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Feasibility of using remote-operated vehicles (ROVs) for vessel biofouling inspections

Government of **Western Australia**
Department of **Fisheries**

NIWA
Taihoro Nukurangi

Fish for the future

Department of Fisheries
3rd floor SGIO Atrium
168 - 170 St Georges Terrace
PERTH WA 6000
Telephone: (08) 9482 7333
Facsimile: (08) 9482 7389
Website: www.fish.wa.gov.au
ABN: 55 689 771

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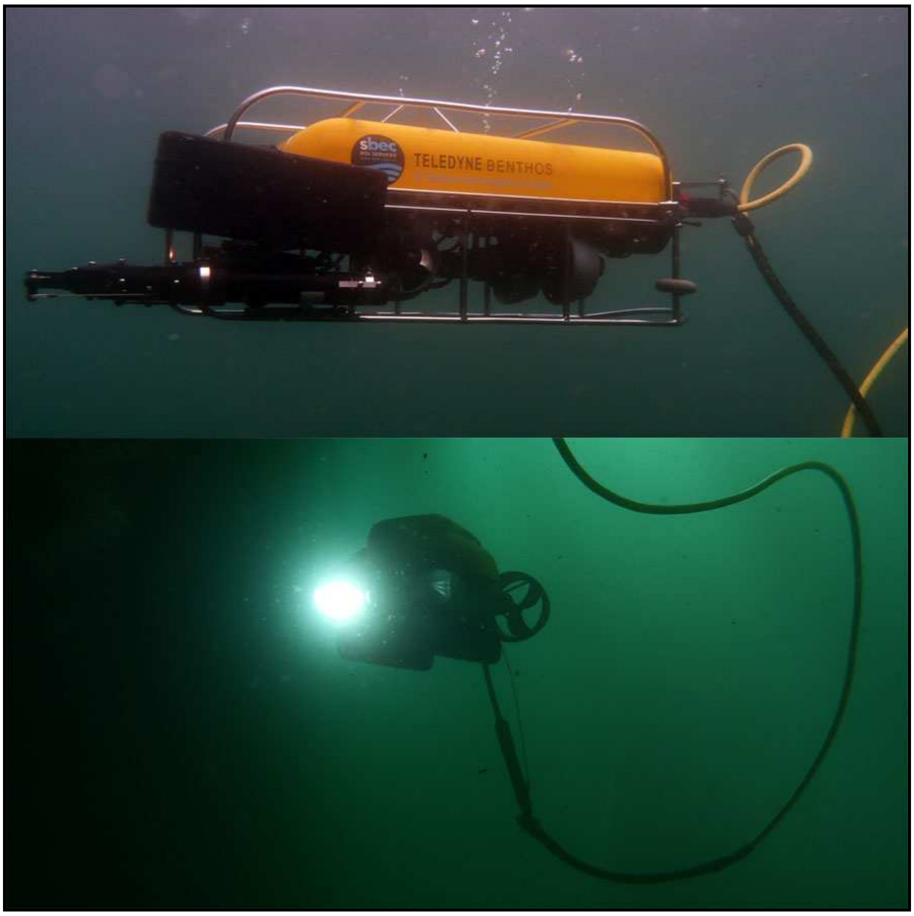

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Authors/Contributors:

Oliver Floerl
NIWA Ltd.
10 Kyle Street
Riccarton, Christchurch
New Zealand

Ashley Coutts
Biofouling Solutions Pty. Ltd.
244 Summerleas Road, Kingston
Tasmania, 7050
Australia

For any information regarding this report please contact:

Dr Oliver Floerl
Marine Biodiversity and Biosecurity
+64-3-348 8987
o.floerl@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
10 Kyle Street
Riccarton
Christchurch 8011
PO Box 8602, Riccarton
Christchurch 8440
New Zealand

Phone +64-3-348 8987
Fax +64-3-348 5548

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Cover page images: The Stingray and VideoRay Remotely Operated Vehicles trialled during the study.

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1 Executive summary

The arrival of non-indigenous species via biofouling on vessels and towed infrastructure presents a biosecurity risk to Western Australia (WA). The State's ongoing oil and gas boom is attracting a wide range of vessels that support the extraction and exploration industry and that arrive in WA from a wide range of global locations. In recent years, biosecurity inspections of vessels and infrastructure intending to operate in the WA marine area have been increasingly used to prevent accidental introductions of NIS. Traditionally, such inspections have been carried out by commercial dive teams supervised by suitably qualified marine scientists. However, such inspections are expensive and pose a range of occupational health and safety (OH&S) risks. This report describes a feasibility study commissioned by the WA Department of Fisheries into the use of Remotely Operated Vehicles (ROVs) for underwater biofouling inspections.

In July 2011, biofouling inspection trials were conducted in two locations in the Fremantle region: the sheltered Fishing Boat Harbour and a more exposed location in Cockburn Sound, approximately 2 nautical miles off Fremantle. A total of four different vessels (a dumb barge, a large stern-trawling fishing vessel and two smaller side-trawling fishing vessels) were inspected using three methods: a commercial dive team, a free-flying ROV and a crawler ROV that was able to attach to and 'drive' along horizontal hull surfaces. All inspections were supervised by a qualified marine scientist who directed the divers and ROVs via closed-circuit TV (CCTV) and communications equipment. The overall aims of the inspections were to determine the ability of the divers and ROVs to: (1) access and inspect all submerged hull and niche areas associated with the vessels, (2) generate CCTV and still imagery that enables detection of biofouling organisms and identification of broad taxa or individual species, and (3) collect biological samples for verification of the taxonomic identity of species on the hulls. A further objective of the project was to determine the costs and benefits of ROVs relative to divers, to enable an overall assessment of the feasibility of using ROVs for conducting biofouling inspections.

Both ROVs and divers were able to access all submerged hull and niche areas present on the vessels. ROVs are able to inspect the entire laminar hull area of a vessel, provided the inspector and operator are able to trace the ROVs' progress and ensure that no surface area is missed. ROVs were also able to inspect most niche areas to the same degree (% of surface area inspected) as divers; often 100 % inspection was achieved. However, divers were able to inspect a higher proportion of some structurally complex niche areas, such as bilge keels, transducer/sonar domes, external piping and some anodes.

The ROVs used in this study generated better and more stable CCTV footage than the divers, particularly in exposed conditions affected by oceanic swell. On average, biofouling taxa were easier to distinguish using CCTV imagery transmitted from the ROVs than from divers However, still images taken on a high-resolution camera by the divers were of far

greater quality and more useful for post-inspection analysis than still images captured off the ROVs' CCTV footage. Divers were also able to recover a higher proportion of artificial marine pest organisms (mimics of bivalves and tubeworms) than were ROVs. This was largely a consequence of the divers' ability to do independent searching beyond the field of vision of the CCTV footage. ROVs had great difficulties collecting samples using their single- or dual-joint manipulators. When samples were collected they were frequently lost. ROVs were unable to collect and store multiple samples without the need for resurfacing.

ROVs are a suitable tool for carrying out biofouling inspections on vessels and other maritime infrastructure. They are able to access and inspect the majority of a vessel's submerged surface area and their imagery is of sufficient quality to enable the detection and characterisation of biofouling assemblages or even of specific target species, including situations where these are hidden within existing biofouling. Compared to inspections using divers, biofouling inspections by ROVs can be cost-effective and associated with minimal OH&S risks. In exposed conditions affected by swell and currents, ROVs with crawler capability provide particular value and outperform free-flying models and divers with regard to provision of high-quality imagery, provided the inspection surfaces are suitable for crawler attachment. ROVs have greater transportability than divers and a better ability to travel to remote inspection sites cost-effectively.

However, the ROVs evaluated in this project were unable to collect targeted samples of biofouling organisms. Where the collection of samples is required for taxonomic identification and verification purposes, support from suitably trained divers who are able to collect high-quality specimens effectively and efficiently is required. We suggest that a useful role for ROVs is their use as a 'screening tool' for initial determination of the abundance and composition of biofouling on a hull. A combination of these data and information on the voyage and maintenance history of the inspected vessel should enable a basic assessment of the likely biosecurity risk the vessel poses to WA (or Australia). If required, the initial assessment can be verified via the collection of targeted samples by commercial divers.

The table below outlines the main findings of the project in relation to four specific objectives.

	Divers	**Free-flying ROV**	**Crawler ROV**
Objective 1: Effectiveness of ROVs and divers to inspect all submerged hull and niche areas	Excellent – able to inspect complex niche areas in full	Very good – but unable to inspect some parts of complex niche areas	Very good – but unable to inspect some parts of complex niche areas
Objective 2: Effectiveness of ROVs and divers to provide imagery for identification of biofouling organisms	Good	Very good – best image quality of all three methods	Very good – best imagery in exposed offshore conditions
Objective 3: Ability of ROVs and divers to collect samples of biofouling organisms	Excellent	Poor	Very poor
Objective 4: Cost-benefit evaluations of divers and ROVs	Very effective method but high cost	Very effective method, cheaper than divers but unable to collect samples	Very effective method, cheapest of all, but unable to collect samples

2 Introduction

Western Australia's (WA) mining and oil and gas industries are important components of Australia's national economy. These industries are supported by a wide range of vessels and towed infrastructure that frequent WA's ports and coastal waters and that are used for exploration and extraction (e.g., anchor handling tugs and supply vessels, oil rigs, drilling rigs/ships and seismic survey vessels), construction (dredges, jack-up barges, dumb barges, pipe laying vessels) and import or export of cargo and commodities (e.g. bulk carriers, container vessels, tankers, Floating Production Supply and Offloading Facilities). In addition to this, WA's ports are visited by fishing, cruise, naval, recreational and illegal foreign fishing vessels.

Most vessels operating in the marine environment harbour biofouling on their submerged hull surfaces that they acquired in their various ports-of-call (Inglis et al. 2010, Piola & Conwell 2010). Many of the vessels and infrastructure frequenting the WA region arrive from international destinations where there are populations of Invasive Marine Species (IMS) that pose a biosecurity risk to Australia (e.g. the Asian green mussel, *Perna viridis*; CCIMPE 2006). The WA Department of Fisheries (DoF) is the lead agency charged with the prevention or mitigation of biosecurity threats to WA waters.

In recent years, biosecurity inspections of vessels and infrastructure operating or intending to operate in WA waters have been increasingly used to prevent accidental introductions of IMS. Traditionally, such inspections have been carried out by commercial dive teams supervised by suitably qualified marine scientists. However, such inspections are relatively expensive (dive teams typically consist of 4-5 persons and require a dive support vessel including a skipper), and pose a range of occupational health and safety (OH&S) risks in certain circumstances (e.g., low visibility, currents, overhead vessel traffic).

DoF is in the process of developing a new strategy for reducing IMS incursions from vessel biofouling. This will result in an increased requirement for risk assessment and inspection of a wide range of vessels visiting and/or operating around WA. DoF is therefore evaluating cost-effective alternative inspection methods to diving that are capable of conducting biofouling inspections effectively and efficiently. The use of new and cost-effective inspection technologies may have the added benefit of assisting Australian Customs with their need for in-water vessel surveillance for contraband.

In June 2011, DoF commissioned National Institute of Water and Atmospheric Research Ltd (NIWA) and Biofouling Solutions Pty Ltd (BFS) to conduct a feasibility study into the use of Remotely Operated Vehicles (ROVs) for biofouling inspections. ROVs have become an increasingly useful tool for underwater surveys, research and salvage operations. They eliminate many of the OH&S challenges associated with diving and are useful and effective tools for the study of marine benthic communities (Parry et al. 2002). Recently, ROVs have also been considered for studying biofouling on vessel hulls in the United States of America ports where diver access was restricted or difficult (Davidson et al. 2006a, Davidson et al. 2006b).

This report describes a field-based evaluation of the feasibility of using ROVs for biofouling inspections of vessels in WA.

3 Aims and Objectives

The stated objectives of project DoF 10/2011 were to:

1. Determine the effectiveness of ROVs and divers in inspecting all submerged areas of vessels, including niche areas;

2. Determine the effectiveness of the ROVs' and divers' capability of providing sufficient imagery to enable recognition/identification of IMS;

3. Determine whether ROVs are capable of collecting samples and if so, how effectively; and

4. Determine the benefits and costs (time and financial) associated with using ROVs relative to using experienced commercial divers when inspecting vessels.

The project was undertaken with the following agreed conditions and constraints:

1. DoF agreed to assist with identifying suitable vessels to conduct the trials on. NIWA's project budget did not include components for vessel charters and a joint effort was made to approach the shipping and exploration industry for vessel support.

2. The number of evaluation trials conducted was optimized to suit the available budget.

3. DoF required the field trials to be completed in July 2011.

4 Methods

4.1 Selection of ROVs and Commercial Dive Company

A wide variety of ROVs are available for inspection, exploration, construction and repair purposes. The current study focused on the evaluation of two particular types of ROV: free-flying and crawler ROVs. The ROVs needed to be relatively small and transportable in order for them to be feasible as alternatives to commercial divers. This ruled out the consideration of larger, working-class ROVs used in the marine construction and exploration industry. The following ROVs and commercial dive company were chosen for this study.

1). VideoRay ROV (with crawler capability). Imbros Pty Ltd is the Australian importer and distributor of VideoRay ROVs and also offers professional ROV services. Imbros were contracted to supply their Pro 4 Video Ray (P4 PS 300BASE) which is a small (361 x 270 x 210 mm), lightweight (6.1 kg), free-flying ROV with crawling capability (Figure 1a). The VideoRay is small enough to be deployed and operated by one person. It is neutrally buoyant and maneuverable via three thrusters (one vertical and two horizontal thrusters) and rated to a depth of 305 m. The VideoRay is equipped with a forward facing wide dynamic range underwater-optimized high-resolution camera (0.0001 lux – colour or black and white modes). The camera also has variable control tilt with 180 degree vertical field of view with two forward facing ultra high-intensity LED lights providing 3,600 Lumens. The VideoRay is controlled at the surface by a ROV operator via a 100 m umbilical capable of supplying the inspector with high-resolution CCTV footage to a topside monitor. Still images can be captured from the CCTV footage. A manipulator "arm" was also fitted to the front of the ROV to trial for collection of samples. More information on this ROV can be accessed at http://www.videoray.com.

2). Teledyne Benthos 'Stingray' ROV (free-flying). SBec Marine Pty Ltd are a Fremantle based ROV service provider specializing in inshore and offshore inspection and exploration work. SBec were contracted to supply their free-flying Stingray ROV. The Stingray ROV is a relatively lightweight (32 kg), mid-sized (990 x 457 x 457 mm) and transportable ROV (3 x large cases plus umbilical drum fit onto the tray of a utility vehicle) (Figure 1b). Two people are required to operate the system. It is neutrally buoyant and maneuverable via four thrusters (one vertical, one lateral and two horizontal thrusters) and rated to a depth of 350 m. The system has inbuilt heading, gyro, pressure, pitch and roll sensors and a Tritech MicronNav sonar to assist with navigation. The Stingray is equipped with a high-resolution, 18X zoom colour video camera: 470 lines resolution, 1.0 LUX minimum illumination, mounted on tilt bar +/-90Degrees, with 3.24 to 38.9mm auto iris lens, 2.2 to 53 degrees field of view horizontal (NTSC or PAL) and HID lighting systems. A Lyyn Video Enhancer was also incorporated to enhance the footage and image clarity in turbid environments. For the present study, the Stingray was tethered to the topside monitoring systems via a 150 m umbilical cable that is capable of supplying the inspector with high-resolution CCTV footage to a topside monitor. Still images can be captured from the CCTV footage. A manipulator "arm" was fitted to the front of the ROV to trial for collection of samples. More information on this ROV can be accessed at http://www.sbec.com.au.

3). SeaForce Marine Diving Services Pty Ltd. There are many different commercial dive companies in WA and some of them are experienced in vessel biofouling inspections. SeaForce Marine Diving Services Pty Ltd (SeaForce) is one of most experienced companies in this area of work and familiar with Biofouling Solutions ISO 9001 endorsed Standard Operating Procedures for Inspecting Vessels for Biofouling and IMS. SeaForce is based in Fremantle, where the present trials were undertaken, and their divers completed the diver inspections in this study. All SeaForce divers are trained to Commonwealth of Australia's Occupational Diving ADAS Part II and III and operate in accordance with Australian Standard 2299.1:2007. All diving operations undertaken by SeaForce during this project were conducted from their 12 x 5 m catamaran, the *Cormorant* and included a six-man dive team (skipper, two deckhands, a dive supervisor, standby diver and diver) (Figure 1c). Divers used Kirby Morgan Superlite-17B surface-supplied diving helmets equipped with lights, communication and real-time CCTV. Divers also used an independent underwater camera capable of capturing high-resolution (10MP) digital photographs.

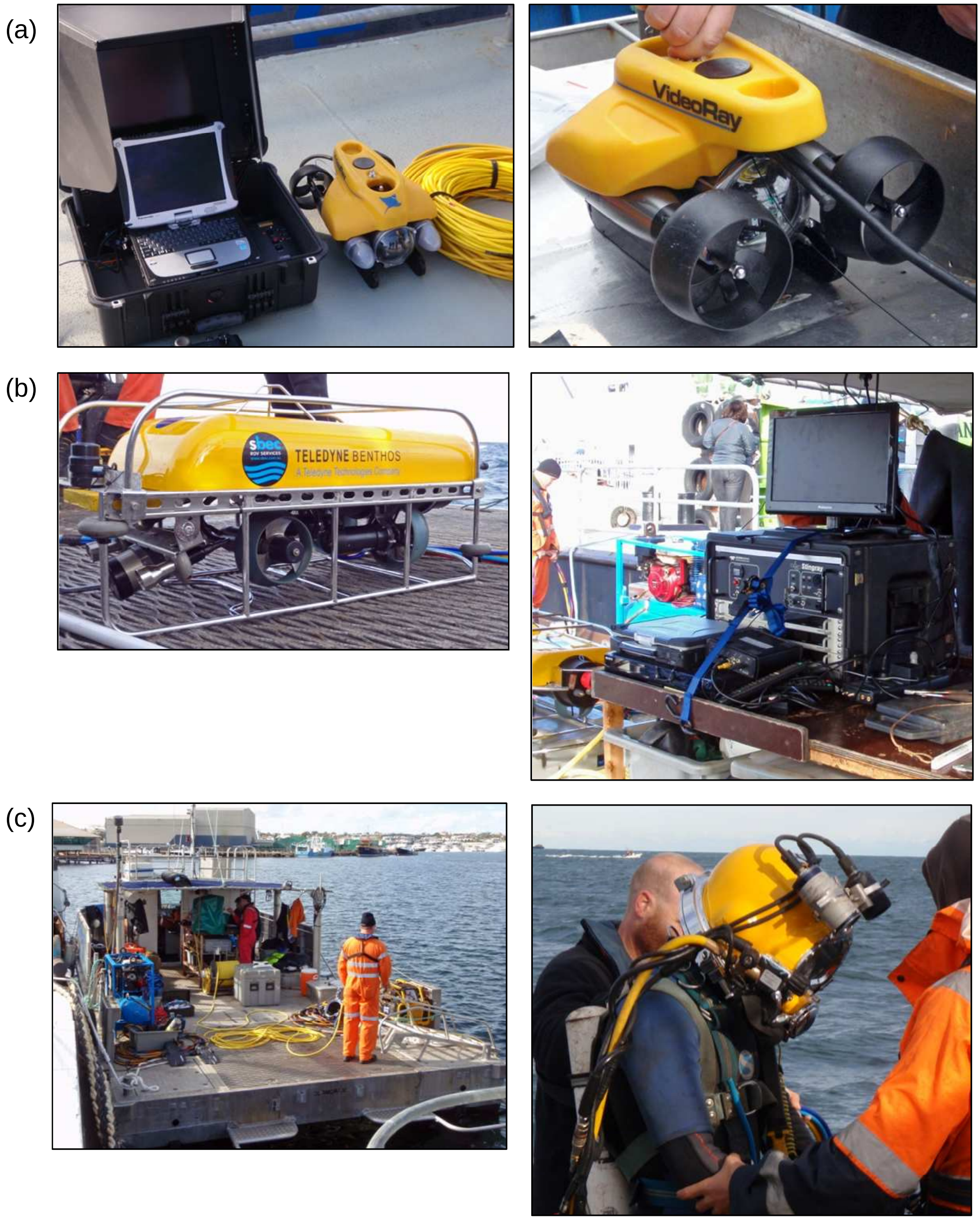

Figure 1: (a) VideoRay crawler ROV and topside control system; (b) free-flying ROV and topside control system; (c) commercial diving vessel *Cormorant* and commercial diver with helmet, CCTV and surface-supply equipment.

4.2 Vessels

The initial intention of this project was to target vessel types that are routinely subject to biofouling inspections in WA waters (e.g., anchor handling vessels, oil rig supply vessels, etc.). However, gaining access to such vessels proved difficult and compromised the timelines of this project. Fremantle-based Kailis Bros Pty Ltd arranged access to four vessels that were available for the diver and ROV trials for the duration of the project: a stern trawler (*Comet*, 40 m), a dumb barge (*LC-20*, 33 m) and two fishing trawlers (*George Michael K* and *Amanda Verne K*; both 18.3 m) (Figure 2). The *LC-20*, *George Michael K* and *Amanda Verne K* routinely operate in WA waters and had received their most recent antifouling coating within approximately 18 months prior to this study. In contrast, the *Comet* has resided in her present location within the Fremantle Fishing Boat Harbour for the past 8 years and has not received antifouling treatment during that time.

(a)

(b)

(c)

Figure 2: The vessels inspected during the field trials. (a) *Comet*; (b) *LC-20*; (c) *Amanda Verne K* (identical in build to the fourth vessel, the *George Michael K*).

4.3 General Inspection Protocol

The ability of the three methods to inspect vessels for biofouling and target IMS was assessed over the 4-day period of 8-11 July, 2011. The inspections replicated 'real-life' inspections of vessels for IMS presently undertaken in WA waters. These inspections typically take place at wharfside in ports/harbours or at anchor offshore. These environments differ in water clarity and exposure to wind and swell, and present different challenges for inspection. The three inspection methods were trialed on two different vessels in each of two different environments: (i) wharfside, in a sheltered port environment (Fremantle Fishing Boat Harbour; *Comet* and *LC-20*), and (ii) approximately 2 nautical miles offshore, where inspections were subject to waves and swell (Cockburn Sound; *Amanda Verne K* and *George Michael K*) (Figure 3). During the wharfside inspections, water clarity ranged from 3-4 m Secchi depth, with calm/flat sea states and wind speeds of 0-15 knots (mode: 5 knots). During the offshore inspections, water clarity was 5-10 m but the divers and ROVs were exposed to swell and chop of 0.5 m and wind speeds of 15-20 knots (mode: 15 knots).

Inspection protocols followed Biofouling Solutions Pty Ltd's ISO 9001 Quality Management System and Standard Operating Procedures for Inspecting Vessels/infrastructure for IMS of Concern. This first required (wherever possible) obtaining a copy of each vessel's General Arrangement and Docking Plan to enable the identification of all hull locations, including niche areas[1]. Once all the hull locations and niche areas were identified, a Toolbox meeting with the vessel Master, Chief Engineer, Diver Supervisor, ROV operators and inspectors (NIWA or BFS lead scientists) was undertaken to discuss inspection protocols, identify operational hazards, tag out any thrusters and propellers and turn off cathodic protection systems.

During each inspection, an inspector sat topside viewing the CCTV footage supplied by each inspection method. The two inspectors coordinated each trial independently. In the case of the divers, the inspector coordinated the divers by communicating through the diving supervisor who then relayed instructions to the diver through their communication system. ROVs were controlled by ROV operators at the surface who were directed by the inspectors. The overall objective of each trial was to inspect all hull locations and niche areas of the vessels for biofouling and target IMS. All inspections concentrated on one side of the vessels at a time (i.e., port or starboard side) and commenced at the bow and systematically migrated in a zigzag motion between the waterline and the keel towards the stern, ensuring all hull locations and niche areas were inspected along the way. The areas inspected were recorded by ticking off all areas on printouts of the General Arrangements for each vessel. The time taken for each inspection was noted by the topside inspector.

Descriptions of methods used to achieve the specific objectives of the project are described in the sections below.

[1] Niche area generally refers to locations on a vessel's hull that accumulate high levels of biofouling and IMS relative to the mainstream areas of the hull due to the absence or in-effectiveness of antifouling coatings

Figure 3: (a) Approximate anchorage of the *George Michael K* and *Amanda Verne K* during the offshore inspections. (b) Location of the *Comet* and *LC-20* in Fremantle Fishing Boat Harbour during the wharfside inspections.

4.4 Specific Methods for each Project Objective

Objective 1: Effectiveness of all inspection methods in surveying all hull and niche areas

The evaluation of the effectiveness of divers and ROVs in inspecting all hull and niche areas was based on a set of simple criteria:

i. Ability of each inspection method to gain access to each hull and niche area;
ii. Ability of each inspection method to inspect the entire surface associated with the targeted area for the presence of biofouling organisms.

As the divers or ROVs moved along the vessels during inspections, the topside inspector noted whether it was possible to access each of the hull and niche areas for inspection. Once access was gained, the inspector estimated the percentage (0-100 %) of the surface area that the diver or ROV was able to inspect. For example, if only one side of a propeller blade was able to be examined, the proportion of the surface areas accesses for this niche was 50 %.

Objective 2: Ability of inspection methods to provide imagery allowing recognition/identification of IMS

Divers and both ROVs were capable of providing real-time CCTV and capturing still images from the CCTV footage. The divers were also able to capture high-resolution still photographs via an independent underwater camera. The ability of the inspection methods to provide imagery of adequate quality for the recognition and identification of biofouling and IMS was assessed: (a) via real-time assessments of the CCTV footage available to the topside inspector and (b) via post-inspection assessments of the freeze-frame images taken from the ROVs' CCTV and the divers' still photographs. The quality and utility of the imagery provided by the three methods was assessed according to the following criteria:

i. Ability to discern what is shown in the CCTV footage or still photographs (e.g., hull area, propeller, sea chest grating etc.);
ii. Ability to determine the presence or absence of biofouling from the CCTV footage or still photographs;
iii. Ability to reliably identify particular taxa from the CCTV footage or images (e.g., barnacles, bivalves, bryozoans, etc.); and
iv. Ability to identify particular target IMS from the CCTV footage or still photographs; (CCIMPE species or experimental mimic "pests" – see below).
v. We also determined whether CCTV imagery provided by each inspection method can be readily examined and 'resolved' in the field, or whether it is necessary to undertake additional laboratory-based still image or video analysis to extract sufficient information for the purposes of the inspection.

The ability of each inspection method to provide imagery from which biofouling organisms could be identified was evaluated using the following rank scale:

5 = Very high - individual biofouling organisms clearly distinguishable on CCTV/image; all organisms identifiable to taxon level; some common organisms to species level;
4 = High - all biofouling identifiable to taxon level (i.e., barnacles, bivalves, etc);
3 = Moderate - level of biofouling (i.e., primary, secondary and tertiary; Appendix A) and some taxa identifiable;
2 = Low - able to determine presence of biofouling, but no identification of taxa;
1 = Very low - unable to determine whether biofouling present or absent

Allocation of the ranks described above was affected by the resolution and quality of the footage and images, by the degree of motion experienced by the ROV or diver at the time the footage or image was taken, and by water clarity (e.g., the amount of sediment dislodged by diver movements or ROV thrusters). In the case of the CCTV footage, waves and swell also affected the ability of the topside inspector (in motion with the vessel) to focus on the real-time footage (in offset motion with the diver or ROV). Therefore, the quality of imagery produced by a single method using the same camera could vary between the wharfside and offshore trials due to differences in wave action and swell.

To evaluate each inspection method's ability to detect particular target IMS, artificial biofouling organisms resembling well-known IMS were hidden around the hulls of the four vessels. These 'mimics' were attached to the hulls via magnets and deployed by a diver (a full description of the process is provided below). There were two types of mimics: bivalves and tubeworms. The bivalves were made to resemble the Asian green mussel (*Perna viridis*) and were constructed from empty New Zealand Greenshell mussel (*Perna canaliculus*) shells filled with builders' resin and a magnet attached. The tubeworms were made to resemble *Ficopomatus enigmaticus*, *Hydroides dianthus* or *H. sanctaecrucis* and were constructed from white electrical cable attached to a magnet (Figure 4). Each type of 'species' had two length classes: small (mussels 15-20 mm; tubeworms 20-30 mm) and large (mussels 60-90 mm, tubeworms 60-90 mm). Prior to the start of the field trials, the diver deploying the mimics was asked to select a number between 15 and 25. He was asked to not disclose this number to any of the other divers, inspectors or ROV pilots. The diver chose 25 mimics and without the knowledge of the inspectors, dive supervisors, inspection divers and ROV pilots, this number of mimics was hidden around each of the vessels prior to each inspection.

The diver placed the mimics haphazardly around the submerged hull and niche areas of each vessel. While the total number of mimics selected (i.e., 25) had to remain consistent across each vessel, the combination of mimic type and size was left to the deploying diver. During the inspection, the topside inspectors recorded, for each hull and niche area, the number of each organism type (bivalve, tubeworm) and size category (small, large) that were detected via CCTV (ROVs) or CCTV and visually by the inspection diver. For each inspection conducted by each method, the proportion of 25 mimics detected by the inspector was determined, and the proportion of detections that were associated with misidentifications (e.g., a large bivalve was mistaken for a small bivalve, or a bivalve was mistaken for a worm).

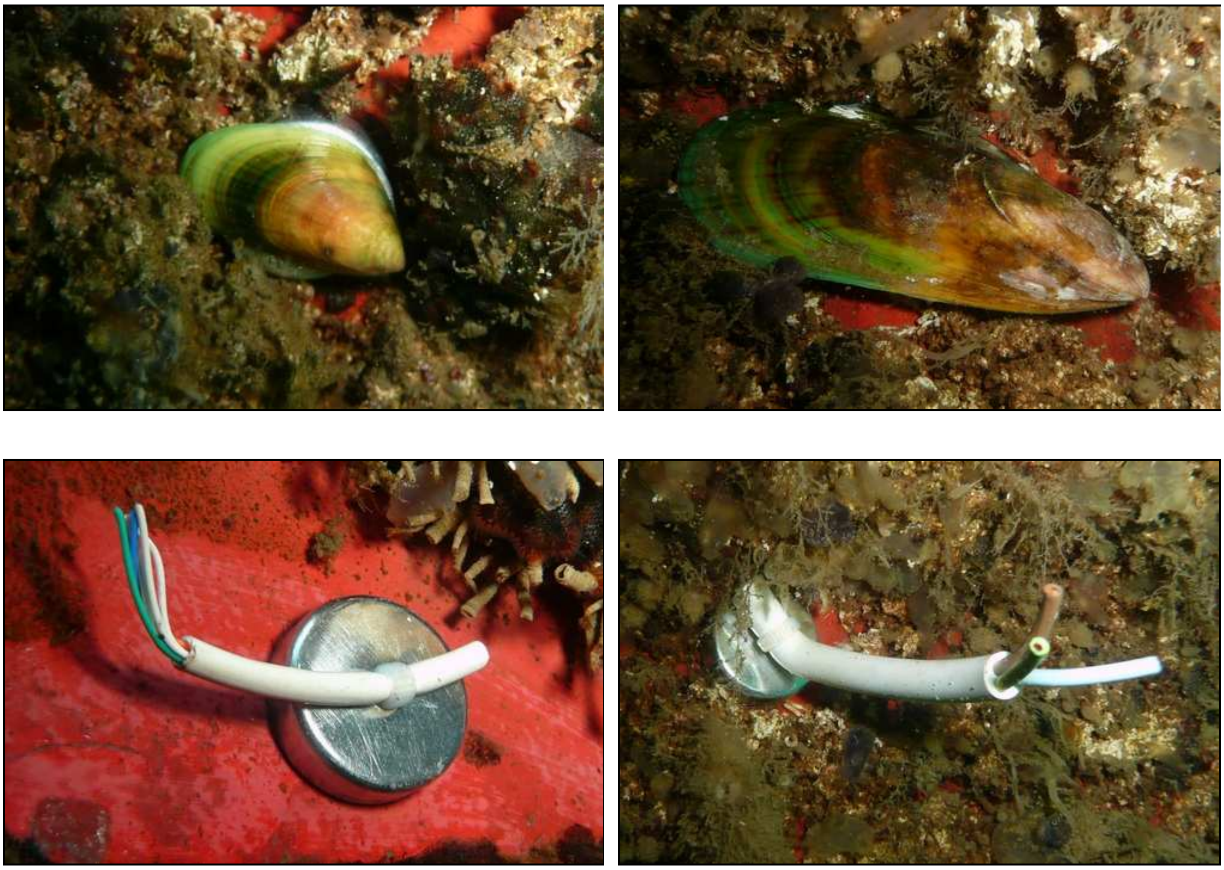

Figure 4: The various type and size of target IMS mimics used to evaluate the ability of the three methods to detect target IMS. Top = Asian Green Mussel look-alikes (left = small 15-20 mm; right = large 60-90 mm); bottom = invasive tubeworm look-alikes, (left = small 20-30 mm; right = large 60-90 mm).

Objective 3: Ability to collect samples

To evaluate the ability of each inspection method to collect biofouling samples for taxonomic identification, divers and ROVs pilots were asked to collect five replicate samples of each of the following three organism types:

i. Firmly attached organisms such as barnacles and bivalves,
ii. Loosely attached organisms such as aborescent bryozoans and hydroids, and
iii. Fragile organisms such as tubeworms, ascidians, sponges and encrusting bryozoans.

The collection of replicate specimens of the various organism groups using each inspection method and performance was evaluated according to the following criteria:

i. Ability to remove the organisms from the surface;
ii. Proportion of attempts that were successful in removing and retaining the organisms;
iii. Proportion of collections resulting in damage to the organisms that may compromise later identification;
iv. Time taken to perform the collection; and
v. Ability to collect multiple samples without returning to surface;

Objective 4: Cost-benefit evaluation of using ROVs relative to commercial divers

To support an evaluation of the costs and benefits of biofouling inspections using ROVs or divers, the following additional information was gathered throughout the project (i.e., during the field trials or via desktop assessment):

i. Time taken for the inspections. This includes mobilization time, time to conduct the inspection and demobilization time.
ii. Cost of the inspection. This includes mobilization costs and rates charged by the commercial dive company and the ROV providers for the inspections carried out during this project. Cost estimates are therefore not generalised across the dive and ROV industries.
iii. Mobility and flexibility of the inspection method (i.e., ability to travel for the purpose of conducting inspections).
iv. Operational Health and Safety and Security requirements, constraints or advantages.
v. Ability to enhance the effectiveness of the inspection methods by upgrading the standard configuration of the ROVs.

5 Results

5.1 Objective 1: Effectiveness of ROVs and divers to inspect all submerged hull and niche areas

Divers and both ROV types were able to gain access to all niche areas and the general hull surface of each vessel during the wharfside and offshore trials. There were no instances where divers or ROVs could not gain any access to a targeted area. No attempt was made to gain access to the internal cavity of the *Comet*'s sea chests as this would have required removal of the grates.

5.1.1 Inspection by divers

During both the wharfside and offshore trials the divers were able to inspect 100 % of the surface area associated with the hull and each of the niches, with the exception of the external cooling pipes on the hulls of the *George Michael K* and *Amanda Verne K* (Table 1). Here, the CCTV footage from the diver (monitored by the topside scientist) showed only ~ 75 % of the surface area. However, the topside scientist was able to direct the divers to run their hands along the unseen area (the gap between the upper side of the pipes and the hull) to feel for biofouling organisms. This resulted in an overall access to ~ 98 % of the pipes' surface area (Table 1).

5.1.2 Inspection by free-flying ROV

During wharfside inspections, the free-flying ROV was able to access 100 % of the surface area associated with the general hull and low-profile niche areas, such as draft markers, keel, rudder and sea chest gratings. It was also able to access 100 % of more complex niche areas that could be inspected from a range of angles, such as the propeller blades (front and back), Kort nozzle (inside and outside), boss, pad eye (port and starboard sides) and rope guard (Table 1). However, the free-flying ROV was unable to inspect the entire surface area of protruding or recessed niche areas, such as anodes, bilge keels and lateral stabilizer fins (on average, 93 % of the surface area of these structures were inspected), transducers and sonar domes (85 %) and the inspection hole (95 %). In all of these cases, the ROV was unable to gain full access because the adjacent hull limited the ROV's ability to fully move around the targeted structure.

The free-flying ROV was still able to inspect all niche areas in the more exposed, offshore conditions. Because of the increased motion of the vessels, it was more challenging and time-consuming for the free-flying ROV to maintain a stationary position, leading to a slight decrease in the proportion of surface area inspected of, for example, the keel bottom (Table

1). The free-flying ROV was able to inspect only approximately 68 % of the surface area of the cooling pipes that ran longitudinally along the hull of the *George Michael K* and *Amanda Verne K*. The inaccessible surface area was the upper portion of the tubes that face the hull surface. On both vessels, this was an area that was heavily colonized with biofouling organisms. Table 1 shows an apparent increase in this ROV's ability to inspect anodes and transducer/sonar domes compared to the wharfside environment. However, this was because these structures were easier to access on the fishing vessels (sampled offshore) than on the *Comet* (sampled wharfside).

5.1.3 Inspection by crawler ROV

The crawler ROV was able to attach to and 'drive along' horizontal or near-horizontal surfaces only. This is because the mechanism for attachment requires continuous upward thrust by the vertical thruster, vertically (or near-vertically) against gravity. During the wharfside trials, it was impossible for this ROV to attach to any submerged areas of the *Comet*, including horizontal undersides of the hull. The heavy biofouling growth on the entire submerged surface of this vessel exceeded the 'clearance' of the ROV's crawler mechanism. To examine the *Comet*, the VideoRay ROV was therefore used exclusively in free-flying mode. The crawler mode worked very well on the horizontal undersides of the *LC-20* and enabled the ROV to 'drive' around the entire submerged surface area and inspect any of the weld seams and anodes associated with the bottom of the barge. To enable inspection of the vertical sides of the hull the ROV had to engage its free-flying mode. This enabled the complete inspection of all anodes and draft markers (Table 1).

In the more exposed conditions of the offshore trials, the crawling ROV's ability to attach to a horizontal area and maintain a steady position was advantageous for the topside inspector monitoring the CCTV. The ROV was able to use crawler mode to navigate around the horizontal portion of the hull (100 % of surface area inspected), the underside of the keel (100 %), any anodes on the horizontal underside of the hull (100 %), the undersides of the cooling pipes (68 %) and the recessed stabilizer ribs (95 %) (Table 1). To inspect the diagonal and vertical sides of the vessels, the ROV had to switch to free-flying mode. Due to the lack of lateral thrusters on this ROV model, the ability to maintain a horizontal position while inspecting the vertical sides was compromised by waves and swell. The same applied to any anodes or draft markers encountered on the non-horizontal surfaces (Table 1).

Table 1: Percentage of hull and niche areas each method was able to inspect on the vessels. Values represent means and standard deviations based on n=2 inspections. The crawling ROV was used only on one vessel (*LC-20*) for wharfside sampling. This barge did not feature many of the niche areas encountered on the other vessels.

	Divers		Free-flying ROV		Crawler ROV	
	Wharf side	**At anchor**	**Wharfside**	**At anchor**	**Wharfside**	**At anchor**
General hull	100 (±0)	100 (±0)	100 (±0)	100 (±0)	100	95 (±7.1)
Anodes	100 (±0)	100 (±0)	92.5 (±10.6)	100 (±0)	100	95 (±7.1)
Bilge keels	100 (±0)	n/a	92.5 (±10.1)	n/a	n/a	n/a
Cooling pipes	n/a	97.5 (±3.5)	n/a	67.5 (±10.6)	n/a	68.3 (±9.4)
Draft markers	100 (±0)	100 (±0)	100 (±0)	100 (±0)	100	100 (±0)
Intakes, outlets	100	100	100	100	n/a	100
Keel (including dry docking support strips)	100	100 (±0)	100	90 (±14.1)	100	100 (±0)
Propeller						
Propeller	100	100 (±0)	100	100 (±0)	n/a	100 (±0)
Kort nozzle	n/a	100 (±0)	n/a	100 (±0)	n/a	100 (±0)
Boss	100	100 (±0)	100	100 (±0)	n/a	100 (±0)
Shaft	100	100 (±0)	90	100 (±0)	n/a	100 (±0)
Pad eye	100	100 (±0)	100	100 (±0)	n/a	100 (±0)
Rope guard	100	100 (±0)	100	100 (±0)	n/a	100 (±0)
Inspection hole	100	n/a	95	n/a	n/a	n/a
Cooling channels	n/a	100 (±0)	n/a	95 (±0)	n/a	95 (±0)
Rudder						
Blade	100	100 (±0)	100	100 (±0)	n/a	100 (±0)
Hinges	100	100 (±0)	100	100 (±0)	n/a	100 (±0)
Ribs	100	100 (±0)	85	100 (±0)	n/a	100 (±0)
Stock	100	100 (±0)	100	100 (±0)	n/a	90 (±0)
Sea chest gratings	100 (±0)	n/a	100	n/a	n/a	n/a
Skeg	100	n/a	90 [a]	n/a	n/a	n/a
Transducer / sounder, sonar	100 (±0)	100 (±0)	84.6 (±10)	100 (±0)	n/a	92.5 (±10.6)

[a] Reason for inspection of < 100 % of surface area was not associated with an inherent limitation of the ROV. The tide receded at the time of the inspection and the ROV was unable to manoeuvre below the skeg because of the proximity of the sea floor

5.2 Objective 2: Effectiveness of ROVs and divers to provide imagery for identification of biofouling organisms

5.2.1 Quality of the CCTV imagery available to topside inspector

During ROV inspections, the CCTV footage available to the topside inspector is the only way in which the inspector is able to determine “on the job” the presence and (as far as possible) identity of biofouling in submerged hull and niche areas of a vessel. During inspections using commercial divers, the 2-way radio link between the surface team and the diver provides an additional means for detecting biofouling. The field of vision of divers is greater than that of the CCTV camera on their helmet and an experienced diver may alert the inspector to the presence of biofouling outside the field of vision of the CCTV camera.

Wharfside

During wharfside inspections, the free-flying ROV received the highest overall CCTV imagery scores (5) across all hull and niche areas inspected (Table 2). In the calm and protected conditions inside the Fishing Boat Harbour, this ROV was able to maintain a stationary position and generate a very clear image of the surface area within the camera’s viewfinder. The ROV was able to access all hull and niche areas either close to or in their entirety, and generated topside CCTV footage that enabled the inspector to clearly distinguish individual biofouling organisms and, at times, particular familiar genera or species (e.g., *Watersipora subtorquata*, *Bugula neritina*).

The crawler ROV’s on-board camera provided slightly poorer resolution than that of the free-flying model. However, due to the crawler system’s low clearance (i.e., distance between ROV and hull), a close distance to the subject was achieved and the ROV was able to access any features or biofouling to which the topside inspector directed the ROV pilot and maintained a completely stationary position. By varying the angle of the lens and the intensity of the on-board light system it was possible to detect biofouling in any hull or niche areas and generally distinguish broad taxa and at times conspicuous species within the assemblage (Table 2).

The divers’ CCTV footage was of similar quality to that of the crawler ROV, and of lower quality than the free-flying model. However, the divers tended to move about more and it was difficult to direct them to maintain a continuously slow and steady position at all times. The increased motion of the camera relative to the ROVs meant that is was slightly more difficult to distinguish detail in the CCTV footage on-the-fly than it was using the ROVs.

Overall, the distribution of biofouling visibility scores varied between the three inspection methods for the wharfside environment (Chi-square test of association, $P<0.001$, Table 2). In this environment, the free-flying ROV received the highest overall scores.

Offshore

The clarity and detail of the CCTV imagery delivered to topside by all three inspection methods were lower during the offshore inspections than during those conducted within the sheltered harbour. The divers were particularly affected by the significant wind-induced wave and swell (~0.5 m oceanic swell) encountered during the sampling of the *George Michael K*. This resulted in a “shaky” CCTV image topside, particularly during the inspection of the upper areas of the hulls (vertical sides, transom, upper draft markers, etc., Table 2). Deeper areas of the hull were less affected by water motion and the divers achieved similar CCTV imagery as in the wharfside environment.

The free-flying ROV consistently provided the clearest CCTV footage but, like the divers, was particularly affected by the influence of waves and swell when inspecting the upper submerged regions of the vessels (shallow hull, anodes and draft markers, Table 2). The ROV was able to inspect deeper hull and niche areas while remaining reasonably stationary, although not quite as stationary as in the protected wharfside environment. The crawler ROV was able to attach to the submerged horizontal part of the hull and delivered a motion-free image of the lower hull areas and anodes, cooling pipes and keel that enabled clear detection of biofouling and occasional identification of particular species (Table 2). When inspecting the non-horizontal upper parts of the hull it had to operate in free-flying mode and was equally affected by waves and swell as the divers and the other free-flying ROV. The deeper hull and niche areas were inspected with comparable image quality to the free-flying ROV.

The overall distribution of biofouling visibility scores also varied between methods in the offshore trials (Chi-square test of association, $P<0.001$, Table 2), with a slightly better image quality achieved by the two ROVs than by the divers.

Table 2: Biofouling visibility scores allocated to the CCTV footage available to the topside scientist during vessel inspections by divers and the two ROV types. These scores were allocated from an ordinal scale of 1–5 (see Methods). The scores shown here represent the overall score agreed on by the topside scientists following the inspection of two vessels in each location using each inspection method. The wharfside crawler ROV scores are based on a single inspection. The *LC-20* lacked many of the niche areas found on the other vessels.

	Divers		Free-flying ROV		Crawler ROV	
	Wharfside	**Anchored**	**Wharfside**	**Anchored**	**Wharfside**	**Anchored**
General hull	3	2	5	4 (deep) 3 (shallow)	4	5 (crawl) 3 (fly)
Anodes	3	2	5	4 (deep) 3 (shallow)	4	5 (crawl) 3 (fly)
Bilge keels	3	3	5	4	n/a	4
Cooling pipes	n/a	3	n/a	4	n/a	5
Draft markers	3	2	5	3	4	3
Intakes, outlets	3	3	5	3	n/a	3
Keel incl. dry docking support strips	3	3	5	4	n/a	5
Propeller region						
Propeller	3	3	5	4	n/a	4
Kort nozzle	3	3	5	4	n/a	4
Boss	3	3	5	4	n/a	4
Shaft	3	3	5	4	n/a	4
Pad eye	3	3	5	4	n/a	4
Rope guard	3	3	5	4	n/a	4
Inspection hole	3	3	5	4	n/a	4
Cooling channels	3	2	5	3	n/a	3
Rudder						
Rudder blade	3	3	5	4	n/a	4
Hinges	3	3	5	4	n/a	4
Ribs	3	3	5	4	n/a	4
Stock	3	3	5	4	n/a	4
Sea chest grates	3	2	5	4	n/a	4
Skeg	3	3	5	4	n/a	4
Transducer / sounder, sonar	3	3	5	4	n/a	4

Distribution of biofouling visibility scores wharfside: $X^2 = 92$, df = 8, $P < 0.001$
Distribution of biofouling visibility scores offshore: $X^2 = 50.9$, df = 8, $P < 0.001$

5.2.2 Ability of divers and ROVs to enable IMS detection based on CCTV imagery

The inspections using commercial divers consistently detected the highest average number of IMS mimics. During wharfside and offshore inspections, an average of 96 ± 5.7 % and 98 ± 2.7 % of the 25 mimics were detected, respectively (Table 3). In contrast, the ROVs detected a considerably smaller proportion of mimics in both the wharfside (free-flying ROV: 37 %; crawler ROV: 39 %) and offshore inspections (free-flying ROV: 68 %; crawler ROV: 60 %) (Table 3). The higher number of mimics detected during the offshore inspections is likely to be a consequence of the smaller size of the vessels inspected offshore (resulting in a higher density of mimics) and the heavy levels of biofouling encountered on the *Comet*. The differences in the proportions of mimics detected by divers and the two ROV types were similar in both inspection environments (Chi-square test, $P > 0.05$; Table 3).

Overall, the inspection using divers misidentified ~4 % of the detected mimics during wharfside inspections and ~8 % during offshore inspections. The misidentification rates of the ROVs were similar in both environments (note the substantial standard deviations) and ranged from ~5 % to 11 % (Table 3). Misidentifications generally involved the size of the mimic (large vs. small) rather than of the type (bivalve vs. tubeworm).

Table 3: Recovery of hidden biofouling mimics by the three sampling methods. Values represent means and standard deviations based on n=2 inspections.

	Diver	Free-flying ROV	Crawler ROV
WHARFSIDE			
% mimics detected	96 (± 5.7)	36.8 (± 11.5)	39.1
% misidentified	4.2 (± 5.8)	5.6 (± 9.6)	11.1
OFFSHORE			
% mimics detected	98.1 (± 2.7)	68 (± 22.6)	60 (± 17.0)
% misidentified	8.0 (± 5.6)	4.8 (± 6.7)	5.6 (± 7.8)
Mimic detection:	$X^2 = 0.98$; df = 1; $P > 0.05$		
Mimic misidentification:	$X^2 = 3.65$; df = 1; $P > 0.05$		

5.2.3 Quality of still images available for post-inspection examination

The still images taken by the divers during both the wharfside and offshore inspections were generally of very high quality, and of a higher clarity and resolution than those captured directly off the ROVs' CCTV footage (Chi-square, $P<0.01$; Figure 5; Figure 6). On average, ~75 % of still images taken by the divers were allocated a biofouling visibility score of 5. In these images, biofouling organisms and mimics could be clearly distinguished to taxon and in some cases to genus or species. In contrast, all of the images taken by the ROVs were allocated a score of 2 (enabling detection of biofouling presence but not to taxon level) or 3 (enabling biofouling detection and differentiation of some broad taxa) (Figures 7 and 8).

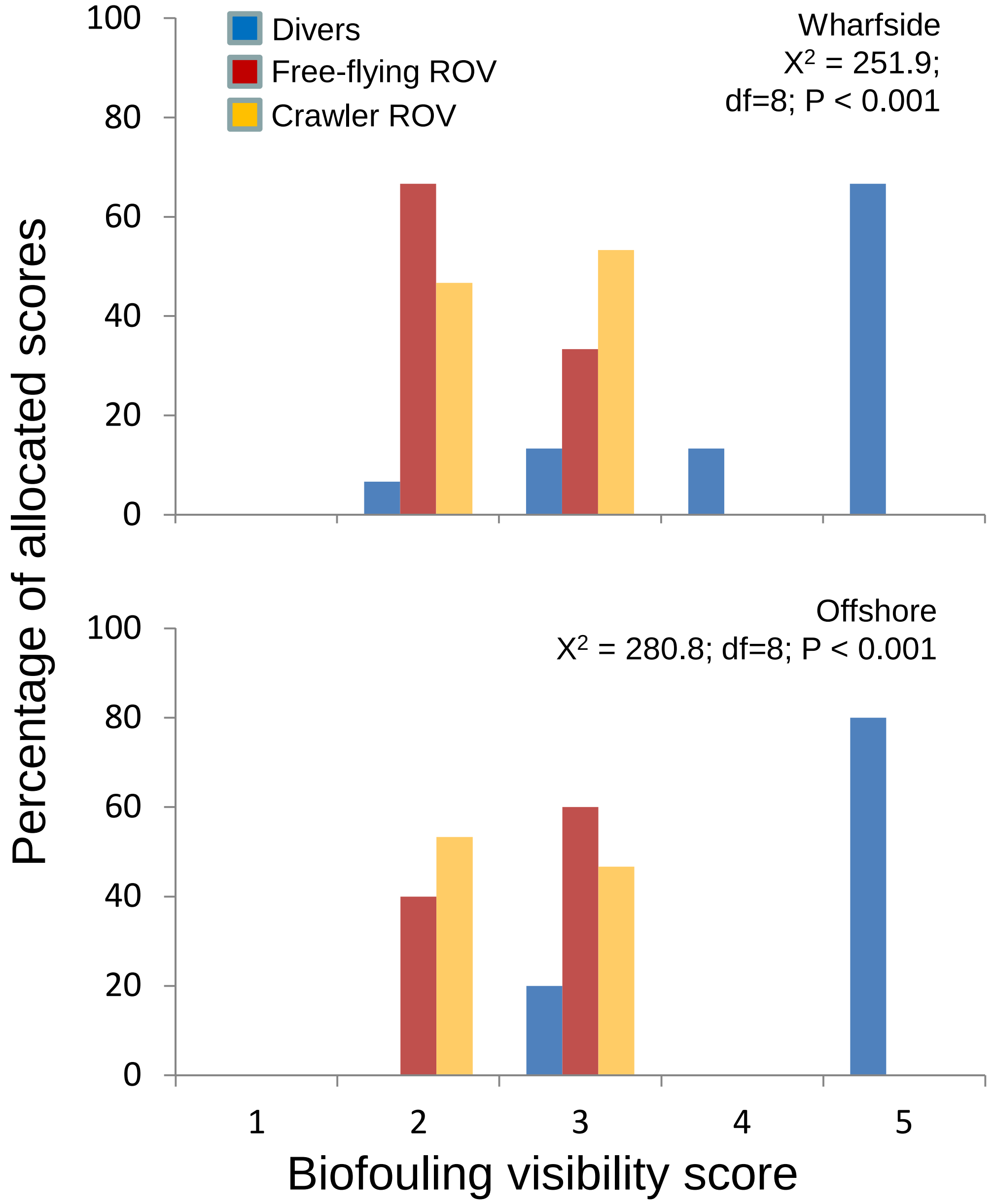

Figure 1: Distribution of biofouling visibility scores (1-5) allocated to n=15 still images taken during vessel inspections by divers or ROVs. Diver images were taken with a handheld 10MP camera, ROVs still images were captured off the CCTV footage.

(a)

(b)

(c)

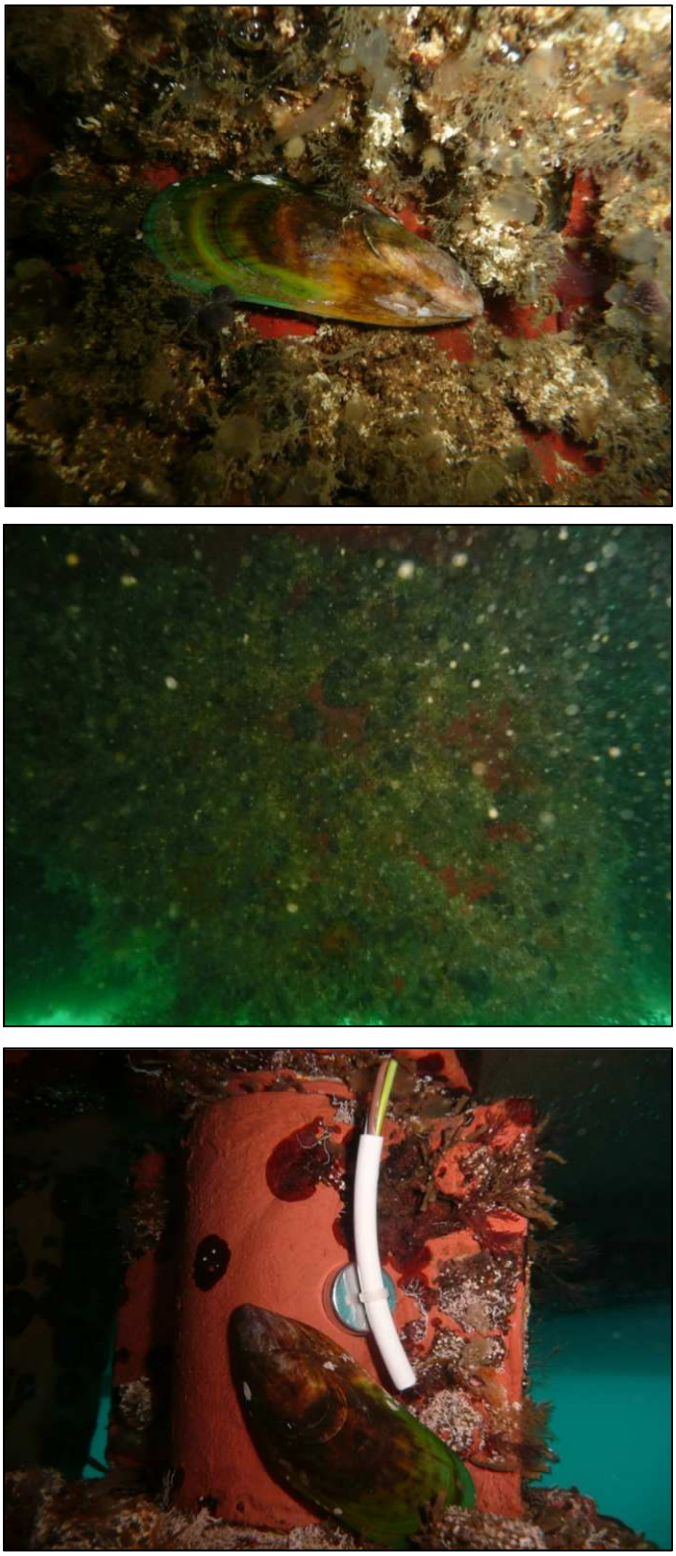

Figure 6: Inspection still images taken by commercial divers using a handheld digital camera. (a) large bivalve within other biofouling; (b) biofouling assemblage on the *Comet* obscured by disturbed sediment; (c) large bivalve and tubeworm on rudder shaft.

(a)

(b)

(c)

Figure 7: Inspection still images taken by the free-flying ROV (captured from CCTV). (a) small bivalve within bryozoans and other biofouling (b) bryozoans and other biofouling on cooling pipes; (c) bivalve within other biofouling.

(a)

(b)

(c)

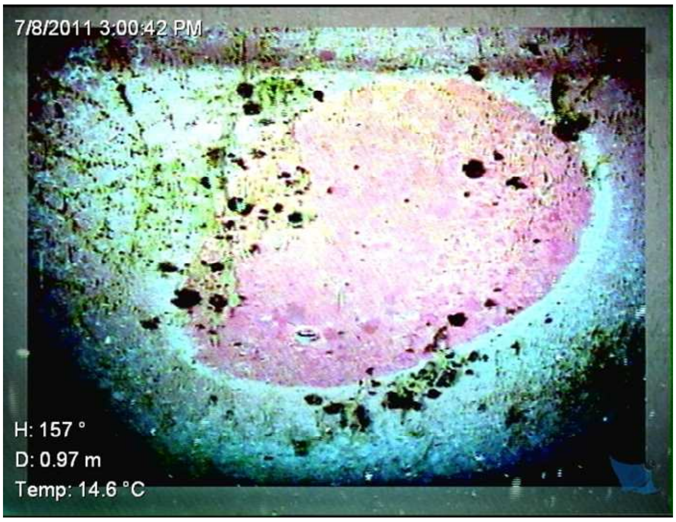

Figure 8: Inspection still images taken by the crawler ROV (captured from CCTV). (a) rudder and propeller on the *George Michael K*, (b) small bivalve, (c) patch of bryozoans and microfouling on the *LC-20*.

5.3 Objective 3: Ability of ROVs and divers to collect samples of biofouling organisms

There were large differences in the ability of the three inspection methods to collect samples for taxonomic identification. The commercial divers were able to remove the requested number of samples of each organism type (firmly attached, loosely attached, fragile) with relative ease using a paint scraper and collection bags. The divers required a single attempt to remove target organisms (pointed out by the topside inspector via CCTV and radio communications) from the hull, transfer them into a plastic specimen bag and store multiple specimen bags inside a catch-bag (Table 4). Collection of a sample generally took approximately 1 minute. In some instances some material was lost during the collection process, such as fragments of calcareous acorn barnacles, tubeworms and encrusting bryozoans damaged during the collection process. All samples were returned to the surface in a condition suitable for taxonomic identification by a specialist.

A total of four samples were collected using the free-flying ROV. The ROV had difficulty collecting individual biofouling organisms, despite the calm conditions within the Fishing Boat Harbour. This ROV was unable to remove firmly attached organisms such as acorn barnacles and calcareous tubeworms. Three samples of loosely attached hydroids were collected. The collection of each sample required 2-3 attempts and took 1 – 5 minutes (Table 4). One sample was lost at the surface and could not be examined. The other two samples were in good condition and suitable for taxonomic analysis. A sample of fragile organisms was collected also but the sample was lost from the ROV's manipulator at the surface.

The crawling ROV's manipulator arm contained no joints and the only moving part of it was a claw at the manipulator's distal end. In crawler mode, the ROV had to be repositioned several times to 'hit' the target organisms with its claw. The crawler ROV was unable to collect firmly attached or fragile biofouling organisms but was successful at collecting a sample of erect bryozoans. However, these were not targeted specifically but obtained by 'grabbing' at a haphazardly chosen aggregation of biofouling. The bryozoans were returned to the surface intact and in good condition appropriate for taxonomic analysis (Table 4).

Table 4: Results of sample collection using divers or ROVs.

Method and organism type	Sample contents	No. samples taken	Attempts made to take each sample	Time taken to collect each sample	Sample condition	Comments
(a) Divers						
Firmly attached	Calcareous tubeworms	5	1	1-2 min.	Good. Material appropriate for taxonomic identification.	Some material lost during transfer to zip-lock bag. Diver able to store several samples without need to surface.
Loosely attached	Hydroids	5	1	1 min. or less	Good. Material appropriate for taxonomic identification.	No material lost
Fragile	Solitary ascidians	5	1	1 min.	Good. Material appropriate for taxonomic identification.	No material lost
(b) Free-flying ROV						
Firmly attached	n/a	0	5 attempts at first sample	2-3 min. per attempt	n/a	Unable to remove target organisms
Loosely attached	Hydroids or empty sample	3	2, 2, 3	1, 2, 5 min.	One sample lost at surface. Others good. Material appropriate for taxonomic identification.	ROV needs to return to surface team following collection of each sample.

Method and organism type	Sample contents	No. samples taken	Attempts made to take each sample	Time taken to collect each sample	Sample condition	Comments
Fragile	Empty	1	1	2 min.	Sample lost at surface.	Some more attempts made but aborted due to time taken.
(c) Crawler ROV Firmly attached	n/a	0	5 attempts at first sample	Attempted for 5 min.	n/a	Unable to remove target organisms
Loosely attached	Erect bryozoan	1	8	5 min.	Good. Material appropriate for taxonomic identification.	ROV needs to return to surface team following collection of each sample.
Fragile	n/a	0	5 attempts at first sample	Attempted for 5 min.	n/a	Unable to remove target organisms

5.4 Objective 4: Supporting information for cost-benefit evaluations of divers and ROVs

5.4.1 Time required for inspection

The dive team took considerably longer than either of the ROVs to set up for inspection (45 minutes prior to each inspection; Table 5). Setup required the diver and stand-by diver getting dressed and ready to dive, starting of the compressor, connection of CCTV and communications equipment and lights, and completion of a team briefing by the dive supervisor. The free-flying ROV was ready for operation within 25 minutes prior to each inspection, and the smaller crawler ROV was set up and operational within 10 minutes. ROV setup involved connection of the umbilical to the ROV and topside control panel, connection of the system to a power source (240V) and brief testing of the ROVs' thrusters and on-board cameras.

Generally, there was not a distinct difference in the time each of the three methods took to inspect the same vessel. The average time taken for wharfside inspections ranged from 117 to 140 minutes, with no obvious differences between the three methods. The offshore inspections took less time to achieve and, depending on method, averaged 65 to 98 minutes. Divers completed the offshore inspections in the shortest average time. The shorter inspection times offshore were a consequence of the offshore vessels being smaller (18.3 m) than the two wharfside vessels (*Comet*, 40 m; *LC-20*, 33 m) and because the *Comet* was heavily colonised with biofouling and required more time for inspection (Table 5).

Table 5: Times taken for vessel inspections using either of the three methods. Data are number of minutes ± standard deviation (n=2 inspections).

	Divers	Free-flying ROV	Crawler ROV
Setup	45 min	25 min	10 min
Wharfside	117 ± 18 min	130 ± 51 min	140 min
Offshore	65 ± 7 min	98 ± 13 min	92 ± 2 min

5.4.2 Costs of inspection

We present the costs associated with inspections by the three methods on the basis of *day rates* charged by the dive and ROV service providers used during this project. This is a reasonable approach for two reasons. First, most of the vessels that are currently subject to biofouling inspections in WA are larger vessels operated by the oil and gas industry. They are thus likely to take considerably longer to inspect than the vessels inspected in this study (personal observation of the authors based on previous inspections). Second, dive and ROV service providers generally charge per full day once field teams are mobilised.

Overall, the costs of the local commercial dive team to conduct a wharfside inspection of 1 day duration were approximately twice the cost of the larger, free-flying ROV hired from a local company and also approximately 45 % higher than the costs associated with flying the smaller crawler ROV (VideoRay) in from interstate (a 1-day job in WA would incur costs for flights, freight, 3 days per diem (1 day on site, 2 days travel) and 2 days operator time (1 day on site, 1 day travel)) (Table 6). Had the smaller ROV been available locally, its daily rate (AU$1000) would have been approximately six times lower than that of the dive team and three times lower than that of the larger, free-flying ROV (Table 6). Because travel costs are not incurred every day, flying the crawler ROV in from interstate would have resulted in a cheaper average daily cost for multi-day hire. For example, while the daily cost of the dive team and locally sourced free-flying ROV would not change for 3 days of wharfside inspections (AU$6650 and AU$3500 per day, respectively), the average daily cost of the crawler ROV (including travel and expenses) would amount to AU$2200, approximately a third of the costs of divers and 63 % of the cost of the larger free-flying ROV.

Commercial dive teams require a support vessel for both wharfside and offshore inspections due to the large amount of diving and support equipment and the team size required for an inspection. In contrast, ROV inspections conducted wharfside will not include the costs for a support vessel because the ROV's topside control systems can be set up on the deck or bridge of the vessel that is being inspected. However, a support vessel may be required to transport ROVs and their operators to offshore inspection sites. If a charter vessel is required to transport an ROV to an offshore location for a 1-day inspection, flying the crawler ROV in from interstate and chartering a support vessel would cost approximately the same as using a local commercial dive team, while the locally sourced, larger Stingray ROV would cost 17 % less than the dive team, including a support vessel (Table 6). However, for inspection contracts lasting multiple days, the smaller ROV that requires a single operator would provide the most economic option. If no support vessel charter is required to transport the ROVs, the relative costs associated with offshore inspections of the three methods are the same as those for wharfside inspections.

Table 6: Costs associated with the three inspection methods. The dive team and free-flying ROV were provided by local Fremantle-based companies. The crawler ROV was flown in from Brisbane (Queensland).

	Divers	Free-flying ROV	Crawler ROV
Mobilisation/demob.	No charge	AU$300 (one-off)	No charge
Day rate (team)	AU$3900	AU$2400	AU$1000 [a]
Day rate (vessel)	AU$2200 [b]	(AU$2200) [c]	(AU$2200) [c]
Day rate (equipment)	AU$550	AU$800	n/a
Travel-related charges	n/a	n/a	AU$3600 (flights, freight, per diem, travel time)
Total cost per day			
Wharfside inspections	**AU$6650**	**AU$3500**	**AU$4600** (incl. interstate travel)
Offshore inspections	**AU$6650**	**AU$3500** (support vessel not required) **AU$5700** (support vessel required)	**AU$4600** (incl. interstate travel; support vessel not required) **AU$6800** (incl. interstate travel; support vessel required)
	Daily cost constant	Daily cost constant	Average daily cost decreases with multi-day hire

[a] Includes charges for ROV and operator.

[b] Additional fuel charges may apply according to distance of inspection from support vessel berth.

[c] Vessel charter may be required for offshore inspections, when ROV equipment, operator and inspector require transport to the inspection site (additional fuel charges may apply according to distance of inspection from support vessel berth). This cost is not incurred where transport can be arranged by other means. ROV equipment and operators can easily be transported by a tender vessel associated with the vessel targeted for inspection. Dive teams and their extensive equipment, on the other hand, require a specialised and dedicated vessel.

6 Discussion

The evaluations of divers and ROVs for vessel biofouling inspections described in this report were conducted on three fishing vessels and a dumb barge. Most present biofouling inspections in WA target vessels employed by the oil and gas industry, rather than fishing vessels. However, the fishing vessels used in this study featured a wide range of niche areas that are also present on vessels associated with the oil and gas industry (e.g., sea chest grates, rudder and propeller assemblages, bilge keels, stabiliser wings, pad eyes, etc.). The performance of divers and ROVs was thus evaluated in relatively realistic conditions, including both sheltered (wharfside) and exposed (offshore) conditions, and we are confident that the observed relative performances of the three methods are suitable to support the initiation of a decision process regarding the use of ROVs for future inspections.

6.1 Feasibility of using ROVs for biofouling inspections (relative to commercial divers)

In the following sections the pros and cons of divers and ROVs are discussed by way of a range of criteria evaluated during the field trials and subsequent industry surveys. These are summarised in Table 7.

6.1.1 Ability to access and inspect hull and niche areas

In our evaluation, ROVs were able to access all submerged hull and niche areas that divers were able to access. ROVs are able to inspect the entire laminar hull area of a vessel, provided the inspector and operator are able to trace the ROVs' progress and ensure that no surface area is missed. ROVs are also able to inspect most niche areas to the same degree (% of surface area inspected) as divers. However, divers are able to inspect a higher proportion of some structurally complex niche areas, such as bilge keels, transducer/sonar domes, external piping and some anodes. This is usually the case when access to one side or aspect of the structure in question is obstructed (e.g., the narrow gap between the inner side of a transducer and the hull; the side of external pipes facing the hull; anodes placed close to angles in hull shape, etc.). Divers are better able to gain access to these structures or use their hands to feel for the presence of biofouling. However, the use of video endoscopes (the availability of which is currently limited in Australia) would improve the ability of ROVs to fully inspect some of these niche areas (Table 7 and see Section 6.1.7).

6.1.2 Capability of imagery

The ability of a topside inspector to detect biofouling from the real-time CCTV footage is at least as high during ROV-based inspections as when divers are used. In the evaluation trials described in this report, ROVs 'detected' mimic IMS when present at low densities on relatively clean vessels (e.g., the barge *LC-20*) as well as on vessels that were covered in a diverse and almost continuous assemblage of biofouling organisms (i.e., the *Comet*). An experienced ROV operator is often able to generate a steadier image than that transmitted from a moving diver. However, the ability of divers to carry high-resolution still cameras is advantageous for situations where post-inspection analysis of still images may be required to resolve the results of the inspection. Such images are considerably clearer than stills frozen off the ROVs' CCTV footage. Nevertheless, given the availability of high-resolution camera technology, there is no reason why divers and ROVs could not feature the same high-resolution imaging capability. Experienced divers have the advantage of independent decision-making and searching, which may lead to a diver alerting the topside inspector to the presence of biofouling that may have been missed by the CCTV camera (Table 7). This was the principal reason why in this study divers detected a larger proportion of the hidden mimic IMS than did the ROVs.

6.1.3 Ability to operate in exposed environments

Both ROV types were able to operate in the protected port environment, as well as in the more exposed offshore anchorage in Cockburn Sound. Like the divers, the ROVs were affected by swell and wave action, resulting in a reduced ability to inspect the vertical sides of vessels, and reduced confidence in the inspection results for these areas. However, ≥ 90 % of biofouling biomass and numbers of species present on vessel hulls are usually associated with niche areas in deeper areas of the hull (Coutts 1999, Coutts & Taylor 2004, Inglis et al. 2010). The free-flying ROV was able to transmit relatively clear and relatively motion-free CCTV footage in offshore conditions once it had descended ~ 1.5 m below the sea surface. The same was the case for the divers. The crawler ROV's footage was clear and absolutely free of shaking as soon as the ROV was able to attach to a near-horizontal surface, irrespective of depth and wave action. Our evaluation suggests that ROVs are suitable to conduct biofouling inspections in calm and moderately exposed conditions, and that crawler capability is an important feature for inspections in high-energy environments (Table 7).

6.1.4 Ability to collect samples of biofouling organisms

Experienced commercial divers are able to collect biofouling samples with ease and, if given appropriate instructions for care, without damaging or losing the specimens. This results in a high ability to verify the identity of suspected high-risk species on a vessel. In contrast, ROVs have great difficulty collecting biofouling samples (Table 7). They are unable to dislodge and collect firmly attached or fragile organisms, and they are unable to collect specific individuals pointed out by the topside inspector. In the process of attempting to collect samples, ROVs were found to generally dislodge a considerable amount of other biofouling (via their manipulator arm or thruster wash), which may present a biosecurity risk in itself. The ROVs evaluated in this study are absolutely unable to collect samples when exposed to water motion from swell or waves.

6.1.5 Costs

ROVs and divers take similar amounts of time to inspect a vessel, particularly in wharfside situations. In our evaluation, divers were on average able to conduct offshore inspections quicker than were ROVs but these averages were associated with considerable variation. For inspections that can be accomplished in a single day, minor differences in inspection times between ROVs and divers are likely cancelled out by the fact that both industries charge for a full day once the teams are mobilised. Inspections requiring multiple days (e.g., those on vessels several hundred meters in length) were not examined in this study. There are OH&S related aspects to diver inspections that may result in increased time requirements. Such situations were not encountered in this project but are discussed in Section 6.1.8 below.

The financial costs associated with diver-based inspections can be considerably higher than those associated with ROVs. This is principally due to the smaller team size required for ROV inspections (1-2 operators, compared to 5-6 person dive teams) and the fact that ROVs can be launched from the vessel that is being inspected. In contrast, dive teams require use of a support vessel carrying compressors, generators and other crucial equipment. The daily costs for ROVs are likely to be considerably lower than those for a dive team where ROV services are hired locally and where no vessel charter is required to transport the ROV to the vessel targeted for inspection. This is likely to be the case for all wharfside inspections and those offshore inspections where in-kind support (e.g., from the vessel operator) is available to transport the ROV to and from the vessel. Where support vessel charter is required, the differences in cost between divers and ROVs decrease.

The financial cost of diver-based inspections may increase further if OH&S requirements require dive companies to undergo safety and planning meetings prior to an inspection. This is discussed in Section 6.1.8 below.

6.1.6 Mobility and flexibility

ROVs have a higher degree of mobility than dive teams. The ROVs and support equipment used in this project were able to fit onto the back of a utility vehicle (Stingray: ROV, umbilical drum and three large transport cases) or into the boot of a small vehicle (VideoRay: two small transport cases for umbilical and topside controls; one medium transport case for the ROV). They are therefore able to be taken on aeroplanes (VideoRay: check-in luggage plus costs for ~15 kg extra baggage) or freighted ahead of the operator (Stingray). The costs of road freight for a medium-sized inspection-class ROV (including equipment) such as the Stingray are reasonable (return cost ex-Perth based on quotes: Karratha, AU$1085; Brisbane, AU$1290) but transit times of 2-7 days apply. Overnight air freight is available to all major destinations but associated with considerable costs (return cost ex-Perth based on quotes: Karratha, AU$9119; Brisbane, AU$8204; Darwin, AU$13115). Given availability, an ROV and its operator/s can be on site anywhere in Australia within 24-48 hours. However, given the costs associated with air freight it is likely that only small ROV models requiring a single operator and minimal freight charges are likely to be a cost-effective option.

Dive teams, in comparison, are less mobile. Unless the site of an inspection is within reasonable driving distance, the costs of mobilising a dive team (including essential equipment) to another region (or state) are likely to be substantially higher than the costs for mobilising ROVs by a similar distance. Due to the risks associated with flying after diving, dive teams may need to charge an extra day's rate and expenses between their final dive and their flight back to base. Overall, when an inspection is carried out by divers it is most cost-effective to utilise a local diver-services provider. The thoroughness of the inspection and validity of its results are dependent on the competence of the divers and their experience with biofouling inspections. It is therefore suggested that only teams trained and/or experienced in the conduct of biofouling inspections are used.

6.1.7 Potential for enhancement or adaptation

Given sufficient funds, it is possible to enhance the effectiveness of both divers and ROVs for biofouling inspections, including those in challenging environments. Tools that are not currently standard use but are available include: (i) High-Density (HD) CCTV capability to increase the resolution and clarity of real-time footage available to the inspector and of freeze-frame images captured off the CCTV, (ii) DIDSON acoustic cameras to detect the presence of biofouling in extremely low-visibility conditions, and (iii) video endoscopes to enable access to particularly inaccessible niche areas such as thruster tunnels and the inside of sea chests. All of these technologies are associated with costs of thousands to tens of thousands of AU$.

6.1.8 Risks, requirements and restrictions associated with OH&S

Diving is a commercial activity associated with a range of risks and hazards. Australian commercial diving regulations are amongst the most stringent globally and require detailed hazard analysis and risk minimisation procedures. Likewise, the OH&S requirements of vessel operators, port companies and production facilities (e.g., Floating Production, Storage and Offloading Facility, oil rigs) are comprehensive and require a high degree of preparedness from the dive team and the vessel targeted for inspection.

Dive teams generally require permission from the relevant authority (e.g., Harbour Master, Port Company) to dive within port and harbour environments and diving can occur only at certain agreed times. Prior to conducting an inspection, time needs to be budgeted for the preparation of OH&S plans and pre-inspection toolbox meetings with the dive team, vessel master (or facility manager), engineer and, potentially, port company representatives. In contrast, ROV operation is not a hazardous occupation and does not require extensive OH&S meetings with vessel and port company staff. ROV operators require a Maritime Security Identification Card (MSIC) to access port facilities and offshore structures in Australia. The MSIC can be readily obtained through port companies or relevant government authorities. The acquisition of a local Port Access Card provides an additional advantage and covers local OH&S requirements (e.g., in Fremantle).

Any diving around a vessel or production facility (e.g., oil rig) requires the shut-down of any engines, thrusters and sonar systems that may interfere with diver safety. On some oil or gas rigs, some operations may be disrupted while divers are in the water. This may present a cost to the production company, but may also restrict the timeframes available for conducting the inspection. ROVs, in comparison, are not subject to the same severe restrictions imposed on divers and are able to be deployed more easily.

Divers are subject to considerable OH&S risks when diving in areas with frequent vessel traffic (e.g., risk of impact injury or damage to umbilical and air supply) and in areas that are exposed to strong currents or wave action. They are also confined to relatively shallow depths. The use of divers in areas inhabited by dangerous marine creatures such as jellyfish, crocodiles or sharks is often limited to avoid encounters/attacks.

Diving accidents can have very serious consequences involving injuries or fatalities. In contrast, accidents involving ROVs are limited to material and financial losses.

Table 7: Performance of, and pros and cons associated with, the use of dive teams and ROVs for vessel biofouling inspections. All estimates of cost and specific abilities of divers and ROVs are presented in relative terms (e.g. high vs. low) and based on specific findings presented in the Results section.

Criteria	Divers	ROVs
Ability to access and inspect hull and niche areas	Access: very high Inspection: very high	Access: very high Inspection: high
Ability of imagery to enable detection and identification of biofouling	Quality of CCTV imagery moderate, quality of still images very high Trained and experienced divers can contribute to target searches	Quality of CCTV imagery high, quality of still images moderate or low Relies exclusively on imagery
Ability to operate in exposed environments	Moderate	Free-flying ROV: moderate Crawler ROV: high
Ability to collect biofouling samples for identification	High	Poor
Cost (time)	Similar to ROV, particularly for 1-day engagements	Similar to divers, particularly for 1-day engagements
Cost (financial)	Relatively high	Can be substantially lower than divers
Mobility and flexibility	Limited due to large team and large amount of equipment. To avoid very high cost best to use local dive service provider	High mobility and flexibility. Small systems require airfare and minor freight charges and are able to travel fast and efficiently. Larger systems incur considerable freight charges
Potential for enhancement or adaptation	HD CCTV capability (very expensive), DIDSON acoustic camera, video endoscopes	HD CCTV capability (very expensive), DIDSON acoustic camera, video endoscopes

Criteria	Divers	ROVs
OH&S requirements and risks; access restrictions	Require permission to dive from Port and Harbour authorities	Permission may be required
	Require safety plans and OH&S briefings with vessel master, engineer, facility managers	Less safety planning required
	Dive times may be restricted depending on adjacent vessel traffic at inspection site	Restrictions less likely
	Require complete shut-down of vessel's systems including sonar	Do not require systems shut-down (except thrusters)
	May require temporary isolation of (parts of) production facilities (e.g. oil rigs); interferes with other operations and activities	Do not require temporary isolation or cessation of facility operations
	High OH&S risks in locations with vessel traffic or exposed to swell and currents	No OH&S risks
	Restricted to shallow depths.	Suitable for greater depths
	Susceptible to crocodile and shark attacks	May be prone to attacks
	Accidents have very severe consequences	Accidents (damage or loss) has only financial consequences

6.2 Conclusions and recommendations for the use of ROVs for biofouling inspections

The results of this study suggest that ROVs are a suitable tool for carrying out biofouling inspections on vessels and other maritime infrastructure. They are able to access and inspect the majority of a vessel's submerged surface area and their imagery is sufficient to enable the detection and characterisation of biofouling assemblages or even of specific target species, including situations where these are hidden within existing biofouling. However, relationships between the number of high-risk organisms present on a vessel and the detection probabilities achieved by ROVs or divers have not yet been examined. Compared to inspections using divers, biofouling inspections by ROVs can be cost-effective and associated with minimal OH&S risks. In exposed conditions affected by swell and currents, ROVs with crawler capability provide particular value and outperform free-flying models and divers with regard to provision of high-quality imagery, provided inspection surfaces are suitable for crawler attachment. This is not the case for a range of niche areas.

However, the smaller, inspection-class ROVs evaluated in this project are unable to collect targeted samples of biofouling organisms. Where the collection of samples is required for taxonomic identification and verification purposes, support from commercial divers who are able to collect high-quality specimens effectively and efficiently is required. We suggest that a useful role for ROVs is their use as a 'screening tool' for initial assessments of vessel hygiene (i.e., the determination of the presence, abundance and composition of biofouling on a hull). There are known positive relationships between the biomass of biofouling assemblages and the numbers of species and non-indigenous species they contain (Inglis et al. 2010). Provided that ROVs with image quality capable of differentiating and quantifying marine taxa (e.g., barnacles, bivalves, solitary ascidians, tubeworms, etc.) are used, a combination of these data and information on the voyage and maintenance history of the inspected vessel should enable a basic assessment of the likely biosecurity risk the vessel poses to WA (or Australia). If required, the initial assessment can be verified via the collection of targeted samples by commercial divers. ROVs are also likely to be of value in situations where the deployment of divers is prohibitively dangerous.

In New Zealand, management of biofouling threats is addressed via a simple approach based on vessel hygiene (microfouling vs. macrofouling; MAF Biosecurity New Zealand (2010)). ROVs would be capable of undertaking inspections to determine whether a vessel is compliant. Australia, in contrast, insists on the absence of particular high-risk IMS from vessels entering the country (CCIMPE 2006). In our evaluation of ROVs, inspectors were frequently able to detect small (~ 20 mm) individuals of two particular IMS mimics within existing biofouling assemblages. While they were less successful at detecting IMS mimics than divers were, ROVs certainly showed potential for being used for target searches. However, despite the ROVs capability of detecting IMS, the identity of suspect organisms detected by an ROV may still require the assistance of divers to collect samples for verification. In contrast to the divers, both ROV operators used in this study had not previously been involved in vessel inspections for IMS. Ability to detect IMS is likely to be enhanced with adequate training and/or experience and familiarity with target searches. The potential of ROVs for target searches should further improve when their configuration is optimised and includes the use of advanced sensory equipment. A suggested optimum configuration is discussed in the next section.

6.3 "The perfect ROV" for vessel biofouling inspections

Based on the field trials conducted during the present study and our conversation with ROV industry representatives throughout the project, an ROV used for inspecting vessel hulls for Australian marine biosecurity purposes should have the following minimum capabilities:

1. High quality CCTV camera to the standard of the Stingray ROV's camera described in Section 4.1, or higher. The camera should enable the inspector to clearly identify taxa and individual organisms within biofouling assemblages. The camera should have both optical and digital zoom capabilities, both auto and manual focus, as well as a high dynamic range.
2. Lateral thrusters - this enables the ROV to pan across a surface and increases its manoeuvrability without having to move the camera off the object of interest. It also enables superior stability control in environments subject to currents.
3. High-quality lights (HID or LED with dimmer function) that move with the camera and allow the object in focus to be properly illuminated at all times.
4. Camera and lights that have a full 180 degree vertical movement allowing the ROV to view both directly above and directly below itself.
5. Ability to operate in free-flying and crawling modes, as required. It would be highly preferable if the ROV could also operate in crawling mode on non-horizontal surfaces.

Additional capabilities that would benefit the effectiveness of biofouling inspections include:

1. LyyN video enhancement for use in turbid environments.
2. Separate, high-resolution still camera that can be accessed via a topside monitor.
3. Large monitor (24" or larger) with glare shield.
4. "Ruggedized" topside control equipment to provide protection from rain and dust.
5. Back-up hard-drive.
6. Minimum of 150 m umbilical. Large vessels may require a 300-m umbilical. Primary and back-up umbilical's should not be the same type but should have different

buoyancy ratings (e.g., 1 x positively buoyant and 1 x neutrally buoyant) to enable choice according to conditions.

7. High portability for transport on plane (e.g., in several hard cases) and when inspections on several vessels in the same geographical location are required. This will minimise setup and dismantling time and enable transfer to next inspection.

6.4 Building additional ROV capability in WA

Australia already has considerable ROV capability. Larger “working-class” ROVs are used for offshore construction and exploration purposes but these models are large (e.g., 5 m x 2 m x 2 m) and expensive, and not suited to vessel inspections. The operators of the ROVs evaluated in this project informally estimate that at least 50 VideoRay ROVs and at least 20 Stingray ROVs are in use around Australia. In addition to that there are likely to be several dozen ROVs of other popular models, such as the Seabotix LBV-150.

The cost of ROVs varies with model and configuration. The smaller inspection-class ROVs used in this project range from approximately AU$45000 (plus freight and import duties) for the Seabotix LBV-150 to AU$65000 for the VideoRay Pro 4 system (Australian distributor) to AU$130000 for the Stingray (plus freight and import duty). These prices buy the complete LBV-150 and the VideoRay systems but do not include the auxiliary computer and monitors required for the Stingray. A wide range of optional add-ons are available for all three models. For example, the Stingray can be fitted with an external manipulator (~AU$10000), MicroNav Sonar (~AU$10000) and a Lyyn Video Enhancer system (~AU$7000, all prices exclude import duty). The VideoRay can be upgraded to crawler capability for AU$4000; upgrading the LBV-150 to crawler mode is substantially more expensive.

Details on a range of popular ROVs available in Australia, and options for additions to the basic configuration, can be obtained at:

1. VideoRay Pro 4: http://www.videoray.com/products/42-p4-cd-300base
2. Teledyne Benthos Stingray: http://www.benthos.com/rov-unmanned-underwater-vehicle-stingray.asp
3. Seabotix LBV-150: http://www.seabotix.com/products/lbv150-4.htm

There is currently no requirement for training or accreditation of operators of smaller “inspection class” ROVs. Imbros Pty Ltd in Tasmania, the Australian distributor for VideoRay provides basic training with every ROV unit sold. The Perth-based Challenger Institute of Technology offers a basic entry-level course in ROV operation aimed at offshore employees (http://www.challenger.wa.edu.au; ~AU$9000). As long as ROV operators have a professional affiliation, sufficient experience with operating their ROVs and have adequate insurance cover, OH&S qualifications, and a Maritime Security Identification Card, they are able to engage in commercial ROV work around Australia. Special conditions may apply for access to particular offshore oil and gas production facilities but details on these were not available at the time of writing of this report.

6.5 Project limitations

The ideal design for the field trials would have included vessels actually used by the oil and gas industries. Most present inspections are targeted at these vessels and by using these vessels the field trials would have achieved maximum representativeness. However, the fishing vessels used instead featured some important niche areas that also occur on oil and gas industry vessels and the relatively consistent performance of the three methods evaluated suggests that similar relative performance would have been observed during trials on other vessels.

It had been our original intention to conduct the wharfside and offshore inspections on the same two vessels. This was not logistically achievable. By using different vessels for the offshore trials, any differences in the ability of the divers and ROVs to perform inspections in sheltered vs. exposed conditions were confounded by differences between the vessels sampled in the two environments. However, our principal interest was to evaluate the relative abilities of divers and ROVs in conducting inspections, not whether inspections should be conducted wharfside or offshore. We suggest that by sampling a wider variety of vessels in two types of environments where inspections are usually conducted, we achieved a sampling design that was appropriate for evaluating the feasibility of using ROVs for biofouling inspections relative to commercial divers.

Given Australia’s requirement that vessels do not carry particular IMS of concern upon their arrival in Australian waters, it is important to know the statistical probability with which vessel inspections will detect a target species if it is on the hull and, conversely, the probability that the species is absent from the vessel when it is not detected. These probabilities are currently unknown and represent a knowledge gap. We recommend that future research be carried out to quantify the detection probabilities of common inspection methods for a range of IMS densities.

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9 Appendix A:

The Commonwealth of Australia has devised a simple, but pragmatic method of assessing the risk and likelihood of vessels/infrastructure containing NIS. The colonisation and accumulation of biofouling on surfaces submerged in sea water follows a very complex process from the initial settlement of microscopic organisms to the establishment of macroscopic biofouling organisms. In its simplest form, the biofouling process that occurs over a period of time (such as the in-service period of a vessel/structure) can be classified into three main categories that can be used to assess a biofouling community at the time of observation (i.e., primary, secondary, and tertiary levels of biofouling; see Figure 9 below). However, it is important to emphasise that these three categories are not entirely definitive as they are constantly evolving and tend to overlap.

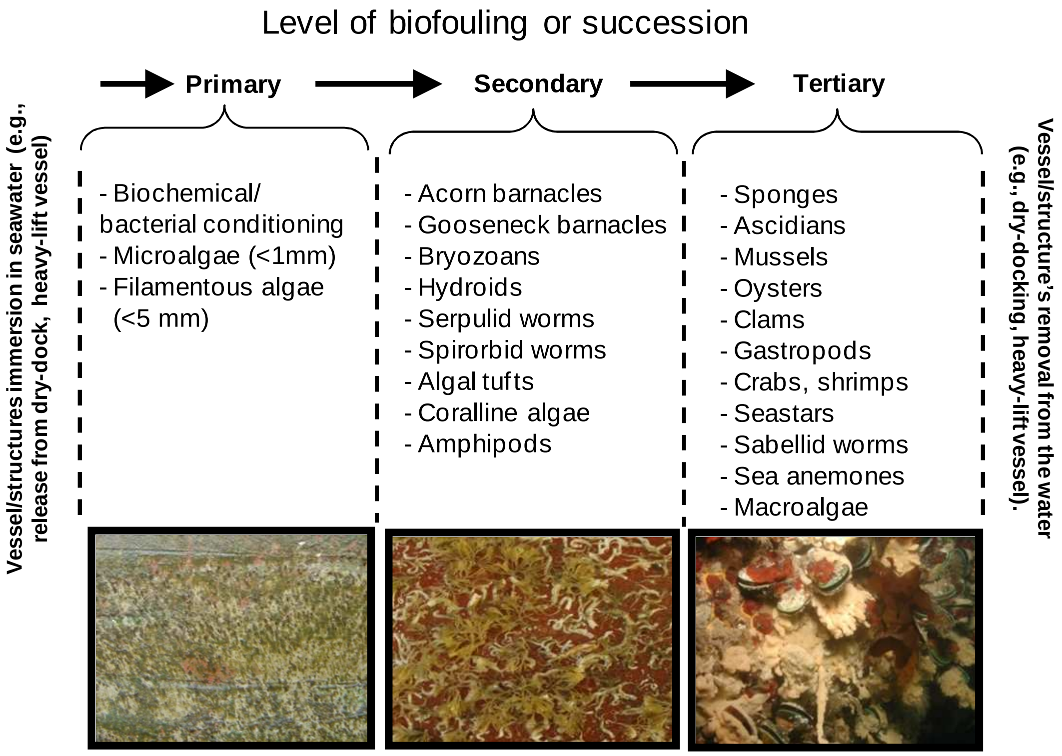

Figure 9 A simple, but pragmatic approach to assessing biofouling risk using three levels of biofouling or succession.

Primary biofouling begins the moment a vessel/structure's hull is submerged in sea water, with immediate biochemical and bacterial conditioning followed by colonisation by bacteria, diatoms, protozoans and multi-cellular organisms. Such conditioning and colonisation of microscopic organisms provides a substratum for more visible organisms, such as filamentous algae, some of which are resistant to the toxic biocides contained in antifouling coatings. The establishment of these organisms tends to provide a suitable, but not necessarily mandatory, substratum for the settlement of secondary biofouling organisms, which tend to be the most dominant and frequently encountered biofouling organisms on vessel/structure hulls. Secondary biofouling communities are likely to progress to tertiary biofouling, particularly in niche areas of vessels/structures that are protected from strong hydrodynamic forces, when vessels remain stationary for long periods of time, or simply over longer in-service periods.