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Autonomous Surface Vehicle Docking Manoeuvre with Visual Information

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Abstract- **This work presents a hybrid coordinated manoeuvre for docking an autonomous surface vehicle with an autonomous underwater vehicle. The control manoeuvre uses visual information to estimate the AUV relative position and attitude in relation to the ASV and steers the ASV in order to dock with the AUV. The AUV is assumed to be at surface with only a small fraction of its volume visible. The system implemented in the Autonomous Surface vehicle ROAZ, developed by LSA-ISEP to perform missions in river environment, test autonomous AUV docking capabilities and multiple AUV/ASV coordinated missions is presented.**

Information from a low cost embedded robotics vision system (LSAVision), along with inertial navigation sensors is fused in an extended kalman filter and used to determine AUV relative position and orientation to the surface vehicle

The real time vision processing system is described and results are presented in operational scenario.

I. INTRODUCTION

We propose a system implemented in the Autonomous Surface Vehicle (ASV) ROAZ see figure 1, developed by LSA-ISEP to perform missions in river environment, test autonomous AUV (Autonomous Underwater Vehicle) docking capabilities and multiple AUV/ASV coordinated missions [9].

ROAZ double hull structure and mechanical design takes in account the necessary space requirements for small AUV docking and handling (such as REMUS, Bluefins 9 or GAVIA AUVs).

Autonomous surface vehicles have been developed for science applications ranging from standard oceanographic ones [8] air-water microlayer studies [2], and also for AUV support either in navigation or providing communications surface relays [7], [10].

Docking for AUVs have been treated in the literature usually in the context of AUV docking to fixed stations. Terminal guidance is achieved by acoustic navigation [12], electromagnetic field [6] or visual information [3], [5]. Low cost vision sensors have been applied to AUV navigation [4]. Our approach to AUV docking takes other direction. We propose a docking manoeuvre with the AUV floating at surface, and a mobile docking station mounted in a ASV performs the manoeuvre.

Docking manoeuvres for ASV and AUVs provide improved multiple vehicle operation capabilities and AUV support in launch and recovery. In addition allow the overall systems autonomy extension providing autonomous underwater vehicle recharging, data retrieval, communications to land based systems and on site AUV mission reprogramming.

II. PROBLEM

A. Problem

The problem to be solved is the docking of an ASV with a free-floating torpedo shaped AUV. The AUV may or may not have power and communications. It is assumed that the ASV can visually detect the AUV on surface. The initial AUV position can be communicated by the vehicle or can be estimated by visual identification.

The surface vehicle is assumed to have a suitable navigation system capable of determining its position, attitude and velocity in a local inertial coordinate frame.

The vision system relies in a monocular camera. Moreover the ASV does not have active roll and pitch control and the vision camera is rigidly fixed in relation to the hull.

Two stern mount thrusters control the ASV with local low level control.

The problem is then to determine each thruster velocity (revolutions) in order to perform the docking with the AUV docking from the front and aligned with the ASV hull. This problem can be extended to recovery of suitable free-floating objects.

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B. *Approach*

Our vision based approach to docking in relation with other methods such as GPS position information retrieval from the AUV, acoustic relative positioning (such as USBL) or other very short range methods (such as electromagnetic guidance), is motivated by several advantages.

The AUV can be floating dead without power excluding GPS methods, and without DGPS and with antennas so near water surface it is possible to have errors in the vicinity of 1,2m, clearly in excess for short range docking. Acoustic methods have in general higher cost and provide bad solutions for shallow water environments.

Although roll an pitch perturbations can deteriorate vision results, the envisioned river, dams and estuarine operational scenarios (also due to size and power limitations on the surface vehicle) result in relatively calm waters.

This approach can also be used in harsher environments with visibility problems (such as wave occlusion) or high roll and pitch perturbations (as in open sea), by its application at closer ranges and coupling information by other navigation aids such as the above mentioned methods.

III. ROAZ SURFACE AUTONOMOUS VEHICLE

The vehicle was developed under the research activity pursued on multiple autonomous robots, developed by the Autonomous Systems Laboratory at ISEP - Institute of Engineering of Porto. Its overall dimensions are 1.5x1x0.52m. Twin hull separation distance was defined in order to achieve: good hydrodynamic characteristics, ease for logistics and operation and the possibility of docking for a shallow water AUV such as the Isurus vehicle (a REMUS based AUV).

Figure 1. Roaz autonomus surface vehicle.

A custom-made low cost inertial navigation system is used coupled with multiple GPS receivers for navigation.

A CAN bus network is implemented to connect the vehicle subsystems, from the navigation sensors to the thruster controllers.

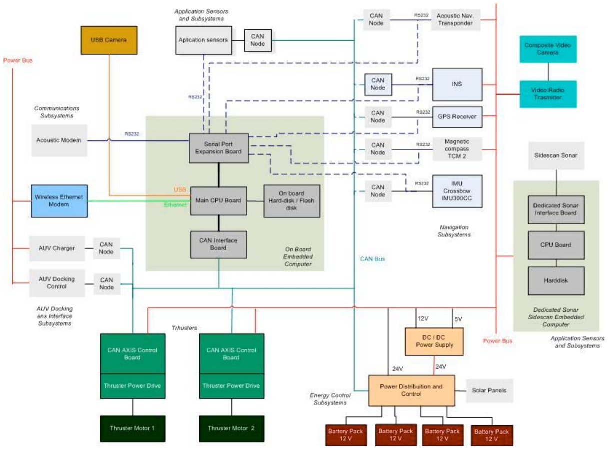

Figure 2. Vehicle hardware architecture.

The vehicle uses 12V NiMh battery packs with 24V nominal voltage for the thrusters.

Radio communications are achieved through an external IEEE 802.11 a b/g ethernet modem with external antenna (in various configurations and gains). Currently IEEE 802.11a is used since the operation in the 5GHz band provided clearly higher range and bandwith in near water conditions in comparison with previous experience with 2.4Ghz Wifi.

A dedicated thruster control board was developed, with local processing in an integrated DSP and with current monitoring.

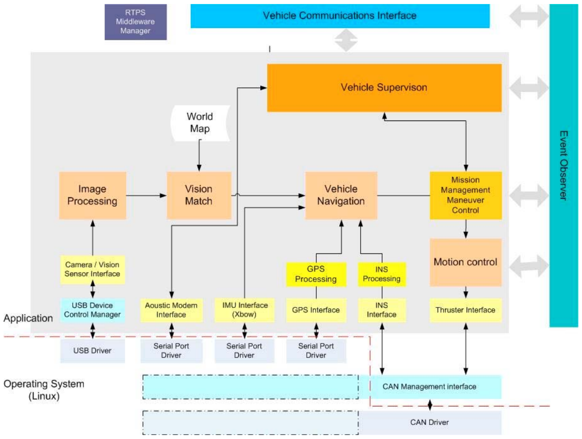

Figure 3. Vehicle software architecture.

Control, navigation and mission control are performed in a low power embedded computer running a modified Linux operating system (Fig.3)

IV. VISION SYSTEM

The vehicle vision system is a particular application of a more general vision system developed for robotic applications (LSAVision). Information from the low cost embedded robotics vision system (LSAVision) [11] is used to determine AUV relative position and orientation to the surface vehicle. Existing technology demonstrated on other stringent mobile robotics scenarios (such as ISePorto Robocup's robotic soccer team or FALCOS autonomous aerial vehicles) is applied to this case.

The vision system processes image in real time, with edge detection and object identification, extracting surfaced AUV image characteristics (position, orientation). Colour based image segmentation is used as a first stage in a pipeline structure with increased abstraction.

Currently one USB camera (Philips PVC740K) is used. It acquires images at 30 fps with a resolution of 320x240 or 15fps at VGA resolution (limitation from the USB bus). At lower resolution it is possible to process 2 cameras in real time.

Lower stages implement image acquisition (Video4Linux camera interface) and image segmentation. The image processing threads are capable to process all the acquired images. This processing is mainly done in a colour-segmented image.

The colour segmentation algorithm implementation follows a very efficient method proposed in [1]. This process is still sensitive to lighting conditions.

Upper layers perform edge and blob detection along with object recognition. Only relevant features are processed. A set of additional modules performs statistics measurement, image calibration and overall control on elements to process.

The vision system allows the use of conventional digital low cost cameras or can use dedicated hardware vision sensors (BoaVista system) with significant energy consumption reduction in image processing. Relevant image information can be retrieved by only one camera (distance to target and orientation measures are provided) although the vision system can incorporate stereo information for increased precision.

V. VISION BASED TARGET ESTIMATION

A. *Target measurement*

Consider the coordinate frames depicted in figure 4:

{W} – inertial, global earth fixed coordinate frame with North-East-Down orientation, fixed in a suitable local point at mean water level

{B} – body fixed reference frame

{C} – camera fixed reference frame with z axis aligned with principal optical axis

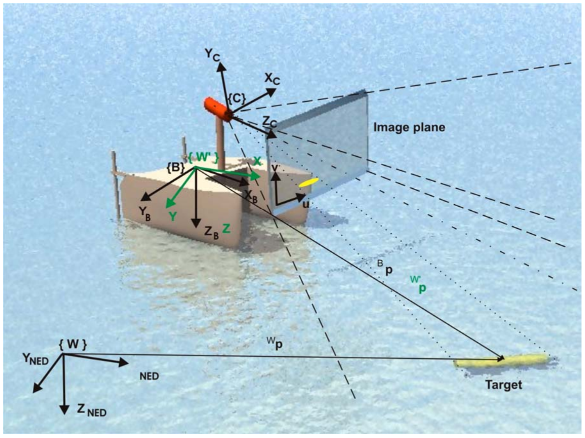

Figure 4. Coordinate frames.

Considering a pinhole camera model, image plane points relate to the camera frame points by the camera intrinsic parameters:

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f\,k_u & k_\theta & u_0 & 0 \\ 0 & f\,k_v & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} {}^C x \\ {}^C y \\ {}^C z \\ 1 \end{bmatrix} \qquad (1)$$

Where (u,v) are the point projection in the image plane, f the camera focal length and (u_0,v_0) the principal point. k_u and k_v are scaling factors converting from space metrics to pixels in image. An additional scaling factor k_θ could be used to correct skew in the CCD, however is usually considered zero.

Lens distortion (such as occurring in wide angular lens) can be corrected prior by correcting the relevant pixel through a pre-calculated lookup table.

Using the camera extrinsic parameters it is possible to determine the correspondence between a point in an external frame, such as {B} and its representation in {C}.

Consider ${}^C\mathbf{p}$ the AUV position in {C} coordinate system, and ${}^B\mathbf{p}$ the position in the body fixed frame.

We have

$$^C\mathbf{p} = \mathbf{R}_B^C\, {}^B\mathbf{p} + \mathbf{t}_{ext} \qquad (2)$$

where $\mathbf{R}_B^C$ and $\mathbf{t}_{ext}$ are the camera extrinsic parameters and can be determined by identification experiments [13], the rotation matrix is also the rotation transformation matrix from {B} to {C}.

We want to obtain **p** in the global reference frame {W} so an additional rotation must be performed from {W} to {B}. The rotation is parameterised by the Euler angles (ϕ, θ, ψ) (roll,pitch and yaw respectively) with the rotation matrix given by:

$$\mathbf{R}_W^B = \begin{bmatrix} \cos\theta\cos\psi & \cos\theta\sin\psi & -\sin\theta \\ -\sin\psi\cos\phi + \sin\phi\sin\theta\cos\psi & \cos\phi\cos\psi + \sin\phi\sin\theta\sin\psi & \sin\phi\cos\theta \\ \sin\phi\sin\psi + \cos\phi\sin\theta\cos\psi & -\sin\phi\cos\psi + \sin\theta\sin\psi\cos\phi & \cos\phi\cos\theta \end{bmatrix} (3)$$

thus:

$$ {}^{C}\mathbf{p} = \mathbf{R}_B^C \left[\mathbf{R}_W^B\ {}^{w}\mathbf{p} + \mathbf{t}_B \right] + \mathbf{t}_{ext} \qquad (4) $$

If one ignores $\mathbf{t}_B$ in eq. 4, the AUV position is given instead in a referential parallel with the inertial frame and translated to the body fixed origin {W'}. Pre-multiplying by $\left[R_B^C\right]^{-1} = \left[R_B^C\right]^T = R_C^B$, we have:

$$ \left[\mathbf{R}_B^C\right]^T\ {}^{C}\mathbf{p} = \mathbf{R}_W^B\ {}^{W'}\mathbf{p} + \left[\mathbf{R}_B^C\right]^T \mathbf{t}_{ext} \qquad (5) $$

the last term on the right-hand side is the origin of {C} in {B} $(xc_0,yc_0,zc_0)^T$. So:

$$ \left[\mathbf{R}_B^C\right]^T \begin{bmatrix} {}^{C}x \\ {}^{C}y \\ {}^{C}z \end{bmatrix} = \mathbf{R}_W^B \begin{bmatrix} {}^{W'}x \\ {}^{W'}y \\ 0 \end{bmatrix} + \begin{bmatrix} xc_0 \\ yc_0 \\ zc_0 \end{bmatrix} \qquad (6) $$

AUV position in the inertial frame {W} is given thus by:

$$ \mathbf{p} = {}^{W'}\mathbf{p} + \mathbf{p}_{ASV} \qquad (7) $$

The AUV z coordinate is zero since the vehicle is at the surface. This allows to solve eq. 1 and eq. 6 in order to ${}^{W'}x$ and ${}^{W'}y$ and thus determine the AUV position.

B. Target estimation

AUV position is continuously estimated in the global frame {W} using vision measurements obtained by the ASV.

A five state kalman filter is used to estimate AUV position and velocities, and relative orientation (fig 6.).

In the problem statement the AUV is considered to be drifting on surface and if water current is relatively constant for both vehicles, both drift so the AUV velocity is not relevant for docking purposes. However it is assumed that the ASV can have a relatively complex and accurate navigation system providing a precision estimate in the earth fixed frame {W}, so water current estimation can be obtained.

The process model is given by:

$$ \mathbf{x}_{k+1} = \mathbf{F}\mathbf{x}_k + \mathbf{w}_k \qquad (8) $$

and the measurement model by

$$ \mathbf{z}_k = \mathbf{H}\mathbf{x}_k + \mathbf{v}_k \qquad (9) $$

with :

$$ x_k = \begin{bmatrix} x_{auv} & y_{auv} & v_{x\_auv} & v_{y\_auv} & \beta \end{bmatrix}^T,\ z_k = \begin{bmatrix} p_x & p_y & \beta_v \end{bmatrix}^T $$
(10)

where $(p_x\ ,\ p_y)$ are AUV positions obtained by the ASV vision system, β_v the relative orientation also obtained from vision (with edge detection and second moments in blob description), v_{x_auv}, v_{y_auv} are AUV velocity components in frame {W}, corresponding to water current. **F** represents a constant velocity model and H is the measurement relation. Process noise $\mathbf{w}_k$ is assumed gaussian with covariance **Q** and measurement noise $\mathbf{v}_k$ with covariance **R**.

The use of the global coordinate frame for sensor fusion and target estimation was chosen since the ASV is assumed to have a good navigation precision and thus easily allows integration of further sensory information (such as other vehicles or systems).

VI. HYBRID MANOEUVRE

A hybrid systems approach is used in the docking manoeuvre synthesis. The control law is represented by a hybrid automaton with both discrete and continuous states.

Vehicle controls are each thrusters thrust force. This can be approximated by a proportional term with revolutions squared minus a deduction factor related with relative water axial speed. Since a low level control subsystem exists, the designed outputs are the propeller velocities (n_L,n_R) and in particular their common and differential mode (providing thrust force in surge and yaw moment respectively).

$$ n_L = n_c + n_d\ ,\ \ n_R = n_c - n_d \qquad (11) $$

Simplified schematics for the hybrid automata can be observed in the next figure. Each discrete state or control mode corresponds to a specific phase in the docking manoeuvre process.

Starting from a neutral state (*STANDBY*) the ASV turns towards the target (in the *PREPARE* phase). Then follows a LOS guidance scheme to the AUV position until it reaches a neighbourhood of radius r_{near}

In general the AUV must be docked facing towards the ASV in order to minimise the risk of impact on fins or propeller. When the ASV reaches close to target, either the AUV is properly aligned (with the front facing the ASV bow) or is approached from behind. If the ASV is properly aligned with the AUV, the final docking is made on *DOCK* phase by following a virtual approximating point $\mathbf{p_{ap}}$ and reducing velocity.

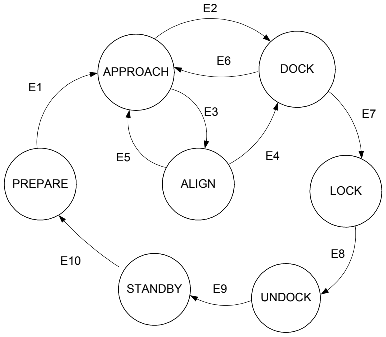

Figure 5. Hybrid manoeuvre discrete states.

If the AUV is not aligned to perform final docking the virtual point is defined at a larger distance and with an lateral offset to possibly avoid running into the AUV (*ALIGN* phase).

Upon successful docking the AUV is mechanically locked.

To undock the vehicle the ASV unlocks the AUV and moves backward to a sufficiently safe distance.

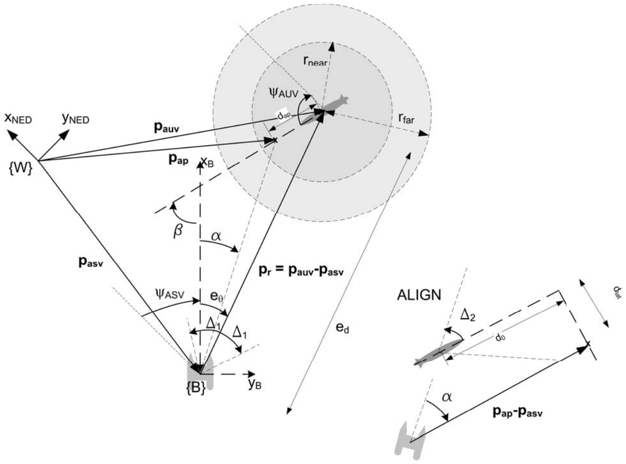

Figure 6. ASV guidance.

The control in each discrete state in figure 7 depends on overall vehicle state and AUV position and orientation.

In figure 6 one can observe the relative positioning between ASV and AUV, with a graphical description of quantities used in different guidance stages.

In each discrete state the system follows a continuous flow, and there is associated an invariant. The control (n_c,n_d) is given by different relations according with the discrete state. The events in figure 6 are triggered by conditions on the state variables or by external commands.

TABLE I
CONTROL FOR HYBRID MANOEUVRE DISCRETE STATES

State	*Control*
Prepare	$n_c = 0, \quad n_d = n_{nom}$
Approach	$n_c = n_{nom} + k_1(\dot{e}_d)$
	$n_d = k_2 e_\theta + k_3 \dot{\psi}_{ASV}$
Dock	$n_c = k_4 e_d,\ n_d = k_5 \alpha \qquad d_{ap} = k_6 e_d$
Align	$d_{lat} = k_7 d_1$
	$n_c = n_{nom},\ n_d = k_8 \alpha + k_9 \dot{\psi}_{ASV}$
Lock	not specified
Undock	$n_c = -n_{nom,}\ n_d = 0$
Standby	not specified

The event trigger conditions are:

TABLE II
EVENT TRIGGER CONDITIONS

Event	*Condition*
E1	$\psi_{ASV} \leq \gamma + \Delta_1 \wedge \psi_{ASV} \geq \gamma - \Delta_1$
E2	$\lVert \mathbf{p}_\mathbf{r} \rVert \leq r_{near} \wedge \psi_{ASV} \in \left]\psi_{AUV} + \pi \pm \Delta_2\right[$
E3	$\lVert \mathbf{p}_r \rVert \leq r_{near} \wedge (\psi_{ASV} < \psi_{AUV} + \pi - \Delta_2 \vee \psi_{ASV} > \psi_{AUV} + \pi + \Delta_2)$
E4	$\lVert \mathbf{p}_r \rVert r_{near} \wedge (\psi_{ASV} > \psi_{AUV} + \pi - \Delta_2 \wedge \psi_{ASV} < \psi_{AUV} + \pi + \Delta_2)$
E5,E6	$\lVert \mathbf{p}_\mathbf{r} \rVert > r_{far}$
E7	AUV docked (mechanical lock)
E9	$\lVert \mathbf{p}_\mathbf{r} \rVert \geq r_{free}$
E8, E10	external command

In *LOCK* state, the ASV control is not provided by the docking manoeuvre, and also as in *STANDBY* state. Exiting is made by external commands (events E8, E10).

VII. RESULTS

Field tests were performed in Montemor canoeing course under calm waters.

In the following table vision system performance is presented in terms of computation time, running with all the vehicle navigation and control processes on a Pentium III 900MHz embedded SBC running Linux, for a dedicated hardware solution or standard USB camera.

TABLE III
VISION SYSTEM PROCESSIING TIME

	Image tion	Segmenta-	RLE	Blobs	Edges	Objects	Total
Hardware vision system (640x480)	-		-	3.5	3.0	0.7	7.2ms
USB camera (320x240)	3.0		2.5	0.3	1.4	0.6	7.8ms

In the next figure colour segmentation results for a floating REMUS AUV and a navigation buoy are presented.

Figure 7. Image captured at test site with buoy and ISURUS AUV at surface. On top real image, real time segmented image (red, yellow) on middle and bottom (only segmented colours).

Vision target relative orientation measures at a distance of 2m are presented in the next figure.

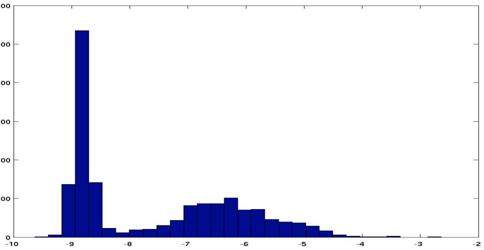

Figure 8. Target relative orientation (degrees).

Although a variation of approximately 6 degrees in relative orientation (clearly acceptable for control in the docking manoeuvre final stages), the quality of results increase with the approaching of the ASV to the AUV.

A docking manoeuvre was performed in calm water conditions. The final phases were tested and in the following figure one can observe a target approach from a near region.

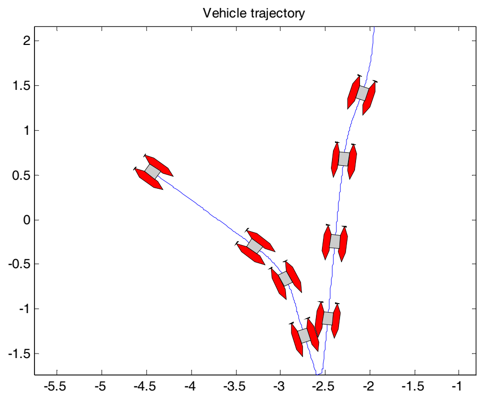

Figure 9. Vehicle trajectory (robot dimensions not in scale).

Target is positioned (–1.7,-2.6) and the ASV starts from the left and after contact moves backward.

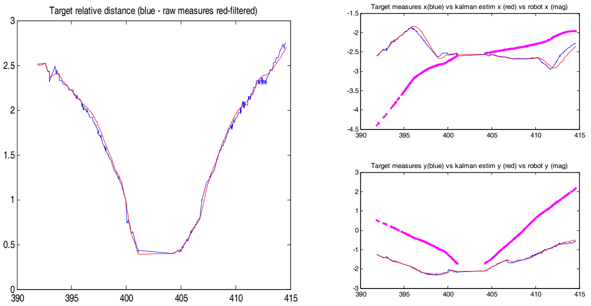

Figure 10. Target to robot relative measures.

The target relative position to the robot is given in figure 10, along with the filtered estimates used in control.

AUV was detected and its position determined by the vision system up to 8m of distance to the ASV. This was accomplished in the calm water scenario but even in almost sunset conditions with low angle of light incidence.

VIII. CONCLUSIONS

An hybrid docking manoeuvre to a floating AUV for an small ASV was presented. Vision based information was used to estimate AUV position and processing was performed in real time.

Vision processing results were presented validating the approach.

The real time vision processing system is described and results are presented in operational scenario.

Field tests were performed in river like conditions.

Int the experiments conducted in operational scenario the AUV orientation was not considered yet (in order to dock with increased safety from the front).

Further work is still necessary to validate the approach under stronger varying light and wave conditions.

Currently only passive AUV strategies have been tested, the AUV simply emerges and waits to be picked up by the ASV. AUV active behavior is under consideration, by use of USBL navigation towards the ASV and incorporating vision on the submarine for proximity approach.

Further multiple coordinated vehicle missions involving aerial unmanned vehicles are to be performed, to detect surfaced AUV in power-off conditions and out of visual range of the ASV.

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