Technical Communications

Simulating an Optical Guidance System for the Recovery of an Unmanned Underwater Vehicle

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***Abstract*—The underwater environment is hazardous, remote, and hostile. Having a look and interacting in this environment is a challenge for a human supervisor. Moreover, to design an unmanned underwater vehicle (UUV), or evaluate its performance in operation, access to the underwater world is required. A powerful way to visualize the behavior of the vehicle is to create a virtual world with all functionalities of the real world, and to operate the vehicle in this virtual world. This implementation of a virtual laboratory is an excellent way to perform meaningful simulations and complex system testing.**

In order to study the problem of UUV recovery by a submarine, simulations can be a great help. After the vehicle has finished its mission, it has to proceed to a predetermined rendezvous area to return to the submarine. When the UUV and submarine have detected each other, the recovery begins. The vehicle needs a very accurate guidance mode in order to steer itself to the recovery device. An additional guidance system coupled with a nominal navigation system may be a way to ensure safe vehicle navigation through the flow around the slowly moving submarine.

When considering the different technological possibilities concerning the additional guidance system, a functional design approach leads to the choice of an optical technology. The assumptions for the optical guidance mode are that the UUV is fitted with a camera and a high-powered light is located at the edge of the recovery device. The principle is that the UUV tracks the highest intensity light source. This system is easy to operate, but the distance between the UUV and the submarine must not exceed 200 m, due to light attenuation. In order to simulate and stimulate such a guidance system, it is interesting to create realistic views representing what the UUV may see according to this environment. A software program was designed, taking into account the physical phenomena occurring during the light propagation under the water, to simulate the kind of images that can be obtained from a camera. An underwater scene is generated, including any object and any light source, and including the physical properties of the sea water (reflection, refraction, absorption, and scattering). A ray-tracing algorithm simulates the operation of a camera by calculating and rendering the path inverse to the light path. Because both camera optics and hydrodynamics response are simulated using high-resolution physics models, this virtual camera provides physically based sensor inputs to the robot software in the laboratory.

Control orders concerning the vehicle result from the real-time robot interpretation of the generated image. To steer the vehicle to the light source, the navigation system has to take into account the image and the information carried by the image: shall the vehicle go up or down, starboard or port, or slowly or quickly to navigate in the direction of the light? To answer these questions, the image synthesizer module is integrated with an underwater virtual world. The vehicle performs a mission described in a file with simple keywords. When the mission controller reads a keyword activating the additional guidance mode, the image synthesizer computes the image of the camera and returns ordered data for the depth, heading, and speed to the navigation system. At the next step, another image is processed and new orders are returned, until the vehicle reaches the area around the light source. If the light source is put directly on the recovery device, stable guidance through recovery becomes possible.

A variety of simulations were performed, with varying light sources and positions, to verify proper guidance system operation during different UUV/submarine configurations. The results obtained during the simulations were used to create an optical guidance control mode. All the steps for designing such a simulated guidance system are described in this communication.

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I. Introduction

A. Operational Context

AUTONOMOUS underwater vehicle technology offers significant potential enhancements for naval forces in new contexts such as coastal areas or narrow waterways [1], [2].

Consider a heavyweight torpedo-shaped unmanned underwater vehicle (UUV), enabled with autonomous capabilities, launched from a submarine to perform a mission, trying to find its way back to the recovery device of the submarine.

The recovery begins when the vehicle ends the assigned mission and steers to the rendezvous zone, waits for the submarine, and then moves to the recovery device of the submarine. The recovery ends when the vehicle is in the drained launching tube ready to be hauled back into the torpedo room [3]. The vehicle needs an accurate guidance mode in order to steer to the recovery device. An additional guidance system coupled with the nominal navigation system is the proper way to ensure safe vehicle navigation to the submarine in hostile and hazardous surroundings. This guidance system must not depend on an optical fiber communication system due to security constraints. It must also be able to avoid a collision with the submarine and maneuver the path to the recovery device.

B. Purpose of the Study

The purpose of this study is to demonstrate the feasibility of an additional guidance system which supports the recovery.

TABLE I
COMPARISON BETWEEN THREE TECHNOLOGIES TO DESIGN A GUIDANCE SYSTEM

Criteria	**Acoustic**	**Magnetic**	**Optical**
Low vulnerability to external detection	-	★★	★★★★
Good directional accuracy	★★	★★	★★★★
Capacity for a different use	★★	-	★★★★
Good propagation in the environment	★★★	★★	★
Low sensitivities to parasites	★	★	★★★
Proven technology	★★★★	★	★★
Low cost	★★★★	★★★	★★
Conclusion	★★	★★	★★★

Legend: - bad ★ medium ★★ good ★★★ very good ★★★★ excellent

Simulating the recovery is a cost-effective way to study the challenges inherent to this problem. A way to evaluate the behavior of the vehicle is to create a virtual world with all the functionalities of the real world and to operate the vehicle in this world. The use of such a virtual world allows designers to observe and interact in remote, hostile, or hazardous environments [4]. A virtual lab can provide critical support to study topics related to the use of a UUV. Using such a lab improves understanding of the phenomena that occur during the recovery of a UUV [7]. This communication focuses on an optical guidance system simulation, integrated with an underwater virtual world.

II. A LIGHT-SOURCE TRACKING SYSTEM

A. Choice of an Optical Technology

As discussed previously, the UUV sensing capabilities for the navigation to the recovery device may be increased by adding an auxiliary guidance package. This guidance system must be able to do the following:

- guide the UUV to the submarine recovery device;
- help the UUV navigate in its environment;
- maintain the stealthness and the security of the submarine;
- be integrated in the submarine;
- be compatible with the other elements of the UUV navigation system;
- be integrated into the UUV hull;
- be easy to maintain.

Many sensing technologies can be considered when designing a guidance system: optical, acoustic, magnetic, radioactivity, thermal, chemical, electrical, etc. The first three are the most compatible with the underwater medium. They are compared in Table I from a functional point of view.

Short-range optical technology is well suited for designing an underwater guidance system [8]. Choosing an optical-based guidance system should enable the UUV with short-range vision (20–40 m), offering adequate underwater performance.

Two prospects are possible for an optical system: either the UUV is fitted with a complete recognition system (including an image processor) that searches for the pattern of the recovery device, or the UUV steers toward the bearing of the highest-intensity light source. Although an image-recognition system can be of great use on-board a UUV, it is expensive, difficult to operate, and expensive in calculation time (not very compatible with real time). The effective range of an image-recognition system cannot exceed 100 m. A light-source tracking system has a better range (up to 200 m), is accurate, and is easy to use, and its camera can be used for different tasks. These two possibilities are compared in Table II to illustrate their consequences on UUV design.

Because it can be easy to operate, robust, and fast analyzing, the best choice for the UUV recovery guidance system appears to be a light-source tracking system.

B. Technological Solution

Light-source tracking by a UUV camera will be used due to its simplicity, stealthiness, and robustness. The high-powered light source will be installed on the edge of the recovery device of the submarine. Onboard the UUV will be an ICCD-type camera and a processor that will analyze the images and deduce ordered speed, depth, and direction (Fig. 1). The UUV will base its navigation on the light-source tracking. This should give acceptable performances for tasks where a limited range is required [8].

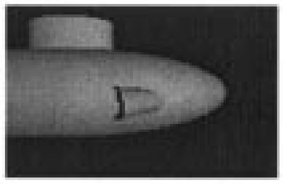
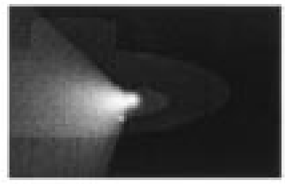
III. IMAGE SYNTHESIS

A. Software Design

Software was designed to perform simulations of the optical sensor system based on ray-tracing algorithms, including the physical phenomena characteristic of water (attenuation due to absorption and scattering). An image is computed at each time step simulating an image from a camera operating in real underwater conditions [9]. The goal of the software is to obtain images simulating what a camera onboard the UUV may see underwater when looking at the submarine from a near distance. These images need to provide acceptable information, first to know if our system is feasible, then to validate the algorithms for the guidance system.

First the image synthesizer needs a description of the underwater scene it has to draw. The scene is defined as the set of physical objects found in the camera field of vision, as well as characteristics of the medium in which they are found. Then the software generates an image of the scene from the viewpoint perspective of the underwater camera: a set of colored pixels, which is the predicted performance of the optical system. To realize ray-tracing software, two types of algorithms are needed: algorithms concerning the objects describing the scene and algorithms of color calculations including precisely colored light

TABLE II
IMAGE RECOGNITION VERSUS. LIGHT-SOURCE TRACKING: CONSEQUENCES FOR UUV DESIGN

	Image recognition	Source tracking
Principle:	optical recognition of the submarine and the recovery device	track of highest light intensity
View from the UUV:	 Lighting on the UUV	 Lighting on the submarine
Equipment:	The submarine has reflective marks. The UUV has an optical sensor and appropriate lighting.	A high-powered light source is on the recovery device of the submarine. A camera is onboard the UUV.
Power consumption	High current drain limits UUV endurance and threatens vehicle survivability.	Ample electrical power is available on the recovery submarine.
Scenario:	The UUV analyses the image and searches the pattern of the recovery device	The UUV tracks the highest intensity light under the horizon or in an approximately given sonar direction. Movement relative to the light source helps to determine an accurate heading.

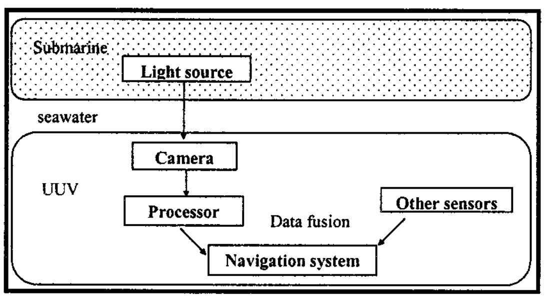


Fig. 1. Principle of the technological solution.

rays [11]. It is important to note that ray-tracing methods are recursive so they need large calculation times.

According to object-oriented modularity principles [10], the overall system software is made of modules. Each module deals with a logical set of classes realizing functions or services (Fig. 2):

the human–machine interface module manages the input/output with the user;

the syntactic analysis module reads, analyses, and prepares the data for the ray-tracing module;

the ray-tracing module transforms the scene description into an image;

the mathematical process module realizes the mathematical functions used by the ray-tracing module.

B. Scene Description and Simulation

The scene shall be described with keywords according to the specific grammar of the syntactic-analysis module (Fig. 3). A scene is composed of an atmosphere, objects, and light sources. Five types of geometric objects may comprise the physical scene: rectangular parallelepipeds (box), spheroids (sphere), circular cones (cone), circular cylinders (cylinder), or planes (plane). They may be colored or textured.

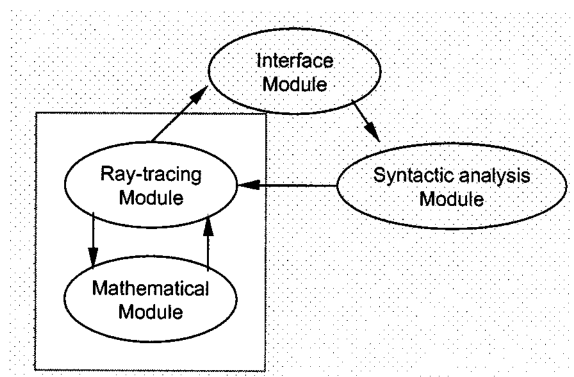


Fig. 2. Modules organization.

Lights are introduced by the keyword *light_source*, followed by the source position, the source color, and/or the keyword *atmosphere_interaction_off*, indicating that this source does not distribute any light. The atmosphere description is introduced by the keyword *atmosphere*, which then defines multiple terms: the refraction coefficient of the medium, the De Beer absorption distance (63% of the light is absorbed at this distance), the scattering distance (63% of the light is lost by scattering at this distance), the color filter, the scattering calculation accuracy, and the type of scattering interaction (different relationships between emergent light flow and incident light flow: isotropic, Rayleigh, Mie–Hazy, Mie–Murky, Henyey–Greenstein). In the objects or light description, some keywords can add translations, rotations, or scale effects. The camera characteristics are also described. Once the whole scene is described, the syntactic analysis module analyzes it and the ray-tracing module computes the corresponding image.

C. Example Display

Consider a scene including a submarine. This submarine is described very simply in terms of spheroids, cylinders, and

```
atmosphere ={ior = 1.33;
             scattering = {color = green 0.3;distance = 100;
                           type = mie_hazy();samples = 50;};
             absorption = {color = green 0;distance = 100;};};

light_source = {center = <6, -0.6, -5>;
                translate(<0.0, 0.0, 70.0>);
                color = blue .9 green 1. red .9; };

object = { sphere(<0,0,0>,1); scale(<15,5,5>); color = blue 1.0
           green 1.0; translate(<0.0, 0.0, 70.0>);};
object = { cylinder(<1,0,0>,<-30,0,0>, 5); color = blue 1.0
           green 1.0; translate(<0.0, 0.0, 70.0>);};
object = { cone(<-42,0,0>,1, <-30,0,0>,5); color = blue 1.0
           green 1.0; translate(<0.0, 0.0, 70.0>);};
camera = {height = 96;width = 96;};
```

Fig. 3. Example of an image synthesizer scene file.

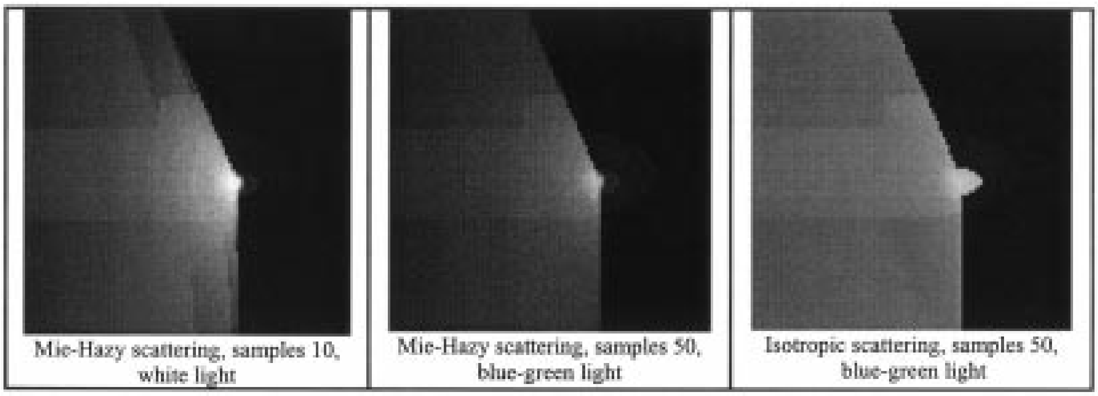


Fig. 4. Computed images with varying parameters.

cones. A light source is put on the side of the submarine, emitting in varying domains. Several images are computed, with varying scattering calculation accuracy, different scattering interactions, and different light colors. The images shown in Fig. 4 are examples of display with different scattering interactions and accuracies.

IV. Optical-Based Guidance System

A. Introduction

The guidance system will be made of an ICCD camera in relation to a processor that will track the direction of the highest luminosity in order to feed the navigation system with motion orders. This section explains how the processor will transform the images into commanded orders (see Fig. 5).

The image synthesizer (IS) computes an image, and then the vision module (VM) computes navigation orders from this image and feeds the virtual world simulator.

It is worth noting that there is a major difference between the real cycle and its virtual abstraction: the real scene is dynamic. Indeed, the IS, the VM, and the virtual world allow one to simulate the motion and recovery of a UUV in a permanent scene or environment. This scene may include, for example, the description of a fish but it will remain motionless in the coordinate system of the scene. Nevertheless, this current simulator limitation does not negate the validity of the vision module algorithms, since the primary interaction of interest is the relative motion between the UUV and the recovering submarine.

Consider that the UUV moves in the direction of the submarine, responding to the data from the other sensors (sonar). Based on vehicle depth, the ambient luminosity is low and diffuses enough so that the luminous flow emitted by the source onboard the recovery device is not overwhelmed by another source of light (e.g., sunlight). Further assumptions are that the UUV speed allows it to reach the submarine and the roll angle of the UUV is zero or negligible.

B. Principles

The principles of the IS and the VM are simple.

The UUV mission is described in the "mission.script" file (including the keyword *followlight* to trigger the recovery), then the scene the vehicle is supposed to watch is described in the IS scene file (position of the different light sources and objects).

The virtual world of the scene and robot is run: as soon as the keyword *followlight* is analyzed, the IS module computes an image.

The VM gets a BitMap image and tracks the barycentre of the highest luminosity areas onto the BitMap.

The VM deduces a commanded heading angle, a commanded depth, and a commanded speed for the vehicle.

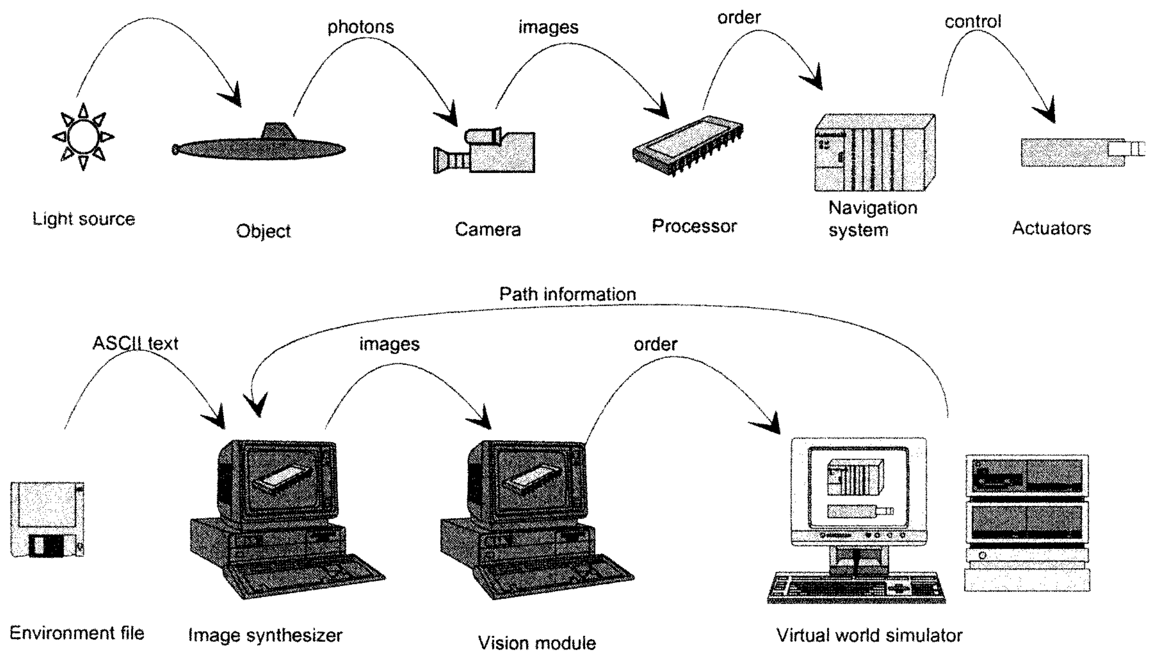


Fig. 5. Real versus virtual cycle.

The VM sends these orders to the navigation system in the virtual environment.

At the next step, another image is computed and new orders are returned, until the vehicle reaches the area around the light source.

The IS module and the VM stop when the guidance-approach termination conditions are valid.

C. Integration to the Virtual Navigation System

The IS and the VM were integrated into the "Naval Postgraduate School Underwater Virtual World" software (refer to Fig. 6) [5], [6].

During normal operation, the following occurs:

From the orders read in the mission.script file (1), "execution" computes the orders to send to thrusters, propellers, and plane surfaces. These orders are transmitted to the physical data and orders socket (2).

"dynamics" gets (3) these orders and processes the static and dynamic parameters of the UUV. These parameters are sent back to the physical data and orders socket (4) and to the DIS bridge (5).

"viewer" gets the UUV position (6) to display (7) a view of the scene on "screen: views of the scene."

When "execution" finds the keyword *followlight* to begin the recovery, the following occurs:

"execution" pauses the reading of (1) mission.script file and asks to the vision module (A) the orders.

The VM runs the IS (B) who reads (9) "IS scene" and gets (8) the UUV position in this scene. The image synthesizer processes then the scene image viewed from the UUV.

The VM gets (10) this image, calculates the subsequent orders, and sends them (11) to "execution."

Other flows or processes of robot and virtual world simulation are not disturbed.

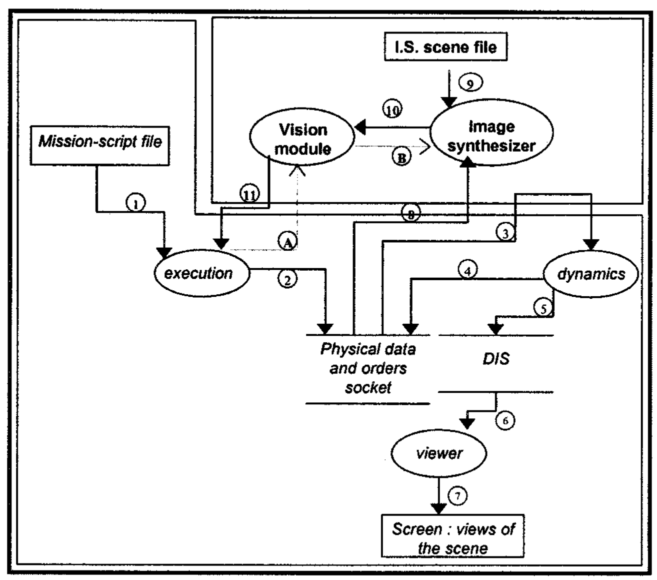


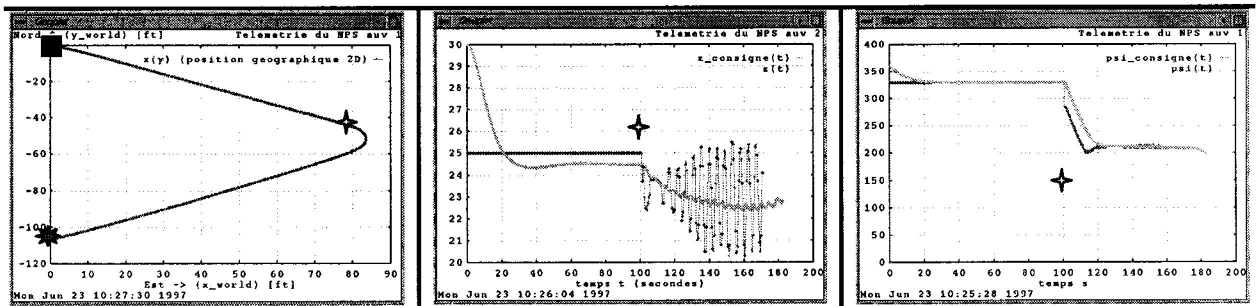
Fig. 6. Architecture of an NPS-AUV-UVW with the optical guidance simulator [5].

To visualize a scene or the vehicle behavior with the virtual world "viewer," it is possible to create a 3D object representing for example a lightsource, and to add this object to the "viewer" source file. Then the position of the light needs to be added into the scene description file. Thus observers see a 3D graphics picture analogous to the image seen by the UUV. Images presented to the vision module are viewed separately.

D. Execution and Example: UUV Recovery by a Submarine

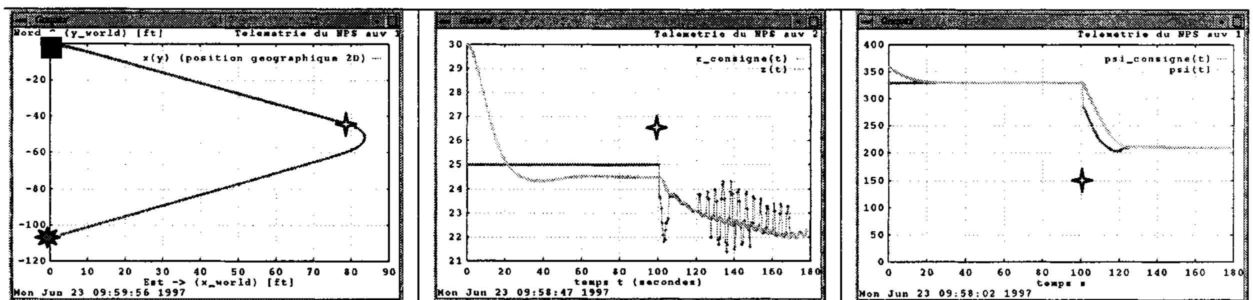
In this example, the scene is made of a static submarine, a recovery device, and a light at the edge of the recovery device. This scene is described in the IS scene file (light source, simple objects for the submarine, and the recovery device). The optical

TABLE III
NAVIGATION RESULTS WITH ONE LIGHT SOURCE



2D motion (x vs. y)	depth vs. time	heading vs. time
✦ signal light becomes visible	— z depth (m)	— heading (degrees)
■ initial position	····· z depth rate (m/sec)	····· heading rate (degrees/sec)
✸ light source barycentre	✦ light visible at time 100 sec	✦ light visible at time 100 sec

TABLE IV
NAVIGATION RESULTS WITH TWO LIGHT SOURCES



2D motion (x vs. y)	depth vs. time	heading vs. time
✦ signal light becomes visible	— z depth (m)	— heading (degrees)
■ initial position	····· z depth rate (m/sec)	····· heading rate (degrees/sec)
✸ light source barycentre	✦ light visible at time 100 sec	✦ light visible at time 100 sec

properties of the seawater are described. The same scene is described in the virtual world "viewer."

It is important that readers understand the difference between the two representations.

The IS scene represents what the vehicle is supposed to watch with its camera when the submarine activates the light of the recovery device.

The Viewer scene is a way for human designers to visualize how the vehicle behaves in its environment.

The orders given by the IS module come from the processing of an image onto an IS scene, and not a Viewer scene. The image synthesizer module terminates under two conditions: when the distance from the center of the light to the center of the camera is less than a chosen value (this means the vehicle is in the axis of the light) and when the sonar detects an object in a chosen range (this means the vehicle is very close to the recovery device).

A way to adjust the trajectory of the vehicle to the recovery device is to place the light sources around the edge of the recovery device in order to guide the vehicle into the recovery device. Adding light sources increases the processing times, and there may be a problem diagnosing guidance system effectiveness if the Viewer is not fed in real-time.

E. Results

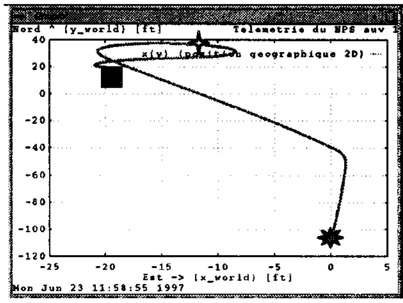
Many simulations were performed in order to verify that the vehicle reaches the light, even if its initial ordered trajectory is not in the direction of the submarine.

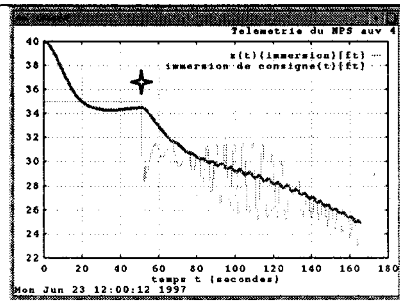
In the first example (see Table III), the initial position is $(0, 0, 30)$ (x, y, z in meters) and the initial orientation is $(0, 0, 0)$. The orders are to go up to a depth 25 m and to take a 330° course. At a given instant, the keyword *followlight* asks the vehicle to track the light. There is only one light source at $(0, -106, 23.5)$.

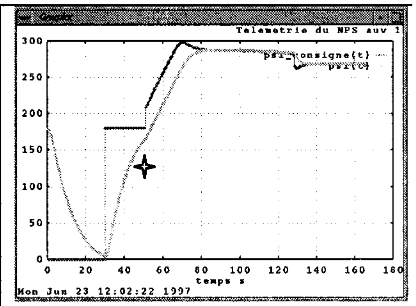
Considering the ordered depth versus the actual depth, we can see that there is a "pump" phenomenon for the reacting ordered depth. This phenomenon is attenuated for the actual depth. A different depth-control law shall damp this phenomenon. The depth of the light source is 23.5, and the vehicle reaches 23.

In the second example (see Table IV), the initial position is $(0, 0, 30)$ and the initial orientation is $(0, 0, 0)$. The orders are to go up to a depth of 25 m and to take a 330° course. At a given instant, the keyword *followlight* asks the vehicle to track the light. There are two light sources at $(0, -106, 23.5)$ and $(0, -108, 23.5)$.

TABLE V
NAVIGATION RESULTS WITH TWO LIGHT SOURCES







2D motion (x vs. y)	**depth vs. time**	**heading vs. time**
✦ signal light becomes visible	—— z depth (m)	—— heading (degrees)
■ initial position	······ z depth rate (m/sec)	······ heading rate (degrees/sec)
✸ light source barycentre	✦ light visible at time 100 sec	✦ light visible at time 100 sec

In this example, the position accuracy towards the recovery device is better (x, y), but the light source depth is not reached. Again, a modified depth-control law is expected to improve the gap between the ordered depth and the actual depth. Improvements to depth control can be achieved by damping planes response, time-averaging the optical depth estimate, Kalman filtering, and more rapid optical image sampling.

In the last example (see Table V), the initial position is $(-20, 20, 40)$ and the initial orientation is $(0, 0, 180)$. The orders are to go up to a depth of 35 m and then to take a 180° course. At a given instant, the keyword *followlight* asks the vehicle to track the light. There are two light sources at $(0, -106, 23.5)$ and $(0, -108, 23.5)$.

Even if the initial trajectory of the vehicle is opposite from the submarine, the vehicle, provided that its camera can sense the light, reaches the recovery device. This is a significant success.

V. CONCLUSIONS

An optical-based guidance system simulation was integrated with a virtual world for an autonomous underwater vehicle. Numerous navigation simulations were performed, proving that the concept of light tracking is feasible for successful guidance during recovery.

Simulation is ordinarily insufficient by itself and needs to be verified by experimental results. The simulation presented in this communication served as a feasibility study, providing necessary evidence that design and construction of a new sensor/control system are warranted. Such work is a crucial step in system development.

Future work may deal with the improvement of the navigation laws of the optical guidance system and the implementation of strategies for vehicle behavior before the release of the light tracking. The simulation can be further enhanced if experimental results become available, serving as a tool for system and model refinement. Integration with a virtual world provides a powerful tool to study the recovery of an unmanned underwater vehicle by a submarine. Optical-based guidance for recovery appears to be feasible for a short-range approach.

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