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Underwater Optical Imaging to Aid in Docking An Unmanned Underwater Vehicle to a Submarine

Preliminary Experimental Investigations

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IMPORTANT INFORMATIVE STATEMENTS

Abstract

This report discusses preliminary experimental investigations into the use of optical imaging to track a UUV (Unmanned Underwater Vehicle) that would be docking with a submarine. Two different types of underwater cameras were used to image a variety of optical "targets", under controlled but realistic conditions, at Defence R&D Canada – Atlantic's Acoustic Calibration Barge (ACB) in Bedford Basin near Halifax, Nova Scotia. A variety of imaging methods are employed and evaluated.

The investigation provides a baseline assessment of the potential for imaging a UUV, both passively and with an active light source on the UUV. The results show that UUVs can be imaged at ranges of at least 16 metres under certain environmental conditions, but that the effective range will be highly dependent on water turbidity and ambient light.

Significance for Defence and Security

The overall project goal is to find an affordable and viable approach for docking Unmanned Underwater Vehicles (UUVs) onto submarines. Other common tracking methods include acoustic and electromagnetic sensing, which are not viable at short ranges. Optical imaging can be an accurate way to track underwater objects over short distances, but the useful range can be limited by the absorption and scattering of light found in murky coastal waters. Optical tracking is therefore complementary to these other methods.

These tests show that optical imaging can provide crucial high-resolution tracking data during the terminal rendezvous and capture phase of the underwater docking operation between a UUV and a submarine. Results of these preliminary investigations lead the way to developing an optical tracking capability, and further towards the objective of being able to reliably dock a UUV on a Victoria-class submarine.

Résumé

Le présent rapport examine les vérifications expérimentales préliminaires de l'utilisation de l'imagerie optique pour surveiller l'arrimage d'un VSSE (véhicule sous-marin sans équipage) à un sous-marin. Deux types différents de caméras sous-marines ont été utilisés pour documenter une variété de "cibles" optiques, dans des conditions contrôlées mais réalistes, à l'aide du chaland d'étalonnage acoustique de RDDC Atlantique à Bedford Basin près d'Halifax, en Nouvelle-écosse. Diverses méthodes d'imagerie sont employées et évaluées.

La vérification fournit une évaluation de base du potentiel de création d'une image de VSSE, de manière passive et à l'aide d'une source de lumière active sur le véhicule. Les résultats montrent qu'une image peut être créée à une dis-tance d'au moins 16 mètres dans certaines conditions environnementales, mais que la distance utile dépendra grandement de la turbidité de l'eau et de la lumière ambiante.

Importance pour la défense et la sécurité

L'objectif général du projet est de trouver une méthode abordable et viable d'arrimage des véhicules sous-marins sans équipage (VSSE) aux sous-marins. D'autres méthodes de surveillance courantes comprennent les types de détection électromagnétique numérique et acoustique, qui ne sont pas viables à courte distance. L'imagerie optique peut être une façon de surveiller avec précision des objets sous l'eau sur de courtes distances, mais la distance utile peut être limitée par l'absorption et la diffusion de la lumière dans l'eau trouble des côtes. Le suivi optique constitue donc un complément à ces autres méthodes. Ces essais montrent que l'imagerie optique peut fournir des données de surveillance à haute résolution fondamentales aux étapes terminales de rendez-vous et de capture de l'opération d'arrimage sous-marine entre un VSSE et un sous-marin. Les résultats de ces vérifications préliminaires ouvrent la voie à l'établissement d'une capacité de surveillance optique, et nous permettent de poursuivre l'objectif d'être capable d'arrimer solidement un VSSE à un sous-marin de classe Victoria.

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Acknowledgements

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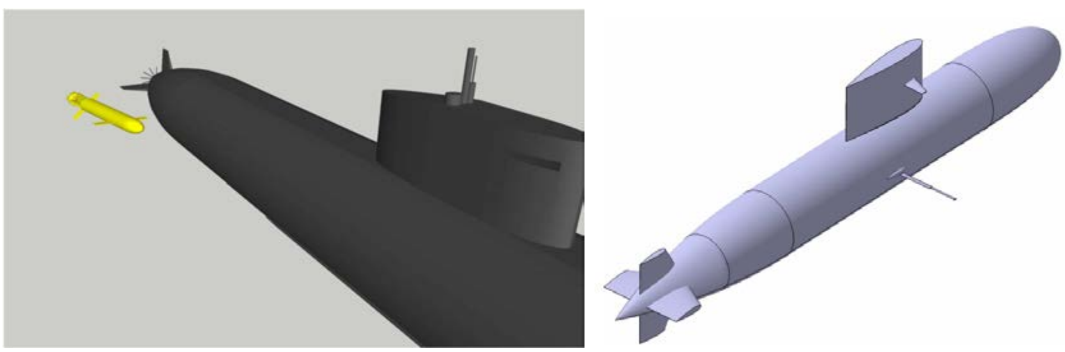
1 Introduction

This report details experiments undertaken to determine methods of underwater optical imaging and tracking. These investigations were performed as part of a Technology Investment Fund (TIF) project that aims to find an affordable and viable approach for docking Unmanned Underwater Vehicles (UUVs) onto submarines. The overall problem is not an easy one—the United States Navy has reportedly spent billions of dollars in developing UUV docking systems.

The major limitation to conducting UUV operations from submarines is recovering the robotic vehicle after its mission. Ideally, a recovery system would be autonomous, reliable and fast, and would allow recovery in littoral waters in high sea states. The overall system being designed in this project, described by Watt [1], would have two stages: 1) a homing stage where the UUV moves towards the submarine and then holds course beside it, and 2) an active docking stage where the submarine is able to grab the UUV (Figure 1). The concept would be similar to the way aircraft are refueled in-flight.



(a) UUV holding station beside a submarine for docking.

(b) One potential dock configuration.

Figure 1: *UUV/Submarine active docking concept.*

Three types of remote sensing are commonly used to detect and track underwater objects: acoustics, electromagnetic, and optical. To find the submarine during the homing stage, the UUV will use acoustics and electromagnetic sensing which are effective for medium and long range. However, during the final docking phase, while the UUV holds course, a dock mechanism will rapidly adapt to relative motions of the UUV for final capture. For this phase, a fast and accurate tracking method is required for shorter range sensing, on the order of 10–20 metres. This report investigates visual optical tracking for this application. This concept, illustrated in Figure 2, would have a camera system on the dock end effector that would locate the relative position of the UUV to allow for a feedback control loop to guide the dock onto the UUV's path for capture. Some approaches in the literature to optical tracking to aid in UUV docking can be found in [2, 3, 4, 5].

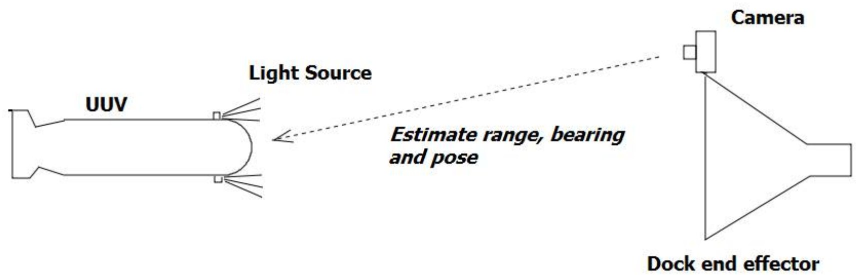


Figure 2: *Optical tracking to enable an active UUV dock.*

For optical tracking for the final docking phase, the camera, tracking equipment, and final docking control can be placed on either the UUV or on the dock. In the design developed for this project, the active dock on the submarine is responsible for the final intercept and capture, and therefore contains the equipment for optical tracking. This has some distinct advantages. Firstly, this arrangement reduces complexity on the UUV, allowing for the camera and image processing computer to be stationed on the submarine where there is more space and electrical power. Secondly, it takes advantage of the transverse maneuverability of the dock to capture the UUV despite relative motions of the UUV and submarine, which would be more difficult to accomplish solely with UUV homing.

This report investigates two potential methods of optical tracking for the docking procedure:

1. Detection of the visual features of a passive UUV. This method would require no modifications to the UUV, but would limit the range and environmental conditions under which the system could operate.

2. Detection of an active UUV which uses lights or another source to make it easier for the camera tracking system. This would improve the range and robustness, but requires modifications to the UUV.

A diagram of the planned system is shown in Figure 3.

1.1 Focus of the Investigations

This work is focused on determining the performance that can potentially be achieved with short range optical tracking in a realistic environment. Optical imaging can be a very effective way to track objects like UUVs, but the useful range can be severely

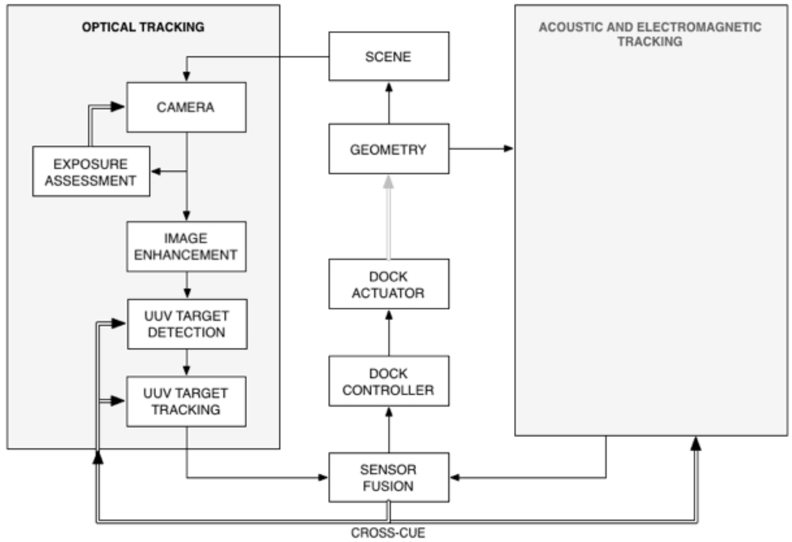
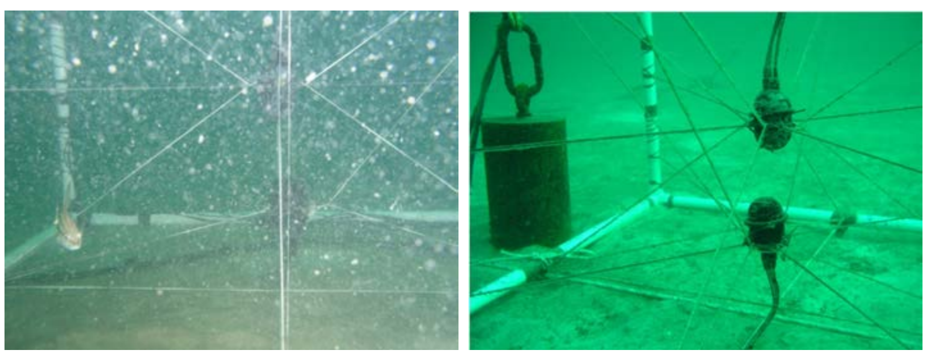


Figure 3: *System diagram for the planned tracking system for the automated UUV dock.*

limited due to the absorption and scattering of light in coastal waters. Heavy concentrations of plankton and other particulate matter (such as suspended sediments) are often found in coastal waters, and these make for murky or hazy waters where it is difficult to view objects at a distance (see Figure 4 for an example.)



(a) (b)

Figure 4: *Flash photo (left) taken 20 seconds after ambient light photo (right) at 20 metres depth, offshore from Gulf Breeze, Florida. Photo credits: Eric Boget, Applied Physics Laboratory, University of Washington.*

The complications that can arise in trying to use optical tracking underwater include but are not limited to:

- Ambient light is widely variable underwater, from very bright near the surface to pitch black at depth making it difficult to get a proper exposure of the target.

- Scattering by particles suspended in the water such as silt or micro-organisms causes a reduction in the brightness and contrast of an object, as well as a change in direction of the light.
- Absorption of light by the water reduces the overall brightness of an object, but also changes its apparent color as some wavelengths are absorbed more readily than others.

The remainder of this report will document experiments conducted to quantify these effects, and the utility of various approaches used to overcome them. Experiments were conducted in two phases: the first phase was during the week of April 25 to 29, 2011 which characterized water clarity and the feasibility of directly imaging a UUV target. The second set of experiments was conducted June 11 to 15, 2012, and used a UUV surrogate with on-board lights to examine the potential of that approach for underwater tracking.

2 Methods

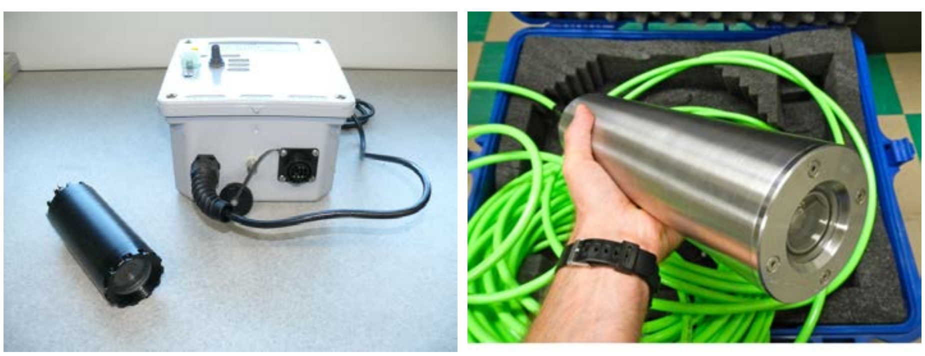
This section discusses the lab facilities, instrumentation and equipment, and activities involved in the measurements and analysis for these experiments.

2.1 Underwater Video Cameras

Underwater video and images were collected with two waterproof cameras, a low-cost general-purpose camera (Shark Marine SV-LL0003), and a scientific low-light camera (SubC uLux).

The SV-LL0003 (Figure 5(a)) has a fixed 3.7 mm lens, 86 degree field of view, monochrome 640x480 CCD, minimum illumination of 0.0003 Lux, and built in auto-exposure. Video was relayed by NTSC signal over 60 m of underwater cable to an Imperx VCE Express capture card on a laptop computer.

The uLux scientific camera, shown in Figure 5(b)) was custom designed and built for this project by SubC Controls Ltd., and it has since been commercialized as the StarGazer model. The camera is based on the Retiga 1350B (QIClick) scientific video camera from QImaging, with 1392 x 1040 resolution, and minimum illumination of 0.000001 Lux. The camera has no auto-exposure, but does have user-controllable gain and exposure settings. IEEE-1394 digital video from the camera is relayed with a pair of FireNEX-COAX-S800 IEEE-1394 repeaters and through 25 metres of coaxial underwater cable. The images were captured from the IEEE-1394 interface using a laptop computer.



(a) Shark Marine SV-LL0003 camera (b) SubC uLux Scientific Camera

Figure 5: *Cameras used to gather underwater images.*

2.2 Underwater Lights

Artificial illumination was provided by the waterproof lights shown in Figure 6. Specific lights used were the C8 eLED dive light manufactured by Underwater Kinetics, the Navi Light Glo manufactured by Navisafe, and Xenon flash strobes including the ACR Electronics model SDU-5/E (NSN 6230-00-067-5209) and ACR Electronics model 1916 Firefly Plus.

Figure 6: *Underwater lights, from left to right, (1) C8 eLed, (2) Navi light Glo,(3) ACR SDU-5/E, and (4) ACR Firefly Plus.*

The large C8 eLED dive light is specified to give 400 lumens of light output and, with its pair of 6 Watt LED emitters, is likely to represent the highest practical brightness for a non-strobed light that would be carried on a UUV.

2.3 Lab Facilities

DRDC Atlantic owns and operates a barge facility in Halifax's Bedford Basin. Shown in Figure 7, the barge is held in place by four permanent mooring anchors and is sited at a location with a water depth of 42 metres. This facility is well equipped to test and calibrate marine equipment such as sonar and oceanographic instruments, and was an important resource in conducting this work.

The barge is valued for providing a lab-like environment during the early phases of experimental research, when prototype equipment is generally unsuitable for use on a ship or on the open ocean. It provides sheltered work space with unfettered access to the ocean beneath, and almost half of the interior floor space is a "well" that is open to the ocean water. The interior, shown in Figure 8, is focused on the barge's 18 m long by 9 m wide well. Movable bridges and platforms (known as well trolleys and cross trolleys), rotating stations, and an overhead crane allow heavy equipment to be suspended at specific depths and locations beneath the barge. A close-up picture of the well trolley is shown in Figure 9.

Figure 7: *Exterior view of DRDC Atlantic's Acoustic Calibration Barge in Bedford Basin.*

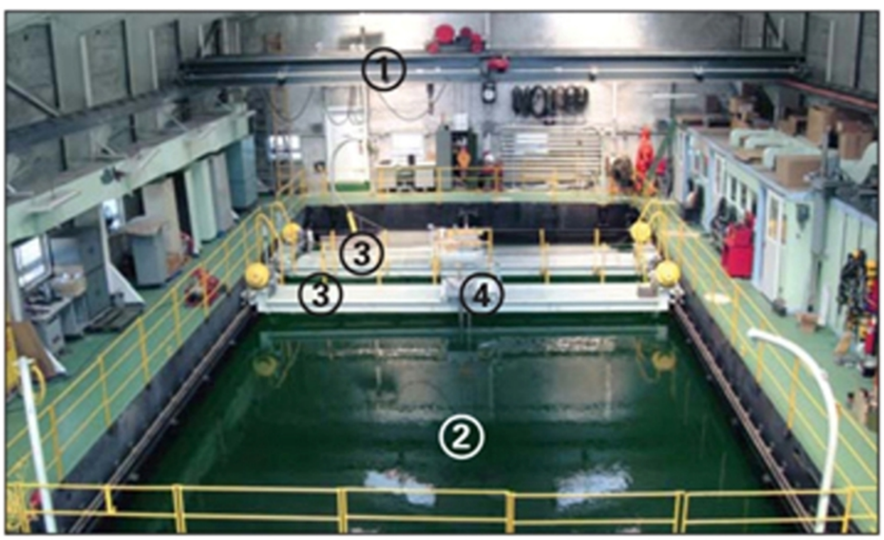


Figure 8: *Interior view of the ACB, showing the overhead crane (1), internal well (2), two well trolleys (3), and cross trolley (4).*

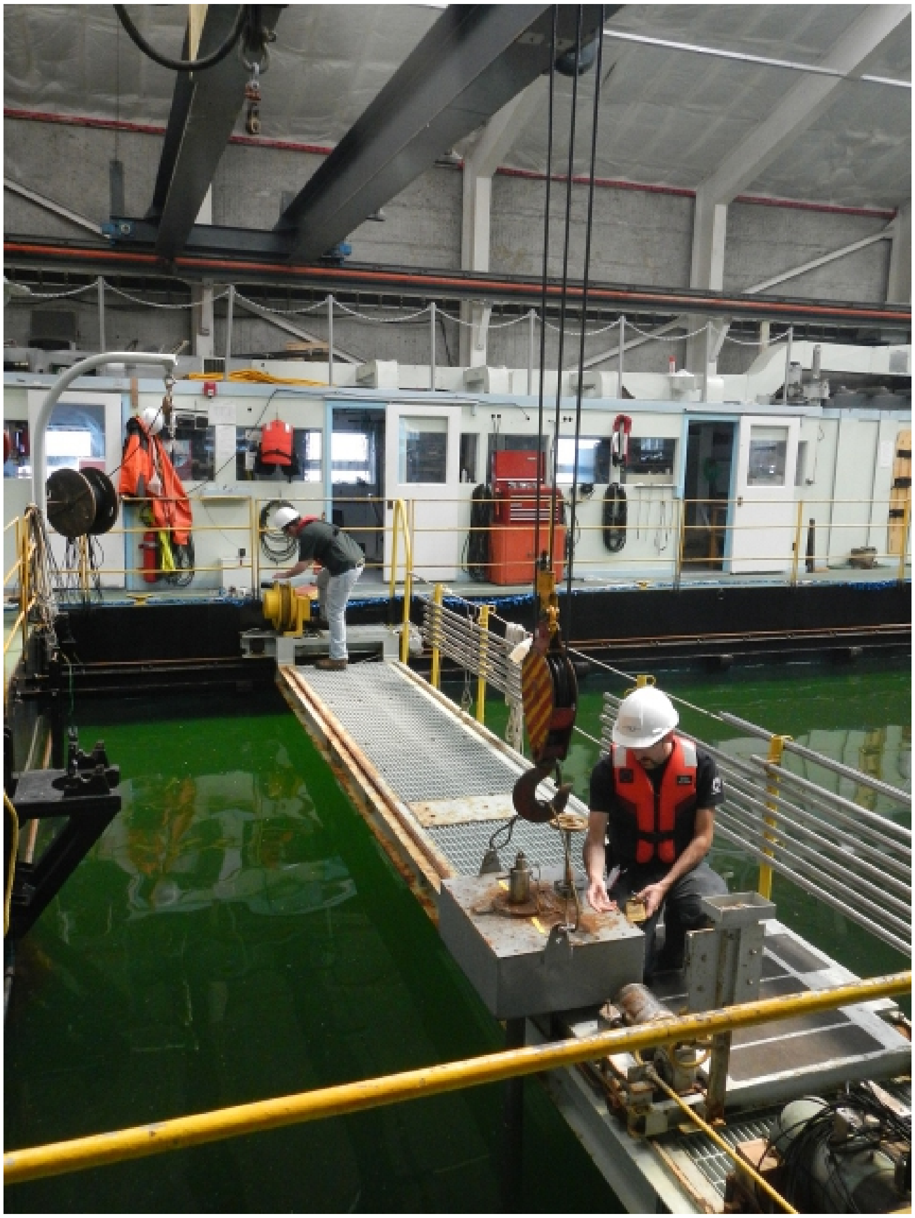


Figure 9: *A view of the barge well and aft trolley.*

Video measurements had the cameras suspended in a fixed position at the southeast end of the well, towards the barge's so called "bow" and near the centerline of the well. The camera was lowered to a depth of 23 metres from the 300-lb rotating station on the forward well trolley. The 23 m operating depth was limited by the length of the camera's umbilical cable. The camera's orientation was fixed to viewing on any heading in a horizontal plane, while the heading could be controlled, by rotation of the mounting pole, through a range of 0 to 360 degrees.

The optical target, operating as a surrogate UUV, was likewise suspended from a 300-lb rotating station attached to the aft well trolley at the northwest end of the well. This arrangement allowed the targets and surrogate UUV to be moved to operate at ranges of 2 m to 16 m and with offsets of 4 m out to either side of the barge well (port or starboard). Two diagrams of the general arrangement for the barge experiment are shown in Figure 10. The moveable optical target is at the stern end of the well (left), and the cameras, which were kept stationary for the experiments, are at the forward end of the well (right).

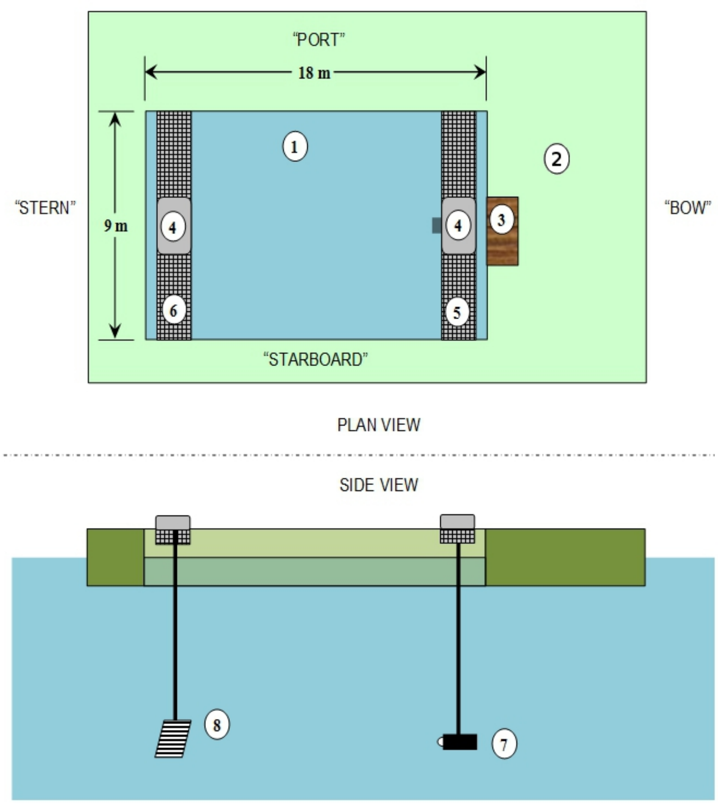


Figure 10: *General arrangement of barge showing (1) well, (2) working deck, (3) work desk, (4) cross-trolleys with 300-lb rotating stations, (5) forward well trolley, (6) aft well trolley, (7) video camera, (8) optical target.*

3 Detection of a Passive UUV Target

The simplest approach to determining the relative pose of the UUV from the dock would be to directly recognize the features of the UUV from the camera without any artificial lighting. There are many image recognition techniques that are used above water that could be used, such as simple color tracking [6, 7], Scale Invariant Feature Tracking [8], etc. However, all of these techniques rely on a certain quality of image in resolution, contrast, color, etc. With carefully controlled water conditions, these methods might be practical. However, with unknown water illumination and clarity, it is unclear how well direct imaging of the UUV will work. This section reports on the first phase of experiments conducted in April 2011 to determine the possibility of using this type of tracking.

3.1 Environmental Optical Characterization

In order to provide a baseline for the underwater measurements, simple visibility measurements were conducted on the water column during the first set of experiments. Secchi disks were used in order to coarsely quantify the water clarity during the experiment. The disks were slowly lowered to the depth at which they were no longer visible, and that depth becomes the Secchi depth. The BIO optical profiler was also deployed in the center of the barge's well. During these tests, outside weather was overcast with fog and rain, and temperatures ranging from 5 °C to 15 °C. This weather was representative of that encountered throughout the week of the experiment. The instrument was suspended from a sheave on the overhead crane and allowed to freefall through the water column a few times to a depth of 25 metres.

3.1.1 Water Transparency Based On Secchi Disk Measurements

Two different Secchi disks targets (shown in Figure 11) were used to evaluate water transparency. This device has been a standard of underwater optics for nearly 150 years, and they continue to be used by researchers for the long-term monitoring and optical characterization of natural waters.

Secchi disks are a good standard to use for long-term monitoring of water quality but they are mainly of anecdotal value in this experiment. The data collected does show some degree of short term and very short term variability in water transparency, but it does not appear to be substantial. Secchi disks can likely provide reasonable estimates of detection ranges for targets but much more data would be required in order to develop this result. The vertical variability in optical properties of the water column will introduce uncertainty into the estimate however it is likely a good candidate for a worst-case estimate, since attenuation is often higher near the surface of the ocean. Results are shown in Table 1.

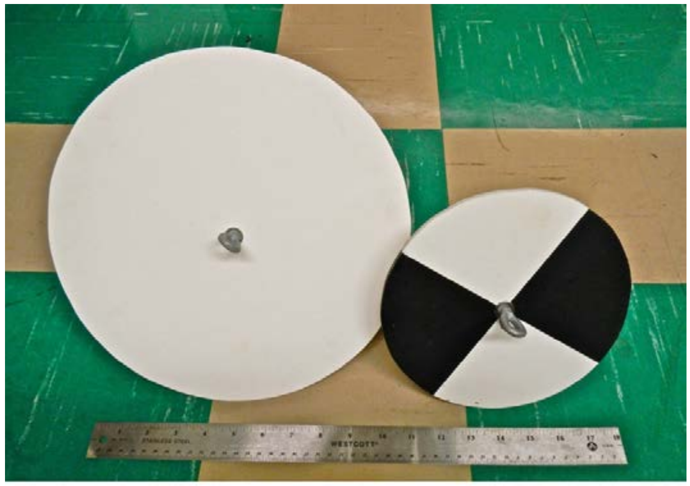


Figure 11: *Secchi disks: 30 cm white disk (left) and 20 cm patterned disk (right).*

Table 1: *Visibility measurements made with Secchi disks.*

Date	Time (ADT)	Secchi Depth 20 cm disk	Secchi Depth 30 cm disk
April 26 (Tue)	12:10	4.03 m	n/a
April 26 (Tue)	12:16	n/a	4.77 m
April 26 (Tue)	12:54	4.82 m	5.00 m
April 27 (Wed)	09:53	4.90 m	5.11 m
April 27 (Wed)	12:47	4.52 m	5.05 m
April 28 (Thu)	09:02	4.37 m	4.75 m
April 29 (Fri)	10:40	5.11 m	n/a
April 29 (Fri)	10:52	n/a	5.08 m

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3.1.2 Water Transparency Based On Improvised Measurements

An alternative (non-standard) transparency measurement was conceived and improvised during these experiments. This measurement attached the flashlights to the Secchi disks in a way that would point their beams back toward the surface, and such that the lights could be lowered to the depth where they would be at the edge of visibility. In these measurements, one Navi light Glo was set to flashing mode and attached to the small Secchi disk; the limit of visibility for that light was 12.75 metres below the sea surface. When the two UK C8 eLED lights were attached to the larger Secchi disk, the limit of visibility for that arrangement was 15.2 metres below the sea surface.

The improvised water clarity measurement was a very good one to use for a quick simulation of the self-illuminated UUV scenario. The beneficial aspects of the technique are that it can be performed without a camera, it replicates the scenario quite well and, as with Secchi depth measurements, it represents average water clarity if vertical stratification presents any strongly attenuating layers. This technique quickly and clearly illustrates that the exponential nature of attenuation results in only marginal improvements of detection ranges when substantially brighter lights are used. However, it also shows that the use of lights on the UUV can substantially increase UUV visibility.

3.1.3 Water Transparency Based On Quantitative AOP and IOP Profile Measurements

In order to document water conditions under which the optical experiments were taken, the Inherent and Apparent Optical Properties (IOPs and AOPs) of the water were measured with a free-falling hyperspectral profiler manufactured by Satlantic Inc. This particular profiling radiometer was equipped with hyperspectral radiometers which measure the power distribution of light in ultraviolet, visible, and near infra-red regions having wavelengths from 350-800 nm. These radiometers measured downwelling irradiance (Ed), upwelling irradiance (Eu), and upwelling radiance (Lu) in over one hundred channels (colors) with 3.3 nm bandwidths. The profiler carried additional sensors for measuring, salinity, temperature, depth, chlorophyll fluorescence, and optical backscatter in blue (470 nm) and red (700 nm) wavelengths. The results from the April 2011 experiments are shown below in Figures 12 to 15. It can be seen that at certain depths there is significant attenuation and backscatter in the water under these test conditions. It should also be noted that there is significant variation in these values with depth, which is significant for some of the optical results presented later in this report.

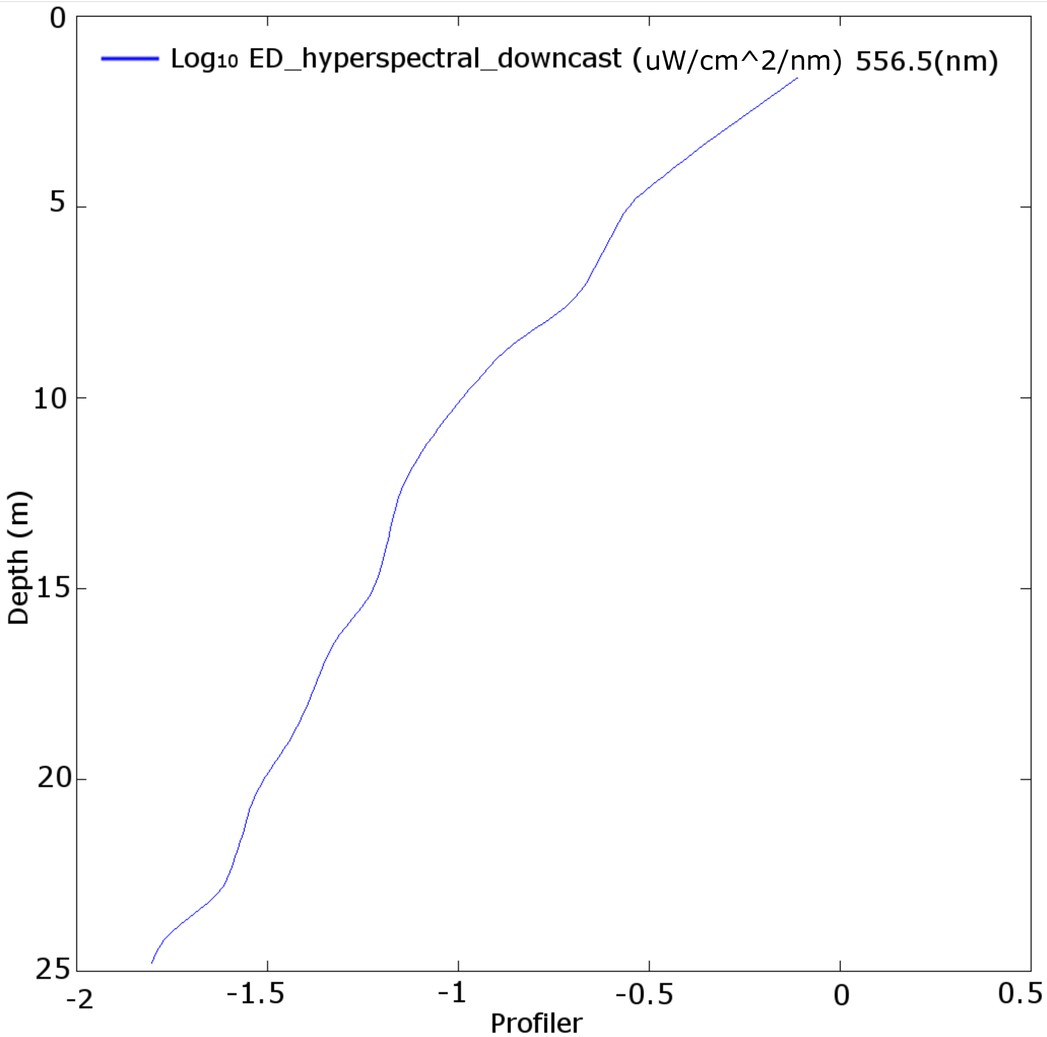


Figure 12: *Down-welling irradiance versus depth, at a wavelength of 556 nanometers.*

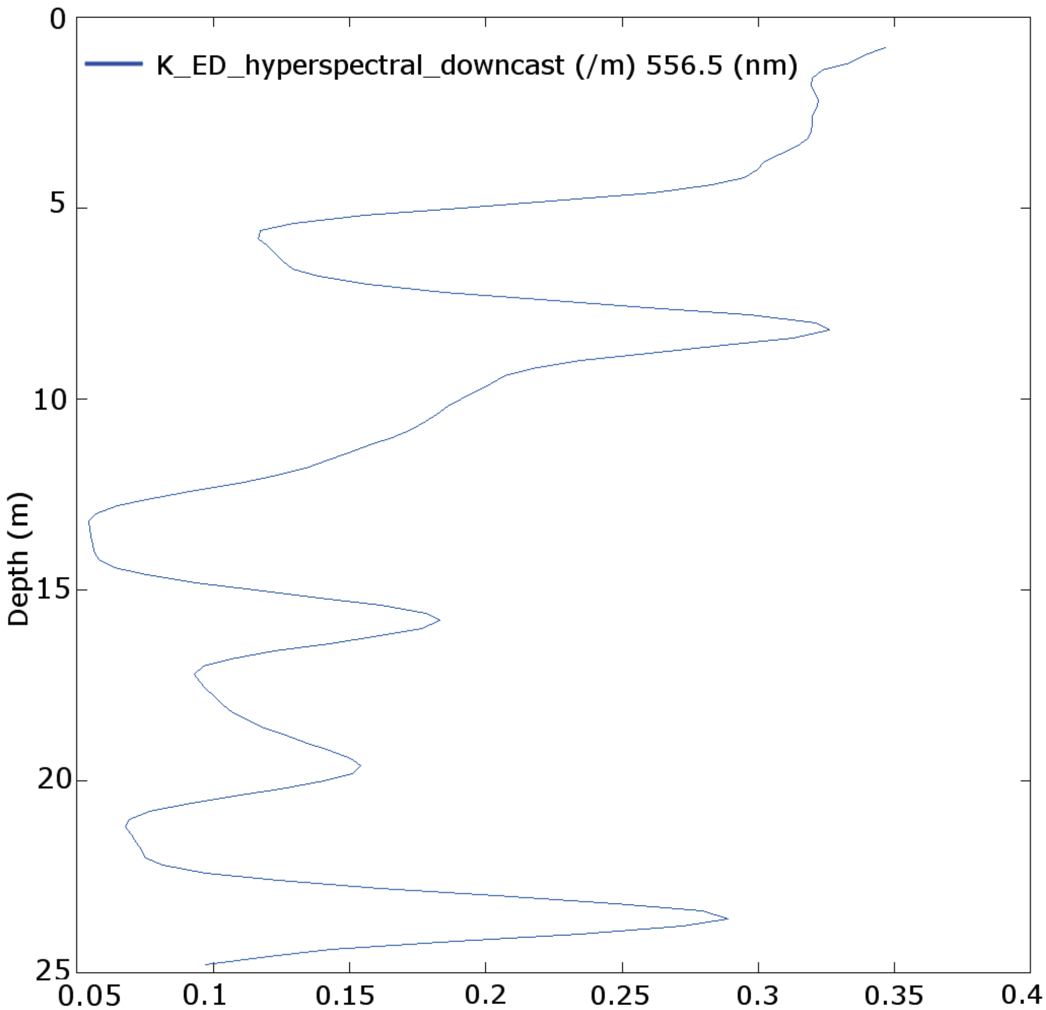


Figure 13: *Computed diffuse attenuation coefficient (k_d) for down-welling irradiance versus depth, in units of [1/m], at wavelength of 556 nm.*

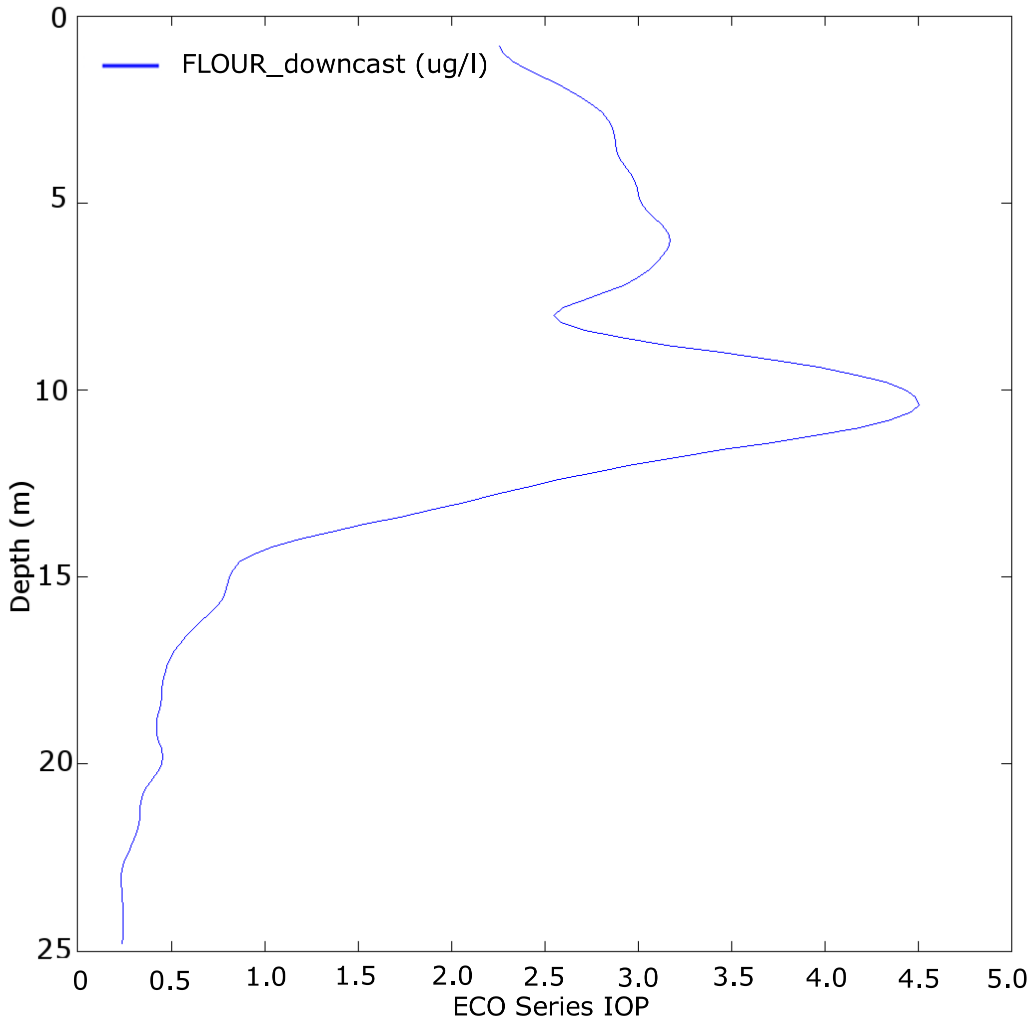


Figure 14: *Chlorophyll concentration versus depth in (ug/l), based on fluorescence.*

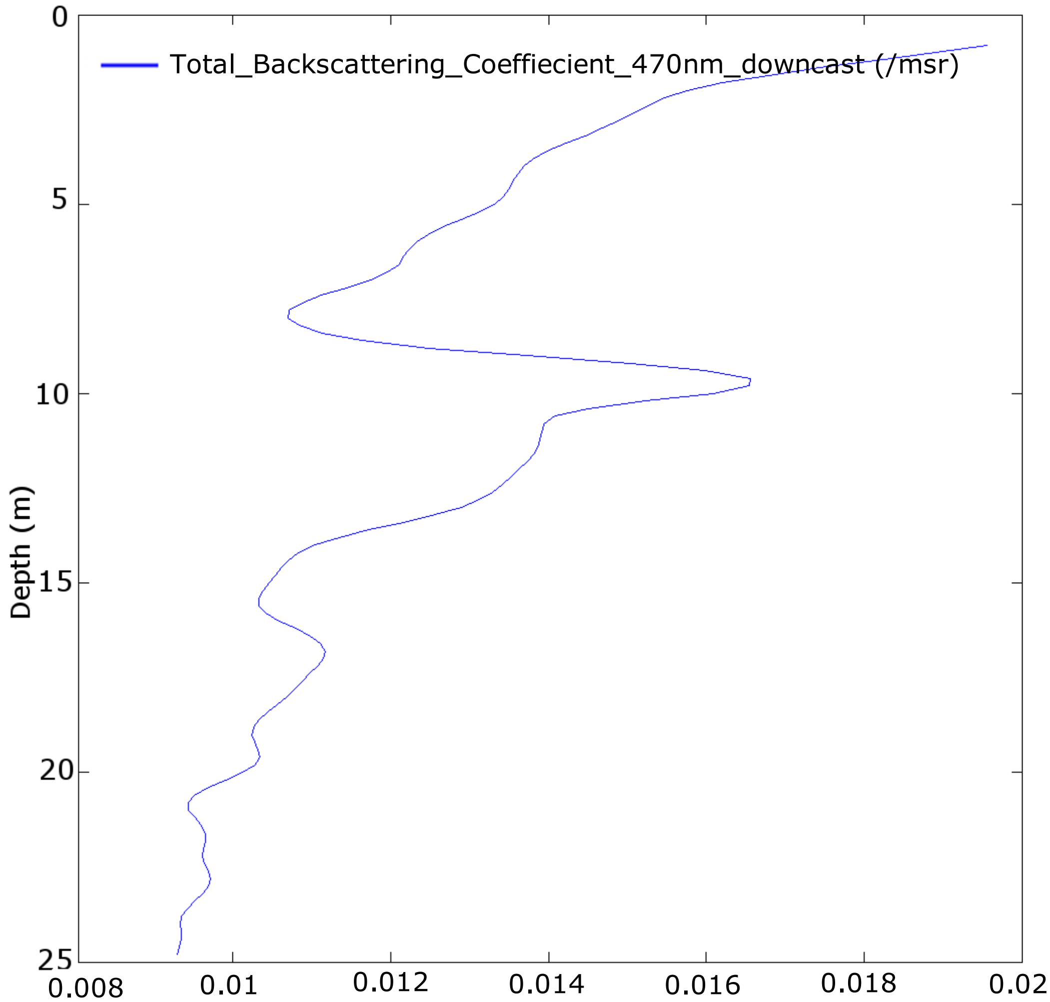


Figure 15: *Total backscatter versus depth,in units of* $[(m * sr)^{-1}]$, *at a wavelength of 470 nm*

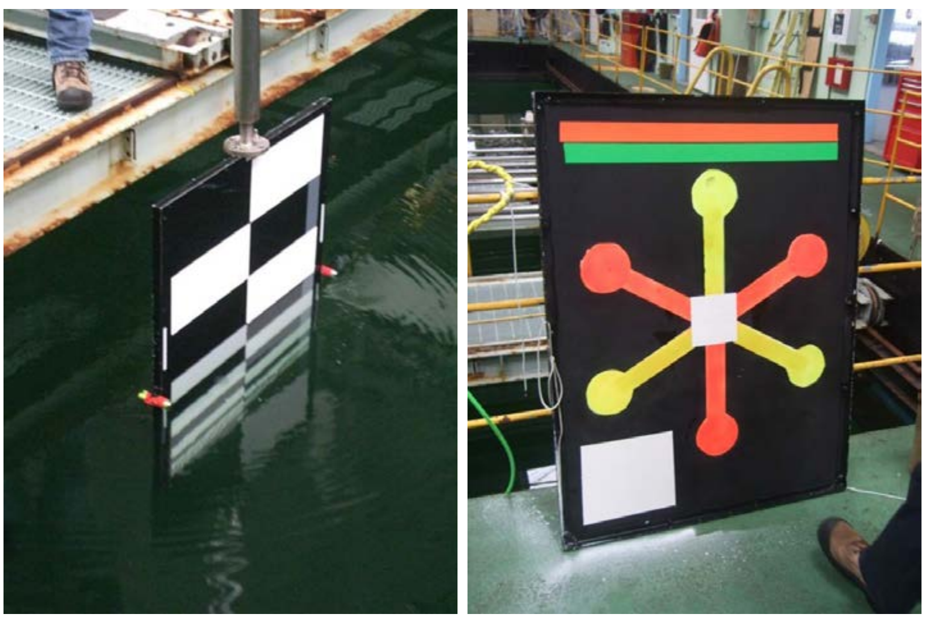
3.2 Target Visibility

To subjectively evaluate the visibility of a target underwater, experiments were conducted using the uLux camera to image pre-fabricated target boards. Three different target lighting methods were used, and their characteristics are described below.

3.2.1 Illumination of Target With Natural (Ambient) Light

The simplest lighting approach for the UUV docking application is to use the natural skylight which enters the water. This approach may be simple in some respects but it can be challenging. Ambient light levels above the sea surface cover a range over a billion to one, and the range is even more extreme when underwater light absorption in water is considered. The goal of this experiment was to determine the ranges that optical targets could be seen at various depths under the conditions found at the Halifax barge site.

The primary optical target was fabricated by DRDC Atlantic's prototype development group and staff painter, Mr. Gary Brown. The target was a framed fiberglass plate (90 cm wide and 120 cm tall) with a non-standard resolution chart on the front side and fluorescent pattern on the back side. The patterns are shown in Figure 16.



(a) (b)

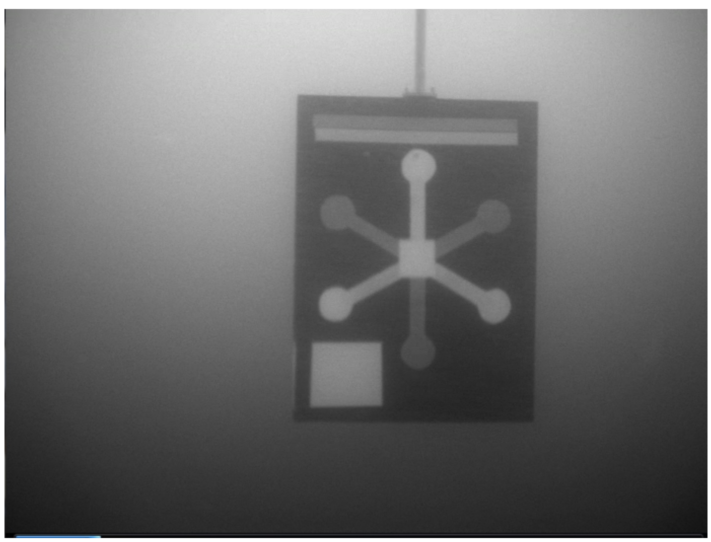
Figure 16: *Optical target photos: front side resolution chart (left) and back side fluorescence pattern (right).*

The resolution chart is intended to permit the evaluation of how far different sized features can be recognized underwater. The black and white blocks on the resolution chart are 41 cm wide and the fourteen vertical divisions have heights of 20 cm, 18 cm, 16 cm, 14 cm, 12 cm, 10 cm, 8 cm, 6 cm, 4 cm, 2 cm, and 1 cm. The fluorescent target pattern is intended to permit a qualitative evaluation of how effective fluorescent imaging might be in a simple underwater configuration. The target is composed of a flat black background with non-fluorescent “reference” reflectors (flat white paint) and a variety of fluorescent features. Fluorescent features were added using Duck brand neon green (#1265018) and blaze orange (#868090) duct tape, and Rust-Oleum yellow (#1942830) and red-orange (#195583) fluorescent spray paints. The fluorescent target contains the following elements:

- Horizontal fluorescent tape strips, 4.8 cm wide and 71 cm long, in orange and green.
- Six fluorescent circles (three yellow and three orange) of 13.5 cm in diameter and located on a radius of 35.5 cm from the center of the panel.
- Six fluorescent radial lines (three yellow and three orange) with 6 cm width joining the circles to the center of the panel.
- A centrally located flat-white square of 14 cm by 14 cm.
- A larger 26.5 cm by 25 cm flat-white square in the lower left corner.

Images of the target board are shown in Figure 17. Identifying targets in these conditions requires long exposure times and a large target. In this experiment at a depth of 23 metres, a target range of 7 metres is nearing the detectable limit, even with this large target board. It can also be seen that the detailed features of the target are not well defined in the images. The front nose of most UUVs is quite small for hydro-dynamic reasons, limiting the size of a target for recognition. This will limit the applicability of image feature recognition algorithms, although it does not necessarily preclude the use of colour or shape tracking algorithms.

(a) Target board imaged at a distance of 7 m with a 100 ms exposure time.



(b) Target board imaged at a distance of 3.5 m with a 300 ms exposure time.

Figure 17: *Images of the target board at a depth of 23 m.*

3.2.2 Illumination of Target With Camera-based Light

One approach to making the UUV target more visible is to illuminate it with an artificial light source on the camera or dock. However, the useful range of camera lights is known to be quite poor under water (as little as a few feet) due to the heavy backscattered glare from fog-like and snow-like particles and plankton that are found in most coastal waters (see example in Figure 4). Putting lights on the dock to illuminate the UUV target has two major problems:

1. For the light to be imaged, it must travel through the water, reflect off the target, and travel back to the camera, being absorbed along both paths.

2. Much of the light from the source will cause backscatter of particles in the water, obscuring the UUV target (as in Figure 4).

For these reasons, illumination of the target from the camera using normal visible light was not tested in these experiments.

There is another system developed at Defence Research and Development Canada – Valcartier that uses laser light to enhance images of underwater targets (LUCIE [9]). The system eliminates the problem of backscatter by sending out a pulse of laser light with the sensor shutter closed. After a specific amount of time, the shutter is opened to image the return light reflected off the target. The result is that the backscattered light from water particles in the near field do not obscure the image of targets in the far-field, increasing the range that objects can be imaged at. However, to use LUCIE in a system for UUV docking, the camera system would still need a method to positively identify the UUV and determine its range, which is a non-trivial undertaking (as discussed earlier).

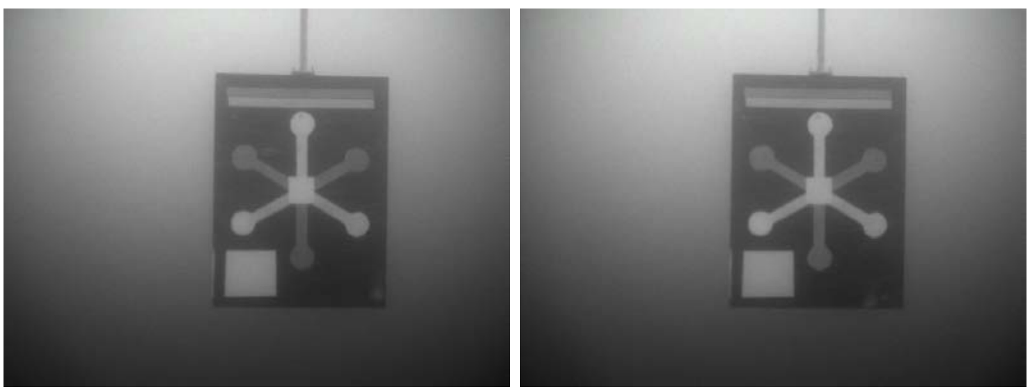
3.2.3 Excitation of Target Fluorescence with Natural and Camera-based Light

Fluorescent colors are commonly used to improve the visibility of SCUBA divers and their equipment. These colours improve the effective scene contrast and make it much easier to see objects (or divers) of interest. Fluorescence is the luminescent behavior of a material that can absorb light of one color (wavelength or waveband) and then re-radiate that captured energy as light with a different color. This behavior causes fluorescent objects to appear “brighter than white”, and brighter than the surrounding environment and sources of light. Commonly encountered fluorescent dyes will absorb non-visible ultraviolet and visible blue light, and give off green, yellow, or orange light.

Fluorescent imaging is simply the exploitation of fluorescence to make a target easier to detect by having it stand out from the background scene. The potential advantage to the UUV docking application is that the blinding backscatter from camera lights can be rejected by an optical filter on the front of the camera. The optical filter can allow the emitted fluorescent light into the camera and block the light which is exciting the fluorescence behavior.

In the fluorescence imaging experiment the white Navisafe LED flashlights were covered by colored glass filters (Schott BG-3 material) to create a blue light source used to excite the fluorescent targets. The camera was also provided with a violet and blue-blocking filter (based on a 525 nm longpass optical coating) that allowed green, yellow, orange, and red light to enter the camera[1].

Two images are shown in Figure 18 of the target board at a distance of 3.5 metres at a depth of 23 metres. On the left, is the target board with the unexcited fluorescent target, and on the right is the target illuminated with the filtered blue light. There is little difference between the visibility of the two targets, even at this range. Through these experiments, it was concluded that this method of improving target visibility and increasing visible range holds little promise, and was not pursued further in this work.



(a) Target board imaged without fluorescent excitation.

(b) Target board imaged with fluorescent excitation.

Figure 18: *Images of the fluorescent target board.*

[1] Two filters were used during the experiment: p/n NT48-638 (2” square, Schott BG-3, bandpass-blue glass filter) and p/n NT64-634 (525 nm OD2 longpass filter, 50 mm diameter).

3.3 Image Enhancement (Post-Processing)

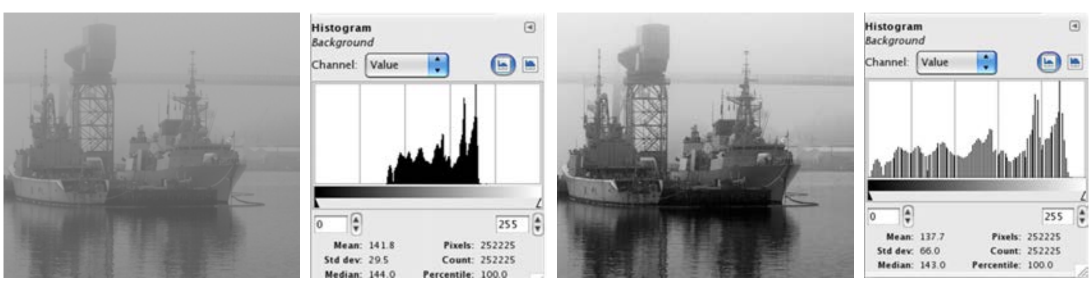
This section investigates the feasibility of using image enhancement techniques to improve the performance of passive imaging underwater. Image composition and exposure challenges can often lead to low-level details of a scene being buried in extremely subtle variations of brightness. This is partly due to the inability of cameras to capture subtle details in scenes with dark shadows and bright highlights, but it is mainly the display media (such as photographs and computer monitors) that limit the range of intensities that can be represented. It is important to note that there is no new information being generated when an image is enhanced, rather the effects of the display media (printed page or computer monitor) and limitations of human vision are being mitigated.

3.3.1 Contrast Enhancement

Traditional algorithms for contrast enhancement tend to be quite simple and computationally efficient due to their age. Global image contrast can be evaluated either by looking at the histogram of pixel values or by looking at the other statistical measures such as the standard deviation. Three basic methods of contrast enhancement follow.

3.3.1.1 Linear contrast stretching

Simple linear contrast stretching modifies pixel intensities through a simple linear equation (such as I' = A ÃŮ I - B) in order to expand the image contrast and have it extend over the entire range of intensities which can be represented by the display. Figure 19 demonstrates this effect in terms of image quality and image statistics.



(a) (b) (c) (d)

Figure 19: *Original low-contrast image (top) and contrast stretched version (bottom).*

3.3.1.2 Histogram Equalization

Histogram equalization is the term that is used to describe a non-linear intensity transformation that attempts to evenly distribute (as closely as possible) the range of brightness within an image. Most scenes have some highlights and shadows present, however some scenes can be highly skewed, and a relatively simple histogram equalization can significantly improve the apparent contrast within the scene. Figure 20 illustrates the effectiveness of this approach to contrast enhancement; note the detail that becomes apparent on the base of the office chair, following equalization.

(a) (b)

(c) (d)

Figure 20: *Original dark image with histogram (top) and equalized image with histogram (lower).*

3.3.1.3 Gamma Correction

Gamma correction is the term that is used to describe a non-linear intensity transformation for which the normalized value of a pixel is raised to some power (gamma). Figure 21 is a gamma curve showing the transformation of relative brightness for gamma equal to 0.5. The dashed lines intersecting this curve are intended to highlight the fact that the curve is expanding the input shadow tones (on the horizontal scale with brightness up to 0.25) into a wider range of output tones (on the vertical scale with brightness up to 0.5).

The results of such a shadow enhancement (with gamma of 0.5) can be as effective as histogram equalization. The gamma corrected image in Figure 22 is notable for appearing more natural than the histogram equalized image results of Figure 20. More detail can be perceived in the darker areas of the image but, quite interestingly, brighter regions of the image are less washed out than the histogram equalized version. However, some compression of bright highlights is evident and should be expected based on the curve of Figure 21.

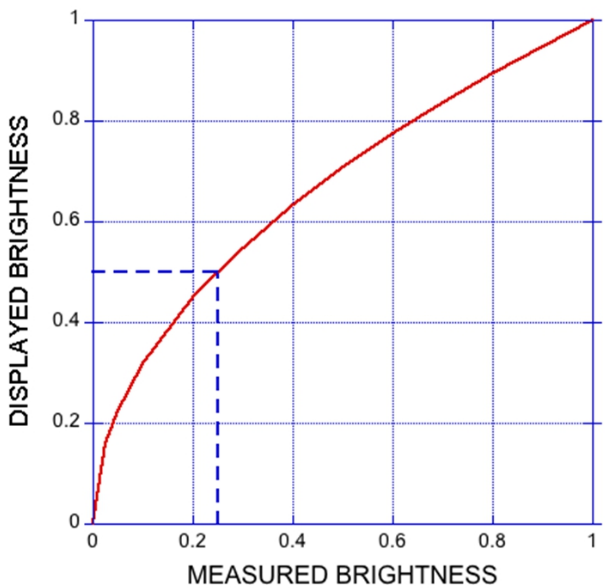


Figure 21: *Curve for gamma correction.*

(a)

(b)

Figure 22: *Original (left) and detail enhanced with nonlinear gamma correction of 0.5 (right).*

3.3.2 Haze Estimation and Removal

With reference to Figure 19, traditional contrast enhancement algorithms provide clearer images (to a point) but they never leave the viewer with the impression that the image has been improved through the removal of haze. Fortunately, modern (but computationally intensive) algorithms have been developed to address this problem through an approach called haze estimation. The basic problems with a hazy (scattering) media are twofold. The first problem is that light originating from, or reflected by, the object of interest will be attenuated by diffuse scattering and absorption as it propagates through the medium and to the observer. The second problem is that any ambient light scattered in the transmission path (volume of propagation) between the observer and object of interest can form a bright veil (the so called "airlight" component of the image) that will obscure the object of interest. In haze estimation, a variety of image statistics and physics-based models are used to estimate the airlight component and generate a "depth map" for the distance between the viewer and background image. Impressive results have been achieved with a variety of techniques. Most techniques have some substantial limitations, however the results of He et al. [1] (shown in Figure 23) are some of the most impressive to date.

The dark channel prior is unusual since it can operate on single-channel (grayscale) images. The single-channel feature of the algorithm makes it particularly powerful for underwater applications. Since these experiments are focused on maximum range, a broadband monochrome camera is used to collect images in the predominantly blue-green-yellow spectrum where light can propagate best underwater. Accordingly, haze estimates must either be modeled or derived from the single-channel data of the monochrome camera. Fortunately, a single-channel algorithm based on the Dark Channel Prior is available.

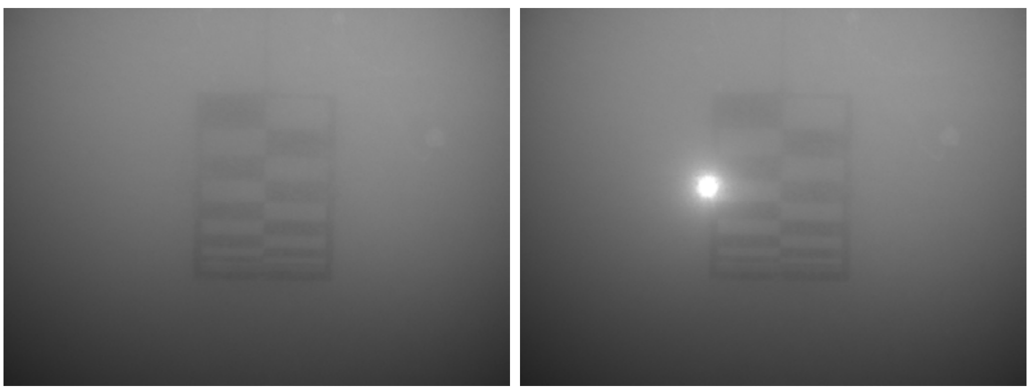
(a) (b)

Figure 23: *Single image haze removal using the Dark Channel Prior algorithm of He et al.*

4 Detection of an Active UUV Target

The use of lights on the UUV itself shining towards the dock camera is a promising approach for detection and tracking of the UUV. In this setup, the absorption and scattering of light only occurs in only one direction (between the UUV and camera), as opposed to occurring in two directions for reflective camera-based lighting systems. Because of the exponential nature of underwater light attenuation, this has the potential to substantially improve the range of detection for a light with a given power.

The effect of adding a light source is illustrated in Figure 24. In Figure 24(a), the black and white target board is imaged at a depth of 11.5 metres, at a distance of approximately five metres, with a 170ms exposure time. Figure 24(b) shows the same target, with one of the Navisafe lights attached, pointing towards the camera.



(a) Target board with no light source. (b) Target board with light source.

Figure 24: *Using a light source to improve the range of detectability.*

For an automated docking scenario, the process of detecting a bright light source through software is much simpler than trying to recognize colors or features of the UUV directly, and has the potential to work at much longer ranges [10]. Furthermore, if a geometry of multiple lights is used on the UUV, it may be possible to reliably recover the relative pose of the UUV with respect to the dock [4]. This could be accomplished by measuring the relative distance and orientation between the different light sources on the UUV.

4.1 Detection Range for Light Sources

Some experiments were undertaken to ascertain the possible detection distance of small lights underwater. This range is highly dependant on the power of the light source, as well as the environmental conditions, including turbidity of the water and ambient light. The exposure time and gain of the camera are also important.

The conditions under which these experiments were undertaken in April 2011 were somewhat worst case: murky harbour water in daylight, near river outflow in spring with significant numbers of micro-organisms in the water. It is quite likely that in clear ocean water, the visible range of the light sources would be significantly longer.

The conditions for these experiments are documented in Section 3.1. Of particular importance is the difference in scattering and ambient light with respect to depth. Two images are presented in Figure 25 to illustrate the fact that detection range can depend strongly on the water conditions. Both images were captured with the Navisafe light source at a distance of 16 m with a 170 ms exposure time. However, in the left hand image, the light source is barely visible as a diffuse glow, while on the right side, the light source is very distinct. This is based solely on the differences in clarity and amount of ambient light between the two depths (which can be seen in Figures 12 to 15).

(a) Light source at 11.5 m depth and 16 m range.

(b) Light source at 23 m depth and 16m range.

Figure 25: *The effect of water conditions such as turbidity and ambient lighting on detection distance.*

Because of these results, it is difficult to state an absolute effective range for an underwater optical system. However, based on the above result, we know that under ideal conditions, the system will be workable to at least 16 metres[2].

The remainder of this section details experiments conducted in June 2012 to investigate the feasibility of using a UUV with lights as a tracking target for docking.

[2] 16 m is the limit of separation between the light source and the camera in the barge facility used in these experiments.

4.2 Challenges In Detecting Lights Underwater

The method of having active light sources on the UUV to track its relative pose is not as straightforward as might be assumed. This section will provide experimental images to illustrate some of the difficulties that can be encountered.

4.2.1 Marine Organisms and Scattering

A variety of marine organisms (including a harbour seal) were observed during these experiments, some of which are shown in Figure 26, and a snow and fog-like mixture of small planktonic species was pervasive. The effects of this biomass clearly dominated optical propagation during the measurements. Larger planktonic organisms such as jellyfish and comb jellies, feeding on the smaller plankton, were also prevalent but were generally less numerous and having a smaller impact on the overall image quality. As can be seen in these images, the lights do not create a simple point source that would be easy to automatically locate in the image using software. These effects will need to be dealt with in order to create an accurate and effective tracking algorithm.

(a) (b)

Figure 26: *Scattering effects of marine organisms (snow-like clouds of plankton, juvenile fish, common moon jelly, and ctenophore or comb jelly) and beam patterns of lights. Exposure times of 100 ms (left) and 10 ms (right) at a depth of 23 m.*

Biological scattering shown in the images is partly misleading because of the fact that the light levels are relative to those of the heavily overexposed lights in the scene. The lights can easily be seen with exposures that are one hundred times shorter, and under those conditions the scattered light would all but disappear. The plankton scatters a small fraction of the energy that is emitted by the lights. Exposure is discussed further in Section 4.3.3.

Sometimes, the light is scattered to such an extent that it impedes the detection of the light source. This effect can be seen in Figure 27, where the light source has become a diffuse glow in the image.

Figure 27: *Scattering effects of marine organisms at longer distances (light source imaged at a depth of 11.5 m, a distance of approximately 10 m, and an exposure time of 170 ms).*

4.2.2 Effects of Ambient Lighting

When detecting lights underwater, the bright spot in the image corresponding to a light source must be separated from the surrounding image. In dark, clear water, with little ambient light or scattering of the light source, this should be straightforward. However, in bright, turbid water, this will be difficult. Figure 28 shows a test rig with 4 lights imaged at a distance of 2 metres from the camera and at a depth of 2 metres. The glow at the top of the image is the effect of daylight shining into the water, with the 4 lights arranged in a cross below. Even at this short distance, it would be very difficult to separate out the location of the individual light sources from each other and the background to provide an effective measurement.

4.2.3 Effects of Relative Angle

In addition to scattering and absorption, the intensity of light received by the camera is highly dependant on the relative angle between the light and the camera. This is of concern for a UUV that may not be approaching the dock directly (i.e. a situation where the dock needs to move transversely to intercept the UUV). If the light is in the field of view of the camera, but turned away from the camera, the light intensity may be significantly reduced or not visible at all.

Figure 29 shows images of a single Navisafe light suspended at a depth of 1.8 m and a distance of 1.8 m. In the sequence, the light is kept at the same intensity and slowly rotated towards the camera. It can be seen that this angle will have an tremendous effect on the ability of any image processing algorithm to accurately find the location of the light in the image. For this reason, it may be ideal to place an optical diffuser on the light source to allow it to be detected more easily and consistently from a wider range of relative angles. This was not tested in these experiments.

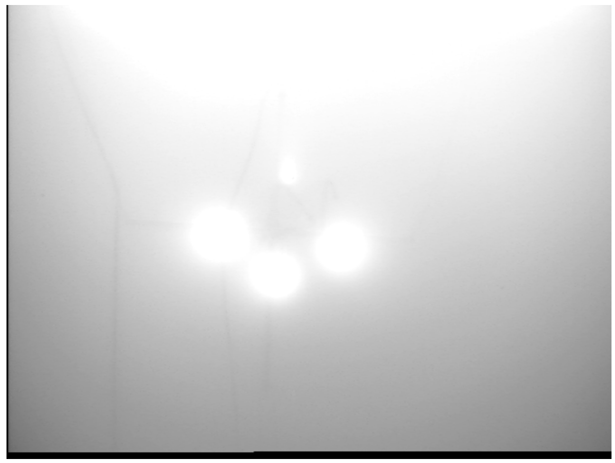
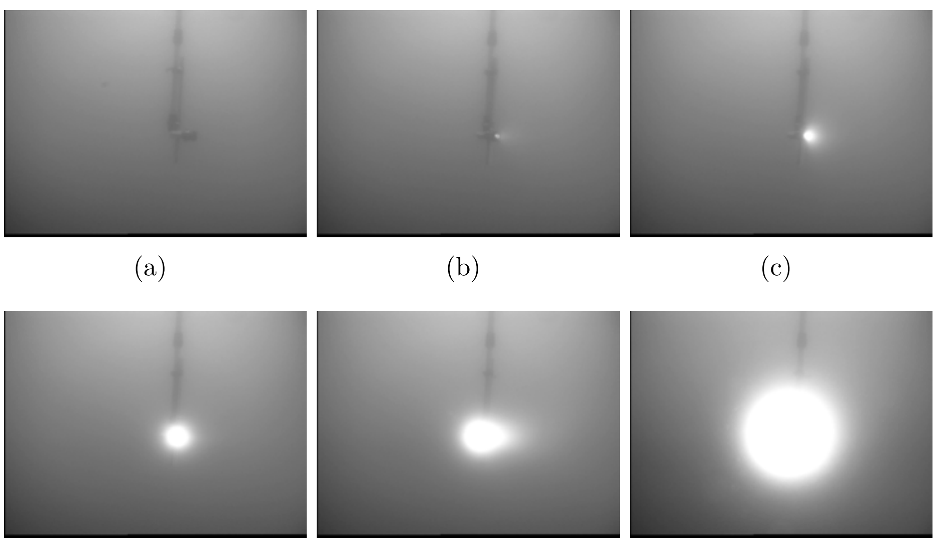


Figure 28: *An image of a 4-light test rig in bright, turbid water.*



(a) (b) (c) (d) (e) (f)

Figure 29: *The effect of relative angle on the perceived intensity of the light in the image.*

4.3 Approaches to Improving Light Tracking

From the above images, it is apparent that the effects of the environment must be managed to effectively track lights in a range of conditions (depth, turbidity, etc.). Some of the adverse effects illustrated above that will cause problems for an image-based tracking algorithm:

- A dim, diffuse target due to a combination of relative angle, ambient light, absorption, and scattering in the water (Figure 27).
- Lights blurring together due to overexposure, turbidity, ambient lighting, etc. (Figure 28).
- The apparent center point of the light not coinciding with the location of the light source due to overexposure or scattering (Figure 26).
- Other bright targets in the image due to ambient light or illumination of other targets in the water such as jellyfish, etc (Figures 26 and 28).

This section details results of experiments conducted to alleviate these problems.

4.3.1 Detection of Lights Using Filters

One approach tested was to use polarizing filters to eliminate the scattered light while permitting light coming directly from the light source. Polarizing filters were placed on the camera lens as well as the light sources under test. The idea was that if the filters were same-polarized, only the direct light from the light source would reach the camera, and scattered light would be rejected. This would create a smaller point source of light in the image that could easily be located and tracked, as opposed to a large, diffuse target.

A polarizing filter was attached to each of the camera lens and the Navisafe light source. Two Edmunds Optics PR032 rotating linear polarizers were used, which have a rotating mount mechanism so that the light source and camera could easily be same-polarized or cross-polarized. The result of one test is shown in Figure 30, where the light source and the camera were same-polarized. Unfortunately, this approach is not effective at reducing the scattered light, as can be seen by the halo around the image of the light. Furthermore, if the camera, the UUV, or its lights should rotate with respect to one another, the light and the camera would become cross polarized and the image would become significantly dimmer, hampering location and tracking. For these reasons, this approach was not pursued further.

A more sophisticated approach to rejecting ambient light could be feasible through the use of laser diodes radiating at a particular frequency in the blue or green spectrum. This wavelength could then be selected for using bandpass spectral filters on the

Figure 30: *A light source with same-polarized filters on the light and camera lens at a distance of 5 m.*

camera to reject ambient light and target the particular diode light. Diffusers on the laser diode could provide for the necessary viewing angles.

4.3.2 Detection of Laser Light

In order to reduce the “flare” observed in many of the images due to overexposure, it was decided to investigate the possibility of tracking laser lights mounted on the UUV. If feasible, the lasers would provide a way to easily find the UUV in the image, while simultaneously providing a method of determining the UUV’s relative pose.

The laser source used, shown in Figure 31, is a model BALP-LG05-B150 laser pointer available from Apinex. The laser is a Class IIIa device with less than 5 mW of output power, and is waterproof to 90 metres. A green laser was chosen (532 nm wavelength) to increase propagation distance through the water.

Several tests were conducted with the lasers mounted on different test rigs. Some sample images are shown in Figure 32. In this test, the laser was mounted on a small ROV that was driven towards the camera.

A number of effects are visible in these images. Firstly, the power of the laser overwhelms the image sensor when aimed directly at the lens, and it would be difficult to pinpoint the source of the light (as in Figure 32(a)). Secondly, the visibility of the laser is poor when it is not aimed directly at the camera, and would only be useful to a distance of about 5 metres, even with a relatively small angle between the UUV and the camera 32(c).

For these reasons, the use of a laser light source was not pursued for this application.

Figure 31: *The waterproof laser used in these experiments.*

4.3.3 Camera Exposure Control

4.3.3.1 Manual Exposure Control

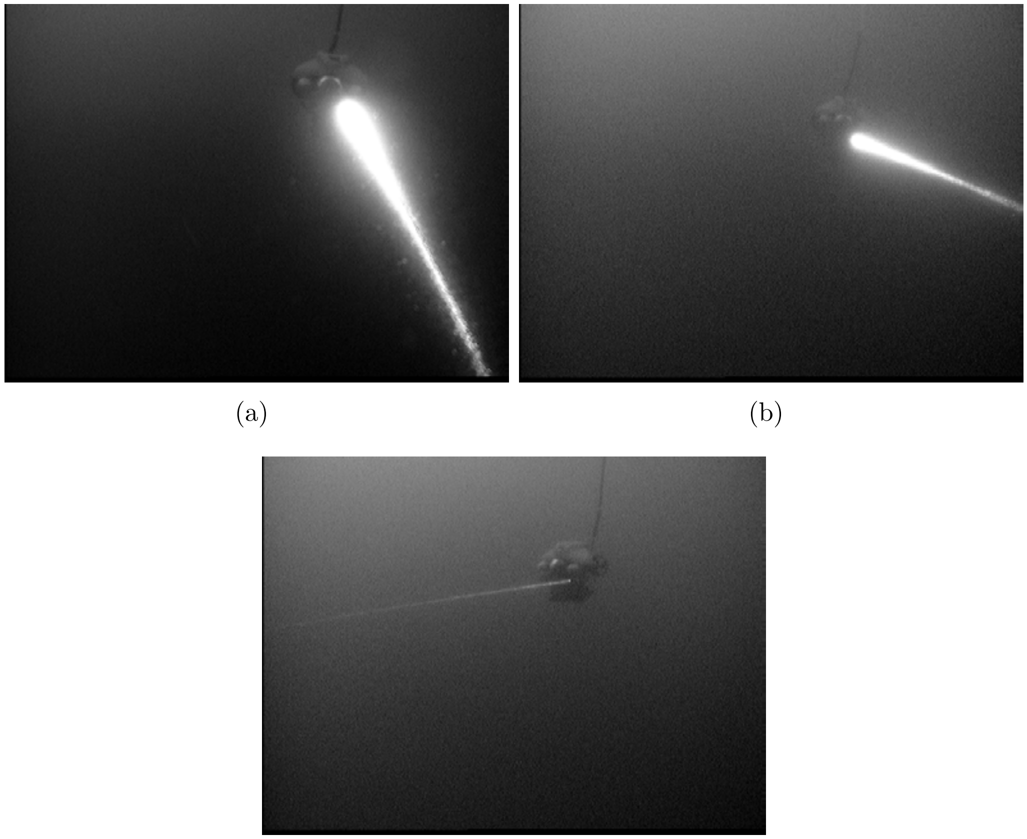
In order to test the ability to control the quality of the images of the lights, numerous images were gathered of different light intensities at different ranges with different exposure times. Some highlights are presented here. Figure 33 shows a test rig with four Navisafe lights mounted in a cross configuration with a 20 cm baseline. The rig was suspended at a depth of 10 metres at a distance of 3 metres in front of the camera with varying exposure times. In Figure 34 it can be seen that with proper exposure, it would be relatively easy to locate and track the source of each of the lights. However, with incorrect exposure, the lights are either invisible, blur together, or wash out the entire image.

This same effect is also present at longer ranges, as shown in Figure 35. One major difference is that the exposure times must be much longer to see the light sources that are further away. Secondly, at long ranges, there is no exposure time which allows all four lights to be resolved, as the scattering of the light causes all 4 sources to be blurred together. Under these particular conditions, with lights of this intensity, the limit of detectability was about 13 metres. However, with clearer water, or more powerful lights, this range could be extended.

The results of these experiments indicate that exposure control is critical to detecting the light sources reliably over a range of distance, light power levels, and ambient light conditions.

4.3.3.2 Auto-Exposure

The Shark Marine SV-LL0003 camera has an on-board auto-exposure controller. However, there is little detail available as to how it operates, and there is no mecha-

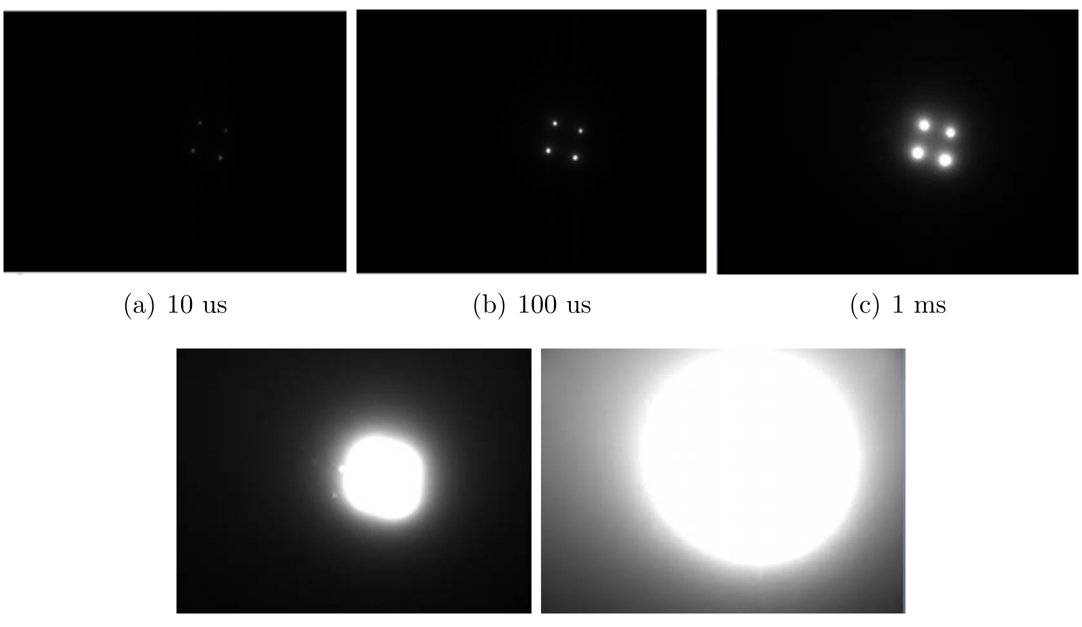


(a) (b) (c)

Figure 32: *An underwater laser mounted on a small ROV.*

nism to adjust the gain of this algorithm such that the light sources always appear at an appropriate size and intensity in the image for tracking. For example, the images in Figure 29 were taken using this camera, and it is clear that in the last image of the sequence, the auto-exposure has not compensated for the intensity of the light shining directly in the camera.

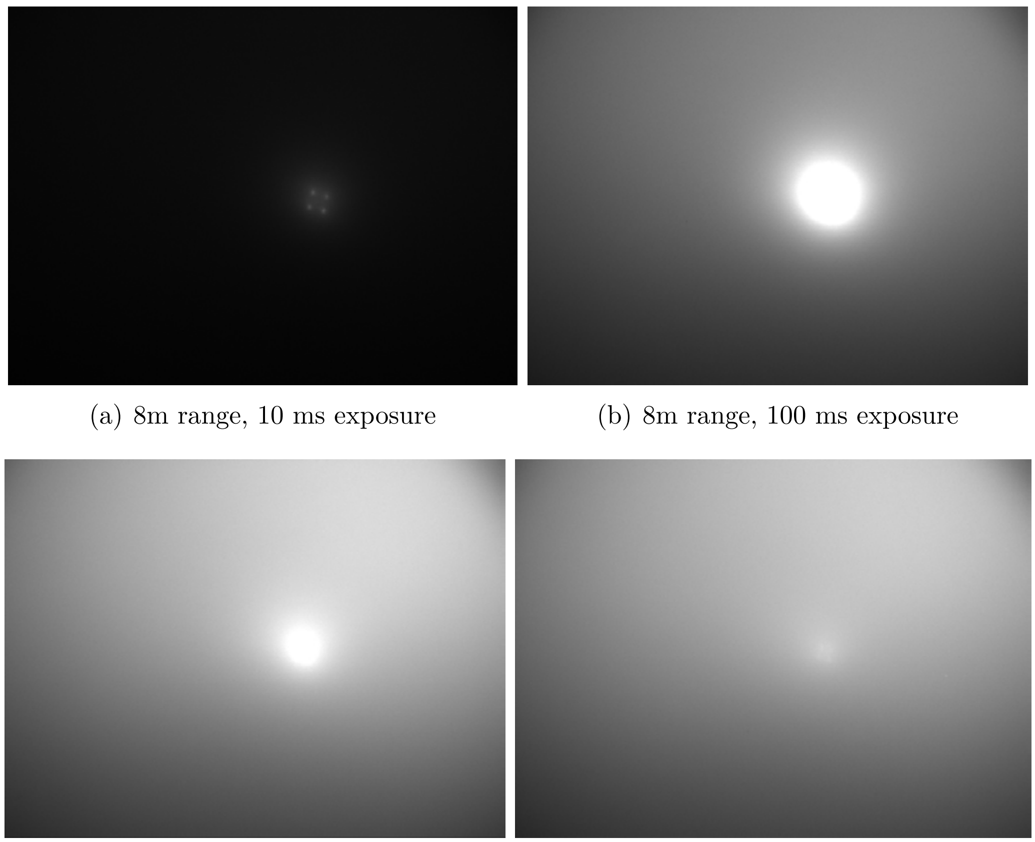
Figure 33: *Light rig used to test exposure control.*



(a) 10 us (b) 100 us (c) 1 ms

(d) 10 ms (e) 100 ms

Figure 34: *Effect of exposure time at short range (3 m range, 10 m depth).*



(a) 8m range, 10 ms exposure

(b) 8m range, 100 ms exposure

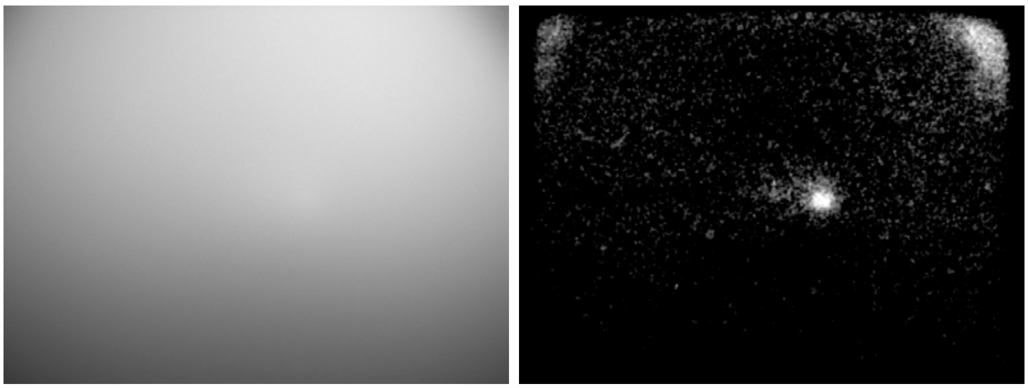
(c) 10m range, 100 ms exposure

(d) 12m range, 100 ms exposure

Figure 35: *Effect of exposure time at longer ranges (10 m depth).*

4.3.4 Image Enhancement

The image enhancement techniques discussed in Section 3.3 can also be applied to images with UUV lights in them. This image processing would be applied to allow the software to more easily detect light sources that might not be visible in the original image. A simple example is shown in Figure 36.



(a) Unprocessed Image

(b) Contrast Enhancement and Bandpass Filter

Figure 36: *A single light source at 10 m depth and a range of 14 m before and after image enhancement.*

A second example is provided in Figure 37. These images were processed using ImageJ software, according to the following steps:

1. Rescale the image intensity to full scale (the original image in Figure 37 has a maximum value of only about 10% of its full grayscale level).
2. Apply a gamma transformation of 4 to highlight the bright areas.
3. Apply a 5–100 pixel wavelength bandpass filter to reduce speckle and the residual light field.

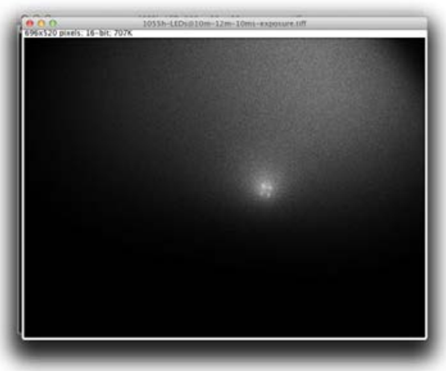
This may not be the final image processing flow used in the system, but these images demonstrate that the improvements will be valuable in detecting the light sources.

4.3.5 Lighting Geometry

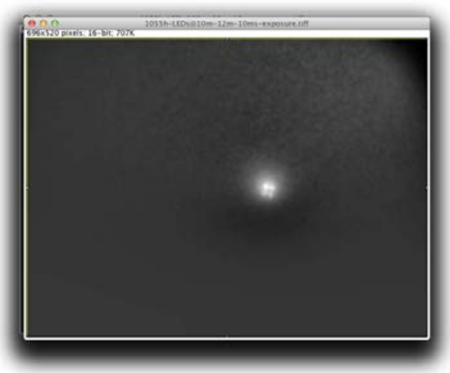
In the course of this work, a mockup of a UUV was created to test the feasibility of determining relative UUV pose. The mockup, shown in Figure 38(a), is based on the Ocean Server Iver2. It is about 120 cm long and has fluorescent panels installed instead of the nose cone.

(a) Unprocessed Image

(b) Contrast Enhanced



(c) Gamma Corrected

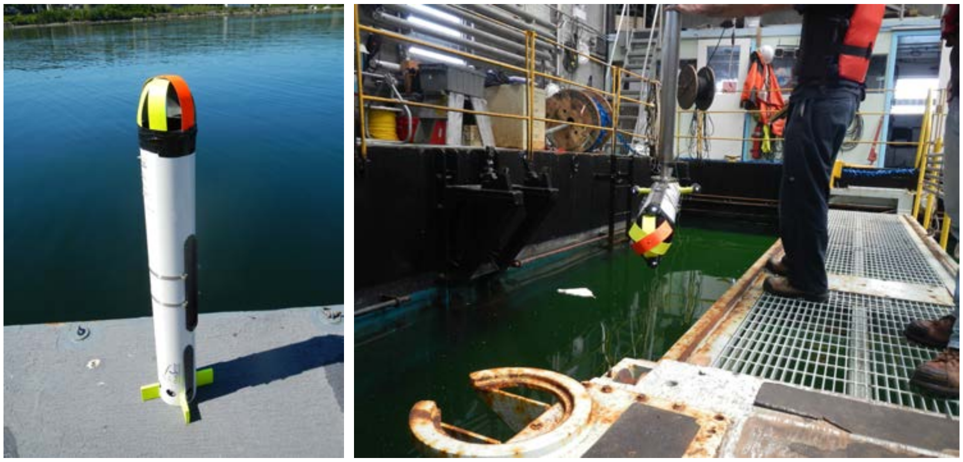


(d) Bandpass Filtered

Figure 37: *A 4-light source at 10 m depth and a range of 12 m improved using image enhancement techniques.*

Four Navisafe lights were also installed on the mockup, two on the nose on the top and bottom, and two on the tail mounted on the port and starboard sides (Figure 38(b)). The two front lights are approximately 20 cm apart from their centers, and the two rear lights are approximately 25 cm apart. The faces of the front lights are approximately 100 cm forward of the rear lights. Each of the lights is skewed outwards at approximately 10 degrees to reduce the amount that they blur together in the image, and to allow detection from a wider range of relative angles between the UUV and the camera. Finally, to reduce flare in the images, the UUV lights were set to low power and “blacked out” with electrical tape so that only a portion of their light was visible. It can be seen in Figure 38(b) that at this level, the lights are actually fairly dim in natural daylight[3]. A colour photo of the UUV mockup was also taken underwater, and can be seen in Figure 39.

[3] The “blackout” of the lights was necessary to accommodate the auto-exposure of the SV-LL0003 camera, which would image the lights as large flare’s if the lights were left at full power.



(a) UUV Mockup

(b) UUV Mockup with lights mounted on the barge well crane.

Figure 38: *Mockup UUV used for experimentation.*

Figure 39: *Underwater photo of the UUV mockup.*

Several experiments were conducted with the UUV mockup at a depth of 10 m. In the first experiment, the UUV was yawed 180 degrees at a distance of 2 m in front of the camera so that it could be seen from all angles. Some images are shown in Figure 40.

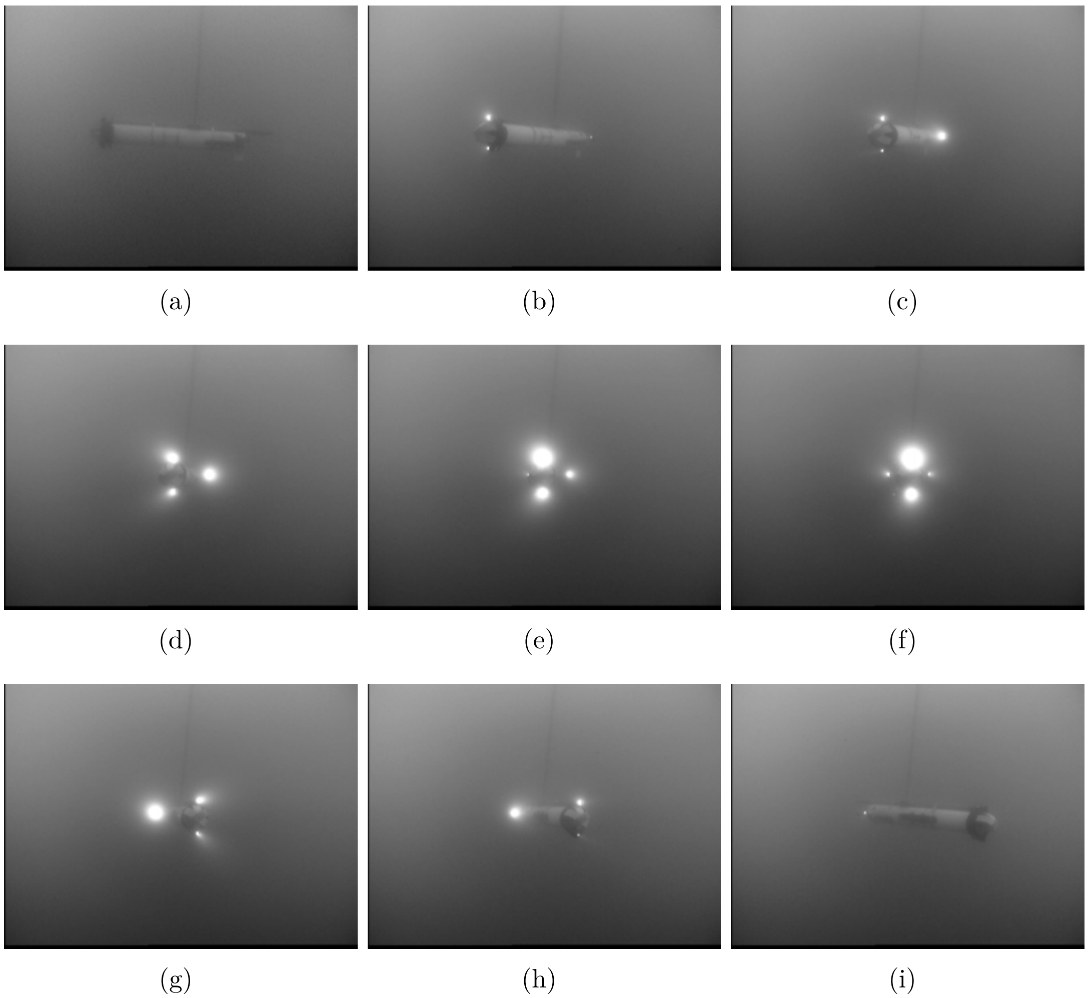
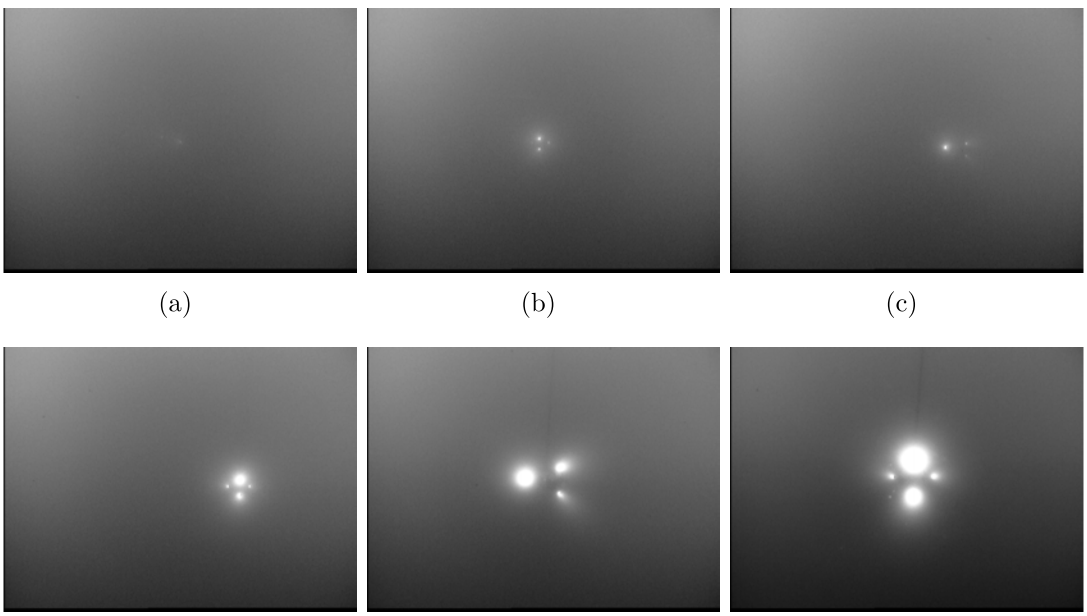


Figure 40: UUV mockup rotating with lights in front of the camera at a distance of 2 m.

The mockup UUV was also tested in a simulated "docking approach". In order to conduct this, the well trolley of the barge with the mockup suspended below was moved at a steady rate towards the camera. At the same time, its yaw and relative horizontal offset from the camera were also changed to simulate possible UUV motions. A sample of images from this sequence is shown in Figure 41. The maximum yaw of the UUV during this sequence was about 10 degrees. No pitch was applied to the UUV during this simulated approach due to limitations of the barge equipment. Once again, it can be seen that the image of the lights become brighter or are obscured by the UUV body as the relative position and angle of the UUV changes. However, despite the relative motions, at least two of the lights were visible at all times, providing a rudimentary way to measure range from the dock to the UUV. Even with these turbid water conditions significantly dimmed light sources, the UUV was visible to a distance of about 10 metres.



(a) (b) (c)

(d) (e) (f)

Figure 41: *Images from a simulated UUV approach.*

5 Conclusions, Lessons Learned, and Future Work

During these wide-ranging experiments, a number of lessons were learned to guide the design of an underwater imaging system for docking UUVs:

- Ambient skylight on a dark day can provide sufficient illumination to track large high-contrast objects at ranges up to 8 metres and depths of 23 metres. This can be done without any artificial lighting. However, the long exposure times required at low light levels is expected to result in blurred images and excessive latency in target tracking solutions.
- With some levels of ambient lighting, absorption, and scattering, the quality of target images will not be adequate for feature-based tracking systems. It may be possible to use colour or shape-based algorithms, but their range will be limited under many environmental conditions.
- Haze estimation algorithms and other image processing techniques are unable to compensate for the scattering caused by distributions of larger visible objects. Heavy concentrations of large metazoan zooplankton such as comb jellies, jellyfish, and copepods will generate video clutter that has the potential to cause significant difficulties for optical tracking algorithms.
- Using a camera-side light source to illuminate or fluoresce a UUV target is not effective enough to greatly improve the image quality because of backscatter and light attenuation issues.
- Using UUV-mounted lights to increase the detectable range of the UUV is a practical approach to the problem. However, several problems need to be overcome, including dim diffuse targets in turbid water, and blurring of lights together when overexposed.
- The key to effectively tracking light sources will be proper exposure control and the use of diffusers on the light to control the intensity of the light reaching the image sensor.

The auto-exposure on the camera used here was not adequate for the task, and a custom algorithm will need to be created. As such, the design of the optical system for this project will have a UUV with an on-board, diffuse light source. On the dock side, a camera system will have exposure control directed from the image processing software. This exposure control algorithm should be integrated with the software that finds the light sources in the image, creating a brighter image for distant targets during the initial detection phase, and dimming the image as the UUV approaches and individual lights need to be resolved for pose recovery. Image processing techniques will also be used to make the light sources easier to detect in the images.

Active lighting is unlikely to have any impact on covert operations during daylight hours, however it may be a legitimate concern at night. The operational concerns of active lighting will need to be investigated further.

The results in Section 4.3.5 confirm that the 4-light geometry is a promising approach to tracking a UUV range, bearing and azimuth. If we make assumptions about limitations to the UUV roll, it will also be possible to recover the full UUV pose from the image. Images of a multiple-light solution may blur together in turbid water and at far ranges. However, light tracking software would at least be able to get a center point for the UUV location, providing data for rudimentary control feedback for the docking mechanism. These experiments have shown that the light tracking should work to a distance of 16 metres or more under certain conditions. Under less than ideal conditions, it should be possible to increase the lighting power on the UUV to increase the detectible range.

The next step in this project will be to develop an exposure control algorithm and to conduct further tests with the UUV mockup to determine if it can be used as a reliable means for short-range tracking for the UUV docking problem.

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This report discusses preliminary experimental investigations into the use of optical imaging to track a UUV (Unmanned Underwater Vehicle) that would be docking with a submarine. Two different types of underwater cameras were used to image a variety of optical “targets”, under con-trolled but realistic conditions, at Defence R&D Canada – Atlantic’s Acoustic Calibration Barge (ACB) in Bedford Basin near Halifax, Nova Scotia. A variety of imaging methods are employed and evaluated.

The investigation provides a baseline assessment of the potential for imaging a UUV, both pas-sively and with an active light source on the UUV. The results show that UUVs can be imaged at ranges of at least 16 metres under certain environmental conditions, but that the effective range will be highly dependent on water turbidity and ambient light.

Le présent rapport examine les vérifications expérimentales préliminaires de l’utilisa-tion de l’imagerie optique pour surveiller l’arrimage d’un VSSE (véhicule sous-marin sans équipage) à un sous-marin. Deux types différents de caméras sous-marines ont été utilisés pour documenter une variété de “cibles” optiques, dans des conditions contrô-lées mais réalistes, à l’aide du chaland d’étalonnage acoustique de RDDC Atlantique à Bedford Basin près d’Halifax, en Nouvelle-écosse. Diverses méthodes d’imagerie sont employées et évaluées.

La vérification fournit une évaluation de base du potentiel de création d’une image de VSSE, de manière passive et à l’aide d’une source de lumière active sur le véhicule. Les résultats montrent qu’une image peut être créée à une dis-tance d’au moins 16 mètres dans certaines conditions environnementales, mais que la distance utile dépendra grandement de la turbidité de l’eau et de la lumière ambiante.

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