Temporal and spatial benthic data collection via mobile robots: present and future applications

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Abstract— The analogies between space and deep sea motivated the German Helmholtz Association to setup the joint research program ROBEX (ROBotic Exploration under eXtreme conditions). The programme objectives are to identify, develop and verify technological synergies between the robotic exploration of the Moon and of the deep sea. In both space and deep sea research orbiters and AUVs/gliders respectively provide a large set of information on the environment but landers and mobile robots are essential to ground truth the data and validate theories. Within ROBEX the mobility of robots is a vital element for research missions due to valuable science return potential from different sites as opposed to static landers. After 2.5 years of project-time three main mobile systems are prepared for demonstration-missions, one wheel-based system for planetary missions, one wheel based system for extended deep-sea missions and a caterpillar system for high resolution investigation of small surface regions in the deep sea. In all cases sufficient on-board intelligence was needed. The mobile robots should also be capable of return to a central station for recharging, with the station equipped with enough battery power to allow multiple missions. The intelligent seafloor robot "iCrawler" is presented here, which is based on a tele-operated robot, which has been successfully used within the ONC (Ocean Networks Canada) cabled observatory project since 2010.

Keywords—seafloor monitoring, mobile robots, ROBEX project

INTRODUCTION

For applications in the marine sector there is no international consensus on how the activities of the offshore oil and gas industry should be monitored. However environmental awareness and technological advances have spurred development of new monitoring solutions for the petroleum industry. Environmental conditions within sensitive seafloor ecosystems such as cold-seep provinces or cold-water coral reefs vary temporally and spatially over a range of scales. They are regularly monitored via short periods of intense ship-borne activity or low resolution, fixed location studies by Lander systems. For a few years now, cabled research infrastructures enable sensor packages to receive power and transmit data from exploitation sites in real-time. By attaching mobile robots to these cabled networks, the investigation of spatial and temporal variability in environmental data is a possibility [1,2].

The analogies between space and deep sea motivated the German Helmholtz Association to setup the joint research program ROBEX (ROBotic Exploration under eXtreme conditions). ROBEX consists of a consortium of German maritime and space research institutions. In this research programme, space and underwater scientists and engineers cooperate to find solutions to similar challenges and to mutually benefit from each other's technologies and capabilities. The programme objectives are to identify, develop and verify technological synergies between the robotic exploration of the Moon and of the deep sea. Within ROBEX the mobility of robots is a vital element for research missions due to valuable science return potential from different sites as opposed to static landers. Three main mobile concepts are developed: one wheel-based system for planetary missions, one wheel based system for extended deep sea missions and a caterpillar system for high resolution small surface regions (up to 1 km^2) in the deep sea. In all cases sufficient on-board intelligence for path planning for the best trajectory to follow was needed. The mobile robots should also return to a central station, which is equipped with enough battery power to allow multiple missions.

The Deep Sea Crawler "Wally" deep sea Crawler provides the basis for ongoing developments in ROBEX.Controlled in real-time via the Internet from any computer worldwide. The crawler has been extensively used since 2010 on the Ocean Networks Canada (ONC, Neptune Canada) cabled observatory network at a cold-seep site at 890 m depth in the Barkley Canyon, NE Pacific [1]. The Crawler was designed as a universal sensor transporting system for the temporal and spatial exploration of any region of deep ocean floor. Mobility for the Crawler was achieved by using two caterpillar tracks, driven by geared plastic transport wheels attached to titanium axles. The drive motors used are brushless Fluorinert pressure compensated motors with planetary gears connecting to the axles. In addition to collecting a unique high resolution temporal data set on environmental parameters such as methane concentration, temperature, conductivity, turbidity, chlorophyll concentration and flow conditions, the vehicles have collected image data on faunal abundance and behaviour [3].

Four additional mobility concepts based on the original Neptune Canada crawler design are developed for ROBEX: one fully autonomous unit with a release weight, which can monitor the seabed for 12 months [4], one (semi-)autonomous tele-operated unit which is deployed via ROV at cabled infrastructures (concept 2); one autonomous unit which is deployed from ships, helicopters or via ROV (concept 3) and one unit, which is deployed from a central station with hangar and power supply (concept 4). This last version from GEOMAR closely resembles the ROBEX “Moon lander approach”. All units are compact and have similar dimensions (130 cm x 110 cm x 90 cm, LWH, Fig. 1), allow high mobility in terrain of medium roughness, and offer to carry payloads of up to 120 kg without intense sediment penetration. The in-situ access to the technical output of the ‘original crawler via the cabled observatory of OOI Canada has allowed the ROBEX

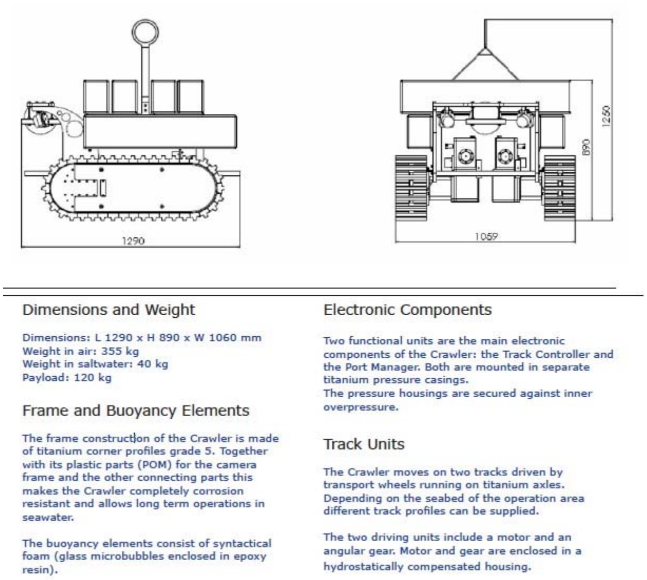

Figure 1 Basic crawler design for tele-operated missions without autonomy

teams to investigate the energy efficiency and hydrodynamic behaviour of the caterpillar propulsion on the seafloor at various vehicle speeds.

AUTONOMY

A prerequisite of autonomous operations in a mobile system is the ability to perform navigation. This can be split into localization, mapping and control of the vehicle. Additional behaviours, such as exploration, coverage, obstacle avoidance and scientific sampling are built on top of this. These behaviours need to be managed to assure consistency with the state of the system and to sequence them according to the mission description. The general software structure to achieve such an autonomous behaviour on the iCrawler (intelligent Crawler) is based on the Rock software framework [5] which has already been used in similar applications in terrestrial and space analogue environments.

The iCrawler extension is based on the hardware and electronics of the Wally crawler [2]. The extension contains a compact embedded PC, which is added to the pressure housing of the track controller. The embedded PC uses a quad-core Intel-Atom processor, to perform the necessary on-board processing and data handling. The embedded PC has direct access to the track controller, and is able to move the tracks individually, and receive motor feedback, like wheel rotations and motor currents. Together with the information from the compass – which provides an orientation estimation – this information is used in an odometry process. The odometry provides a baseline for the pose estimation. Tests on the system have resulted in accuracies of 5% distance travelled in favourable conditions. Accuracies are partially dependant on sediment characteristics, and the number of turns the crawler takes. Additional position information can be fused into the system: visual-odometry from a front facing camera, acoustic sensor data from a USBL system or landmark recognition from visual markers. With the position estimate, the Wally crawler is able to follow predetermined trajectories using a trajectory follower module.

An additional requirement for safe navigation is obstacle avoidance. The requirements and challenges for obstacle avoidance are similar for underwater crawler systems and terrestrial or space systems. A sensor needs to detect the obstacles, and use this information in the control part to perform evasive manoeuvres. The key difference for underwater system is in the choice of sensor systems. Classical laser range finders cannot be used as they operate in the infrared spectrum. For this reason, a line structured light system [6] is used for the iCrawler. From a sensor processing point of view, this is very similar to the data provided by a laser range finder, and the same processing chains can be applied (e.g. [7]). Local obstacle maps are generated from the line structured light system (see Figure 2). These local maps have a size of ca. 5 m x 5 m, and cover the immediate surroundings in front of the system. The general direction the system needs to travel is determined by the global path. Based on this direction, a search algorithm (VFH+) tries to find a combination of movement primitives, which lead to the

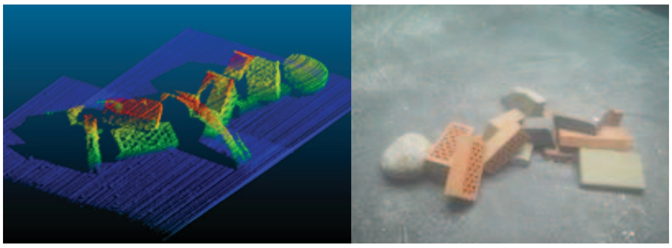

Figure 2 3D reconstruction (left) of an underwater obstacle scene (right) using a line structured light method with a visible laser light.

desired goal direction without running into obstacles. For this purpose, the 3D information from the sensor is converted into a traversability map. Based on slope and surface roughness, each location on the local map is rated according to how well the system is able to traverse that particular patch.

Concept 2 (teleoperated semi-autonomous mode) for cabled infrastructure

This iCrawler (**i**ntelligent **crawler**) is connected to any cabled observatory to carry out pre-determined autonomous operations with real-time data supply. The crawler can monitor and study an area of sediment surface proportional to the length of its umbilical cable. At the NEPTUNE Canada site a 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 is used. It is 70 m long, connected to a junction box, giving a coverage of 15,000 m^2. The caterpillar tracks create a footprint on the seafloor of $0.35m^2$ with a weight of ≈ 10 g/cm^2. A port manager, housed within a titanium pressure housing connects the Crawler to the junction box. It can be accessed via a standard Internet connection. A microcomputer which runs the two software applications required for motor control and running the Crawler web server uses a real-time operating system (RTOS) and can be contacted remotely via Telnet or an ftp connection. A Panasonic 720x480 pixel web camera (model BB-HCM580) is mounted in a pressure resistant glass globe (6000 m rated) at the front of the Crawler. Two 33 W forward facing LED lamps are used for teleoperations. The internet connection allows the data collected by sensors to be transmitted to shore and archived automatically within a Data Management and Archive System (DMAS) as developed by NEPTUNE Canada [1]. For more technical details see [2]. Figure 3 shows the tele-operated version during a transect to a gashydrate mound. A range of sensor components are visible, including a sediment microprofiler (the 'specific payload' on the figure).
The iCrawler is now capable of automatic photogrammetry, generating 3D maps of the area through which it traverses. Examples for missions, which are uploaded via the network connection are:

- follow a predetermined track on the seafloor to produce habitat maps

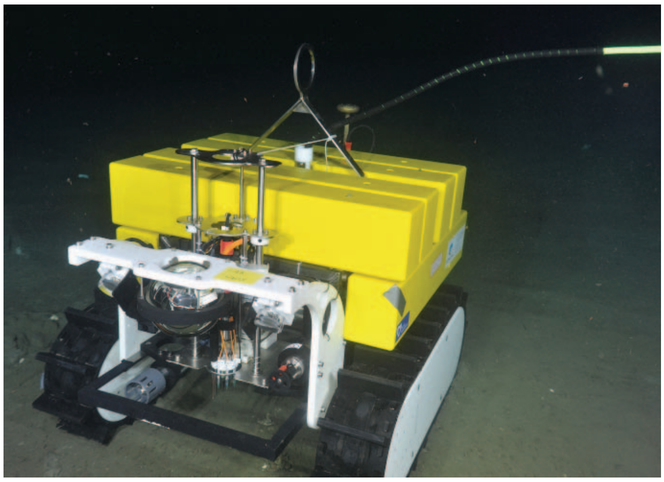

Figure 3 Teleoperated crawler during a transect to a gas-hydrate mound. A range of components are indicated, including the Max Planck sediment profiler

- regularly return to a specific location to monitor environmental changes (e.g. methane/CO_2 seepage, turbidity concentrations).

The first mission is planned for September 2015, when an international research group coordinated by the University of Hawaii and BBC will use the iCrawler to monitor the degradation of a whale carcass in Barkley Canyon, off Vancouver Island. For this mission a Kongsberg OE10-102SS PanTilt unit plus Chimera 4k camera from Subsea Imaging is added to allow HD video-footage of the benthic boundary layer. In 2016 this iCrawler will also be equipped with a camera guided gripper (see Fig. 4), which allows to relocate sensor packages and take samples). The access to the in-situ sensor data of the original crawler via the OOI cabled observatory has allowed the ROBEX teams to investigate the energy demands of moving the vehicles on the seafloor at various speeds, on various gradients and over different substrates, to aid in determination of the required battery capacities of these vehicles.

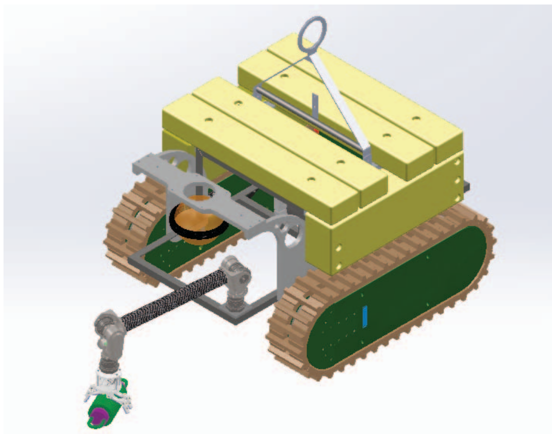

Figure 4 iCrawler with camera guided gripper for the relocation of sensors

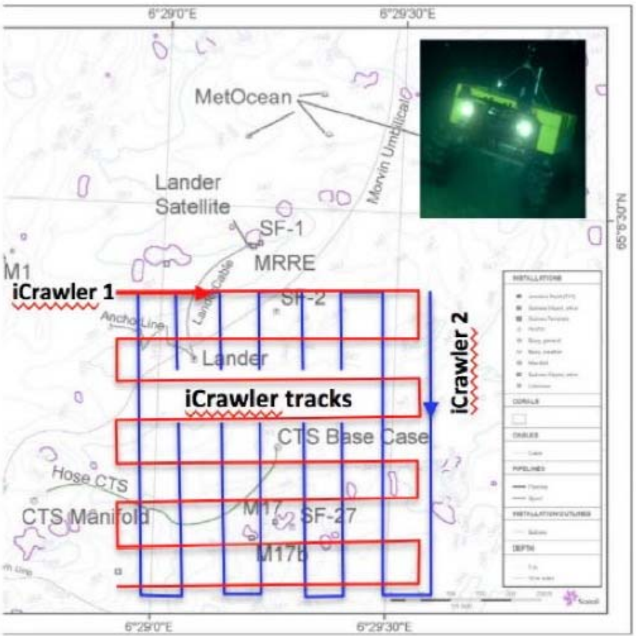

Figure 5 Typical mission for iCrawlers at an exploration site

Concept 3 (fully autonomous mode)

This iCrawler is based on concept 2 but equipped with lithium polymer accumulators (24 V / 80 Ah) and will follow pre-determined missions on the seafloor, create baseline maps with video-mosaics from the environment and geo-reference all incoming sensor data to create one GIS map. The crawler will automatically avoid obstacles on the seafloor. A typical monitoring mission for the offshore industry is presented in figure 5. A baseline study will be provided with one robot 0.5-1 years before drilling operations, followed by detailed monitoring during the 3-6 weeks drilling process and 1 mission after the end of drilling. During exploration, 1–3 robots can monitor the environment and can be maintained via ROVs. During these missions, which allow to cover 0.2 – 1 km^2 of seafloor all data will be stored and retrieved after recovery of the instrument or during ROV maintenance. On demand an emergency ascent through the water column with subsequent contact of the operational centre allows to react on environmental incidents which demand fast response.

Concept 4

In 2016 the final development stage is reached, when an iCrawler can return to a central station/junction box for data transmission and energy supply. Each final mission-plan can also be transferred to the iCrawler via Internet-connection from an operational team on land prior to deployment, thus allowing maximum flexibility for the user. The stationary lander (Fig 7) resembles the GEOMAR MOLAB system [8] which allows video-guided deployment of the central lander. This lander houses the hangar for the iCrawler and is also equipped with enough batteries to allow extended crawler-missions. The hangar is used for transport to the site of

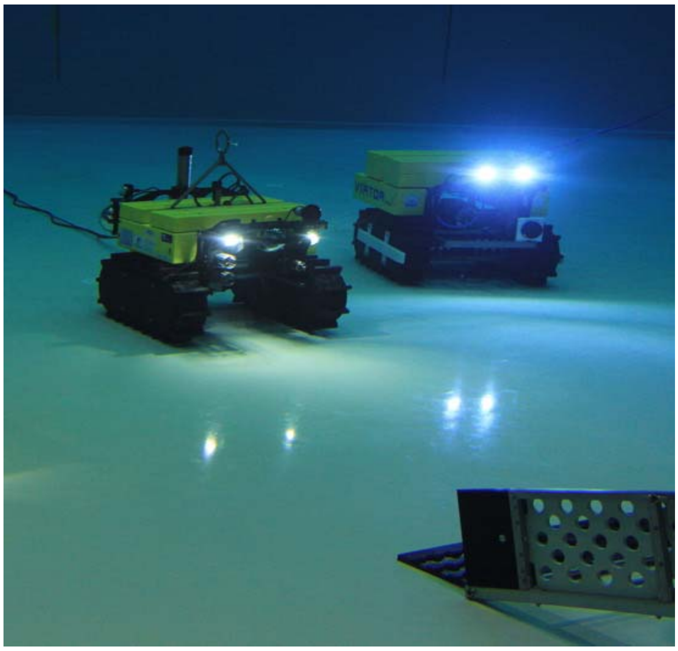

Figure 6 Different crawler prototypes during tests in the DFKI test-basin in Bremen, Germany

investigation and for recovery at the ocean surface as well as to recharge the lithium polymer accumulators on the crawler. The hangar facilitates data transfer from the lander system to the crawler and ultimately to the sea surface by acoustic modem or via a junction box. After a video-guided deployment the system operates fully autonomous for scientific missions of up to one year. The development involved careful evaluation of existing energy resources (rechargeable LiPo cells) as well as development and testing of an inductive energy transfer system (ISys; DLR). For the long-range navigation the laser-camera of DFKI is used while for the docking procedure with the lander, optical, reflecting binary markers from AIRBUS D&S are used. These markers have successfully been applied in space on the ISS for docking operations. During spring 2014 AIRBUS D&S navigation markers were placed within the operational area at 900 m water depth within the Barkley canyon to allow the future autonomous driving of crawlers and testing of navigation procedures for concept 4. These markers are also used on the crawler hanger system with the docking station. The deployment allowed still and video imaging to be made of the markers under real conditions (i.e. during periods of high flow and particle transport, during resuspension events related to crawler movement, and during still, clear conditions). An interesting observation was that the markers performed better in the single light point source conditions of the deep sea, with one crawler light operational, than in a well-lit test basin, where scattered light made the reflective markers less distinctive. In November 2014 a first successful test of the entire system in the marine exploration hall at DFKI, Bremen was conducted (Fig. 6). The crawler deployment, operation of the hangar, docking with inductive coupling, release, flotation and recovery of the

Figure 7 Sketch of the complete system for the proposed 2017 ROBEX demo-mission to Svalbard with RV Polarstern (source: GEOMAR)

system were tested. The test was also used to demonstrate the automated mapping procedures which will be tested at the Barkley Canyon methane seep site in 2015, during a one year deployment. Figure 7 shows a sketch of the complete system for the proposed 2017 ROBEX demo-mission to Svalbard with RV Polarstern.

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The deep-sea crawler projects would not be feasible without the joint efforts of the German Helmholtz Alliance "Robotic Exploration of Extreme Environments (ROBEX)" project. Aspects are the synergy effects regarding autonomy and navigation (near- and far field). Here, DFKI and AIRBUS D&S closely work together to develop hard- and software solutions. Based on the ROCK software package of the DFKI, all additional camera and sensor systems are implemented into the various platforms. This includes mission planning, as well as docking (both AIRBUS D&S) and control of the scientific payload. The inductive coupling and energy transfer are developed and tested in collaboration with the DLR. The creation of a modular robotic infrastructure environment, both in hardware (for lunar/deep sea application, networking of system components, mobility, autonomy etc.) and in software (modular approach in order to cope with re-configurability) is the major synergetic effect of ROBEX.

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