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Docking Techniques and Evaluation Trials of the SWIMMER AUV: An Autonomous Deployment AUV for Workclass ROVs

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Abstract- The **SWIMMER** Vehicle is a EU-Thermie funded project to develop a prototype autonomous vehicle capable of deploying existing work-class ROVs to subsea installations - removing the need for continuous surface support vessels and long umbilical cables (and the associated costs, power restraints and weather dependencies). **To** be able to accurately position and dock a large free swimming AUV (total vehicle and payload in-air mass exceeds 2.5 tonnes, **and** over 6 metres in length), at depths up to 1000m after transits of up to 10km is particularly challenging.

The deployment configuration mounts **the ROV** above the **SWIMMER** AUV. The ROV is inactive during deployment, and the AUV is completely self-contained in terms of power, thrusters and computer-control. During transit, the LRPS (Long Range Positioning System) a combined acoustic Positioning / Data link **provides** autonomous navigation to the seabed, together with top station monitoring. During docking, the SRPS (Short Range Positioning System) directs the vehicle during the final 20 metres of descent and provides the necessary positional information for a precise alignment for a mechanical docking with a seabed station. When docked, the SWIMMER uses computer-controlled clamps that allow the ROV to be disengaged remotely from the **SWIMMER** while on the seabed docking station. **In** this configuration, power and communications are fed from the seabed network to allow the SWIMMER to recharge, and the ROV to be remotely controlled (completed conventionally by pilot's based, in theory, anywhere in the world).

I. INTRODUCTION

Under the Subsea Technology research programme at The University of Liverpool, a novel positioning technique for underwater vehicles called ASOP **(Active Sonar Object Prediction)** has been developed over the last few years.

ASOP is positional technique for use in structured subsea environments such as offshore oil production fields. It uses a 3-dimensional model (map) to drive an active, focused search for specific objects within conventional ultrasonic imagery. The system has been designed for use with both Remote Operated Vehicles (ROVs), and Autonomous Underwater Vehicles (AUVs).

ASOP was originally developed as part of a TUUV (Technology for Unmanned Underwater Vehicles [1-4]) joint research programme funded by the UK Government and partners from the commercial offshore industries. The original prototype provided a Virtual Reality (VR) display to ROV pilots - in effect providing a virtual camera image to improve their navigation and task visualisation within complex subsea environments.

However, ASOP has been developed with the move to greater autonomous operations in mind, and the technology is now being developed further as part of the of the SWIMMER concept vehicle. This is a European Union (EU) funded programme to develop an autonomous prototype / demonstration vehicle capable of deploying conventional work-class ROVs around the next generation of ultra-deep (1000m to 5000m) production fields currently being planned. The SWIMMER research programme is currently ongoing, and is due to finish in September 2001 with deep-water trials on the prototype vehicle.

This paper begins by providing an overview of the SWIMMER AUV (Section II), and the role ASOP provides as part of the vehicle's Short Range Positioning System (SRPS). It describes in detail the ASOP algorithm (Section III), and how it uses sonar data to position the vehicle for docking. Section IV describes some of the ASOP System Trials, both tank, dock and sea-based, and how the technique is being used to facilitate autonomous seabed docking on the SWIMMER AUV (illustrated in Fig. 1).

Fig. 1. Computerised Mock-up of the SWIMMER Sled and Payload Vehicle on Final Approach.

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II. THE SWIMMER "CONCEPT"

A. *The Benefits of SWIMMER*

As offshore exploration and production moves to increasingly greater water depths, the greater the reliance on remote intervention using ROVs (Remotely Operated Vehicles). Any technology that can reduce the cost of deploying and using such vehicles could produce considerable savings.

The aim of EU-Thermie funded SWIMMER project is to construct a prototype AUV (Autonomous Underwater Vehicle) capable of carrying a standard work-class ROV to a seabed installation, in effect an autonomous deployment platform.

This would bring three immediate benefits:

- Remove the need for a permanent *support* vessel, with subsequent cost savings.
- Remove the long tether / umbilical with consequent improvement in vehicle dynamics and energy usage.
- Once docked, the work-class ROV can be operated completely conventionally via a sub-sea fibre optic communications network and short (-100s metres) umbilical. This allows the ROV pilot to be stationed ashore.

B. *Typical Mission Profile*

A typical mission scenario might be as follows. The SWIMMER AUV is to be deployed from an FPSO (Floating Production Storage Offloading) vessel. The work-class ROV is mounted on the SWIMMER AUV. The ROV has a short 200m umbilical that is wound round a self-contained winch mounted on the SWIMER. The ROV is un-powered for the duration of the transit to the seabed. The SWIMMER AUV is tetherless and powered from onboard batteries. The combined SW MMER / ROV vehicle is launched using a crane on the FPSO. A low-speed acoustic data link is established to the SWIMMER, final system checks are done and the command to begin the deployment mission is sent via the acoustic link.

During the ***Transit Phase,*** the SWIMMER uses its LRPS (Long Range Positioning System - based on a Long Base Line network) to fix its position, and autonomously decide on its heading, speed and dive rate. Periodically, navigational fixes are sent via the acoustic data link (part of the LRPS system). The depth of dive could be as deep as 1000m to 3000m, combined with a horizontal displacement of several kilometres.

The *Approach* ***Phase*** commences when the vehicle is 30m above the Docking Station and within l Om radius. Based on a novel technique developed at The University of Liverpool, the SRPS (Short Range Positioning System) uses CAD information to derive a 3D map (profile) of the Docking Station on the seabed and automatically manoeuvres the vehicle from 30m to within 0.2m, with an accuracy between 20 - 50cm. The close quarters approach is illustrated in Fig. 1.

The final alignment in the ***Docking Phase*** *is* aided by the mechanical design of the Docking Station. The sloping design of the top of the Docking Station rig help the SWIMMER align correctly and allow the wet connectors (carrying power and communications) to mate.

Once docked, the SWIMMER AUV is powered down (the onboard batteries are recharged). The work-class ROV is now connected, via the seabed fibre optic communication network, to the pilot ashore somewhere in the world. The ROV can be detached from the SWIMMER, and operated around the seabed installation completely conventionally.

The ROV could stay deployed for months without *further* need of a surface support vessel. The SWIMMER "concept" envisages a network of Docking Station nodes fitted across a whole production field. If the ROV is required elsewhere, the ROV is docked back onto the SWIMMER and powered down. The SWIMMER AUV is then given instructions to proceed autonomously to the Docking Station nearest the work site (using the LRPS and SRPS), recharging at immediate stations as necessary.

C. *System Configuration*

The SWIMMER vehicle (pictured in Fig. 2) is designed to carry a work-class ROV as a payload. This is achieved by mounting the SWIMMER as a tool-skid under the ROV. The SWIMMER has computer-controlled clamps that allow the ROV and the SWIMMER to be disengaged remotely while on the seabed. While docked, power and communications are fed from the seabed network to allow the SWIMMER to recharge and the ROV to be remotely controlled.

Internally, the SWIMMER AUV has three major sub-systems that are primarily involved in the docking process, these are; the MCU (Mission Control Unit), LRPS (Long Range Positioning System) and SRPS (Short Range Positioning System).

D. *MCU: Mission Command Unit*

This *is* PC-based computer with additional interface hardware. The MCU is responsible for coordinating the actions of the various sub-systems, and ensuring the overall aim of the deployment mission is achieved.

Particularly important for navigation of the vehicle, the MCU is responsible for coordinating navigation system's handover from the LRPS to the SRPS when in final Approach (see section F).

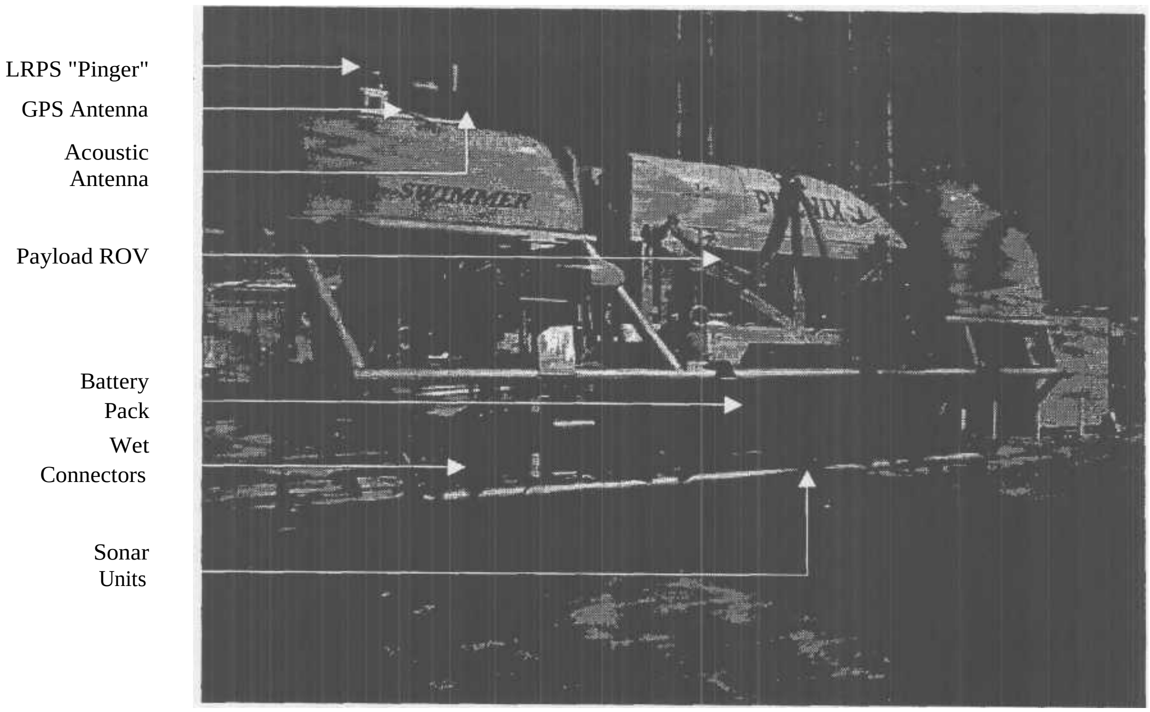


Fig. 2. The SWIMMER AUV with the payload ROV Pheonix vehicle. The work-class ROV is carried as a payload in the central section, and computer controlled clamps allow the ROV to be released and captured underwater.

E. LRPS: Long Range Positioning System

The LRPS (developed by Ifremer) is an integrated system that produces periodical position fixes (at 1 Hz) for the MCU. It uses a combination of dead-reckoning (based on data coming from a Doppler Log), and Long Base-Line (LBL) information (refreshed every 45 seconds) provided by acoustic modules. The LBL system uses a CHIRP modulation scheme, to offer an improved distance / precision ratio and SNR [5-6].

The acoustic telemetry link is used to provide a low bitrate data / position uplink, and vehicle command downlink. It uses the same hardware as the LRPS, although functionally it is considered separate. The LRPS provides positional information to the system from the deployment up until the vehicle is positioned to within a few meters of the docking station. Once within range of the docking station the SRPS is activated.

F. SRPS: Short Range Positioning System

The SWIMMER's SRPS is used by the AUV for the **Approach Phase** of the mission - final manoeuvres and alignment of the SWIMMER with the seabed station, ready for mechanical docking. For the purposes of the project, the AUV enters this phase when the LRPS signals to the MCU that vehicle is 30m above the station, and within a radius of 10m.

The SRPS is a self-contained PC-based unit, with its own dual scanning orthogonally mounted sonar heads. Its uses the ASOP algorithm to calculate at IHz, the relative offset of the AUV from the Docking Station. This information is transferred to the MCU and used to control the AUV's descent. Once within 0.5m in the horizontal plane, the mechanical design of the Docking Station forces the vehicle to align correctly for wet connectors to mate.

III. ASOP: ACTIVE SONAR OBJECT PREDICTION

A. The "Active" Approach: Object Search and Confirmation in Noisy Data

The principle behind ASOP is to use a 3D map or model (derived from existing CAD information), and use this to drive an active search for significant sonar features ("landmarks") in the live sonar data. The system was originally developed as part of the TUUV (Technology for Unmanned Underwater Vehicles) programme [1-4].

The "active" or "attentive" approach is in contrast to the more conventional method of processing the image (or signal) to identify edges and boundaries, with the eventual aim is to classify the detected shapes against a database of known objects [7-9]. This "image analysis" approach is always difficult, and in ultra-noisy sonar images very prone to errors.

The ASOP system determines positional information by comparing *predicting* sonar targets from a model of the environment, together with a confidence factor. The ASOP approach is therefore one in which the model of the environment actively drives the attention of the search algorithm towards specific areas of the data. It turns the process into an *Object Confirmation* task, as opposed to *Object Recognition.* This approach performs significantly better in the presence of noise, and is particularly suited to sonar data.

B. *Algorithm*

The algorithm is illustrated in a flow diagram in Fig. 3. An initial estimate is used to index the 3D map, and generate predictions as to the location of targets within incoming sonar data. An active search is used to match the predictions to the data, and the differences are used to calculate the real position of the vehicle. This is then used as the next estimate as the cycle repeats.

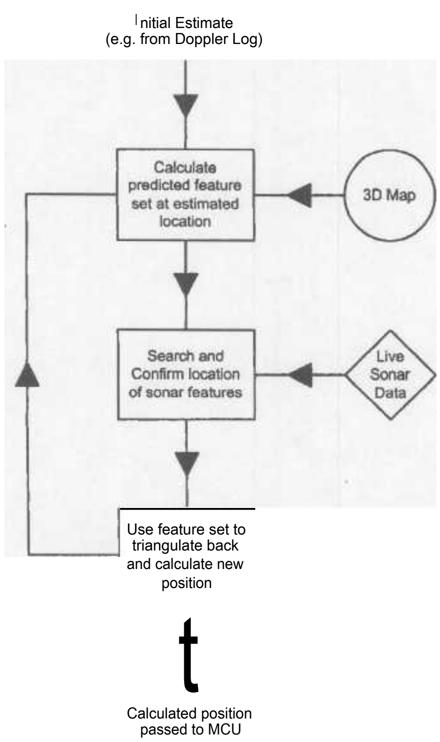


Fig. 3. ASOP flowchart

Stage 1: Access 3D Model database and generate Predicted FRP

The current estimated position of the vehicle (from a previously calculated position, or perhaps from inertial-based instruments) is used to access the 3D simulation of the environment. This software calculates a predicted FRP (First Return Profile) for the vehicle at that position. The FRP gives the range to the nearest significant sonar target in any particular direction (i.e. range vs. heading). For example, the profile in Fig. 5(c) marked "ASOP" is the predicted FRP for the vehicle positioned over one section of the SWIMMER's seabed Docking Station. Since the y-axis gives the target's range from the sonar, the profile is in effect the surface profile of the docking station, but inverted, with the seabed being at the top of the graph. The profile clearly shows the central "dip", characteristic of the central axis of the Docking Station. The transitions between the various sections of the profile (i.e. when the profile changes direction) are used by the ASOP algorithm to calculate the vehicle's position.

Stage 2: Obtain Sonar Data and Generate Sonar FRP

The next stage is to obtain a sonar scan at the vehicle current position, and calculate its FRP. This process is illustrated in Fig. 5(a) and (b). Fig. 5(a) shows the sonar image for the same section of Docking Station. The shape of the Docking Station can easily be made out, together with a significant amount of reflections and echoes (which appear below the seabed).

Fig. 5(b) shows the results of processing the sonar data to produce a FRP. This data can also be seen plotted on the graph in Fig. 5(c), marked as *"SONAR".* The predicted *(ASOP)* and sonar *(SONAR)* profiles clearly show a high-degree of correspondence. The central "dip" is narrower on the sonar profile because of beam interaction / reflection in the narrow opening in the structure. The sonar profile also shows a false "blip" in the profile around 15 degrees (on the x-axis). This is caused by noise in the original sonar data. However, the alignment of the transitions in both profiles is good, and the active search copes well with spurious and noisy data.

Stage 3: Calculate and Compare the Predicted and Sonar-Generated ASOP profiles

To identify and compare the transitions between the different sections of each profile, the 2nd differential of the profile's range data with respect to heading is calculated. This gives the rate-of-change of gradient of the surface profiles, and produces a strong positive or negative impulse at significant points. For the surface profiles in Fig. 5(c), the 2nd differentials are plotted as "ASOP_D2" for the predicted profile and "SONAR_D2 for the real sonar data.

The arrows on the graph indicate the matches found by the ASOP algorithm, and TABLE 1 gives various numerical parameters about the matching process. The algorithm takes each predicted object in turn, searching outwards and calculating a figure for the quality of the match (both in terms of position and 2nd differential) for each possible object in the live sonar data.

This calculation is done by using a Gaussian window function to bias the score so a perfect match (in either position or 2nd differential) scores 1.0, but reduces close to zero further away. The exact size of the window can be chosen to suit the particular spatial requirements of the environment, specification of the sonar system, and accuracy required from the system.

The matching algorithm uses a Gaussian function in the form of:

$$y = e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

where,

m is the zero offset for the peak response, and
s controls the window size (i.e. response fall off)

Stage 4: Perform Back Triangulation to Calculate Vehicle Position

The value of μ is set by the predicted position of the object. It is a well-known characteristic of this function that the response falls off quickly, with approximately 10% at 2q and less than 2% at 3 is

Once the target sonar features are matched against known objects in the 3D map, the real position of the vehicle can be calculated. Since the relative vector to each object in terms of heading and range is now known from the CAD model, it is possible to triangulate the vehicle position. Since each vector produces a slightly different position, these must be combined to give a single position for the vehicle. This can be done by using the simple arithmetic mean of each of the calculated positions, or a more complex biasing to help decrease the sensitivity of the final position to incorrect matches.

Stage 5: Output Calculated Position to External System

Once calculated, the vehicle position can be passed to an external system, such s a Mission Manager or Path Planning process. Another option for piloted vehicles such as ROVs is to render a 3D graphics or Virtual Reality (VR) style display for the pilot.

C. Hardware and Software Design of the SRPS

A system diagram of the ASOP-based system developed for the SWIMMER AUV is shown in Fig. 4. The initial external reference is provided by the Doppler Log (via the MCU). The SRPS can be configured to use either a single or dual sonar head. The system returns position updates back to the MCU at the rate of 1Hz, together with a confidence measure (based of the triangulation geometry and the size of the sonar search field).

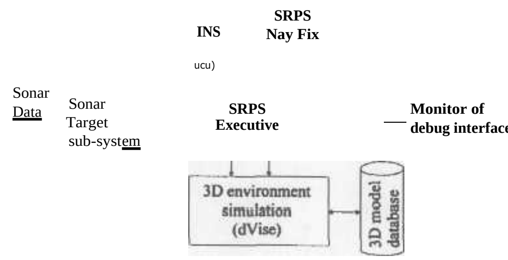


Fig. 4. SRPS system diagram

IV. SYSTEM TRIALS

The section concentrates on the development work and trials undertaken on the Short Range Positioning System (SRPS). A short description of the upcoming deep-water trails of the prototype SWIMMER AUV trials is included at the end.

A. Tank-based SWIMMER Scale Model Trials

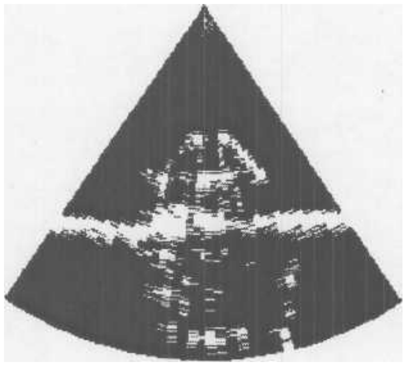
As part of the development process to create a self-contained system SRPS (Short Range Positioning System) for the SWIMMER AUV, a series of tank-based trials were performed to collect an extensive set of synchronised sonar - position data (synchronised both in time and position). This data was then used offline during the development process to accurately gauge the performance of the SRPS, and help diagnose problems.

The synchronised data was collected using a highly accurate motion control rig (a large cartesian, 5-degrees-of-freedom robot) mounted above an indoor tank measuring 4m x 3m x 2m. Due to the restricted size of the tank, the whole environment was scaled by 1/6. This created a space much closer to the nominal 20m diameter cylindrical operating zone of the SRPS specification.

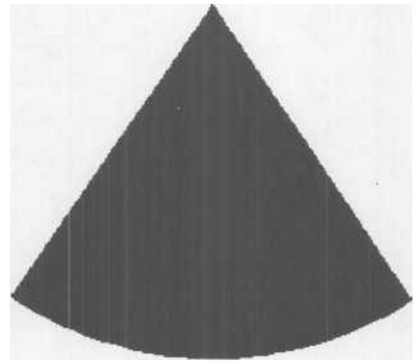
The 1/6 scale model of the Docking Station was placed in the centre of the tank, and the SRPS sonar head was mounted on the robot's end-effector. A series of synchronised sonar - position data sets were collected, at varying speeds and approach angles.

Fig. 6 shows an example the actual sonar data collected form the docking station. The position and orientation of the diagonal cross-members in the station are clearly visible in the image. It is interesting to note some of the internal structure can also be made out. However, ASOP currently only uses the 3D outer profile of the Docking Station to match against.

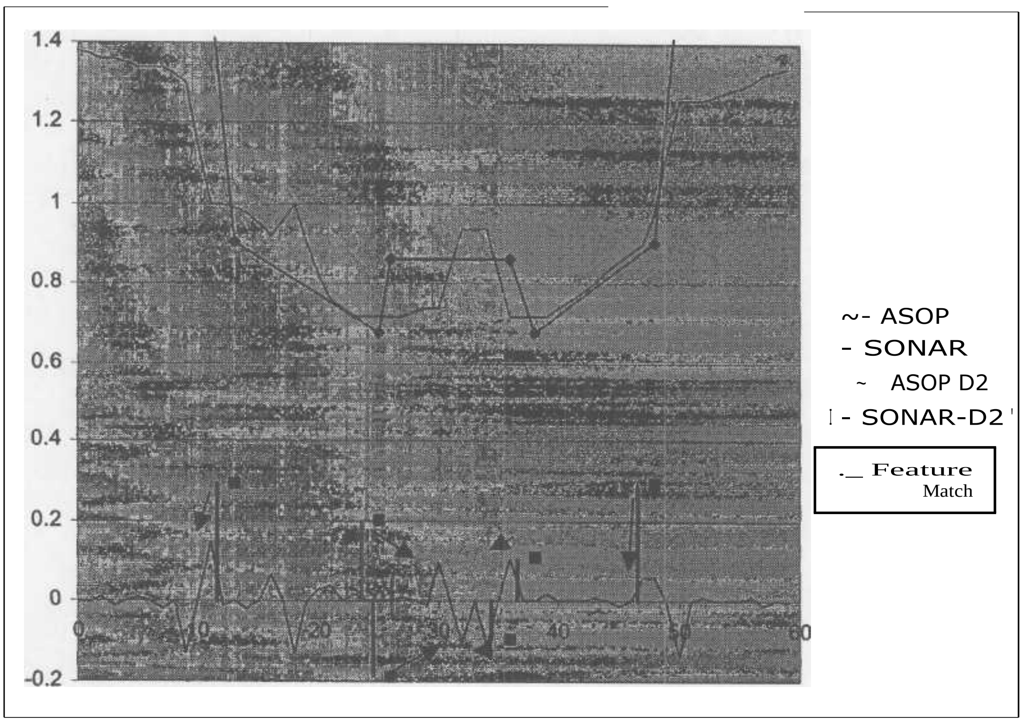
These initial trials established the SRPS could fix the vehicle's position to within 10 - 20 cm, lm above the scale model. Although the results obtained were gathered from a scale model, similar result were expected from the full scale docking station, since the profiling sonar used provided sonar pulses in a very linear conical 1.5° beam.



(a)



(b)



(c)

Fig. 5. (a) Sonar scan of Docking Station. (b) The First Return Profile of the same scan. (c) Predicted and Sonar Profile data (upper trace), together with 2 nd differential signals (lower trace). Arrows indicate the ASOP matched features.

TABLE I

ASOP SEARCH MATCHING PREDICTED AND REAL SONAR OBJECTS FOR FIG 5 (c)

Object Num	Predicted Heading	Predicted 2nd Diff	Best Match object at	Heading Match	2nd Diff Match	Overall Match
1	13	0.296	11	0.923	0.614	0.567
2	25	0.205	30	0.867	0.591	0.513
3	26	-0.187	32	0.801	0.652	0.522
4	36	-0.093	34	0.923	0.936	0.863
5	38	0.115	36	0.923	0.996	0.919
6	48	0.319	47	0.965	0.267	0.258

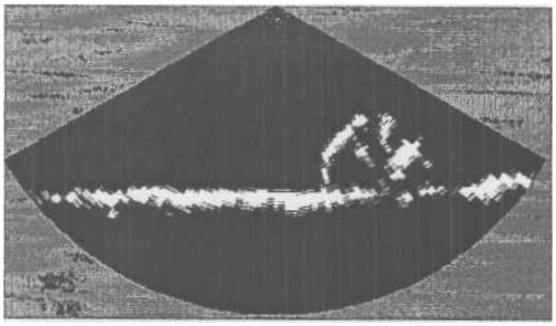


Fig. 6. Real Sonar Image of the above scene captured in Tank Trials of the SRPS

B. Full Scale SRPS Dock Trials

To verify the linear scaling assumptions made when using the model, sonar data was collected from the real docking station as soon as it was available (see Fig. 7).

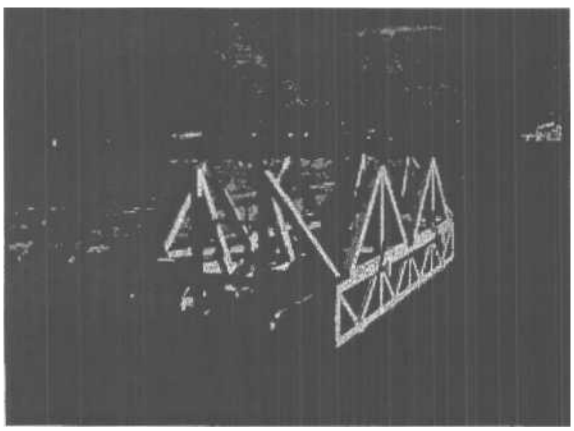


Fig. 7. Docking Station installation, in shallow water for preliminary tests.

The Tri-Tech Dual Frequency Profiling Sonar head was used operating at 1.2 MHz. It was mounted on the robot and arranged to scan downward creating a 120° fan.

Numerous data sets were gathered and later processed in the lab to provide positional fixes.

These predicted positional fixes were compared to the actual position of the sampling point for each data set. The results obtained, concluded that the system is capable of providing positional accuracies between 20-50cm. This verified the initial concept of the sonar units operating linearly.

C. Shallow Water Dock Trials

During summer 2001 numerous test were performed to test the vehicles systems and the overall operation of the vehicle (see Fig. 2). Included in these test were detailed operation tests of the SRPS in order to determine any problems prior to the deployment of the system for the final deep-water trials, the most recent of which was an autonomous deployment from the surface.

During the shallow water dock trials the vehicle went through a series of docking trials stages in order to prove the validity of the concept in small manageable sub-tasks, the first of which was a manual-docking phase.

During the initial deployment of the vehicle into the water it was noticed that the buoyancy of the vehicle was incorrect, the vehicle was approximately 150 kg too heavy, this resulted in the vehicle sinking. Addition buoyancy was addend to the underside of the vehicle to counteract this and the tests proceeded.

1) Manual Docking

The first test was designed to determine the capability of providing positional references using sonar data by manually positioning the vehicle about the docking station, and comparing the predicted position to the known position whilst the vehicle was in motion, the actual position of the vehicle was determined with the use of a GIB system [10]. Positional updates were provided to the pilot whilst the vehicle was manoeuvred into the docking position, this ensured that the system could provide positional information from the internal structures of the docking station. As the vehicle came into position the SRPS confirmed that the vehicle had achieve the correct alignment necessary to enable the vehicle to dock with the station. Once independent confirmation had been obtained (confirmation was given by a diver, docking station cameras and a small observation ROV), the vehicle was mated with the docking station, and the docking clamps were activated. Docking the vehicle in this manner proved that the SRPS was capable of providing positional fixes that were within 20cm accuracy, since if the actual position of the vehicle was out by a greater distance the vehicle would not be capable of docking.

Once the SRPS had been proven thus indicating that the vehicle, docking station and systems integrated and operated correctly, the test was re-ran, this time without the use of the SRPS, but with the use of the LRPS. The LRPS was not designed to operate in such shallow water, however the test was performed in order to observe the effects of operating the system near the seabed. The LRPS was capable of positioning the vehicle to within 3m of the docking station, but in could not provide positional information accurate enough to facilitate in the docking of the vehicle, nor could the vehicle be docked with the use of the docking station cameras and the observation ROV.

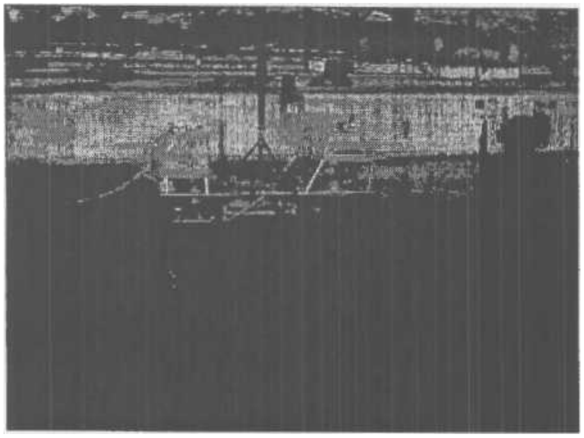


Fig. 8. The SWIMMER AUV during dockside tests

2) Autonomous Docking

Before deep water field trials could be performed the system had to autonomously manoeuvre from a deployment point and mate with the docking station., the scenario of which is as follows:

The vehicle was located approximately 19m above the dockingg station (lm below sea level) within a radius of 5m of the docking station, an initial estimation of the positional was supplied to the SRPS by the MCU. From this initial position the SPRS was capable of providing positional updates from the sonar imagery, the generated positional information was passes to the MCU at a rate. of 1Hz. Once the vehicle was within 0.2m centrally located above the docking station, the MCU navigated the vehicle onto the docking station, this was aided by the sloping member of the docking station structure. Once docked the vehicle was locked into position and the clamps holding the ROV in place were disengaged, allowing the ROV to be separated from the SWIMMER AUV and piloted around the docking station. Once the ROV had manoeuvred around the work site area the vehicle returned to the SWIMMER AUV where it was re-coupled to the vehicle, the docking clamps where then released and the vehicle returned to the surface.

3) Acoustic Telemetry Tests

The acoustic telemetry system was tested by deploying the vehicle from a ship a few kilometres from the coast, and operating the vehicle remotely. During the acoustic telemetry test the vehicle was completely tetherless and powered from its on-board power supply. The vehicle was operated within a maximum radius of 1000m from the ship, and reached a maximum depth of 150m. Operating the vehicle in this manner also had the advantage of testing the onboard systems, such as: the variable buoyancy system, fail-safe recovery and manoeuvrability of the vehicle

D. Deep- Water Field Trials

The details of the final deep-water (200m-500m) trials have yet to be finalised but they will take the form illustrated in Fig. 9. The work-class ROV will be mounted on the SWIMMER AUV and launched from a support vessel. The site, probably off the French Mediterranean cost will be chosen to provide 200 metres of water depth (as close to the coast as possible).

The trials will use an ACHILLE ObsROV and a REMORA 2-seat submarine to install the Docking Station and monitor the SWIMMER AUV during the trials. They will also be able to affect a recovery in case of a technical failure. The trials are currently scheduled for September 2001.

The deep-water trials will test all of the vehicles systems including; the acoustic data link, LRPS, SRPS and mechanical integration of systems i.e. PHENIX ROV to the SWIMMER vehicle, SWIMMER vehicle with the Docking Station.

The objectives of the final trials will be to navigate the vehicle to the docking station using the LRPS, dock the vehicle using the SRPS, release the ROV and pilot it around the worksite are within a maximum radius of 50m. Once completed the ROV will be re-engaged to the SWIMMER vehicle, the vehicle will be released from the docking station once the wet connector has been disengaged, the vehicle and payload will then return to the surface.

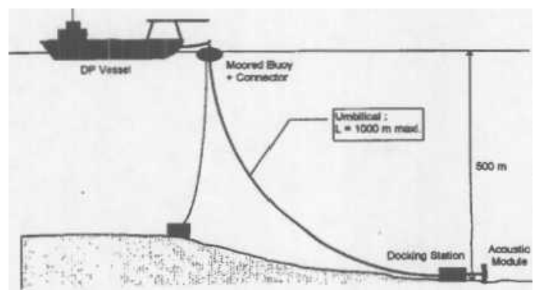


Fig. 9. Proposed Environment for SWIMMER AUV Deep Water Trials

V. CONCLUSIONS

The aim of SWIMMER AUV is to form part of an autonomous deployment system for work-class ROVs in ultra-deep offshore fields. The "concept" envisages a network of Docking Stations, an Acoustic Positioning and Telemetry Network, and a vehicle capable of autonomously carrying a ROV as a payload to the seabed.

One component of the SWIMMER AUV, the SRPS (Short Range Positioning System) has been developed at The University of Liverpool using a novel technique called ASOP (Active Sonar Object Prediction). The system uses a 3D map, derived from existing CAD information, to drive an active search for significant features in the sonar data.

The system has been integrated onto the SWIMMER vehicle and shallow water trials i.e. a maximum depth of 20m has proved that the SRPS is capable of providing positional estimations that can locate the vehicle to within 20 - 50 cm of the docking station during the alignment phase of a deployment.

Although the prototype's deep-water tests are scheduled for September 2001, the SWIMMER "concept" is a promising one. It could significantly reduce the cost of using ROVs in deep-water production fields, and help form an important step in the move towards fully autonomous systems.

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