

The Untethered Remotely Operated Vehicle PICASSO-1 and Its Deployment From Chartered Dive Vessels for Deep Sea Surveys Off Okinawa, Japan, and Osprey Reef, Coral Sea, Australia

AUTHORS

Dhugal J. Lindsay

Hiroshi Yoshida

Japan Agency for Marine-Earth
Science and Technology,
Yokosuka, Japan

Takayuki Uemura

Kowa Corporation, Osaka, Japan

Hiroyuki Yamamoto

Shojiro Ishibashi

Japan Agency for Marine-Earth
Science and Technology,
Yokosuka, Japan

Jun Nishikawa

Atmosphere and Ocean Research
Institute, University of Tokyo

James D. Reimer

University of the Ryukyus

Robin J. Beaman

Richard Fitzpatrick

James Cook University

Katsunori Fujikura

Tadashi Maruyama

Japan Agency for Marine-Earth
Science and Technology,
Yokosuka, Japan

Introduction

Exploration of the oceans is generally skewed toward regions close to marine research stations, seaports,

ABSTRACT

The untethered remotely operated vehicle (uROV) PICASSO-1, which is controlled in real time from a surface support vessel via a $\phi 0.9$ mm fiber optic cable, is capable of dives to 1,000-m depth at a duration of up to 6 h and yet is deployable from ships of sizes as low as 17 tonnes. The vehicle was developed at the Japan Agency for Marine-Earth Science and Technology, has carried out 63 dives to date, and is now operable by a team of four biologists and one technician. PICASSO-1 can collect video (HDTV $\times 1$, NTSC $\times 3$) and environmental information (depth, temperature, salinity, dissolved oxygen concentration, fluorescence [chlorophyll *a* proxy], turbidity) concurrently, and this is output with vehicle heading, camera zoom, and other vital statistics via Ethernet. Acoustically obtained vehicle position information, deck and control room video, and sound data streams are also output via Ethernet, and the whole dive is recorded in a synchronous fashion on a logging/playback system that enables dives to be re-enacted in their entirety to facilitate analyses back in the laboratory. Operations have been successfully carried out overseas using a chartered dive boat, and the system represents a leap forward for exploration of the oceans to significant depths but at relatively low cost and with no loss in data quality. **Keywords:** midwater, mesophotic, untethered ROV, logging/analysis system

and overseas territories of developed nations, and this is particularly so for *in situ* surveys using submersibles or remotely operated vehicles (ROVs). To accurately characterize the biological diversity at any given site, data must be collected on a variety of spatio-temporal scales. This includes the full spectrum from day and night surveys to capture both diurnally and nocturnally active or migratory species through to seasonal and even decadal oscillations in populations and species compositions. At depths below a few hundred meters, the num-

ber of sites for which such data exist can probably be counted on one hand, if not on one finger. This is certainly true for the sessile benthic communities living on the sea floor but is even more so for the denizens of the water column.

Midwater research using submersible platforms suffers not only from the conundrum of needing to be in the right water mass at the right time but also having to fit into the cruise schedules of large ocean-going research vessels, whose primary research focus is usually on chemosynthetic benthic

ecosystems or geology (Armstrong et al., 2004). The lead-up time from the submission of research proposals to enactment of research cruises can be anywhere from 8 to 20 months for cruises within Japan, as an example (Lindsay, unpublished data), or 3 years or more for cruises in areas further than about 1 week steaming distance from Japan's Exclusive Economic Zone. The fluid nature of oceanographic currents and patchy nature of the spatio-temporal distribution of their inhabitants makes the planning of such cruises years in advance quite arbitrary in many respects, and this can negatively impact the success rate of submitted proposals. New tools, techniques and strategies for *in situ* research on midwater communities are desperately needed.

Since 2005, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) has been developing a deep sea survey robot designed specifically for relatively rapid-response, worldwide deployment for midwater surveys at low cost, specializing in video image and environmental data acquisition. The untethered remotely operated vehicle (uROV) PICASSO-1

(Plankton Investigatory Collaborative Survey System Operon-1) is the first stage in the development of a multiple-platform autonomous survey system able to quantitatively characterize the midwater environment, including fragile components such as large particulates and gelatinous plankton (Yoshida & Lindsay, 2007; Yoshida et al., 2007a, 2007b; Maruyama et al., 2009). The PICASSO-1 does not have a designated mother ship and has been deployed successfully for sea trials from a variety of small, medium, and large boats and ships (Table 1).

The present paper introduces the system as it was deployed from chartered dive boats under 16 m in length for surveys in deep coral reef areas in Okinawa, Japan, and Osprey Reef, Coral Sea, Australia, as the first step toward a bilateral collaborative deep-water survey program spanning both the northern and southern hemispheres.

Deep coral reef areas were picked as the remote or overseas test sites for the PICASSO-1 system because, as with the midwater, research on the deep-water communities on and around coral reefs and on the geological-topological and/or oceanographic environment

they inhabit is still in its infancy. As a rule, depths between 60 and 300 m remain largely unstudied, particularly near reefs where the limited maneuverability of large ships precludes the use of tethered ROVs. Such areas can also experience strong tidal runs and currents leading to smaller ROVs being unable to maintain position due to the heaviness and large water resistance of their tether compared to the small power output of their thrusters. Maneuverability of the ROV itself is also quite limited and can be adversely affected by movements of the mother ship due to currents and waves being propagated along the tether. A tether serves to restrain the movement of both the vehicle and the mother ship because of the fixed nature of its attachment. Even with a weight used in lieu of a tether management system to place the vehicle near the sea floor, away from the strongest currents, and to act as a damper on the effects of ship movements, it is often impossible to hold station for scientific observations for more than a few minutes at a time. Due to these same restraints, research on midwater communities in reef areas is even more sparse so as to be

TABLE 1

PICASSO cruises and support vessels.

Cruise ID	Dates	Location	Support Vessel Name	Length	Tonnage	Dives
NT07-04	24 Feb–4 March 2007	Sagami and Suruga Bays	Natsushima	67.3 m	1739 t	1-7
YK07-06	24–30 April 2007	Sagami Bay	Yokosuka	105.2 m	4439 t	8-13
RM001	7–18 January 2008	Sagami and Tokyo Bays	Rinkai Maru	18 m	17 t	14-22
N254	10–14 March 2008	off Nomomisaki Peninsula	Nagasaki Maru	64 m	842 t	23-24
KH09-E03	14–18 Oct 2009	Tokyo Bay	Hakuho Maru	100 m	3991 t	25-30
KT09-25	27 Nov–1 Dec 2009	Sagami Bay	Tansei Maru	51 m	610 t	31-34
NT10-02	30 Jan–5 Feb 2010	Sagami and Suruga Bays	Natsushima	67.3 m	1739 t	35-39
SG001	21–28 Sep 2010	off Ishigaki Island, Okinawa	Sea Gull	15.23 m	19 t	40-47
CE001	29 April–16 May 2011	Osprey Reef, Coral Sea	Coral Emperor	15.75 m	85 t	48-63

almost nonexistent. The untethered nature of the uROV PICASSO-1, where the communications fiber is free to spool out from both the vehicle and mother ship fiber spoolers, makes it the ideal vehicle for surveys of such areas because its movement *in situ* is completely decoupled from the movements of the ship. The superiority of this approach for *in situ* observations in deep coral reef dropoff areas is highlighted by comparing two recent papers on the occurrence of the pygmy seahorse *Hippocampus denise* Lourie and Randall, 2003, in such areas (Nishikawa et al, 2011; Foster et al, 2012). Nishikawa et al. (2011) used the uROV PICASSO-1 and were able to measure swimming distances and breathing rates *in situ* of the 21.5-mm-long fish, while Foster et al. (2012) only became aware of the presence of this fish after the sampled host gorgonian coral was being examined in the ship laboratory!

Vehicle Specifications

PICASSO-1 is a small and light (2.7 m long, 230 kg in weight) untethered ROV (uROV) that, during operations, is only connected to its support ship via a thin optical fiber cable ($\varnothing 0.9$ mm single mode nylon-coated fiber, Fujikura Ltd.). Because it has its own power supply in the form of batteries, much like an AUV, it is not constrained by a heavy umbilical tether and precious deck space no longer needs to be taken up by a huge hydraulic winch. However, like an ROV and unlike an AUV, real-time high-definition video data are available to the pilot as the survey is carried out. Three thousand meters of cable are wound around a spooler inside a transparent acrylic case ($\varnothing 157$ mm, 427 mm L, 5.2 kg in air, 0.7 kg in water) with one case located inside the

vehicle and the other on the mother ship locked into a pan-tiltable fiber deployment head. Fiber spools out of either or both the vehicle and shipside spoolers at forces much weaker than the breaking strain of the cable allowing PICASSO-1 to travel unhindered by water resistance to a distance of up to 6,000 m from the support vessel. The power source of PICASSO-1 is a pair of oil-immersed pressure-compensated batteries, each composed of 56 sheet type lithium ion batteries (7 series \times 8 parallel cells) with a total capacity of about 2 kWh and an energy density of over 210 Wh/L. The pilot controls the vehicle in real time and has access to high-quality, real-time video images using high data rate optical communication tools. The color of the FRP fairing cover is mostly red because deep-sea organisms cannot see light or reflections in the red spectrum as a rule (Widder, 2005), yet red is an easy color to see at the sea surface for sighting of the vehicle before retrieval after a dive (Figure 1). The FRP cover incorporates several hatches and holes to allow access to battery cables, switches and the like without needing to remove the entire fairing.

PICASSO-1 has two lateral thrusters (100 W) with a 120° tilter and a vertical thruster for highly maneuverable cruising. The vertical thruster

FIGURE 1

The PICASSO-1 vehicle starting descent using her vertical thruster.



also acts as a backup for ascent and descent if the tilt mechanism for the horizontal thruster gets jammed due to coral rubble or other material getting caught in the caterpillar track that rotates them. PICASSO has one vertical tail fin and two fins for stability, and a maximum cruising speed of 1.6 knots. The vehicle is able to deploy either an HDTV camera or an autonomous visual plankton recorder in its main payload space.

The main camera of PICASSO-1 is a broadcast quality HDTV camera. This high-resolution, high-sensitivity camera allows scientists to identify organisms to species level, in some cases, rather than only to generic or familial level, which is often all that is possible with traditional NTSC cameras. PICASSO uses a wideband optical communication system, developed in-house at JAMSTEC, with five interfaces: one HD-SDI, three NTSC, four RS-232C ports, two RS-485 ports, and eight-channel parallel I/O for the vehicle. The data from/to these ports are serialized/deserialized by a TLK3101 gigabit transceiver. A 2.488 Gbps bit rate optical transceiver module produced by Sumitomo Electric Industries, Ltd., then converts the electrical signal to/from optical signal. The custom-made optical communication device installed in the vehicle is small (three printed circuit boards of 120 \times 80 mm). On deck, communication between PICASSO-1 and the shipside Main Control System can also be established via Ethernet with the vehicle RS232 input/output being converted to Ethernet protocol by an Ethernet converter (EZL-50, Alpha Project Co., Ltd.). Ethernet communications have been incorporated widely into the design of PICASSO to allow synchronous logging and display of all parameters, including video, both

within the vehicle control room and also in remote locations such as the ship bridge and the science room—which can be over 100-m distant on some large research vessels. Crowding of the control room by eager scientists, students and other personnel can therefore be mitigated to some degree and the ship's crew can check on the temporal status of the pre-dive check or check PICASSO's underwater position without having to resort to frequent communications via handheld radio transceivers.

The main camera is a SONY compact high-definition camera system, HDC-X300K, with an original camera control board employing a CAN (controller area network) interface in an aluminum pressure hull. The CAN bus is based on the broadcast communication mechanism. Every message has a message identifier, which is unique within the whole network since it defines content and the priority of the message. The CAN bus also ensures bit and frame synchronization. The maximum data transmission rate of CAN is 1 MHz. A special coaxial underwater cable with pressure-tight SMB type RF connectors was made for connecting between pressure hulls. The HDC-X300K has the following specifications: effective pixels $1,440 \times 1,080$, sensitivity of 2000 lx at F10, minimum luminance of 0.003 lx at F1.4, smear level of -120 dB, and signal to noise ratio of 52 dB. Its image sensor system consists of three $1/2''$ 1.5M-pixel CCDs. It has a measured camera angle in air of 48.72° (H) \times 25.9° (V). The focus, iris, zoom, shutter speed, gain, slow shutter mode, auto white balance and black balance of this camera can be remotely controlled via a handheld control panel (M-AUDIO Xsession Pro). The HD-SDI output signal of the camera is

directly transmitted to the on-board system as an optical modulation signal via the optical communication system.

The NTSC cameras (WAT-240 Vivid (G-2.5), Watec) on PICASSO-1 have the following specifications: effective pixels 768×494 , 450 lines, minimum luminance of 1.6 lx at F2.0, a signal to noise ratio of >50 dB. The measured camera angle in air is 80° (H) \times 59.3° (V) and the image sensor system consists of one $1/4''$ CCD. Two of the NTSC cameras are forward-mounted and positioned for stereoscopic object scale estimation. One more NTSC camera is positioned to face down at a 90° angle from the other cameras to image the seafloor as horizontal transects are made. A final NTSC camera (monochrome high-sensitivity version of the WAT-240) is positioned on the rear tailfin of PICASSO pointing forward, allowing the thrusters and most protruding parts of PICASSO that might catch on gorgonians, ropes, nets or other obstacles to be directly visualized. This forward-pointing camera is also useful for checking that PICASSO's own fiber optic cable is not in danger of being wrapped around the thrusters and because of the wider angle of view is scientifically useful also for placing the stereo NTSC and HDTV video data in a wider context at a larger scale. Three NTSC signals can be sent from the vehicle to the main control unit at one time so a switch is used to switch within the vehicle between sending the downward-pointing or rear-mounted camera video feed to the surface.

Illumination is by HID lamps (three custom 30-W lamps diverted from car use) and/or two handmade 20-W LED array lights. Two of the HID lights are positioned below and forward of the HDTV camera on a

stainless steel bracket and angled such that the beams of light illuminate targets approximately 50 cm from the HDTV camera lens at an angle of about 45° . This ensures that out-of-focus marine snow particles occurring closer to the camera lens are not illuminated. The single forward-pointing HID light is used when searching for targets and video quality is not paramount. High-power white LEDs (NCCW023S, Nichia Corporation) have been combined with a copper base plate, resistors, an underwater connector, and a $1/2''$ clear tube filled with oil to balance internal-external pressure (Yoshida et al., 2007a, 2007b). One of these LED arrays incorporates red LEDs to allow PICASSO-1 to operate in "stealth" mode due to the fact that most deep sea animals are thought to not behaviorally respond to red light (Widder, 2005; Raymond & Widder, 2007). The other white LED array is used to illuminate the sea floor for the downward-pointing NTSC camera. The LED arrays also serve as backup should problems occur with the ballast to the HID lights. Usually only a single side-mounted HID light and the downward-pointing LED array are used during surveys to preserve battery power—the amount of illumination being more than adequate for the sensitivity of the cameras.

Environmental sensor packages include a CTD-DO (XR-420CTDm, RBR Ltd.) and a backup CTD (XR-420CTDm, RBR Ltd.) for measuring temperature and dissolved oxygen concentration and for computing depth, salinity and water density for real-time input into the logging system, as well as a fluorometer-turbidity sensor (ECO FLNTU Puck, WET Labs, Inc.) to obtain data on chlorophyll *a* and marine snow concentrations.

Other vehicle specifications for the PICASSO-1 are shown in Table 2.

Because PICASSO-1 is neutrally buoyant at survey depth it has several layers of safety built in to ensure its return to the surface. In addition to the main computer onboard PICASSO, a secondary CPU has also been incorporated into the main instrumentation pressure housing to allow monitoring of vehicle status from the main control notebook computer and jettisoning of the ascent ballast (45 × 100 × 200 mm, density 7860 kg/m³, 8 kg SS400 carbon steel block). If optical communications have been continuously interrupted (<-20 dB) for 40 s, both of these systems send a ballast jettison command. Ascent ballast is also

jettisoned automatically by a timer relay if dive length reaches 8 h duration and/or by a low-voltage protection circuit if main battery voltage falls below 21.0 V, thereby triggering a full system shutdown. The working limit of PICASSO's batteries is 21.0–29.4 V and is the lower limit of overdischarge of 3.0 V/cell, with voltage below approximately 2.8 V/cell leading to delamination on the sheet electrode and the ensuing destruction of the battery. A circuit has been installed to nullify residual magnetism in the electromagnet that holds the ascent ballast and a spring protruding from the central surface of the electromagnet exerts a force of 0.6 kg to aid jettison.

Shipside System Power Supply System

Electrical power to the shipside system is supplied via an isolation transformer (1.5KVA, MD-3000, UNION Electronics Co. Ltd.) to an uninterruptible power supply (UPS1010HP [YEUP-101PA], Yutaka Electric Mfg. Co., Ltd.). The UPS will take single-phase electric power between AC80 V and AC130 V to output at AC100 V and therefore in combination with the transformer, power supply to the shipside system of PICASSO-1 can be anywhere from AC80 V to AC260 V with a frequency of 50 or 60 Hz. Output is to a maximum of 700 W (7A) and the PICASSO shipside system draws a maximum of approximately 500 W (5A). The UPS can supply power for up to 7 min at 700 W in the case of a power outage.

TABLE 2

Specifications of PICASSO-1.

Item	Specification	Remarks
Dimensions	2.7 m (L) × 0.94 m (W) × 0.68 m (H)	without VPR
Weight	230 kg	in air
Depth rating	1,000 m	
Cruising speed	1.6 kt	
Endurance	6 h	
Operation mode	uROV	
Propulsion	2 horizontal 100-W thrusters with tilt system, 1 vertical 100-W thruster	descent and ascent ballast (8 kg each)
Communications instrumentation	2 G bps optical communication device, LAN, ARGOS transmitter, flasher	
Navigation instrumentation	MEMS gyro (AHRS400MB-100, Crossbow), Doppler velocity log (Explorer, Teledyne RD Instruments), backup CTD, ^a compass (TruePoint HMR3500, Honeywell), transponder (VLT-1, Desert Star Systems)	DVL measures altitude and velocity vs. bottom ^b
Experiment payload	CTD-DO ^c , fluorometer-turbidity sensor, 4 × NTSC cameras, 3 × 35-W HID lamps, Visual Plankton Recorder*, high definition TV camera*	*pick only one device

^aPressure sensor (circa 2005, Kowa Corporation) used during Okinawa and Australia missions and updated to CTD subsequently.

^bVelocity data not correct during Okinawan and Australian missions due to old firmware.

^cCTD with no DO deployed during Australian mission and used as backup CTD thereafter.

Main Control System

The main control unit for PICASSO-1 is incorporated into a watertight protective case (84.7 × 72.2 × 46.3 cm, model 1690NF, Pelican Products, Inc.) (Figure 2), for ease of portability and setup, and draws approximately 2.4 A (240 W).

The system was designed to be redundant with respect to both control and recording of data (Figure 3). A topside control unit (TCU) communicates with PICASSO-1 via RS232C protocol and a custom controller box allows the following functions of PICASSO-1 to be controlled even if the main control notebook computer running Windows XP (CF-S9JWECPS, Panasonic Corporation) is offline due to hardware or software issues: thruster power [on/off], thruster tilt, forward-reverse-left-right on tiltable thrusters, up-down on vertical thruster, HID light and LED light on/off (each

FIGURE 2

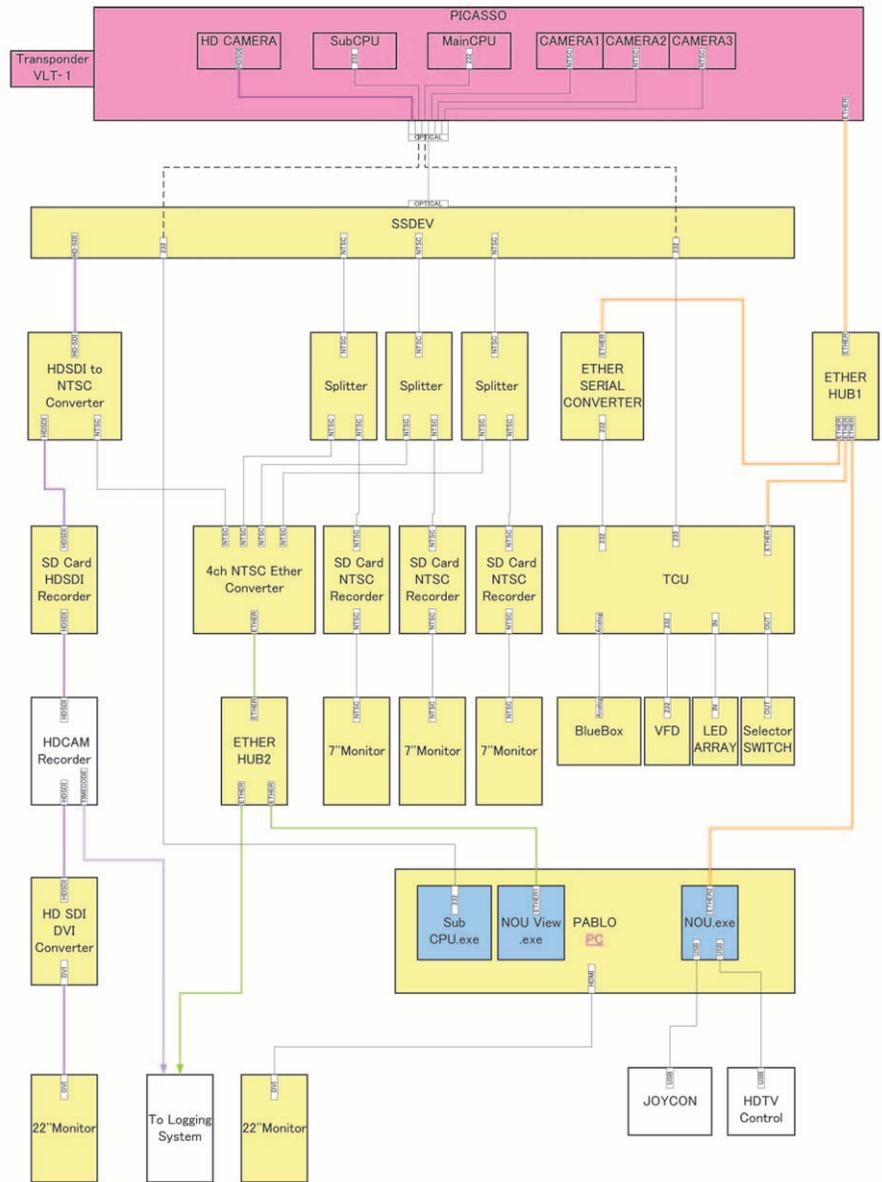
PICASSO-1 being piloted by JN in the galley of the *Coral Emperor* at Osprey Reef, Australia. The main control unit is in the foreground and the navigation unit in the background (top). The main control unit during operations (bottom). The graphic user interface of PICASSO-1 displaying vehicle status parameters, support vessel heading, and environmental data is on the left, high-definition video on the right, NTSC video monitors above, and the main control notebook computer below, displaying the deck-deployed Ethernet camera feed and other real-time technical statistics for PICASSO-1 that are not displayed on the GUI.



separately controllable), rear/forward-looking and downward-looking camera feed switch, communication mode (optical or Ethernet), vehicle mode (boot/initial or dive/cruise mode), descent ballast jettison/remagnetization, ascent ballast jettison/remagnetization. A vacuum fluorescent display panel on the TCU displays the following: link [optical/Ethernet], uplink strength, downlink strength, vehicle depth, battery voltage, compass heading, thruster power status [on/off], and an LED array displays the following: receipt of communications (ether or optical) packets

FIGURE 3

Schematic diagram of the main control system.



from PICASSO-1, vehicle mode (initial or dive), receipt of optical communications packets, ascent ballast drop command sent/not sent, descent ballast drop command sent/not sent, main instrumentation pressure housing leak status, power pressure housing leak status. The TCU communicates with the main control notebook computer via Ethernet and the PICASSO-1

is usually controlled and monitored within the control software (NOU, Navigation Observation Unit) and graphical user interface (NOU_view).

In addition to the equipment outlined above, the main control unit also contains a display (FlexScan S2243W-HX LCD display, Eizo Nanao Corporation) for multimonitor output from the control notebook computer on

which a graphic user interface of PICASSO-1 vehicle status parameters support vessel heading, and environmental data is displayed (Figure 2). A joystick (CH Fighter Stick) for driving and a handheld control panel for camera control (M-AUDIO Xsession Pro) are connected via USB to the control notebook computer. All camera parameters including shutter speed, gain, white balance and black balance can be controlled.

The HD-SDI signal from the SONY compact high-definition camera system (HDC-X300K) aboard PICASSO-1 is demodulated and output from the on-board system (SSDEV-0614), passes through a digital to analog video converter (SDI to Analog mini converter, BlackMagic Design) where it is converted to NTSC format and then converted to an H.264 stream by a four-channel video encoder (AXIS Q7404, AXIS Communications) to be output via Ethernet to the logging system (see below and Figure 5). It is also throughput natively to a solid-state memory recording device (Panasonic AG-HPG20) to be recorded on PS2 cards, channeled natively to an HDCAM recorder (Sony HDW-250), with time code set to local time manually, and then throughput to an SD-HDI to DVI converter (HDLink, BlackMagic Design) and then to the HDTV display (FlexScan S2243W-HX LCD display, Eizo Nanao Corporation) in the Main Control Unit. This parallel configuration ensures that even if a tape runs out or a memory card becomes full, no video data are lost as they are also logged via Ethernet, and if an Ethernet problem occurs data are still recorded by the other devices. The time code output from the HDW-250 deck is output to the logging system by coaxial cable, where it is converted to

USB by a USB-LTC/RDR LTC Reader (Adrienne Electronics) (Figures 3 and 5).

The NTSC signals from PICASSO-1 are channeled through three video splitters (VSP-2M, YKmusen) with the throughput signal being recorded by three MPEG-4 recorder/players (VP6060 [DMV-MP4], VOSONIC Technology Corporation) on SDI cards and then output to three NTSC monitors (702TSV) in the Main Control Unit, while also being output into the four-channel video encoder (AXIS Q7404, AXIS Communications) to be output via Ethernet to the logging system (see below and Figure 5). Again, this ensures that image data are always recorded, even if one or the other of the recording devices malfunctions during a dive.

Navigation System

The navigation system (Figure 4) consists of a navigation unit incorporated into a watertight protective case (63 × 49.2 × 35.2 cm, model 1620NF, Pelican Products, Inc.) and peripherals and draws approximately 1.1 A (110 W). Support vessel position within the GPS is monitored via a DGPS Loop Antenna (GPA019, Furuno Marine Electronics) input into a WAAS/DGPS receiver (GP37, Furuno Marine Electronics) and output via RS232 protocol into the navigation computer—a notebook computer running Windows XP (CF-S9JWECPS, Panasonic Corporation). The same model of notebook computer is also used for the control system and all software necessary for either use is installed on both computers to allow rapid replacement of either computer in the case of a malfunction during a dive. Ship heading is monitored via compass (C100, KVH Industries, Inc.) output via RS232 protocol to the navigation

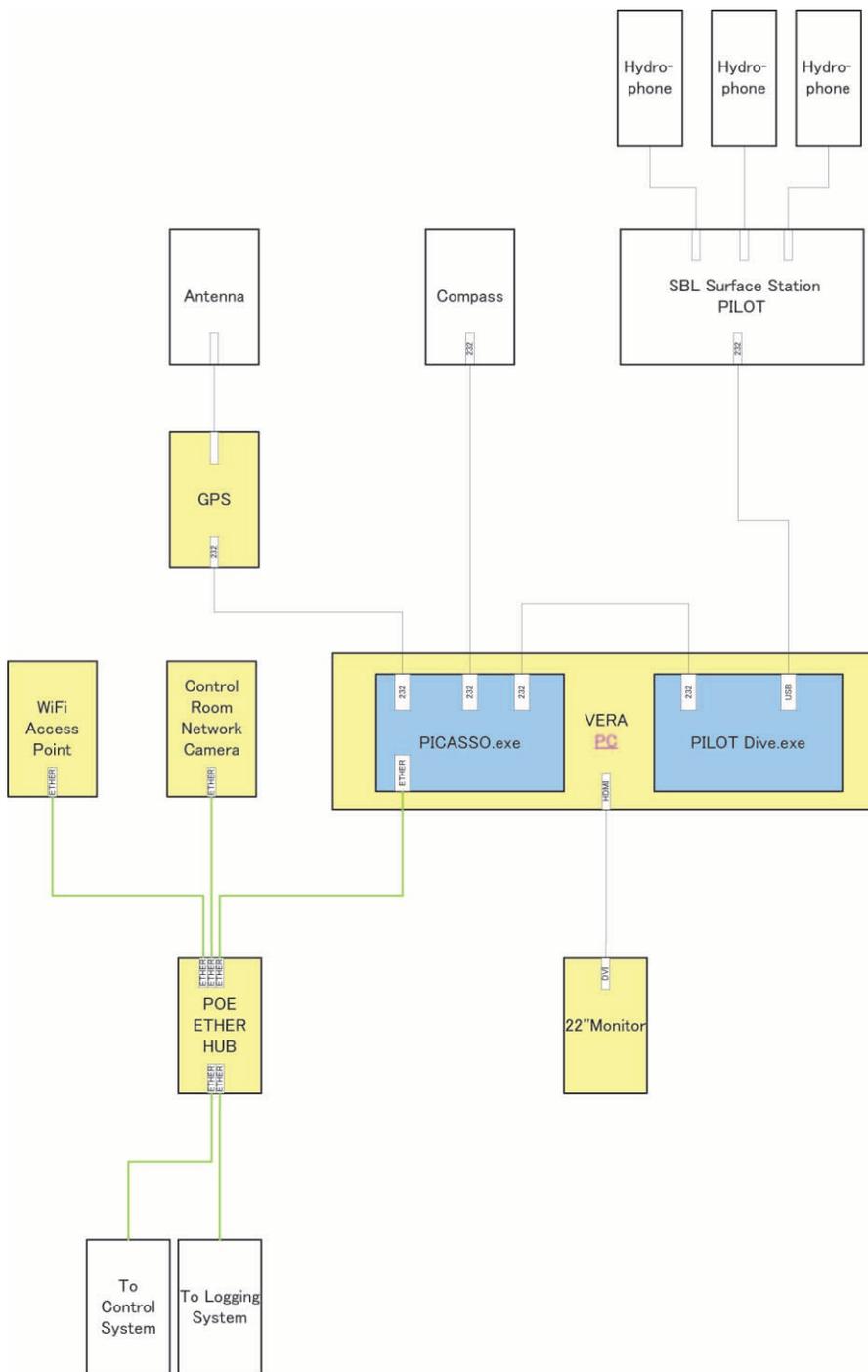
computer. The XYZ position of the PICASSO-1 vehicle beneath the support vessel is monitored at 34-41 kHz using a short baseline acoustic tracking system (PILOT STM-3 VLT-1, Desert Star Systems) and output via USB to the navigation computer. The navigation computer runs Divebase PILOT software, which then outputs XYZ position data to an in-house software package via RS232 protocol. This software uses ship GPS and vehicle XYZ location data to calculate the GPS position of PICASSO-1 for real-time logging and display in a window on the navigation monitor and to be sent via Ethernet to the logging system (see below and Figure 5). GPS and uROV position data can also be acquired from the hull-mounted acoustic positioning system used by JAMSTEC vessels, logged and displayed.

Logging System

Network cameras monitor operations on the back deck (M1011-W, AXIS Communications) and in the control room (M1054, AXIS Communications) and provide a real-time H.264 video stream to the logging computer (MacBook Pro6,1: Intel Core i5, 2.53 GHz, running Windows 7 Professional under BootCamp) via an Ethernet hub (Switch-S8PWR [PN21089K], Panasonic Electric Works Networks Co. Ltd.). The M1054 network camera can be positioned to record the navigation control unit when PICASSO-1 is being monitored acoustically. Sound in the control room is recorded using the MacBook Pro built-in microphone. The video files from the six cameras, GUI screen showing PICASSO-1's status, environmental parameter vertical profile screen and sound file can be played back in a synchronous fashion to

FIGURE 4

Schematic diagram of the navigation system.



reconstruct the dive for trouble-shooting and scientific analysis through reference to the time data recorded from the control notebook computer internal clock and HDCAM time code data. All vehicle status, environmental

parameter and position data can also be output to a csv file which includes fields in Darwin Core format for direct import into the Ocean Biogeographic Information System. Darwin Core format is a standard agreed on by bio-

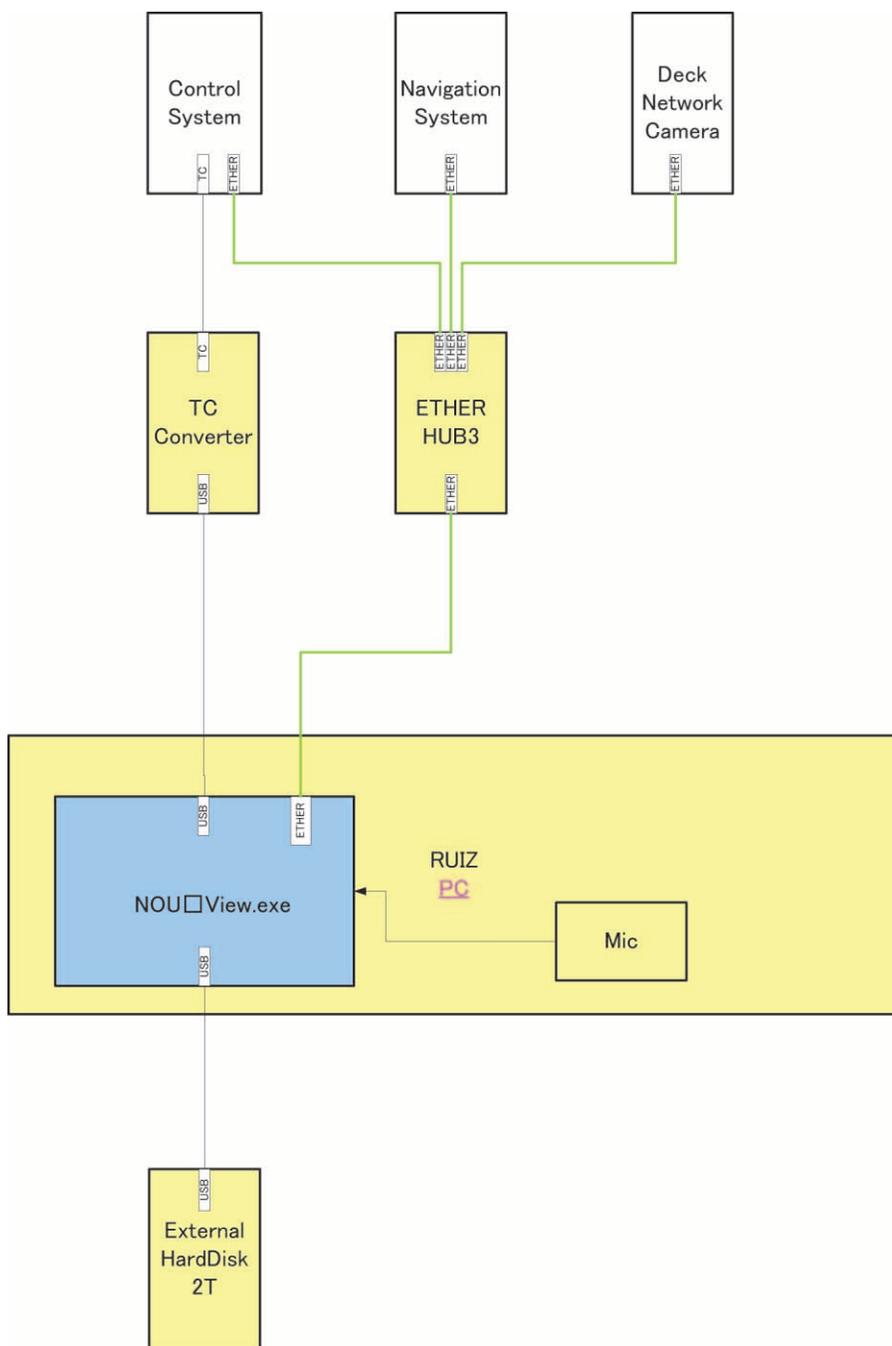
geographical information databases and defines the format in which data must be supplied to such databases. For example, when the time at which an observation is made is to be output to the csv file, it must be a numeric value in the field “Time of Day” and be expressed as decimal hours from midnight (e.g., 12.0 = mid-day, 13.5 = 1:30 pm). For longitude information, the value should be numeric, in the field “Longitude”, and expressed in decimal degrees (East & North = +; West & South = -), with GPS-derived data being referenced to the WGS/84 datum. The full Darwin Core Schema can be found at <http://www.scarmarbin.be/obisschema.php> and/or <http://www.iobis.org/data/schema-and-metadata>.

Size Analysis System

For measuring the distance to an object and estimating its size using stereovision, triangulation is generally used. In the present method, a disparity map is prepared. The disparity map is a depth map where the depth information is derived from offset images of the same scene. To measure disparity in the camera system, a given pixel location in either the right or left image coordinate frame is computed with a stereo matching technique. The disparity map is constructed by imaging a calibration board with the two forward-mounted NTSC cameras prior to a dive. The calibration board is a white acrylic board covered in at least 400 black circles, the center circle being 30 mm diameter and all others 24 mm in diameter with the center of each circle being 30 mm from the center of its nearest neighbors. Images are recorded at a distance of 1 m from the cameras with the board held perpendicular to the vehicle axis, and also sloped left, right, forwards and

FIGURE 5

Schematic diagram of the logging system.



backwards. A further calibration image pair is captured at a distance of 2 m from the cameras. Post-dive the NTSC video is played back using the MPEG-4 recorder/players and frame pairs are captured using a Picolo Alert PCIe video capture card (Euresys

S.A., Belgium) in a Vostro 200 desktop tower computer (Dell, USA) running Windows XP. Objects (distances and volumes) to be measured are manually selected using specially developed software (AVSCalcXYZ_PICOLO, Applied Vision Systems Corporation,

Japan). Accuracy was measured to be $2.7 \pm 2.1\%$ when measuring a 10-mm-long object at a distance of 1 m from the camera lenses. Size measurement data are exportable as a csv file.

Operations

Okinawa, Japan

PICASSO-1 and all associated equipment was sent in a 12-foot shipping container to Ishigaki Island, Okinawa, Japan. The diving boat *Seagull* (Figure 6) was not equipped

FIGURE 6

The chartered diving vessel *Seagull* with PICASSO-1 on the raised platform (top), lowering PICASSO-1 into the water using hand winches and a pivoting-sliding platform attached to the hydraulically operated dive elevator (middle), PICASSO-1 deployed from the chartered dive vessel *Coral Emperor* off Osprey Reef, Australia (bottom).



with a crane, so PICASSO-1 was lowered into the harbor using a rented crane and dragged using ropes to the hydraulically powered lifting platform at the stern of the boat (Figure 6). The platform was unable to be lowered deep enough for PICASSO-1 to be pulled directly on to it so a specially manufactured sliding deployment-retrieval rack was attached to the back deck and lifting platform such that with the use of hand-powered winches it was possible to use the lifting power of the hydraulic platform to raise the vehicle to the level of the back deck where she could be dragged under cover into the working and maintenance space by hand. Deployment needed a minimum of six people: one on each of the two hand winches, two holding guide ropes, one to pull the snap shackles to release PICASSO-1 into the water at the beginning of the dive, and one to handle the fiber optic cable so it was not kinked or damaged during the deployment—thereby ending the dive as optical communications would be lost.

A total of eight dives were conducted between 21 and 28 September 2010 (Table 1). Technical problems with the SBL system (a loose connection within the STM-3 and the VLT-1 transponder battery not holding a charge) prohibited dive surveys in regular survey mode, so dives were conducted by thrusting down straight to the sea floor where it was possible to verify in the video feed that PICASSO-1 was not being swept away from the vicinity of the support vessel by the current.

Eight dives were made with the deepest being only to 111-m depth due to concerns about the whereabouts of the vehicle underwater. If optical communications are suddenly

lost for 40 s the vehicle automatically jettisons the 8 kg steel ballast block and floats to the surface. If waves are large it can be difficult to see the small vehicle from the roof of the support vessel for retrieval so it is very important to know the position of the vehicle as accurately as possible—not just for science but to avoid losing the vehicle to strong surface currents.

Osprey Reef, Australia

PICASSO-1 and all associated equipment was sent in a 20-foot shipping container to James Cook University, Cairns, Australia, unpacked and ferried to the Cairns Marina in a 2-tonne rent-a-truck with a hydraulically-powered lifting platform. The support vessel *Coral Emperor* was equipped with a small crane (560 kg load at maximum horizontal extension 4.36 m), which was used to load PICASSO-1 onto the upper deck where a semidry space had been made using tarpaulins and plywood boards. A total of 16 dives, in-

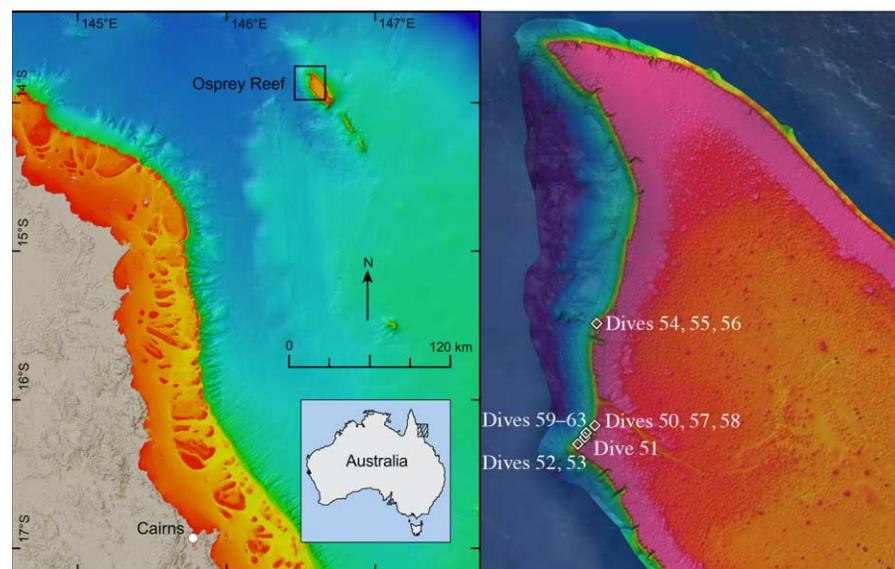
cluding two training dives at Lizard Island, were conducted between 29 April and 16 May 2011 (Table 1, Figure 7).

The SBL system performed quite poorly with the maximum reading taken during operations at only 293 m depth (55 m to port, 135 m from stern, 327 m total distance), far less than the 1,000 m advertised by the manufacturer and closer to the 330 m range advertised for the miniature TLT-3 transponder. The extremely steep slope of the reef wall at Osprey Reef allowed us to zigzag down the wall directly below the mother ship using underwater navigation techniques honed through SCUBA diving.

Midwater dives were done by first anchoring a staple polyethylene (silver) rope to a mooring on the reef face at Raging Horn and running a zodiac inflatable boat due west until the 500-m-long rope was taught. A weighted bait trap (ca. 20 kg) was then tied to the end of the rope before the trap was thrown over the side and left to swing down

FIGURE 7

Hillshade image of northwest Osprey Reef (right) developed using lidar and singlebeam bathymetry data over depth ranges +3 to -815 m. PICASSO-1 dive sites 50-63 indicated on western side of Osprey Reef—the location of which is indicated in the left panel.



until it landed on a sloping shelf on the reef wall at 365 m depth. PICASSO-1 was equipped only with ascent and not descent ballast for all dives at Osprey Reef and was calculated to have no more than 100 g positive buoyancy at 400 m depth. A SCUBA diver guided PICASSO-1 by swimming toward the mooring at a distance of 5-10 m in front of the main camera while the uROV followed him under its own power. After the rope was identified on the main camera, PICASSO-1 was then piloted under the rope and turned around to face due west until the rope was again in frame. It was then possible for PICASSO-1 to follow the rope through the midwater at altitudes of between tens and hundreds of meters above the bottom to the final target depth of 365 m. Observations of midwater animals such as the ctenophores *Thalassocalyce inconstans* Madin & Harbison, 1978 (255 m depth, 17.2°C, 35.36PSU) and *Kiyohimea usagi* Matsumoto & Robison, 1992 (353 m depth, 14.1°C, 35.47PSU) were fleeting since the rope always had to be kept in frame to ensure our safe return to the surface within sight of the mother ship by once again following the rope to the mooring at 40 m depth. The bait trap, complete with cookie cutter shark gouge marks on the bait, was retrieved by using the zodiac's forward motion to lift it back to the surface.

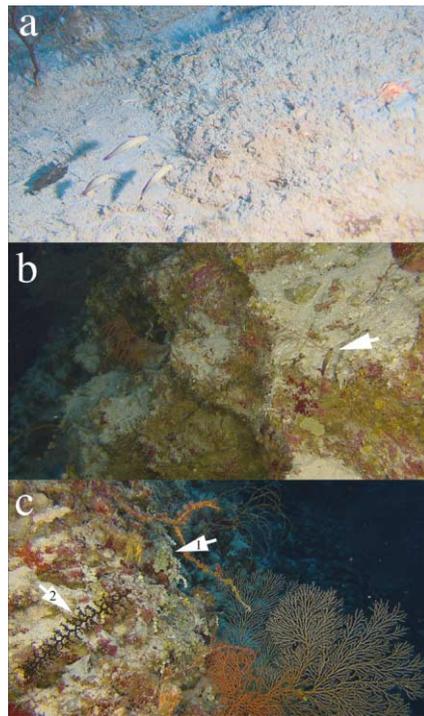
Preliminary Results

Okinawa

Elegant firefish *Nemateleotris decora* Randall & Allen, 1973 were observed during dive 43 at 111 m depth (25.4°C, 34.86 PSU) in a group, suggesting they may have been juveniles (Figure 8a). This is a new depth record for this species as the previous maximum depth record was at 70 m depth (Myers, 1991).

FIGURE 8

Elegant firefish *Nemateleotris decora* during dive 43 off Ishigaki Island, Okinawa, at 111 m depth (a), and at Osprey Reef during dive 50 at 116 m depth (b, white arrow). Frame grab of reef wall at 82.5 m depth during dive 50 (c) showing the calcareous alga *Halimeda* (white arrow 1) and the zoanthid *Epizoanthus illoricatus* (white arrow 2).



Osprey

Elegant firefish *N. decora* were also observed at Osprey Reef on 8 May 2011 during dive 50 at depths of 85 m (24.6°C, 35.8PSU) and 116 m (23.7°C, 35.9PSU), making 116 m depth the deepest record for this species (Figure 8b). At Osprey they appeared singularly rather than in a group and were found over topologically diverse carbonate cliff substrate covered in red coralline algae, gorgonians and patches of coral sand. Their depths of distribution, temperature and salinity environments were therefore similar in both the northern and southern hemispheres, although the substrate they occurred above differed. The green

calcareous alga *Halimeda* was observed just shallower than the shallowest firefish at 82.5 m depth, as was the zoanthid *Epizoanthus illoricatus* Tischbierek, 1930 (Figure 8c).

An attempt was made to construct a large-scale image map of the reef wall using the software package MofixLIGHT v2.1.0 (View Max Service Emaki Co., Ltd.). The NTSC video recorded by the right-hand stereo camera was played back using one of the MPEG-4 recorder/players and the output converted to USB 2.0 using a USB video capture cable (PCA-DAV2, Princeton Technology). The software was run on a Hewlett Packard h8-1080jp Pavilion desktop computer (Intel Core i7-2600 CPU at 3.4 GHz, 4.00 GB RAM, NVIDIA GeForce GT 530 Graphics Card). The neutral buoyancy of the vehicle and the resulting stable video allowed large sections of the reef wall to be mapped (Figure. 9), something that would be difficult using a tether-constrained ROV, but the propensity of biologists to try and capture interesting animals in the center frame on the HDTV camera meant that the vehicle would suddenly face the reef wall from time to time and the software was unable to combine these frames into the map. Dedicated dives for mapping or a 360°-capable camera that can capture images regardless of the vehicle's heading are two possible ways to overcome this problem.

The broadcast-quality high-definition television footage recorded by PICASSO-1 allowed species identifications to be made for well-known and easily recognizable organisms such as *N. decora* (Figure 8), the living fossil cephalopod *Nautilus pompilius* Linnaeus, 1758 (Figure 10a), and the pygmy seahorse *Hippocampus denise* Lourie and Randall, 2003 (Nishikawa

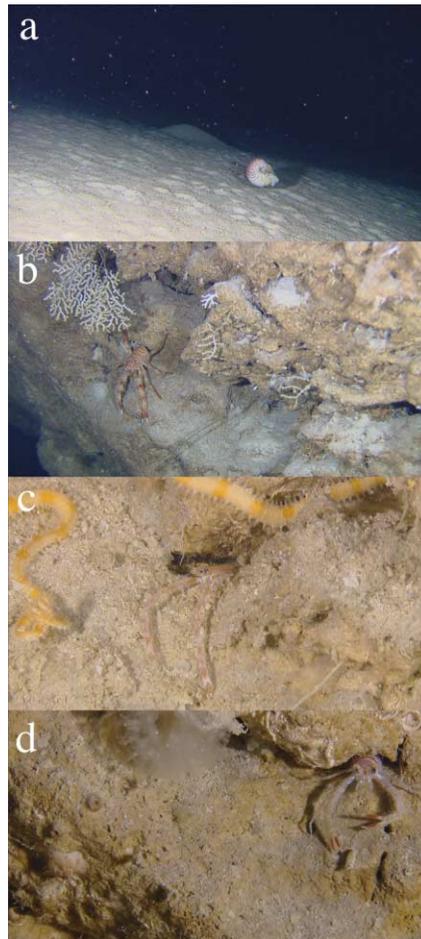
FIGURE 9

A videomosaic of the reef wall at Osprey Reef.



FIGURE 10

The living-fossil cephalopod *Nautilus pompilius* (a), the squat lobsters *Bathymunida* sp. (b), *Munida* sp. (c) and *Babamunida javieri* (d).



et al, 2011). Even the NTSC video from the other cameras allowed species identifications to be made of charismatic macrofauna such as a juvenile tiger shark *Galeocerdo cuvier* Péron and Lesueur, 1822 at 360 m depth—a new depth record for a juvenile of this species. Even for lesser-known groups such as the squat lobsters, it was usually at least possible to identify animals to genus level (e.g. *Bathymunida* sp. and *Munida* sp.; Figures 10b and 10c) if not to species, such as for *Babamunida javieri* (Macpherson,

FIGURE 11

The ruby snapper *Etelis carbunculus* and an oblique-banded grouper *Epinephelus radiatus* under red light (top) and as the HID lights powered on (bottom).



1994)—a first record for Australian waters (Figure 10d).

The red LED array was used to observe organisms attracted to the baited trap on 13 May 2011 at 365 m depth. Large numbers of the ruby snapper *Etelis carbunculus* Cuvier, 1828 and one oblique-banded grouper *Epinephelus radiatus* Day, 1868 came close to the bait when illuminated with red light but were quick to disperse when the HID lights were turned on (Figure 11), suggesting that the use of such red light illumination would be valuable for “stealth” missions to observe the natural behavior of deep-sea animals.

Conclusions

The untethered nature and small size of the PICASSO-1 vehicle makes it an ideal tool for exploration of the ocean’s midwater, mesophotic reef communities and other deep water ecosystems in hard-to-access localities. Perhaps the most revolutionary aspect

of the PICASSO system is the logging and playback system, which allows both recreation of a dive during post-cruise analysis and data output that can be imported directly into JAMSTEC's Biological Information System for Marine Life (<http://www.godac.jp/bismal/e/>) and the Ocean Biogeographic Information System (<http://www.iobis.org/>). The ability to take tissue or DNA samples using the PICASSO-1 would greatly increase its value as a survey tool and the development of such capabilities should be actively pursued.

Acknowledgments

The quality of the HDTV images recorded by PICASSO-1 is such that many of the sea trials and scientific surveys have been able to be subsidized by collaborations with other parties. Sea trials in Japan were subsidized to an extent by NHK (RinkaiMaru cruise) and TV-Asahi (Sea Gull cruise) and by Digital Dimensions, BBC, Discovery Channel and Channel 9 for the Australian cruise on the *Coral Emperor*. High-quality images are also of great value for scientific research, and the authors would like to thank the Australian Institute of Marine Science and James Cook University, who also contributed toward costs of the Australian survey. All other costs were borne by JAMSTEC. The authors express their appreciation to Mr. Kazuhiro Yagasaki, who constructed the videomosaic in Figure 9, and would also like to thank Ms. Asuka Ito, Ms. Atsuko Watanabe, and Mr. Yoshifumi Noiri for logistical office support. This study is supported in part by the fund for interdisciplinary collaborative research by the Atmosphere and Ocean Research Institute, University of Tokyo.

Corresponding Author:

Dhugal J. Lindsay
Japan Agency for Marine-Earth
Science and Technology
2-15 Natsushima-cho,
Yokosuka 237-0061, Japan
Email: dhugal@jamstec.go.jp

References

Armstrong, J., Becker, K., Eagar, T., Gilman, B., Johnson, M., Kastner, M., ... Solow, A. 2004. Future Needs in Deep Submergence Science: Occupied and Unoccupied Vehicles in Basic Ocean Research. Committee on Future Needs in Deep Submergence Science, Ocean Studies Board, Division on Earth and Life Studies, National Research Council of the National Academies. Washington, DC: The National Academies Press. 1-135 pp.

Foster, R., Bridge, T.C.L., & Bongaerts, P. 2012. The first record of *Hippocampus denise* (Syngnathidae) from Australia. *Aqua, Int J Ichthyol.* 18:55-7.

Maruyama, T., Kato, C., Yamamoto, H., Fujikura, K., Sato, T., Fujiwara, Y., ... Sasaki, T. 2009. Research activities of the Research Program for Marine Biology and Ecology from 2004 to 2008. JAMSTEC Rep Res Develop. 9(1):13-74.

Myers, R.F. 1991. *Micronesian Reef Fishes* (2nd ed.). Barrigada, Guam: Coral Graphics. 298 p.

Nishikawa, J., Fitzpatrick, R., Reimer, J.D., Beaman, R. J., Yamamoto, H., & Lindsay, D.J. 2011. *In situ* observation of the Denise's pygmy seahorse *Hippocampus denise* associated with a gorgonian coral *Annella reticulata* at Osprey Reef, Australia. *Galaxea, J Coral Reef Stud.* 13:25-6.

Raymond, E.H., & Widder, E.A. 2007. Behavioral responses of two deep-sea fish species to red, far-red, and white light. *Mar Ecol Prog Ser.* 350:291-8.

Widder, E.A. 2005. Using red light for *in situ* observations of deep-sea fishes. *Deep-Sea Res I.* 52:2077-85.

Yoshida, H., Aoki, T., Osawa, H., Tsukioka, S., Ishibashi, S., Watanabe, Y., ... Ishikawa, A. 2007a. Newly-developed devices for two types of underwater vehicles. In: *Oceans 2007 Conference Proceedings*, 1-6. Aberdeen: IEEE.

Yoshida, H., & Lindsay, D.J. 2007. Development of the PICASSO (Plankton Investigatory Collaborating Autonomous Survey System Operon) system at the Japan Agency for Marine-Earth Science and Technology. *Jpn Deep Sea Technol Soc Rep.* 54:5-10.

Yoshida, H., Lindsay, D.J., Yamamoto, H., Tsukioka, S., Shimura, T., & Ishibashi, S. 2007b. Small hybrid vehicles for jellyfish surveys in midwater. In: *Proceedings of the 17th International Offshore and Polar Engineering Conference*, p. 127. Lisbon, Portugal: International Society of Offshore and Polar Engineers (ISOPE).