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# Temporal and spatial benthic data collection via an internet operated Deep Sea Crawler

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A B S T R A C T

Environmental conditions within deep-sea ecosystems such as cold-seep provinces or deep-water coral reefs vary temporally and spatially over a range of scales. To date, short periods of intense ship-borne activity or low resolution, fixed location studies by Lander systems have been the main investigative methods used to investigate such sites.

Cabled research infrastructures now enable sensor packages to receive power and transmit data from the deep-sea in real-time. By attaching mobile research platforms to these cabled networks, the investigation of spatial and temporal variability in environmental conditions and/or faunal behaviour across the deep sea seafloor is now a possibility.

Here we describe one such mobile platform: a tracked Deep Sea Crawler, controlled in real-time via the Internet from any computer worldwide. The Crawler has been extensively used on the NEPTUNE Canada cabled observatory network at a cold-seep site at ∼890 m depth in the Barkley Canyon, NE Pacific. We present both the technical overview of the Crawler development and give examples of scientific results achieved.



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## 1. Introduction

The spatial scale of data collection can be crucial for many research applications in the deep sea, with a high degree of habitat heterogeneity (on scales of cm to metres) regularly reported (Smith and Kaufmann, 1999). Heterogeneity is particularly evident in deep-sea ecosystems such as cold-seeps (Olu et al., 2004), hydrothermal vents (Hessler et al., 1985) and cold-water coral reefs (Purser et al., 2009), where changes in ecosystem functioning and biogeochemical cycling can occur over spatial scales of cm or m (Fustec et al., 1987). The majority of studies investigating benthic pelagic coupling tend not to focus on local spatial variability in organic matter delivery flux to the seafloor and its subsequent redistribution of material by the benthic community (Levin et al., 2001), but rather estimate the fluxes from data collected by individual or widely spaced Lander/sediment trap mooring systems—giving a coarse spatial resolution of transport processes (Jickells et al., 1996). In addition to studies of purely academic interest, those investigating anthropogenic impacts on deep sea ecosystems also often neglect local scale variability in impact severity (Halpern et al., 2008).

To fully understand the dynamics of deep sea environments time series data are essential (Ducklow et al., 2009; Magurran et al., 2010). The ongoing deployment of Lander based systems and repeated visits to survey stations by research vessels has produced extensive time series data sets from particular sites (Lewis and Allen, 2009; Lampitt et al., 2010). The development of satellite data transfer technologies allow ship and Lander collected data to be available worldwide via the Internet in near real-time, though these systems are often power hungry, and in the case of ship-borne investigations, only possible when a ship is on station.

Real-time data collection is essential for some deep sea applications, such as the gathering of seismic data for the prediction of Tsunami events. The JAMSTEC cabled system east of the Japanese mainland (Kasaya et al., 2009) and the NEPTUNE Canada network (Barnes et al., 2010, 2013, in press) covering the Juan de Fuca plate west of the Pacific Canadian coast are two networks gathering such data, both capable of measuring seismic waves in real time from stations in waters of $>3$ km depth (Barnes et al., 2008; Henthorn et al., 2010). These cabled systems have been designed to supply large amounts of power and return gigabytes of data $s^{-1}$ to land based processing stations, then to the World Wide Web, within seconds of sensor measurement (Barnes et al., 2008; Craig et al., 2009). The development of an integrated European Multidisciplinary Seafloor Observatory (EMSO) is also foreseen (Favali and Beranzoli, 2009) as is the further development of the MARS network from Monterey, USA (Barnes et al., 2008) and other networks in Taiwan (MACHO) and China.

Although real-time data delivery from cabled systems allows scientists to monitor oceanographic conditions at target sites whenever they wish, they can only monitor the conditions at one or a small number of discrete cabled installations. Within some deep sea ecosystems, such as methane seep or hydrothermal provinces, or at deep sea coral reefs, oceanographic, hydrodynamic, substrate and faunal assemblages can vary greatly, both temporally and spatially (Law et al., 2010; Wagner et al., 2011; Gaudron et al., 2012). For the study of such ecosystems, mobile sensor platforms would be greatly beneficial. Such a mobile platform, the ROVER, is in operation on the Monterey Accelerated Research System (MARS) network, investigating carbon transport and soft bottom communities (Smith et al., 1997; McGill et al., 2007, 2009). Similar platforms have been used commercially by the oil and gas industry for inspections around drilling rigs, cables and pipelines for a number of years. These commercial vehicles are commonly operated from a drill rig or ship rather than remotely via the Internet. To enable scientists and engineers from any location worldwide to investigate and monitor dynamic ecosystems and benthic environments in real-time with such sensor platforms, an Internet Operated Vehicle (IOV) is presented in this paper (hereafter referred to as the Crawler) capable of carrying in excess of 100 kg in sensor payload. The Crawler has been developed (Karpen et al., 2007) and subsequently deployed on the NEPTUNE Canada network (Barnes et al., 2010, 2011; Thomsen et al., 2012). In this paper the design philosophy and technical parameters of this latest generation of IOV and recent data collected by the Crawler from a cold-seep site on the NEPTUNE Canada network are presented.

## 2. Materials and methods

### *2.1. Design philosophy*

The Crawler was designed as a universal sensor transporting system for the temporal and spatial exploration of any region of deep ocean floor (and in the case of water flow intensity measurements, the waters above the ocean floor). To ensure this versatility, all the principal components from the camera housing glass spheres to the pressure housings for computers were at the design stage rated for use at up to 6000 m depth. For maximum stability on even very soft sediments (and following the trend in industrial benthic vehicle development) a tracked crawler design was employed. The decision was made for the Crawler to be constructed wherever possible with well tested, commercially available off the shelf (COTS) electronic and mechanical components, with reliability and durability being key factors in component selection. Using COTS components both reduced the development costs of the Crawler and minimised the length of testing required during Crawler prototyping.

To enable Crawler use in different ecosystems and environments (such as at a range of depths, on different substrates, etc.) a modular design approach was taken, so components could be readily changed for particular deployments. The facility to mount different track treads and buoyancy to match the substrate characteristics of a particular deployment location are examples of this philosophy employed. During the testing phase the Crawler was driven on a range of substrates, including soft sediment lakebeds, boulder strewn sand fields and pebble and shell covered sub-littoral seafloors. On very soft sediments tracks with extended tread paddles were found to be the most functional. On sandy seafloors both flat and extended treads were capable of ensuring movement with flat tracks achieving the best locomotion results on pebble and shell covered sub-littoral seafloors.

Aside from these structural considerations, Crawler design was also constrained by the requirement that the vehicle should be connected to a power supply source by umbilical cable, with a real-time internet connection also maintained via the same cable. This internet connection in addition to Crawler control also allows the data collected by sensors to be transmitted to shore and archived automatically—with this in mind compatibility with the Data Management and Archive System (DMAS) developed by NEPTUNE Canada, was designed into the Crawler system (Pirenne, in press). A final governing consideration was that the sensor payload carried by the Crawler should be easily changeable for each deployment, with data recovery and sensor recalibration also possible remotely during deployments. Real-time access to the Crawler and collected data, as well as a much smaller and more transportable structural frame, are two of the key contrasts between it and the ROVER employed by MBARI on the MARS testbed (McGill et al., 2009). The deployment of cabled networks on the seafloor is a costly, time intensive procedure, and connecting mobile platforms to (or removing for maintenance from) these can be a cumbersome endeavour requiring remote operated vehicles (ROVs). The Crawler was designed for long-term deployments of many months duration to minimise the requirements for such actions.

A decade of tests and prototyping was required prior to design finalisation and production of the Crawler as presented here. Perhaps the most problematic parts of development were those related to the development of the internet control interface (see 2.3 and 2.4 below). The operability of this system was refined during 2005 by attaching a small prototype Crawler to an internet and power supplying test station at 10 m depth in the Baltic Sea (Surendorf, Germany). This allowed connectivity to be tested over the world-wide web from Bremen, Germany, from a distance of 200 km. Any mechanical, computational, network or power supply problems during this test period were addressed by dive teams.

### *2.2. Crawler superstructure, power supply and communications umbilical cable, buoyancy and electronic component pressure casings*

The Crawler is a mobile instrument platform (130 × 106 × 89 cm, LWH, Fig. 1), with the compact dimensions of the Crawler selected so that the vehicle may be carried by small vessels working in deep waters (such as Norwegian Fjords) or slung under large 6000 m depth rated ROVs during deployment. The Crawler can monitor and study an area of sediment surface proportional to the length of its

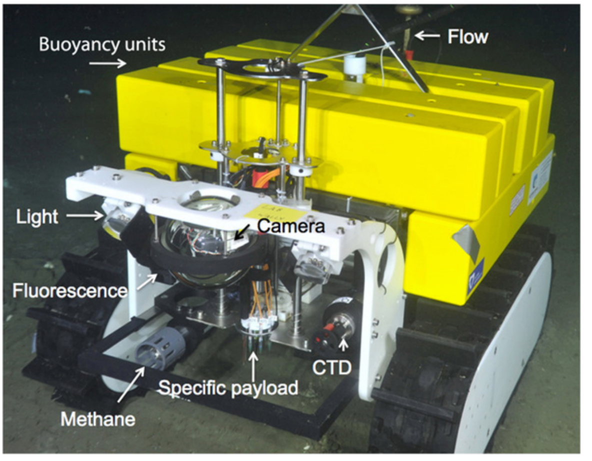


**Fig. 1.** The Deep Sea Crawler prior to deployment on the NEPTUNE Canada network in June 2012. A range of components are indicated, including the Max Planck sediment profiler (the 'specific payload' on the figure).

umbilical cable, with real-time data return. At the NEPTUNE Canada cold-seep location (see 2.10) a 70 m cable connected to a junction box in the Barkley Canyon is currently used, giving a coverage of $\sim$15,000 m$^2$.

The umbilical cable is constructed of a lightweight (though not neutrally buoyant) flexible 20 mm diameter Polyurethane (PUR) sea cable, containing two wires for power supply and 4 twisted-pair wires for Etherbit (100 mbit) communication, and connected to the Crawler and junction box with Subconn connectors. The cable is connected every three metres to a 200 $\times$ 100 $\times$ 80 mm glass foam buoyancy block, which ensures that it floats clear of the Crawler and high in the water column. During deployments the cable is attached to the top of the Crawler in loosely bound loops. The buoyancy of the tether cable ensures that it does not interfere with the seafloor in any way.

There is no automated tether system used as standard on the Crawler. Should the Crawler attempt to drive out of the radius supported by the umbilical cable, the force applied by the vehicle is insufficient to cause damage to the cable. The Crawler will cease moving and this will be immediately clear to the operator (see Section 2.9).

The caterpillar tracks create a footprint on the seafloor of 0.35 m$^2$ with a weight of $\approx$10 g/cm$^2$. The Crawler can be mounted with a range of glass foam buoyancy blocks. For deployments to date blocks with depth ratings of 1100 m have been used, but remounting the umbilical with blocks suitable for deeper deployments is a simple matter of unscrewing the attached blocks and mounting those rated for a greater depth.

### *2.3. The port manager*

The port manager connects the Crawler to a junction box (as on the NEPTUNE Canada network (Barnes et al., 2010, 2013, in press) or vessel via an umbilical power and data cable. Fig. 2 gives an overview of the connectivity of the various Crawler electronic components.

The port manager is housed within a titanium pressure housing (6000 m rated) which also contains the Crawler compass. The port manager can be accessed via a standard Internet connection, independently of the track controller (see 2.4), for interacting with the attached sensors. The port manager also transfers (via the web server software run on the track controller microcomputer, see 2.4) the sensor data in real-time for archiving onshore. Where required, RS232 converters within the port manager facilitate data transfer for sensor packages. See Section 2.8 for an overview of sensor systems which have thus far been used with the Crawler.

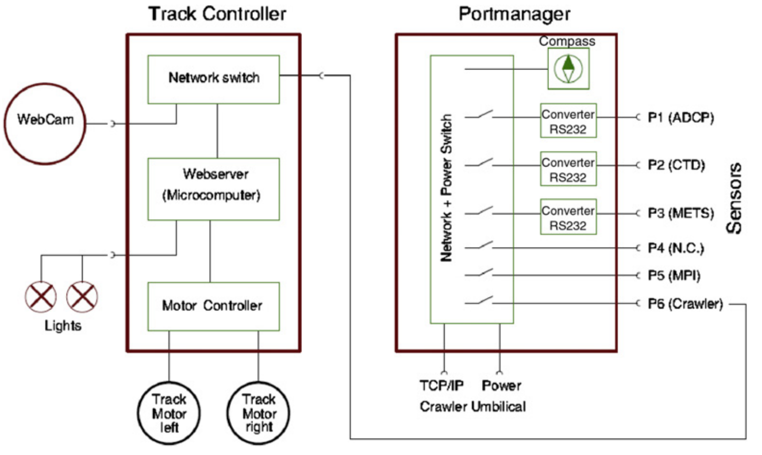


**Fig. 2.** Overview of the electrical components of the Deep Sea Crawler. TCP/IP communication and power are supplied to the port manager, which maintains communication with the sensors attached to the Crawler, the compass and provides communication with the track controller. The track controller contains the microcomputer used to control Crawler motion, lighting and imaging devices.

### 2.4. *The track controller*

The second of the two Crawler pressure housings (6000 m rated) contains the microcomputer which runs the two software applications required for motor control and running the Crawler web server. The microcomputer uses a real-time operating system (RTOS) and can be contacted remotely via *Telnet* or an ftp connection. The software applications were custom written in C. Fig. 3 shows how a remote user can interact with the deployed Crawler and issue movement commands to the track controller remotely (see also 2.9). The track controller housing also contains the network switch connecting the microcomputer to the webcam and lights (see 2.6).

### 2.5. *Motor, gear and track units*

Mobility for the Crawler is achieved by using two caterpillar tracks, driven by geared plastic transport wheels attached to titanium axles. These axles are attached to lateral cover plates with abrasion resistant plain bearings. These lateral cover plates separate the track tension devices from the environment. The drive motors used are brushless fluorinert pressure compensated motors with planetary gears connecting to the axles. Depending on substrate type, different caterpillar track profiles can be used.

### 2.6. *Imaging and illumination*

A well tested, off the shelf Panasonic 720 × 480 pixel web camera (model BB-HCM580) is mounted in a pressure resistant glass globe (6000 m rated) at the front of the Crawler (Figs. 1 and 4). Illumination is provided by 2 × 33 W forward facing LED lamps (2000 m rated—though these may be exchanged for those rated for deeper usage if required), which can be turned on and off remotely by the operator. To reduce impacts on the ecosystem and biasing faunal behaviour, lights are not kept on for extended periods. The camera is operated via a standard Internet webcam portal and is capable of imaging the seafloor several metres ahead of the Crawler and zooming in to take close up images of the seafloor close to the Crawler (Fig. 5). The camera has a field of approximately 330° both horizontally and vertically, with camera orientation adjusted using the ‘Camera Angle Control’ (Fig. 4). Both manual and auto-focus can be used, with the manual option useful in situations where high suspended sediment loads can confuse the auto focus system. Movies in MJPEG format and still image .jpgs can be acquired

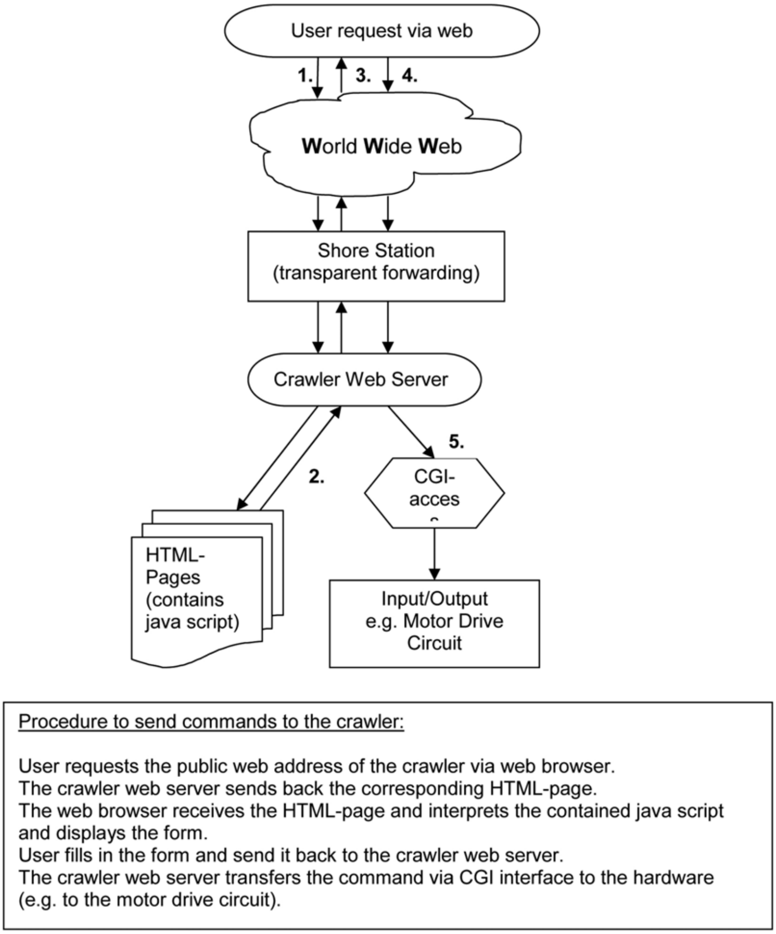


**Fig. 3.** Flow chart schematic showing how a remote operator can interact with the deployed Crawler.

directly through the camera web interface. There is the facility to program into the camera particular orientation angles and zoom settings, which can be useful if particular views are often required, for example below the Crawler if a payload sensor requires penetration into the sediment (such as the microsensor payload from the Max Planck Institute shown in Fig. 1). Sizing of seabed features and organisms is possible by using a three-point laser array (2.5 cm spacing) mounted at the front of the Crawler (Fig. 4). This laser array can be turned on and off by the user as required.

Using standard off the shelf image mosaicing algorithms, such as those provided with Adobe Photoshop CS5, arrays of still images taken at the same zoom but in different directions from a static location can be combined to provide a 330° visual overview of a location. By maintaining or returning to the same location, time series mosaic overviews can be produced, showing general or specific changes in the ecosystem or environment which may be missed by examining images individually. By carefully planning a survey route, for example by travelling between two distant waypoints by repeated use of the same route, seafloor disturbance is maintained at a minimal level. By always taking time series images of areas $>1$ m distance from the Crawler, no progressive impacts on an ecosystem from the Crawler tracks can be seen.

A second, high definition $1280 \times 720$ pixel Panasonic camera (model WV-SC384) is mounted at the rear, right hand side of the Crawler. This camera is fitted with comparable illumination to the forward

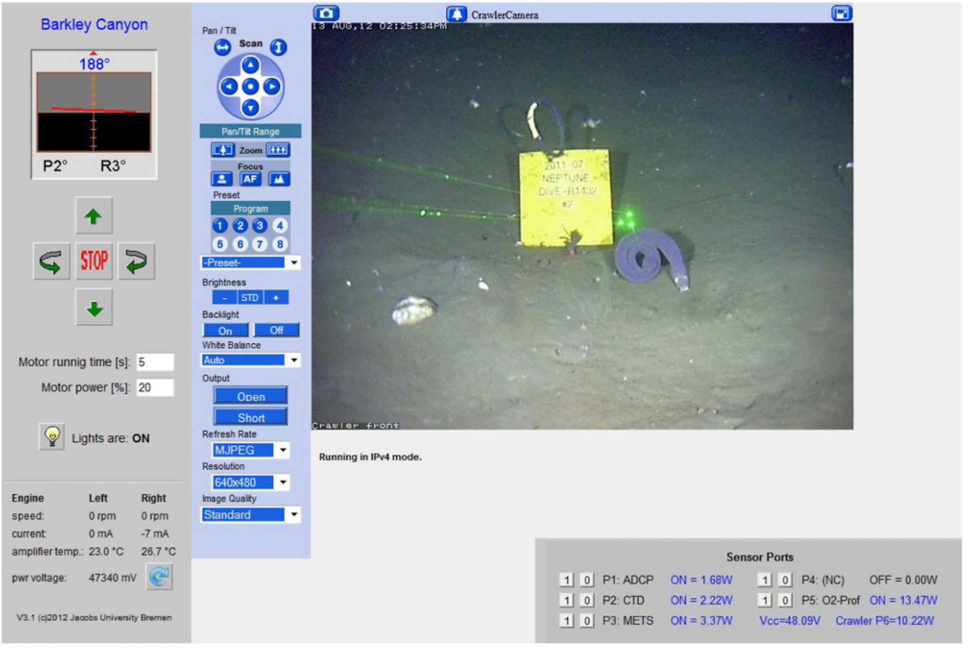


**Fig. 4.** Screenshot of the Crawler control window, incorporating both Crawler and camera movement options bars, and sensor port output bar. The sizing laser is also activated. One of the yellow navigation markers placed on the seabed by an ROV during Crawler installation is evident. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

looking camera. This second camera requires a higher bandwidth than the forward facing Panasonic camera, and although being well suited for close-up work or the capture of high resolution still images for sideways facing mosaics during transit between stations (Fig. 6), it is not suitable for driving, as there can be a lag in camera response.

## 2.7. Navigation

Within the Port Manager pressure casing (see 2.3) an electronic compass is integrated as standard. The output from this sensor gives pitch, yaw and heading direction of the Crawler in real-time, and can be read directly from the drive interface screen (Fig. 4). Aside from the compass, the Crawler is not fitted with any positioning systems as standard, and during deployments thus far made (see Results and Discussion), navigation has been assisted with visual aids—in the form of markers positioned by ROV at time of Crawler deployment (Fig. 5).

## 2.8. Sensors

The port manager is capable of maintaining communication with five sensors or sensor packages. Commonly a current profiler, methane sensor, turbidity meter and fluorometer are fitted during deployments, but this payload can be modified according to specific research interests. Aside from the current profiler, all sensors are located at 20–30 cm height above the sediment, in the front section of the IOV. In 2010 an additional microprofiler with 5 microsensors from the Max Planck Institute, Bremen was attached (Fig. 1).

The Crawler cabled power supply allows instruments to collect data at their maximum temporal resolution—this is uncommon in deep sea research where battery power is often maintained for months by taking periodic measurements.

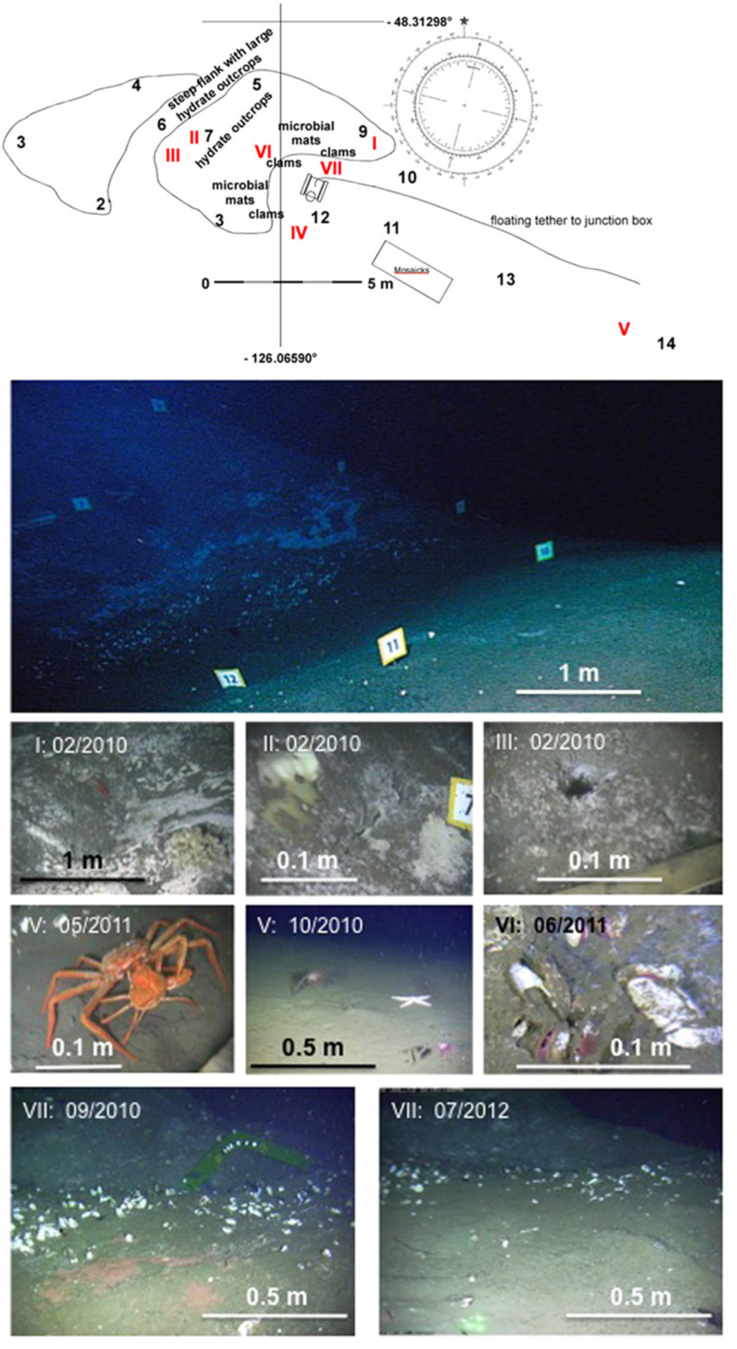


**Fig. 5.** (Upper) Map showing position markers arranged around a hydrate outcrop in Barkley Canyon, Canada, the main investigative focus of deployments of the Crawler on the NEPTUNE Canada network. Photographs taken with the BB-HCM580 camera set at a variety of zooms, showing: active seeping [I, II, and III]; mating behaviour of crabs [IV]; a variety of associated fauna [V]; close up of clams [VI]; time series images of clams in the vicinity of a vent, with the images taken 22 months apart [VII].

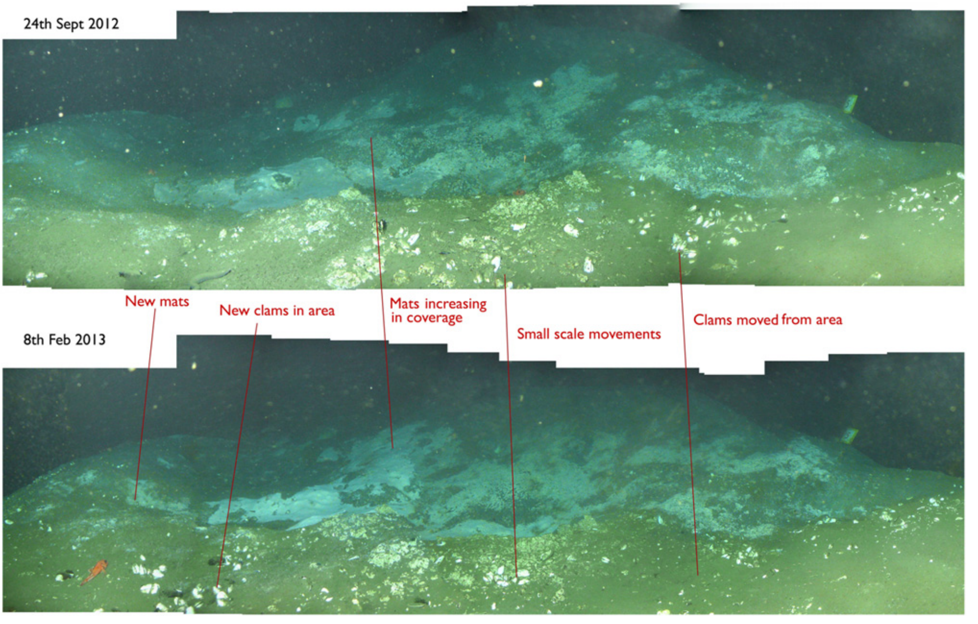


**Fig. 6.** Two photomosaics, each made up of 100 images taken with the rear/side facing KX-HCM280 camera during a short traverse alongside an elevated methane seep mound. The mosaics were taken on 24th September 2012 and 8th February 2013. The two images show that the arrangement of clams surrounding the mound differs between these two time points, as does coverage of the mound itself by bacterial mats.

Reliability is a key issue in selecting sensor packages for attachment to the Crawler for long duration deployments. Aside from the novel in-situ methane sensors only recently coming on the market, the sensors used with the Crawler to date have been well tested previously and utilised 'off the shelf', with no specific Crawler related modifications required. Appendix B provides a list of sensor packages thus far tested with the Crawler in-situ.

### *2.9. Driving the Crawler*

From any internet terminal, a Crawler operator can, with the required passwords, drive the Crawler via the online interface window Graphical User Interface (GUI) (Fig. 4). The operator manually selects the duration of a movement in seconds and presses the appropriate interface button, for forward, reverse or rotate, following which the Crawler drives or rotates for the specified duration. Although no navigation system other than the compass (see 2.3) is used as standard, a short baseline transponder system or similar can be readily mounted on the Crawler to augment the GUI compass output shown in Fig. 4.

### *2.10. Deployment within a cold-seep ecosystem*

Cold-seep ecosystems are spatially highly heterogeneous. Within these ecosystems substrate (Reitner et al., 2005), water column temperature, methane concentration (Olu et al., 1997; Levin et al., 2003) and species abundance (Olu et al., 1997; Levin et al., 2003; Olu-Le Roy et al., 2007) vary over short distances. Though to date not studied in detail, it is likely that all of these sources of heterogeneity may vary over timescales of seconds to years (Cordes et al., 2010). Chemosynthetic organisms such as the Vesicomyid clams found at many cold-seep sites are often reported to be mobile, though there have been few studies which relate changes in methane flux or other environmental conditions with the distribution of clams (or indeed, other organisms) at cold-seep sites (Barry et al., 1997). The rate of methane flux through the sediments is also likely a key factor in determining the extent and species composition of the bacterial mats commonly found covering areas of the seafloor in the vicinity of cold seeps (Sassen et al., 1993; Grünke et al., 2012).

With a real-time operable mobile platform such as the Crawler deployed within a cold-seep ecosystem, researchers may track these environmental and faunal changes over time, potentially illuminating the nature of the relationships between fauna abundance, fauna behaviour and bacterial mat abundance with spatial and temporal environmental variability.

Since 2009 the Crawler has been deployed at the Barkley Canyon cold-seep site of the NEPTUNE Canada cabled ocean observatory network (Pirenne, in press; Barnes et al., 2011) at a water depth of 890 m, ~100 km offshore Vancouver Island, British Columbia (Thomsen et al., 2012). Several maintenance cruises are carried out each year across the NEPTUNE Canada infrastructure, and at ~12 month intervals the Crawler is retrieved to the surface and a second Crawler of the same specifications deployed, usually within a few days. This rotation procedure has been carried out as a precautionary measure, and has not been the required result of any failure with the vehicle. By following this annual rotation regime, the deployed Crawlers have been used to investigate environmental and faunal variation across 15,000 $m^2$ of seafloor, and within the lowest few metres of the overlying water column.

## 3. Results and discussion

### *3.1. Long-term deployments on the NEPTUNE Canada cabled observatory*

From the initial deployment of the Crawler within the Barkley Canyon cold-seep region, a large volume of data has been collected. Fig. 7 shows an example of a high temporal resolution data-set, produced with the Plotting Utility of the NEPTUNE Canada Oceans 2.0 software. The figure shows methane concentration, flow velocity, pressure and temperature within the bottom waters 5 m from a gas hydrate outcrop for the period April 5–15, 2012. The data indicate an oscillatory pattern in methane seepage (top panel), which correlates with the tidal oscillation at the study site (Thomsen et al., 2012). Fig. 8 shows data from the same instruments covering a 9 month period (September 2011–April 2012). Over this timeframe seasonal changes (such as in temperature) are apparent, though the fine temporal scale information (such as diurnal scale variability in pressure or methane concentration) cannot be clearly seen.

Ecosystem specific temporal changes in parameters such as methane concentration within seawater or local physical processes such as substrate collapse following gas carbonate dissolution (Chapman et al., 2004), and more general seasonal environmental changes have also been observed with the Crawlers. These include chlorophyll flux change following variation in surface production throughout the year (Thomsen et al., 2012), differences in storm regularity and suspended sediment load between seasons, local concentrations of benthic fauna during mating-season, specific feeding behaviour of jellyfish under low flow-conditions, and variability of clam movement (Figs. 5 and 6). Many of these observations are currently being written up or are in review in the appropriate academic journals.

Within the area of deployment a number of methane seep pock-marks are apparent. The Crawlers have been utilising their mobility and sideways facing HD cameras to produce transit mosaics of one of these pock-mark features every two days (Fig. 6). These mosaics combine 100 HD images to produce one composite image for each transit, covering an area of approx. 30 $m^2$. A stationary Lander system would not be able to produce such composite images, and even with a comparable camera, the system would only be able to image a much smaller area of the pock-mark. The mobility of the Crawler allows a much more spatially extensive time-series monitoring campaign of this feature to be conducted. Commonly evident on the pock-mark images are highly mobile fauna such as fish, crabs and various molluscs, with large, sulphate reducing bacterial mats also visible. Though the functioning of these mats has been described in papers published in recent years (Hovland et al., 2005; Ruhl et al., 2011), there have been few studies which address how bacterial mat coverage of the seafloor may change over time (Knittel et al., 2003). By producing these regular transit mosaics with the Crawler, we have been able to observe bacterial mat seabed coverage change over a range of timescales. In Figs. 6 and

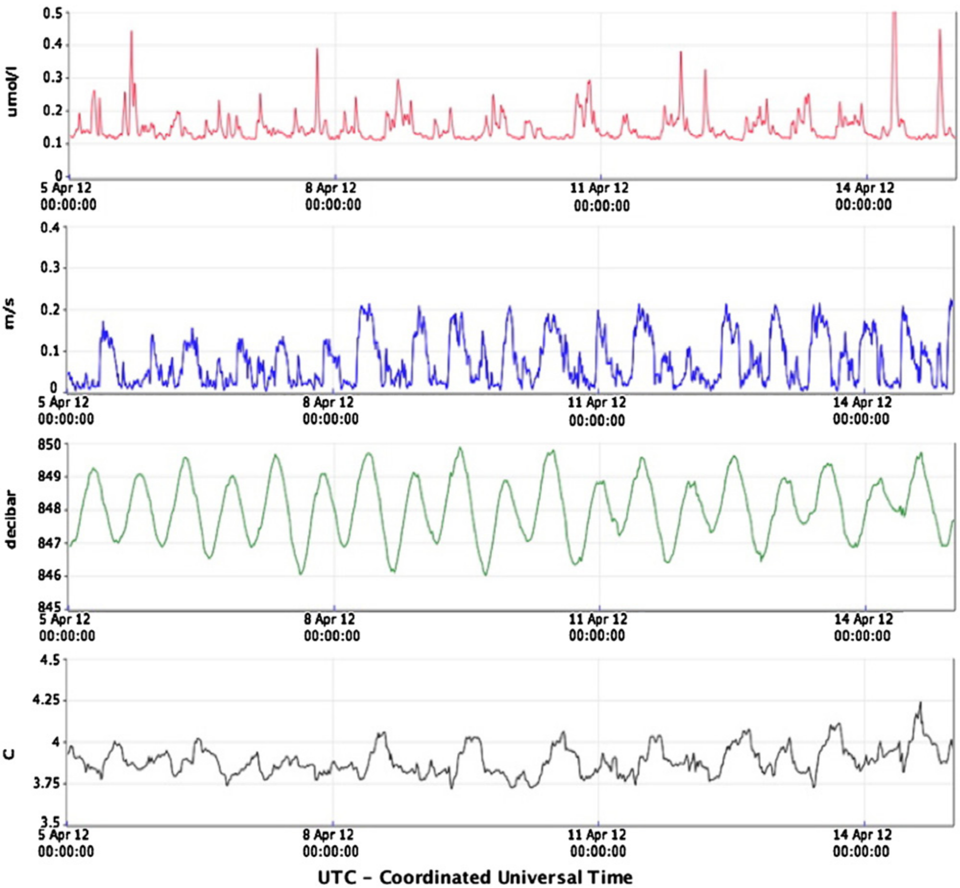


**Fig. 7.** Temporal changes in methane concentration, flow velocity, pressure and temperature recorded by the Crawler in April 2012, at the Barkley Canyon deployment site.

9 composite mosaics of the pock-mark are presented. Fig. 6 is comprised of images taken on the 24th September 2012 and 8th February 2013, with Fig. 9 showing details of the mound taken on the 24th and 26th of September 2012. As is clear from these figures, bacterial mat coverage can vary over a scale of days (Fig. 9), with larger changes in coverage taking place over scales of months (Fig. 6). Also apparent from the figures is the mobility of the vesicomyid clams in the area, with a number having changed position during the two day period between 24th and 26th September (Fig. 9) and larger numbers of clam repositionings apparent between September 2012 and February 2013 (Fig. 6).

Fig. 10 presents a log of scientist/Crawler interaction from 24th–27th September, as well as the pressure, flow velocity and turbidity sensor data recorded during that period. There are apparent correlations between scientist/Crawler interaction and turbidity in this graph, with peaks in turbidity often corresponding with the sending of commands to the Crawler. These peaks are likely those associated with the resuspension of the seabed by the movement of the Crawler. Turbidity also shows correlations with flow velocity and pressure, however. From the pressure data, it can be seen that at times of tidal ebb, flow velocity is generally higher than during tidal flood, with the peak flow velocities associated with the onset of tidal ebb. Turbidity is generally lower during periods of tidal ebb, though there is less of a clear relationship between the start and end of the ebb cycle evident from the turbidity data. Whether the bacterial mats which have greatly reduced in size between 24th and 26th September (Fig. 9) have been resuspended by the elevated flow velocities experienced during

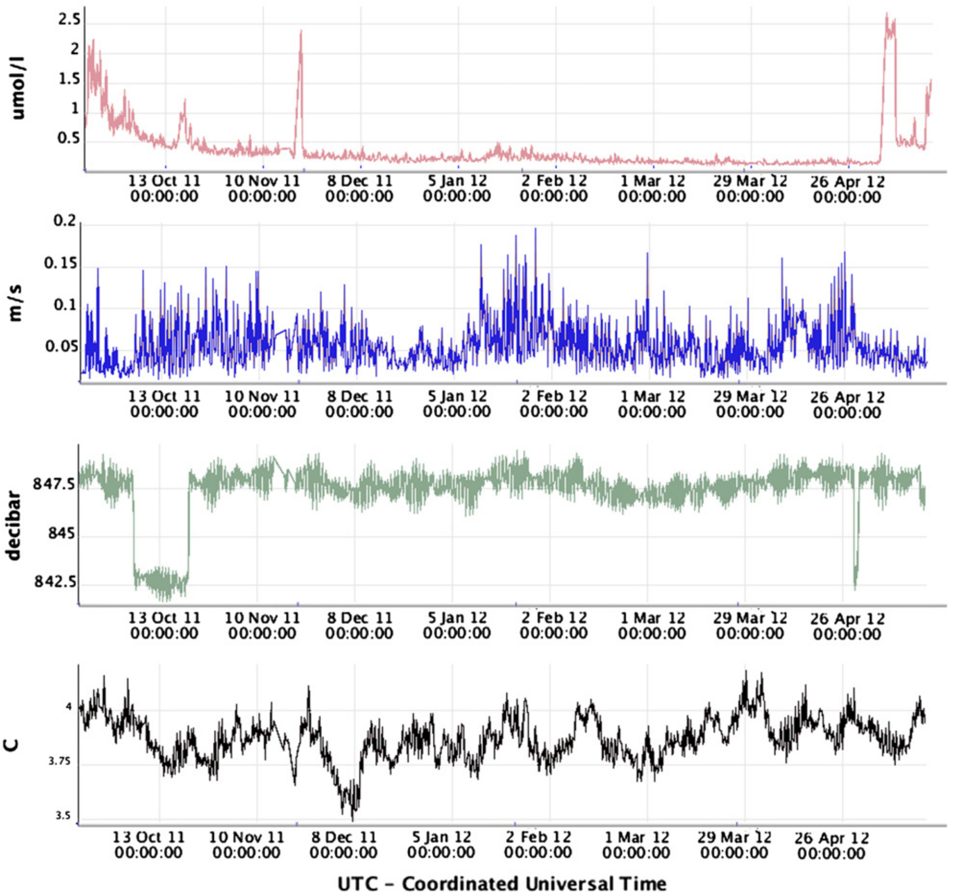


**Fig. 8.** Temporal changes in methane concentration, flow velocity, pressure and temperature recorded by the Crawler from August 2012 to May 2013, at the Barkley Canyon deployment site. The short timescale changes shown in Fig. 7 are not apparent from these 9 month duration instrument plots, though longer scale changes, such as annual temperature variation are apparent, over-stamping diurnal and tidal cycle duration changes.

the periods of ebb flow is unclear from this short dataset. The ongoing collection of sensor and image data is building on that collected during the last three years, becoming progressively more suitable for the statistical investigation of such questions.

All of the data collected via the Crawler from the Barkley Canyon deployment is freely available via the Oceans 2.0 data portal at http://www.neptunecanada.ca/data-collaboration/. In addition to the sensor data (some of which is given directly from the Oceans 2.0 portal as Figs. 8 and 10), technical aspects on Crawler functioning, such as power utilisation, compass position heading, motor power usage etc. are also archived automatically and available online in close to real-time. Although the data portal allows the downloading of many types of processed data products (such as time-averaged sensor outputs or pre-prepared graphs), raw data and sensor calibration files are also kept within the archive and freely available for any interested party to access.

### *3.2. Summary and outlook*

The high resolution data sets presented in Section 3.1 are difficult to acquire at such a resolution using research vessels, given the prohibitive costs of keeping the vessels deployed, the susceptibility

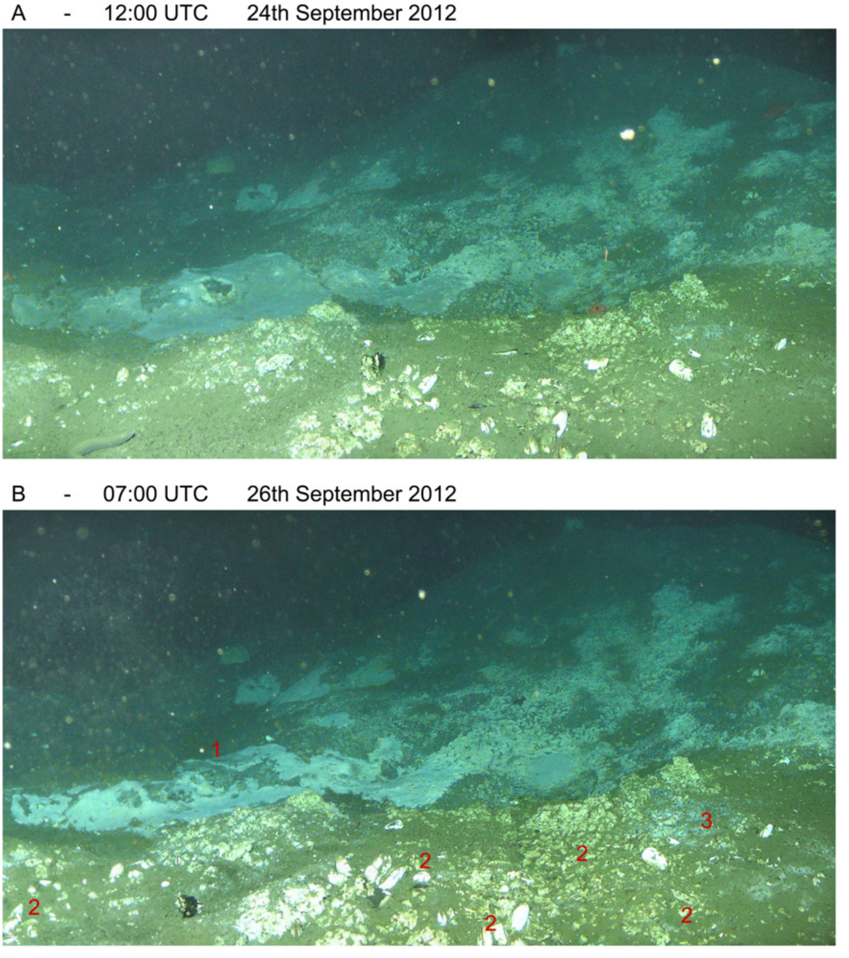


**Fig. 9.** Two mosaic composite images, each constructed from 30 individual images of a gas hydrate pockmark mound. The two mosaics were produced from images taken on the 24th and 26th September 2012 and cover the same region of mound. (1) Bacterial mat coverage of the seafloor is less on the 26th of September (Smith and Kaufmann, 1999). (2) Numerous clams have changed position between the 24th and 26th (Olu et al., 2004). (3) A dark, likely anoxic region, has developed between the times of image collection (Hessler et al., 1985).

of ROV operations to weather conditions, particularly in winter months. By using cabled, powered systems such high resolution time series are achievable throughout the year (Barnes et al., 2008; Thomsen et al., 2012).

The ability to move sensors in real-time in the deep sea with the Crawler opens a host of research questions for investigation. In the cold-seep and hydrothermal environments, the movement of benthic organisms may change over time (Best et al., in press; Lartaud et al., 2011; Decker et al., 2012), and movements of fauna such as chemosynthetic bacteria hosting clams can be monitored (Figs. 6 and 9). The response of such organisms to changes in methane concentrations in the bottom waters is currently being investigated.

The Crawler has proved to be an extremely reliable research platform and a great volume of data has been generated during the deployments on the NEPTUNE Canada network. We believe the stability and mobility of the Crawler system, when coupled with a cabled infrastructure and constant availability to scientists offers a very promising platform for many aspects of marine benthic research

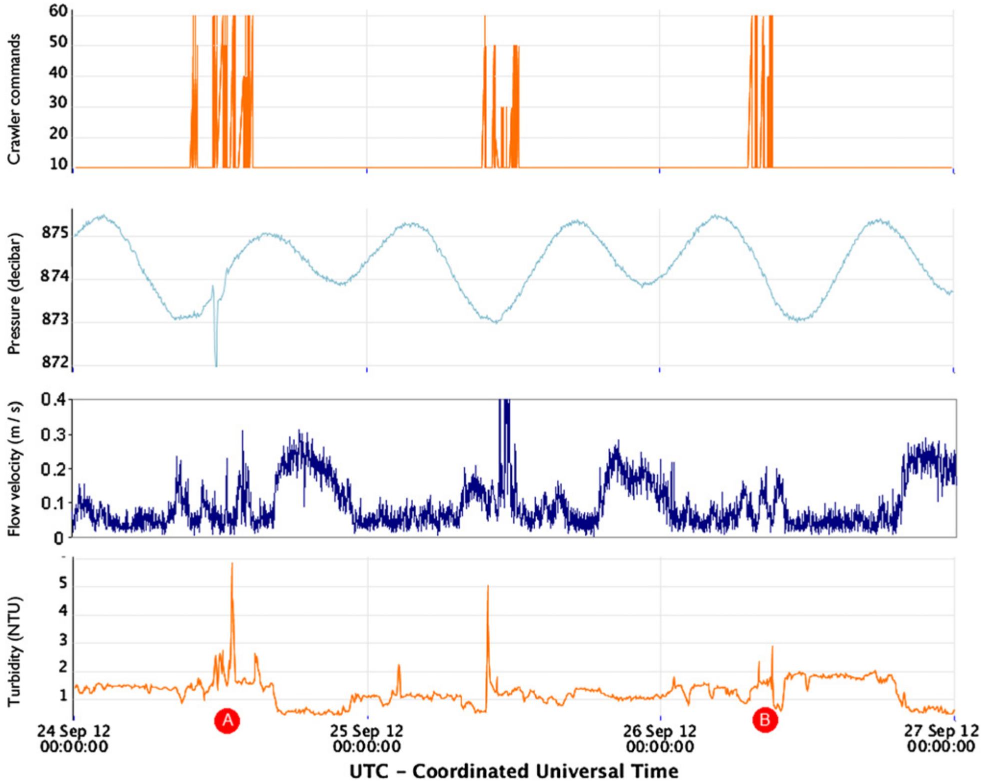


**Fig. 10.** Figure showing a history of communication with the Crawler and outputs of several sensors over a three day period (24th September–26th September 2012). A and B indicate the times at which the images used to construct the mosaics in Fig. 9 were collected. The Crawler commands graph shows that over the three days, there was operator contact and control of the Crawler on three occasions. The pressure graph clearly shows a strong tidal effect on pressure. The flow velocity graph shows flow ∼1.2 m above the seafloor, and indicates that at times of tidal ebb, flow velocity is generally at its highest. The turbidity graph shows that there are some high turbidity peaks which correlate with periods of communication with the Crawler, but also that during ebb tides, turbidity is reduced.

and offshore monitoring. The crucial difference between the Crawler system and free-flying AUV systems or Lander systems is that, when coupled with the real-time internet accessibility, an operator can change a survey plan during a deployment. Should the Crawler spot a biological interaction of interest, for example a display of mating behaviour (Fig. 5), an operator can delay a transect to collect video data of the phenomena of interest. Although such unexpected events can be recorded during ROV operations, the cost of ship time and ROV deployments is prohibitive, and therefore these opportunistic studies tend to be short in duration.

Data collected by the Crawler has already been incorporated into published peer-reviewed papers (Thomsen et al., 2012) with others in preparation, primarily focusing on both the role methane seep sites may play in biogeochemical cycling, and how the behaviour of fauna on the small spatial and short to mid-term temporal scales at the Barkley canyon seep site may vary.

As of early 2013, three fully autonomous Crawler systems are being developed in cooperation with the Alfred Wegener Institute for Polar and Marine Research (AWI), the Geomar and the robotics groups of DLR and DFKI (German aerospace and artificial intelligence centres) for deployments in extreme environments.

During 2013 we intend to deploy a Crawler system at the Tisler reef, Norway, to monitor temporal and spatial community change across a typical cold-water coral (CWC) fjord reef ecosystem in real time. The last decade has seen a great increase in research into the functioning and significance of cold-water coral reefs (Murray Roberts et al., 2006, 2010) as deep sea biodiversity hotspots (Henry and Murray Roberts, 2007), centres of elevated carbon sequestration (Van Oevelen et al., 2009; Wagner et al., 2011; White et al., 2012) and habitats for commercially significant fish species (D'Onghia et al., 2012). Further studies have addressed species distribution (Purser et al., 2013) and ecosystem susceptibility to anthropogenic damage (Purser and Thomsen, 2012) at such reefs. It is clear that faunal composition (Tong et al., 2012; Tracey et al., 2011; Herrera et al., 2012), flow dynamics (Wagner et al., 2011; Rüggeberg et al., 2011), oxygen utilisation (Dodds et al., 2007), pollutant deposition (Lepland and Mortensen, 2008; Larsson and Purser, 2011), coral growth rate (Larsson and Purser, 2011; Brooke and Young, 2009) and feeding behaviour of organisms can vary temporally over a scale of seconds and spatially over cm. By using the mobility of the Crawler, and positioning sensors and high resolution cameras directly where required within a reef complex, it is hoped that we can improve the current level of knowledge on the functioning of these dynamic ecosystems.

As the offshore hydrocarbon industry moves into deeper waters and increasingly uses internet connectivity in operations, they are driving technological developments in this area. IOVs now represent a cost efficient monitoring technology for the sustainable development and management of deep sea resources.

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## Appendix A. Technical specifications of the Crawler

### *A.1. Frame construction and buoyancy*

The majority of the frame consists of grade 5 titanium corner profiles, with some lesser components (such as sensor and camera mounts) made from polyoxymethylene [POM] (Titanium Solutions, Germany).

Crawler buoyancy is provided by syntactical foam [glass micro bubbles enclosed in epoxy resin] modules, which can be attached to the Crawler as required, dependent on payload, substrate type at deployment location and depth.

In addition to the titanium frame and buoyancy units, two titanium pressure casings are mounted within the frame to house the port manager and the track controller. These casings were tested to ensure 2000 m pressure resistance, with overpressure valves installed to ensure no danger following recovery to the surface should either case fail during deployment.

### *A.2. Track unit technical specifications*

A driving unit is attached to each track drive wheel, each containing a Dunker BG75×75, BLDC-Motor 600 W, 3370 rpm, 150 Ncm motor, contained in a polyoxymethylene housing filled with 2800 ml Fluorinert FC77 oil. Oil volume change with heat build-up during motion is ensured by incorporation of pressure compensation membranes within each housing. These motor units, in combination with the various track designs, have been tested extensively on a variety of substrates (e.g. clayey mud, sand, rubbly gravel) at a range of depths from 1–900 m. Each motor is connected to the track controller via waterproof cable.

The Crawler is moved by setting 'Motor Running Time' and 'Motor Power' manually via a custom built web interface, then clicking on a direction [forward or reverse] or rotate button (clockwise or counter-clockwise). The Crawler will then move as commanded, automatically cutting out if communication is lost for any reason, ensuring delicate structures are not driven over and the umbilical cable connection is not damaged.

## Appendix B. Technical components and manufacturer details

| Component | Specifications | Supplier |
|---|---|---|
| Frame | Titanium and polyoxymethylene | Titanium Solutions, Germany |
| Titanium computer Housings [×2] | Titanium, 6000 m rated | Titanium Solutions, Germany |
| Track motors | Dunker BG75×75,<br>BLDC-Motor 600 W, 3370 rpm,<br>150 Ncm motor,<br>polyoxymethylene housing filled with 2800 ml Fluorinert FC77 oil | Dunker |
| Track controller | Beck microcomputer | Beck microcomputers, Germany |
| Port manager | Connects to a50 m power and TCP/IP umbilical cable [48 VDC +−10%, 12.5 A nominal current, Ethernet 10/100 Mbit]. | In house construction |
| Drive camera | Web camera | Panasonic model KH-HCM280 |
| HD camera | HD web camera | Panasonic model WV-SC385 |
| Camera housings | Glass globe (6000 m rated) | Nautilus, Germany |
| Sizing laser | Three-point (2.5 cm spacing) laser array (532 nm wavelength), high temperature range, −4 +−1 mW Output Power | In house production |
| Electronic compass | TCM 2.6 | PNI Sensor Corporation, USA |

### *B.1. Standard sensor packages*

| | |
|---|---|
| ADCP current | Nortek, Norway |
| CTD | ADM-Electronics, Germany |
| Methane sensor | Franatec, Germany |
| Turbidity metre | Seapoint, USA |
| Fluorometer | Seapoint, USA |

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