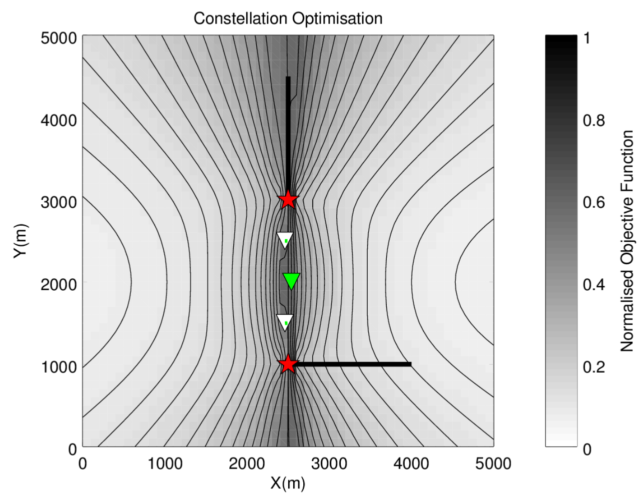


Figure 7. Initial formation of the constellation nodes and survey nodes.

## V. Experimental results

The dynamic constellation optimisation algorithm was deployed and tested during the REP14 sea trial between the $22^{nd}$ and $24^{th}$ of July 2014 of the coast of Sesimbra, Portugal. The sensor network was composed of four nodes: one AUV of Folaga class, one moored buoy and two Wavegliders. The nodes were deployed from the NRV Alliance. Every node was equipped with a medium frequency Evologics modem [6].

For the purpose of testing the constellation adaptation performance, a scenario similar to the first one shown in

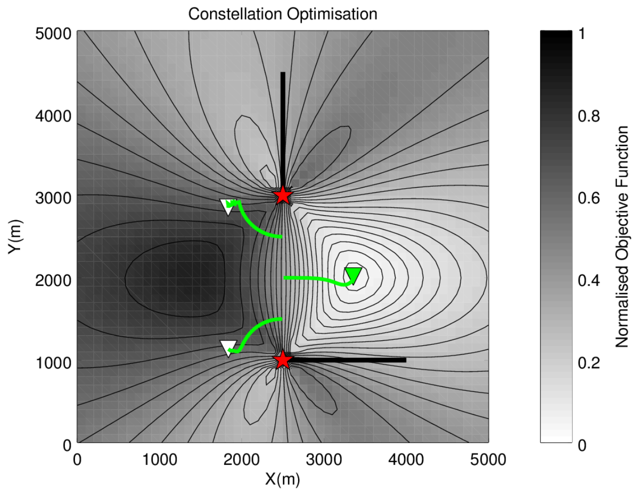


Figure 8. constellation nodes adapt to the new optimum static configuration.

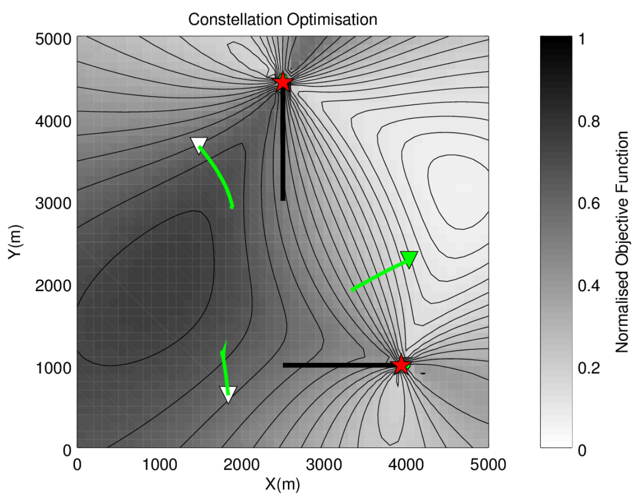


Figure 9. constellation nodes dynamically adapt in order to optimise the localisation of the two moving target nodes.

Section IV was set up. The target vehicle was Waveglider 2. This allowed to have heterogeneous vehicles in the constellation, with one slow moving vehicle (Waveglider 1) and one faster moving (the Folaga). Since the Folaga does not have any inertial navigation system, it was kept on surface to get GPS. In any case all communication was only acoustic-based. No vehicle was able to measure the current profile in this experiment.

Adaptation results are shown in Figure 10. Folaga, deployed at 'S' moved towards the south-east region to improve the localisation performance of Waveglider 2. During the same time period, Waveglider 1 tried also to adapt its position, but the presence of a strong current in the area made the vehicle movement extremely difficult. Once the Folaga reached a stable location ('X') creating a triangle with the target and the gateway buoy, the Waveglider 1 position was modified to put Wavegliders and Folaga again in an bad localisation position. This made Folaga move again to a better point (south most 'X').

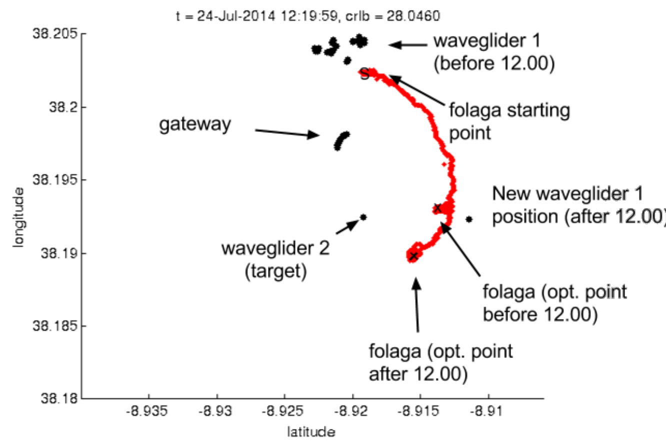


Figure 10. Constellation optimisation result obtained on July 24. The Folaga vehicle was the faster moving asset in this scenario. Note that the initial configuration was set up to be very localisation unfavourable with all the nodes aligned along a straight line. Folaga, deployed at 'S' moved towards south-east to improve the localisation performance of the target. Once the Folaga reached a stable location ('X') creating a triangle with the target and the gateway buoy, the Waveglider 1 position was manually modified to put the AUV again in an bad localisation position. This made Folaga move again to a better point (south most 'X').

## VI. Conclusion and Future Work

This paper shows an adaptive algorithm for network nodes to improve the localisation performance of target AUVs, which are using a range-only localisation scheme. The performance of the dynamic optimisation algorithm was shown through simulation and in-the-field experiments. Results show how the algorithm was effective in driving the network nodes based on the positions of the other constellation nodes and of the target position decreasing the overall uncertainty (CRLB) of the target localisation.

Future work will involve using multi objective optimisation including communication performance together with localisation, and/or clearance from unwanted areas. One limitation of the presented method is that it only provides a locally optimal solution. When the objective function presents several local minima this might limit the adaptation performance. Further work will include adding an additional control layer to track multiple minima and to follow the most favourable ones. In addition, future work will investigate how to include the nodes power consumption into the optimisation algorithm to increase the persistency of the network in the field.

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