A new deep-sea crawler system - MANSIO-VIATOR

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Abstract

The exploration of space and deep-sea environments faces significant similarities. As in space, the exploration and utilization of the deep sea is performed under extreme environmental conditions. Recently, deep sea systems are becoming increasingly autonomous, resulting in challenges that are similar to autonomous space systems limited energy supply, communication, as well as navigation system control and failure handling.

The analogies between autonomous robotic space and deep-sea technologies motivated the German Helmholtz Association to setup the joint research program ROBEX (Robotic Exploration of Extreme environments). In this research program, space and marine scientists and engineers cooperated to find solutions to similar challenges and to mutually benefit from each other's technologies and capabilities. ROBEX consisted of a consortium of German maritime and space research institutions and was funded from 2012-2017.

Within the deep-sea crawler project MANSIO-VIATOR, a consortium of marine and space-related institutes developed a new underwater system uniting the advantages of a fixed sea-floor observatory harboring a mobile crawler component to map and monitor large areas on the seafloor.

Introduction

The expanding need for tools to investigate larger parts of the world oceans such as the shelf seas and continental margins for scientific reasons is continually increasing. Simultaneously, our ability to address questions concerning a changing ocean is fundamentally limited by the lack of autonomic robotic key technologies to enable longterm in-situ experiments and observation.

Since the technological and scientific exploration of space and the deep-sea is based on similar approaches, in 2012 a joint research project was financed the German Helmholtz Association. The ROBEX (Robotic Exploration of Extreme environments, see ref. 1) Helmholtz Alliance was a co-operation between 16 German research institutes, companies and universities, operating either in the field of deep-sea or space exploration. The major goal of this co-operation was the mutual exchange of information, experience and joint developments concerning the exploration of extreme environments such as the deep-sea or extra terrestrial surfaces. The program objectives were to identify, develop and verify technological synergies between the robotic exploration of the Moon and of the deep-sea.

Robotic exploration of extreme environments requires an advanced robotic development that focuses on reliable systems and components. The operation of such complex robots in their individual environments demands advanced operational concepts and operational architectures. Suitable control strategies range from tele-operated robotics, where a human operator is always part of the control loop with the robot, to fully autonomously operating robotic systems. Solutions in between include shared autonomy with partly autonomous subtask execution or way point navigation. All of these technological developments are common in both communities. The scientific and operational crews, which are controlling and operating the remote robots in their space or underwater environments, respectively, are facing similar goals, tasks and challenges. Therefore, both communities benefit from the collaboration regarding the ability of inspection, sample extraction and handling, in-situ specimen analysis and robotic manipulation.

Fig. 1: MANSIO-VIATOR on deck RV ALKOR (© S. Flögel).

Within this context, a consortium including the GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany, AIRBUS (Bremen, Germany) and the DFKI (Robotics Innovation Center, Bremen, Germany) was formed to design and build the deep-sea crawler system MANSIO-VIATOR (latin: harborage-traveller, Fig.1).

Technical components and first results

The MANSIO-VIATOR system comprises a stationary lander system (MANSIO) and a mobile deep-sea crawler (VIATOR) and is an approach close to the lander-rover systems used in space research and thus a true space analogue.

The hangar is used for transport to the site of investigation and for recovery at the ocean surface as well as to recharge the lithium polymer (LiPo) accumulators on the crawler. Currently, the hangar is improved to facilitate data transfer from the lander system to the crawler, and vice versa, and ultimately to the sea surface by acoustic modems. The system carries 12 kWh, four 2 kWh LiPo blocks are located on the crawler and two additional 2 kWh blocks on the lander. Energy transfer between the two components is provided via induction. Depending on CPU load, this allows for transects of about 2 – 4 km.

After a video-guided deployment the system has been designed to operate fully autonomous for scientific missions of up to 3 months. In 2013 and 201, the design and construction of both, the crawler VIATOR and the lander/hangar system MANSIO were carried out. This involved careful evaluation of available energy resources that led to the implementation of rechargeable LiPo cells as well as development and testing of an inductive energy transfer system. Furthermore, we decided upon hard- and software needs for the far-field (camera system, line laser) and near-field navigation (optical, active markers) that included the design and construction of multiple pressure housings. Furthermore, the system uses an USBL system to improve navigational and communicational over longer distances and up to the ocean's surface.

The system has been designed to be operational from mid-sized research vessels. After a video-guided deployment the crawler will leave the hangar and starts its pre-programmed scientific mission. After completion VIATOR returns to the lander for energy recharge in the lander. During its mission, the crawler records oceanographic and biogeochemical parameters such as temperature, salinity, pressure, currents, oxygen, pH, turbidity, and chlorophyll. The system can be deployed in water depths of up to 6000 m. In addition to the physical and biogeochemical sensors the system is equipped with a pan and tilt unit (PTU) that includes a camera and a line scanner that is used for navigational purposes and to collect data for a 3D-reconstruction of the seafloor. Optionally pCO_2 and CH_4 sensors can be implemented.

Fig. 2: MANSIO-VIATOR during deployment on Polarstern PS108 (© Lemburg).

2016 and 2017 saw vigorous testing of the system under offshore conditions in the Baltic Sea and in the Greenland Sea west of Svalbard in water depths up to 1300 m.

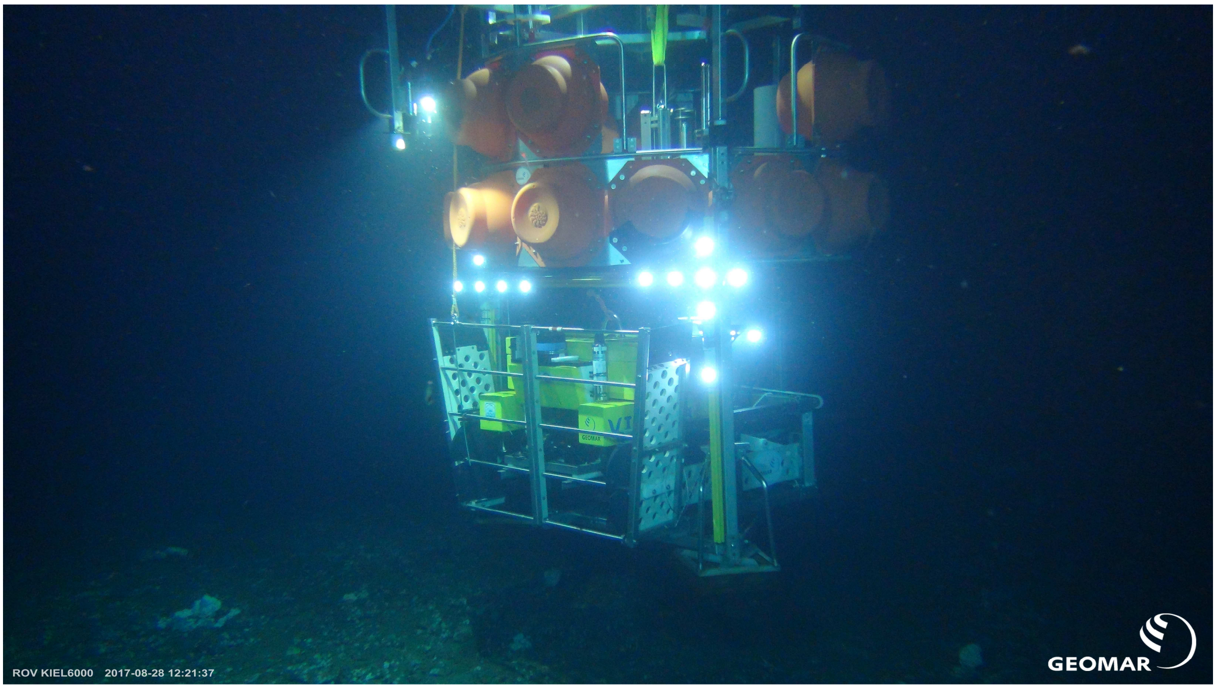

Fig. 3: MANSIO-VIATOR on the seafloor at 1270 m water depth off Svalbard (© GEOMAR).

Mission planning – AIRBUS
Christof

Marker based navigation – AIRBUS

The Autonomous Docking Function of VIATOR
The VIATOR crawler is equipped with an autonomous docking function that allows automatic homing of arbitrary positions and orientations pointing towards the MANSIO. This function is foreseen to bring the VIATOR into a defined position and orientation directly in front of the MANSIO ramp. From this position – the docking point – the VIATOR is usually able to return into the MANSIO by simple forward movement commands that stop after a mechanical end switch is pushed.
For the navigation between the VIATOR and the MANSIO, an active light pattern is used that can be recognized by VIATOR. The known positions of the light markers allow the accurate computation of the relative transform between the docking point and VIATOR's current position.

Docking process
Once the VIATOR shall return to the MANSIO, the autonomous docking function is initiated by the mission manager. Since it is not precisely known at the beginning of the docking process where the MANSIO is located the first step consists of a search mode. In this mode, the pan-tilt-unit starts turning from left to right and vice versa in order to get a first view of the MANSIO and the light-markers. During this search-process the marker-detection and tracking module is running trying to recognize the markers and to compute the relative position and orientation between VIATOR and MANSIO. After several recognitions, the docking process analyses the quality of the computed transformations and if the quality is sufficiently good the guidance-module of the docking-function generates a cubic spline as a trajectory towards the MANSIO. This trajectory is then transferred to the control-function that commands the left and right drivetrain of VIATOR to move along the planned trajectory. During this process, the controller needs permanent updates of the current positions and orientations w.r.t. the light-markers of MANSIO. Since it is possible that VIATOR moves along curves, the pan-tilt-mounted camera has to keep the markers in the camera's field of

view. For this purpose, the marker tracking is also used to command the pan-tilt-unit to track the MANSIO during VIATOR's approach movements.
Figure 4 shows all components of VIATOR involved in the docking process.

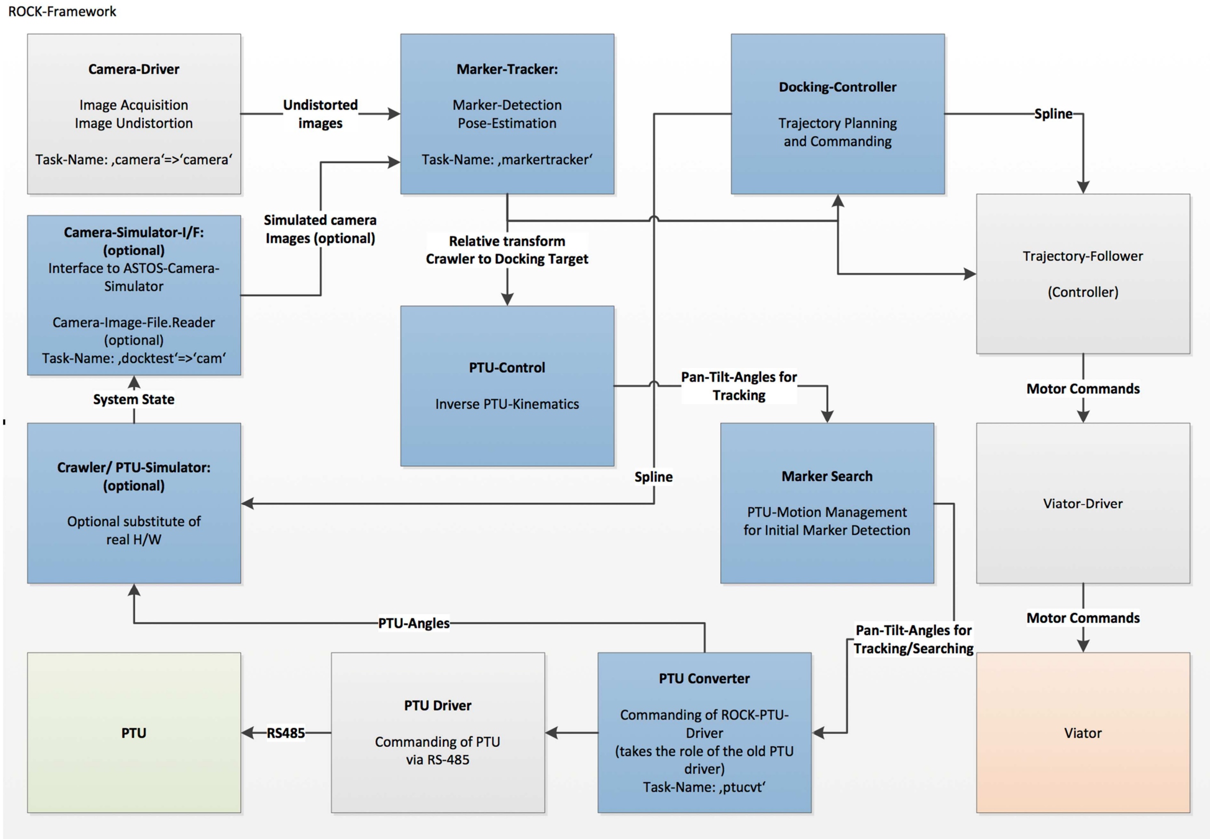

Fig. 4: Block-diagram of VIATOR's docking function.

Marker-Based Navigation

The MANSIO is equipped with three marker-crosses each consisting of seven LED lights. The markers are quite bright to assure maximum visibility even in poor visibility conditions due to marine snow or turbidity. The marker-recognition is able to recognize each marker cross even in the presence of other bright objects. For this purpose, the marker recognition applies the well-known cross-ratio of the distances between 4 collinear points. The cross ratio is invariant under perspective projection and therefore very useful for the identification of groups of four collinear points. The intersection of two such groups forms a marker-cross and provides the basis for the relative pose-estimation. The pose-estimation is running a perspective-n-point algorithm.
An essential function of the navigation module is the automatic exposure-time control. That controls the exposure time of the camera such that the markers of the MANSIO are perfectly depicted without seeing too much disturbing background features in the image. Furthermore, this function allows the detection of the lights even in difficult visibility conditions caused e.g. by suspension-clouds.

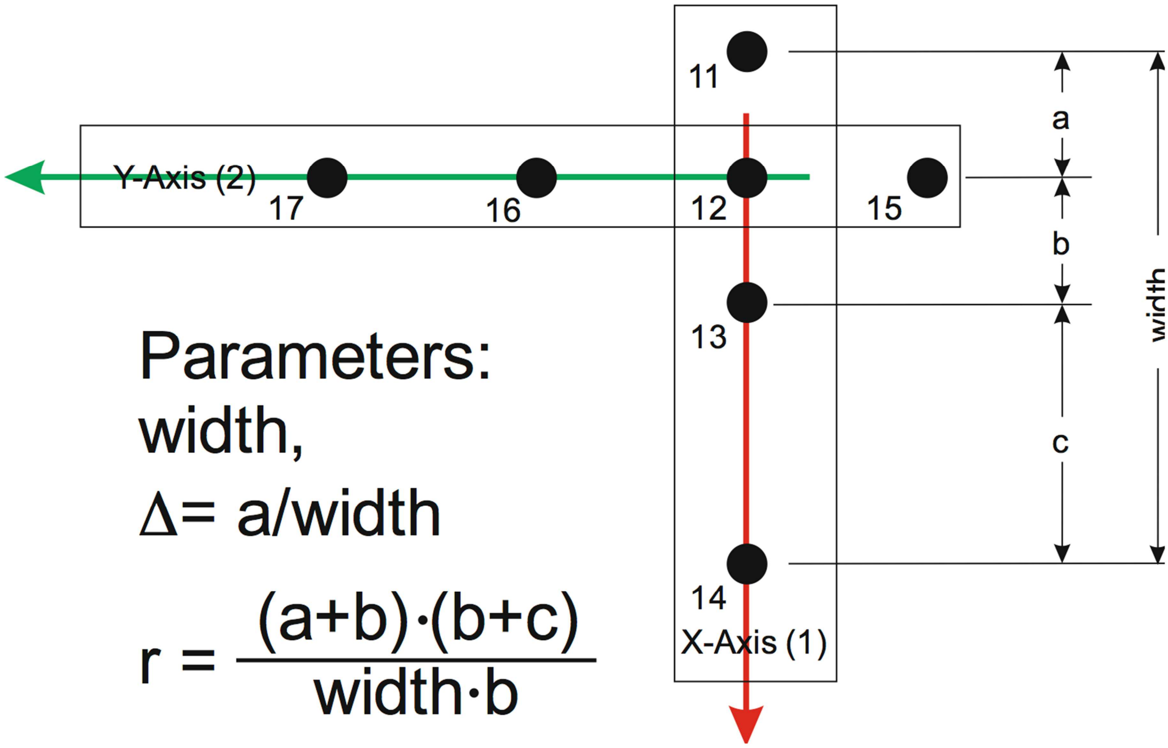

Fig. 5: Coordinate system of a cross-ratio marker-group and definition of marker-group by its cross-ratio parameters width, delta and r (cross-ratio).

Field experiments

After several tests in laboratories, tanks and on medium-sized research vessels, the final demonstration of this functionality has been shown during the PS-108 expedition of RV POLARSTERN to the Fram Strait West of Svalbard.

At a depth of more than 1270 m the VIATOR has left its hangar and performed several movements before it successfully docked to the MANSIO with the above mentioned docking-function. The following figures (5 & 6) show some snapshots from these experiments.

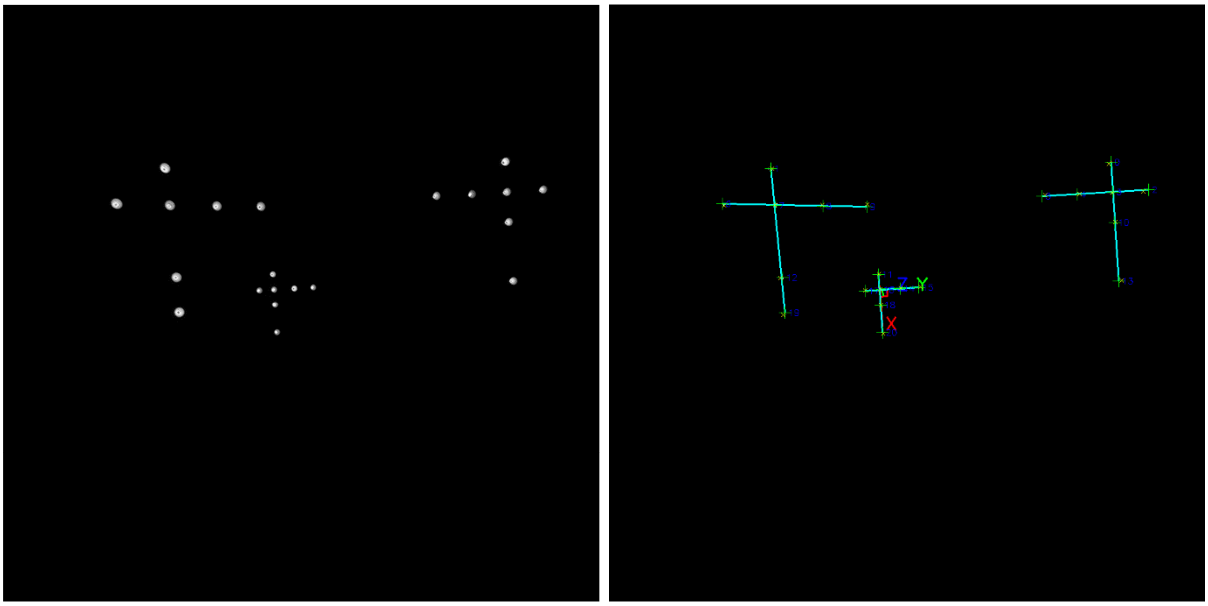

Fig. 5: Left: Camera image taken from the three marker crosses in front of the MANSIO. The exposure control assures a robust view of the LEDs without any disturbing background in the image. Right: Visualization of the marker-cross recognition.

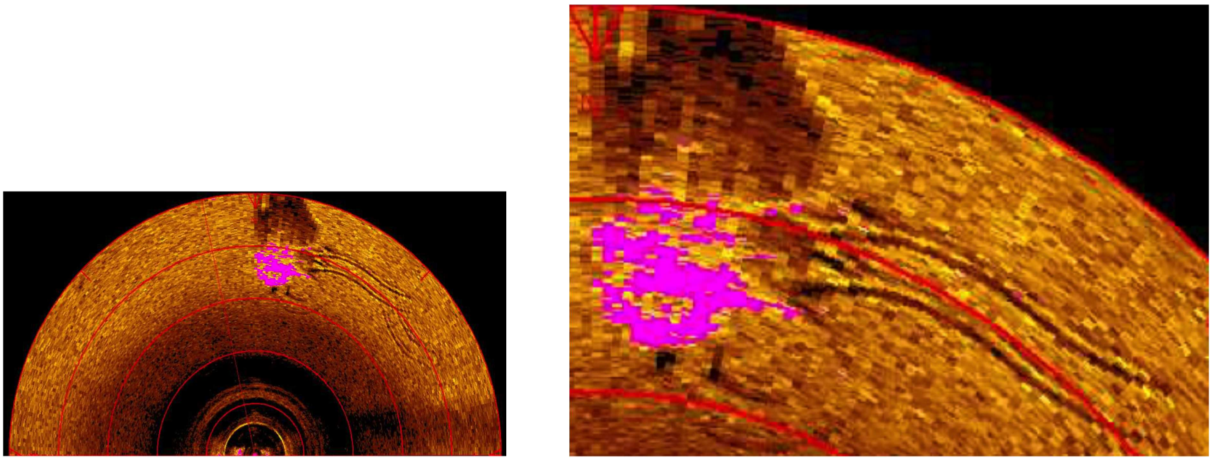

Fig. 6: Left: Sonar image taken from a remote-operated vehicle that observed the full process. Right: Zoomed sonar image showing the track of VIATOR after it performed one docking maneuver.

System command and control framework – DFKI

The VIATOR consists of a number of sensors, actors and auxiliary systems, which all need to act in a tightly coupled fashion. This co-ordination is being handled by the ROCK middle-ware, developed at DFKI-RIC in Bremen. Each component of the robot is encapsulated as ROCK-component, which provides a unified communication layer between components. A supervision layer (called Syskit) provides the means to model the functionality of the robot using the ROCK-components as building-blocks. The Syskit layer also provides an interface to the mission-manager developed by AIRBUS. Once the system is modeled and all individual components have been implemented, the Syskit system can start and supervise the robot. It also handles logging of all exchanged data which is crucial for post-mission analysis, especially in a fully-autonomous system as used here.
During the sea-trials the Syskit system performed as expected, documenting the two missions undertaken. A total of 150Gb of data were recorded in the second, 11h deployment of the MANSIO-VIATOR system, consisting of camera images, robot odometry and scientific sensor readings to name a few. The only limitation recognized was the ability to log the camera data with more than 5 FPS due to the resulting load on the system. The reason for this was two-fold: due to a mistake during the modeling phase each recorded image was also pre-processed (camera calibration rectification and de-bayering), which should only have happened to the images being further processed by one of the on-line algorithms (e.g. docking). Secondly the processing power of the robot's PC system was not sufficient for logging of 15 FPS of 4MP images.

Positioning and localization

There are three systems which handle localization and positioning during missions with the VIATOR robot: dead-reckoning using odometry and AHRS data, USBL positioning between MANSIO and VIATOR and a visual-marker based docking procedure using the camera and pan-tilt-unit on the robot. The dead-reckoning component fuses the information of track-revolutions with the orientation data from the AHRS to produce a position estimate of the robot relative to its starting position in the MANSIO lander. This system relies on the assumption, that there is minimal track-ground slippage, which would decrease its accuracy. While the AHRS used (Xsens MTi-G) has magnetometers in addition to gyroscopic sensors for angular velocities, they could not be used for orientation stabilization due to the presence of too many sources of magnetic disturbance on both the robot as well as the lander.
The USBL positioning uses two devices: a USBL head mounted onto the lander and an acoustic modem head mounted onto the robot (Evologics 17/7 USBL-System). The robot modem interrogates the lander USBL, which uses this interrogation message to calculate the spatial angles relative to the modem, and communicates them back to the modem. The modem can then use the round-trip-time to calculate its distance to the USBL, and combine

this distance with the spatial angles, resulting in a Cartesian position relative to the USBL head on the lander. This procedure is called reverse-USBL positioning. While its update rate is a lot smaller than the dead-reckoning described above (in the order of 0.2Hz), it has the advantage of being globally stable in its accuracy, providing a long-term stabilization for the dead-reckoning system. The visual marker-based docking is described separately in the section “Marker-Based Navigation”.
During the sea-trials on the dead-reckoning and USBL-positioning were working as independent localization entities, no cross-correction between the two modalities was performed. This was due to the fact, that the USBL was deployed for this purpose for the first time, and not sufficient data was available to perform a long-term stabilization of dead-reckoning using the USBL. Nevertheless both systems performed individually as expected.

A plot of the estimated robot position and the different actions performed is shown in figure 7. The recorded data will be post-processed in order to estimate the suitability of the combination of both sensor modalities in the future.

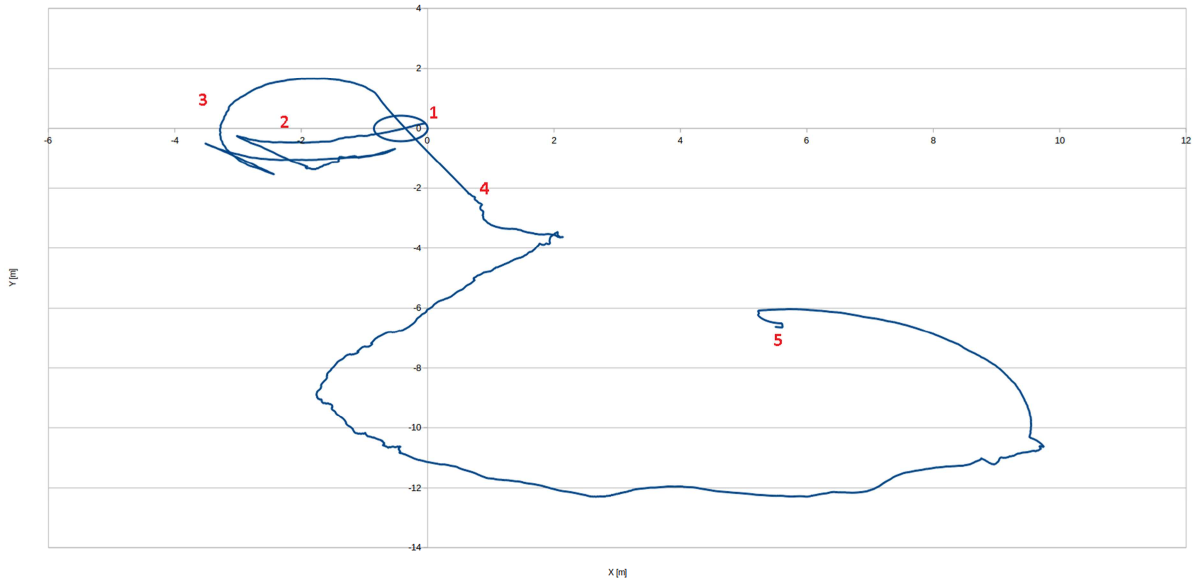

Fig. 7: Odometry track of the crawler during its deep-sea mission. 1: Descent phase in lander, AHRS records spinning of the lander on cable resulting in ellipse; 2: Backing out of the lander and successful docking; 3: Malfunction of left track visible in odometry, ROV intervention; 4: Attempts to dock; 5: Reboot of control PC

Communication and in-situ control
While the MANSIO-VIATOR-System has been conceptualized as fully-autonomous system (in accordance to the ideas presented in [3]), the addition of the USBL/Modem system onto lander and robot provided the possibility for remote intervention using a third USBL head deployed on the surface. This enabled the tracking of both systems from the ship as well as limited intervention during a mission. For this purpose two communication modes were implemented: a direct communication from the ship to the lander or robot, as well as an indirect communication with the robot using the lander as relay. The second mode was necessary, since the robot has no direct acoustic line-of-sight to the ship while parked inside the lander. A simple ASCII-based protocol was implemented discerning the different messages. This communication protocol was originally developed in the Europa-Explorer project [4]. The following commands have been implemented:

* Ship-Lander: Change brightness of docking-lamps
* Ship-Lander: Activate/Deactivate charging
* Ship-Lander: Activate/Deactivate message-forwarding
* Ship-VIATOR: bash-shell
* Ship-VIATOR: syskit-shell

The commands for the syskit- and bash-shells would be forwarded by the lander to the crawler if message-forwarding was activated on the lander. Having access to the robot over one of the two shells complete control of the system is possible. The two limiting factors are bandwidth and dropped messages. The bandwidth of the USBL data channel is severely limited, each message can only transport 55 8-bit characters. Due to the limited speed of sound in water a transmission to a depth of 1500 m takes about one second each direction. This makes transfer of larger sections of data nearly impossible, only commands can be transferred. The second limitation is more severe in comparison: since the USBL requires direct line-of-sight for reliable operation, all objects between lander/crawler and the ship result in dropped messages. This could be remedied in theory by addition of a more secure transport-protocol, which will be investigated and developed in the future.
During the sea-trials the in-situ control mechanism had to be used to a far greater extent than expected: while it was only designed to change mission parameters and supervise the autonomous execution of missions, due to a mechanical malfunction in the left track of the robot (it was not turning at the commanded speed but much slower), the command-line shell was used to directly control the robot remotely. Due to the limitations described above this was tedious but the only option to utilize the allocated mission time. After aborting the mission execution and reverting to manual control it was attempted to dock the VIATOR into the MANSIO, since this is necessary for recovery of the system to the surface. During these attempts it was necessary to reboot the control PC in order to get it into the correct configuration – all done using a narrow acoustic data channel. While the remote-command system is far from being optimal in its functionality it enabled orderly recovery of the VIATOR parked in the MANSIO garage, and prevented manual recovery using an ROV system.

Structure from light/motion – Kraken Robotik

Jakob/Alex

Conclusion and Outlook

While the docking process using the marker system described in this paper worked in the conditions found during the sea-trials, there are a number of ideas which could increase its robustness. A major drawback of the current system is its minimal stand-off distance: due to the large base-line of the markers they can only be observed until the VIATOR is about 2m in front of the MANSIO. The rest of the way to the mechanical docking port has to be driven blindly, guided by rails on the MANSIO. One idea was to add a second, smaller marker system consisting of a visual marker and a strong magnet near the mechanical docking port, which then could be used for the final approach. This was evaluated successfully in [2] for AUV usage and should be easily adaptable for this system.

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