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How AI and Robotics can support marine mining

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Abstract

Marine Mining initiatives open up a completely new field of subsea operations. Offshore oil and gas sites are still primarily located in areas, where divers can support maintenance and repair, while future marine mining will take place in greater depths and with a complexity of machines that require support from robotic systems equipped with a substantial amount of artificial intelligence.

At the Robotics Innovation Center, a department of the German Research Center for Artificial Intelligence (DFKI), technologies are being developed that have the potential to support marine mining in all stages from prospection to decommissioning. Various robotic technologies from systems, subsea-residence operation, inspection manipulation as well as autonomy are presented in the following chapters. Finally, a proposition for a robotic mining system is presented, that strives for minimal invasiveness of the marine environment.

Introduction

With the increased demand of rare earth metals, deep-sea mining gains increasing interest. As most mining areas are located well out of reach of divers, robotic technology is required to support operations in high-depths. Sub-sea resident autonomous underwater vehicles for instance can help to continuously monitor operations and report the requirement of human intervention using remotely operated vehicles. Speical miniaturized autonomous vehicles can even help to monitor structures from within. Multi-modal inspection that also works under limited visibility can extend mission time. Besides monitoring, manipulation is a key aspect for remote-controlled or even autonomous maintenance. Dexterous grippers with tactile feedback that works independent of the surrounding pressure are presented as a key technology for this aspect. Combining this technology with algorithms for autonomous behavior and from artificial intelligence helps to assess the sensor information and allows for autonomous decision-making. All these mentioned technologies are presented in the following sections followed by a proposal how a deep-sea mining platform that strives for minimal invasive interaction with the marine environment.

Robotic system technologies

Nowadays, robotic systems used for offshore asset inspection mostly consist of manually-operated tethered ROVs and waypoint-following AUVs, whose endurance and onboard intelligence are limited. While ROVs allow for flexible inspection campaigns, enabling the operator to react to any unforeseen defect or anomaly, OpEx costs for the support vessel and crew are high.

Current AUVs on the other hand can perform simple waypoint-following missions on their own while recording sensor data, but have limited endurance (hours to days) and, most importantly, often cannot react to detected irregularities, obstacles or incorrect pre-programmed locations of the assets to be inspected.

Recent research in the field of autonomous underwater robots thus focuses on making the onboard software more capable and intelligent while at the same time creating underwater battery charging and data handover infrastructure for AUVs.

Towards more intelligent AUVs

Commercial off-the-shelf AUVs mostly rely on acoustic and inertial sensors for their navigation. Speed measurements from a DVL (Doppler Velocity Log) are combined with orientation values from gyroscopes and accelerometers to estimate the current position. These only relative updates are sometimes augmented by absolute position fixes from a USBL.
But during the mission, the inspection assets might not be located exactly at their expected positions. This might be due to incorrect positioning during the installation campaign, objects being dragged off location by fishermen or sediments slowly hiding a pipeline from the view of standard sensors.
So it becomes essential to equip modern AUVs with sensors and software which can search, detect, track and re-acquire their inspection targets.
In addition, classical sensor suites consisting of cameras and sonars can be augmented with higher-resolution 3D sensing such as Laser-line projectors (structured light). This enables the AUV's onboard software to create a millimeter-precision 3D model of the asset, which can be compared to CAD models or previous inspection run data. By employing a fully automated 3D model cross-check, the AUV could then detect asset deformations, defects, CP depletion or marine growth, even while still submerged during the ongoing inspection run.

Seafloor AUV support infrastructure

Current AUVs have limited endurance, mostly due to their battery capacity. Depending on the sensor suite, onboard data storage space can also be a limiting factor. This causes AUV missions to run no longer than between several hours and a few days, depending on the size and shape of the AUV, propulsion and sensor efficiency as well as environmental conditions in the deployment area.

To remedy this, current AUV research focuses on subsea docking stations featuring underwater battery charging as well as broadband data links to the AUV.
Depending on the desired charging time, either inductive energy transfer or underwater-pluggable connectors are used. While both require precise positioning, the latter allows for higher charging currents but also requires a more complex and higher-force plugging mechanism.
To transfer inspection results from the AUV and also upload new missions, a high-bandwith data link is required. Technologies employed in current research include LED- or Laser-based optical links as well as sub-centimeter-range RF links. While an optical data connection is more robust to incorrect transmitter positioning, RF links can achieve much higher bandwidths, albeit only across few millimeters of saltwater.

To charge its battery and transfer data, the AUV has to find its way back home and correctly execute the docking process fully autonomously. Here, a combination of dock-relative positioning sensors are employed. They range from kilometer-range USBL positions to mid-range dock-mounted Sonar reflector tracking down to camera-based visual marker tracking and servoing while in close proximity.

The full chain of autonomous dock-relative navigation, docking and undocking as well as establishing a broadband data link and recharging the AUV battery while submerged has been developed and successfully tested in the FlatFish project at DFKI in Bremen, Germany (see Figure 1).

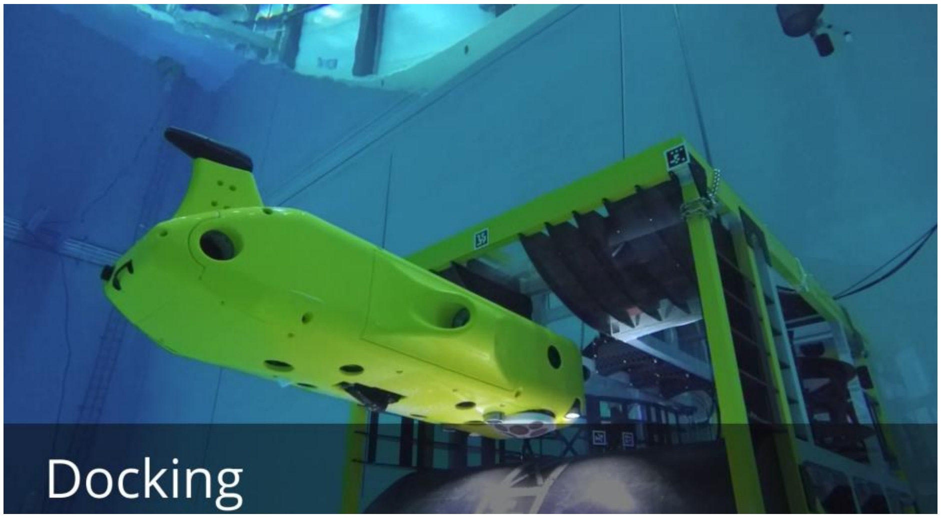

Figure 1 The FlatFish AUV fully autonomously enters its docking station at DFKI's saltwater basin in Bremen, Germany. Once fully docked, data transfer and battery charging commence

The FlatFish project is a venture undertaken by the German Research Center for Artificial Intelligence (DFKI), the Brazilian Institute of Robotics (BIR) and Shell. It aims at designing an autonomous underwater vehicle (AUV) for repeated inspections of oil & gas subsea structures whilst being submerged for extended periods of time.

In System Inspection

Due to the harsh environment and the high degree of complexity, underwater mining machines are prone to failure. Inspection and maintenance are therefore mandatory steps towards an uninterrupted and economical operation. Currently mining machines are being brought back to the surface to be serviced or inspected. This usually interrupts mining operations and causes high costs. To minimize costs and human intervention it is desirable to fulfill these tasks autonomously in the underwater environment. Especially internal components of mining machines are a particular challenge during inspection, since they are usually difficult to access. The in-field inspection of parts and components inside mining equipment thus may require the use of miniaturized underwater vehicles that can operate largely autonomously.

AUV^{x}

Figure 2 - The AUV^{x} shortly after an experiment (Photo: Annemarie Popp, DFKI GmbH)

The AUV^{x} was developed as a miniaturized exploration and research vehicle (see Figure 2). The vehicle can be operated both autonomous or remotely as a hybrid ROV with a near field optical communication modem or a copper wire cable.

With its small small dimensions of only 393 x 188 x 200 mm^{3}, miniaturized robots like the AUV^{x} [1] can accomplish inspection and potentially maintenance tasks of poorly accessible, internal parts of a mining machine (see figure 20170509_ AUV^{x} _1081.jpg). In this particular case, the camera of the AUV^{x} cannot only serve as a sensory input for navigational tasks, but also as a means of visually examining the object under inspection.

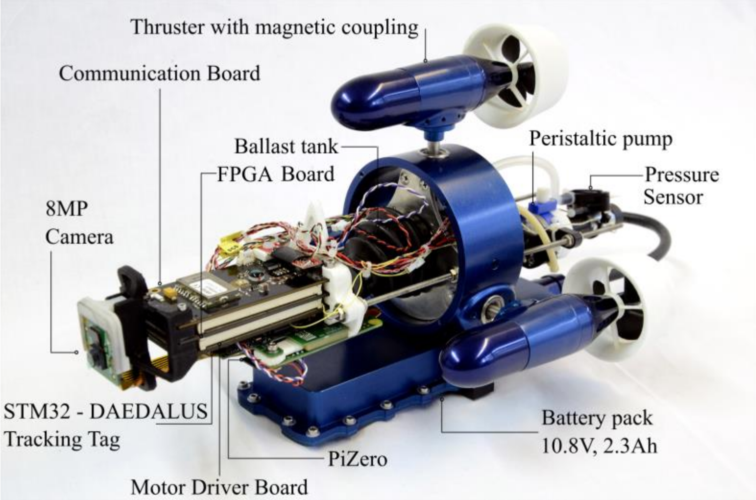

Figure 3 - AUV x without acrylic glas domes (bow and stern) and battery module cladding

Though being very small, the AUV^x has sufficient computing power to process the upcoming data. In order not to burden the AUV^x's main processor with low-level tasks such as position control, a multi-layered approach consisting of an FPGA, a microcontroller and an embedded PC was chosen for the AUV^x (see Figure 3). What makes this system an ideal candidate for the usage in underwater inspection tasks are its 6 DOF and the use of 3 thrusters which ensure that the vehicle is very agile and potentially redundant concerning thruster setup.

Inspection sensor suites

For inspection of a marine mining or production site, higher resolution of survey data allows the detection of smaller problems. While a side scan or imaging sonar can give a good overview of the situation, it can be vital to go more into detail to detect e.g. cracks or dents in pipelines as early as possible. With an optical camera, a high resolution is easily achievable. In addition, the small size and weight of modern cameras in comparison to imaging sonars allows much smaller inspection vehicles. Those vehicles are easier to deploy and can get much closer to the object of interest. However, optical sensors become unreliable in turbid waters and depth information is not available by a single camera system. To address these problems, a structured light projector can be combined with a camera, allowing an increased penetration in turbid water and 3D reconstruction of the observed area through intelligent algorithms. The setup of this combined sensor normally consists of a line laser mounted in a fixed distance and a fixed angle to a camera. The combination of distance and angle specify the depth resolution and working distances of the system. When an object is inside the working area the laser line on the object can be detected in the camera image and the position of the line can be used to calculate the distances on this line. Doing this while moving the system along the object of interest allows the creation of a detailed 3D-model. Experiments [2] have shown that this setup is able to scan objects even in turbid water with minimal reduction in precision where a human operator cannot recognize the object anymore (see Figure 4 Brightness distribution at different turbidities while scanning a pipe at 1.8m distance[2] and Figure 5). Of course, artificial intelligence algorithms are needed to filter and match vehicle movement and sensor data to minimize distortion in the resulting object.

The high detailed 3D models may be used to

- create a three-dimensional map for the vehicle operator or an autonomous system to aid collision free navigation
- create an immersive virtual reality to analyse the mining site
- automaticaly compare the scanned objects with construction data and detect changes

Especially the third possibility is of high importance as it allows an AUV to automatically patrol a mining site or any other underwater structure. By using its intelligent algorithms is is able to decide which changes can pose a problem in the future and should be reported while it remains silent in normal operation and no suppoting vessel is required to stay in the area. Using a high-resolution sensor in combination with small resident autonomous vehicles [3] can therefore help to detect potential problems before serious consequeces are happening. This helps avoiding production down times, environmental disasters, damage to machines and danger for workers.

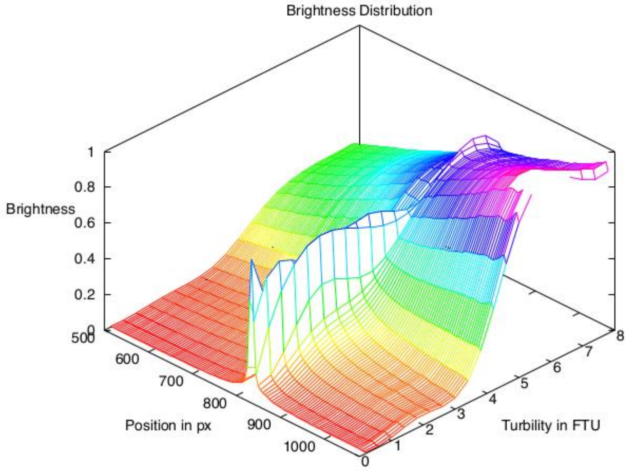

Figure 4 Brightness distribution at different turbidities while scanning a pipe at 1.8m distance[2]

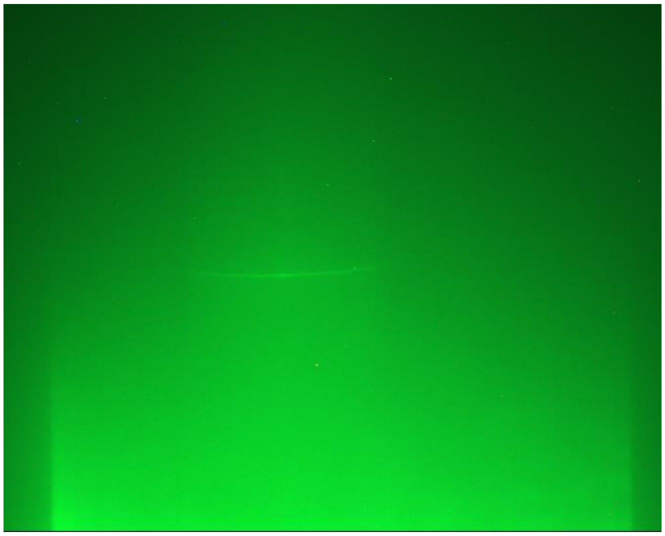

Figure 5 Camera image at 1.8m distance to pipe and 5.1 FTU[2]

Fine manipulation

Inspecting operational areas, vehicles and structures is just one part of the tasks that robots can perform in order to support marine mining operations. As most of the areas of interest in the Clipperton Fracture Zone are in depths below 3000 m [4], divers cannot support maintenance and repair operations at the sea-floor. While ROVs still could be used for these tasks, most of them lack tactile- or even force-feedback, which is crucial for fine manipulation operations. Attempts to include tactile feedback into underwater grippers are reported in several publications [5-7]. However, most of these are rated for depth ratings that are from the deep-sea areas or lack required gripping forces.

A three-fingered gripper system comprising pressure-tolerant electronics as well as multi-modal force sensing independent of the ambient pressure of the water column was presented in [10]. The gripper system is actuated using hydraulics [9] and is thus compatible with most deep-sea manipulators. The sensor configuration consists of force-torque sensors in each finger, piezoelectric sensor arrays as well as fiber-optic contact sensors. The output of the contact sensors is shown in Figure 6.

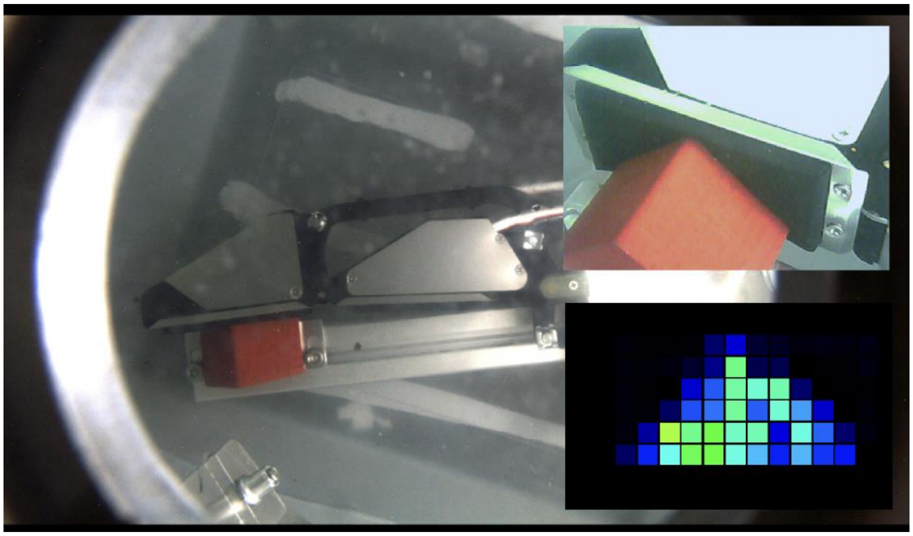

Figure 6 Tactile feedback (lower right) from contact with a triangular shaped building brick (upper right) at 600 bar within a pressure chamber (center) [8]

Using the integrated processing architecture that is able to locally pre-process the information obtained by the tactile sensing system, information regarding the object dimensions can be transmitted out of the gripper reducing the data that needs to be transmitted to central processing systems.

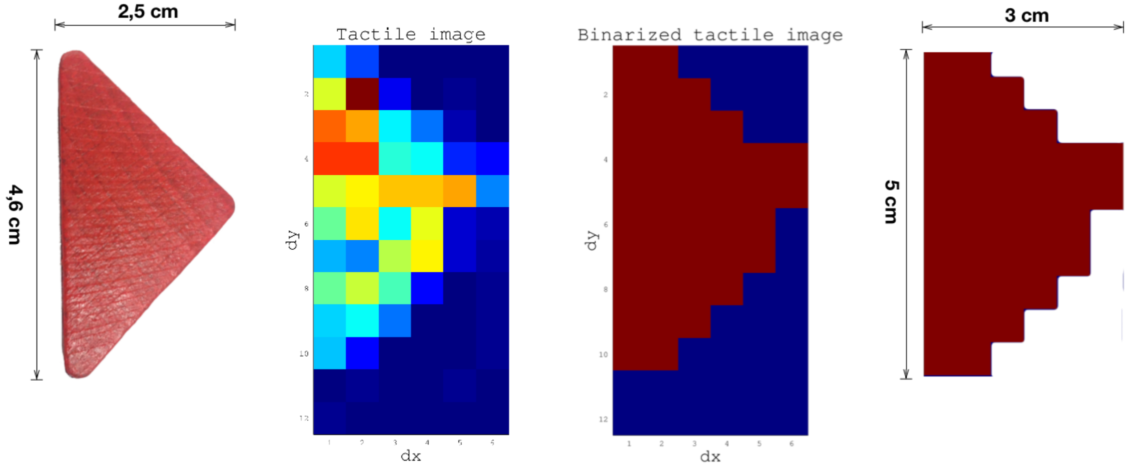

Figure 7 Calculating the object dimensions based on the tactile image [20]

Figure 7 shows how the shape of the grasped object can be calculated using the spatial resolution of the tacticle sensor of 5 mm. Further increase of the resolution can be obtained by applying triangulation of the sensor signal strength.
Such kind of systems build the foundation of autonomous manipulation using AUVs and allow the execution of remote controlled manipulation tasks even under limited visibility. It was shown that tactile reconstruction of objects is possible with such a system [11].

Robot autonomy and AI

Although we have seen advances in autonomous vehicles in several areas in recent years, most production scenarios still use systems, where every degree of freedom or feature of a machine has to be directly controlled by a trained expert. With systems becoming more and more complex to tackle the challenges of operating in increasingly difficult environments, this direct control approach will reach its limits soon, if it has not reached it already. Not just to lower costs in human resources, but to be able to use such systems at all and furthermore to use them in a sustainable and secure manner, the level of autonomy in these systems has to be increased significantly. In order to achieve this, the autonomous system (the 'robot') not only needs means to perceive its environment using suitable sensors, but it also has to act on them. While purely reactive behaviors have their advantages in real-time scenarios and may even lead to some desired emergent behavior, for example in obstacle avoidance, in order to act deliberately the system needs to reason on the data. To be able to do so, the system usually relies on models. Such a model is an abstraction of the reality and allows the robot to interpret the incoming data. For example, a beam-based proximity model of its sonar range finder would allow the robot to interpret the sensor data and deduct physical properties of its environment (e.g. the actual range to an object) from that. Probabilistic models explicitly integrate the noise of the sensors or of robot motion in order to deal with their inherent uncertainties and allow for a belief of the most likely robot state in an environment [12].

In robotics, those models are mostly analytical models based in physics, for example dynamic motion models, fluid dynamic models or optical sensor models. Such models require a deep knowledge of the underlying physics, but are usually quite computationally efficient, once the correct parameters are found. However, they have two main drawbacks: first, the parameter identification and optimization can be very difficult and tedious, and often has to be reiterated to adapt to changing environments. Secondly, these analytical models may not be able to precisely describe highly complex or intertwined observations.

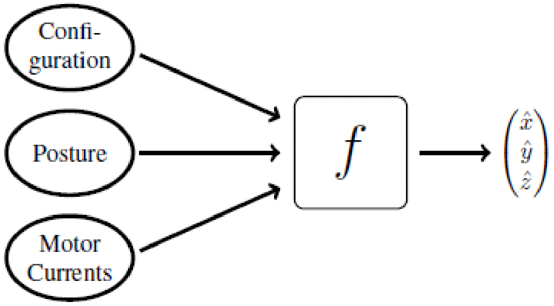

Figure 8: Multi target function regression approach with robot posture, motor currents and present configuration as inputs to describe magnetic field distortions

In these complex cases, which are quite typical for robotic application scenarios, machine learning techniques like neural networks or support vector machines are well suited AI tools still be able to come up with high quality models. Admittedly, enough data to train such classificators or function regressors like a multi layer perceptron (MLP) or a support vector regressor (SVR) is needed and care has to be taken to avoid overfitting. A discussion of those techniques for a concrete robotic scenario is described in [13], where machine learning techniques are applied to model the dynamic distortions of the magnetic field in order to enhance magnetometer-based orientation estimation and localization (compare Figure 9).

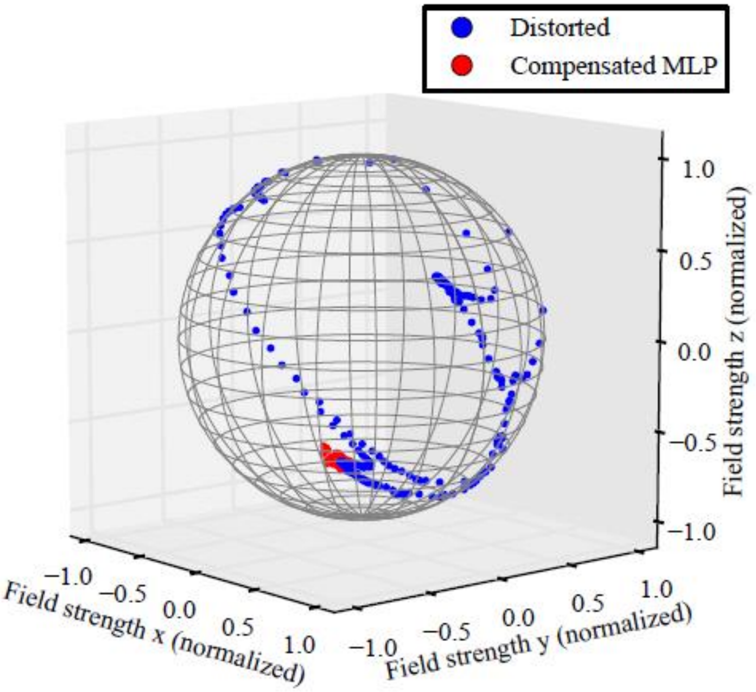

Figure 9: 3D scatter plot of distorted vs. MLP compensated direction measurements on a robot. Every dot represents the direction of a magnetic field measurement [13]

Especially in the area of marine mining, secure navigation close to subsea assets or cooperating robots will be necessary and become more and more frequent. Current localization techniques for unmanned underwater vehicles are often limited in there robustness depending on the current state of the environment, due to e.g. turbidity, changing sound propagation velocity, etc. In [6], a close range localization system combining cameras and magnetometers is described, that utilizes machine learning techniques to enhance robustness for docking and homing of underwater vehicles (see Figure 10).

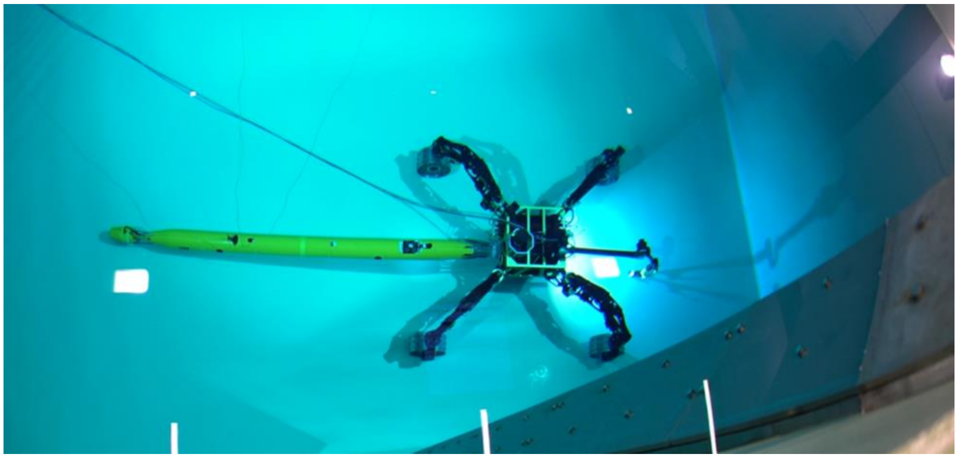

Figure 10 AUV Leng and hybrid crawler SherpaUW during docking tests in the DFKI RIC test basin

A severe limitation of currently-deployed autonomous systems (AUVs, autonomous benthic crawlers) is the necessity to be manually retrieved, recharged and re-programmed after executing a single mission. For a persistent autonomy scenario, all of these tasks will have to be executed autonomously as well. With current technology, this requires a docking-station (no long-term energy system available, no broadband communication for underwater scenarios available). For such a mission, the behavior of the system needs to be reliable additionally to the navigation system. When a problem occurs that may hinder or prevent the autonomous system from returning to the docking station, the device must decide on its own how to handle this situation without the possibility of human intervention. So again, the ability for a robotic system to equip complex, adapting software components is a key requirement for the advent of long-term autonomous robotic systems. Visions for such long-term Real-Time Monitoring systems have been detailed in [15].

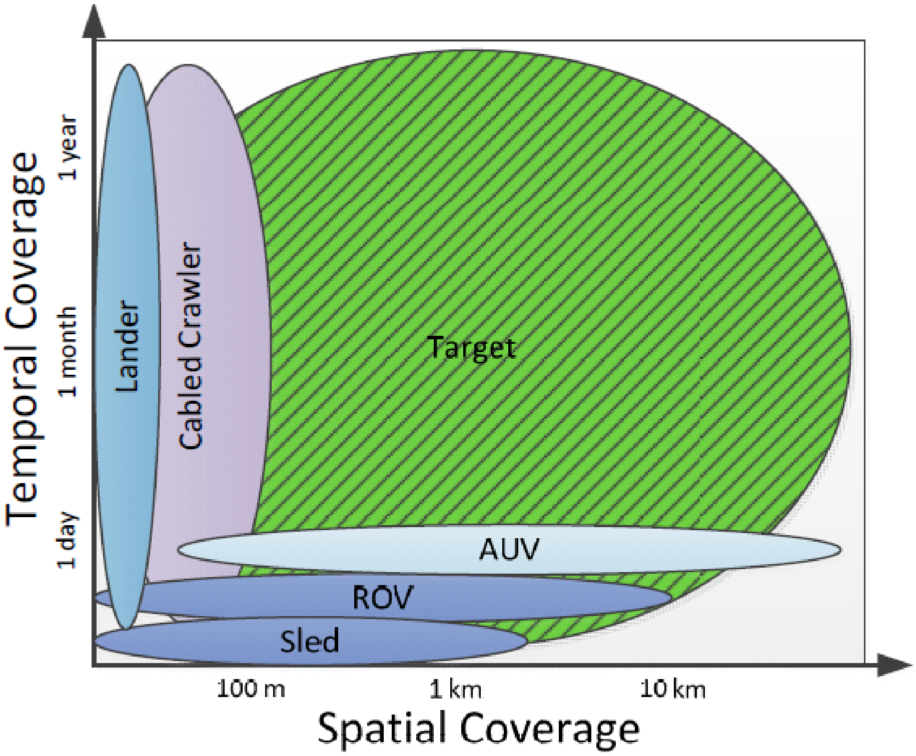

Figure 11: Spatial and Temporal Coverage of Different Sampling Devices [5]

Such long-term autonomous systems will most-likely consist of more than one vehicle – a number of different designs have been proposed on how this could look like. The additional requirement of coordinating more than one vehicle are demanding, but breaking down the tasks can be a key to enabling systems to perform its task. Two examples for such systems are the Mansio/Viator system by Geomar [16] and the Leng/Teredo system by DFKI [17]. The Mansio/Viator consists of a docking station (Mansio) which is designed as a garage for the mobile rover (Viator). The system is deployed by crane with Viator safely docked into Mansio. After touch-down, a ramp is lowered and the crawler can start its scientific measurement. It can use the Mansio dock for a number of important tasks: 1) recharging its batteries 2) navigation beacon 3) launch/recovery system 4) communication relay to top. The software components needed are extensive, since the Viator has to operate autonomously and reach its decisions (when to charge, when to return) on its own. It is especially important to be able to return to the garage dock at the end of its mission, as it is not equipped for manual ascent. In the Leng/Teredo system an AUV (Leng) is transported to its destination within an "ice shuttle" called Teredo. Teredo is equipped with a melting head, able to melt through sea-ice. After reaching the ocean, the AUV is deployed. During the following mission the Teredo has similar tasks as the Mansio system. Since the Leng AUV is a swimming system, the requirements for its navigation and reasoning capabilities are even more complex than with the crawler, requiring extensive sensors and computational capabilities [18][19]. At the end of the mission, the AUV is re-integrated into the Teredo and the complete contraption is returned to the surface (see Figure 12 for details).

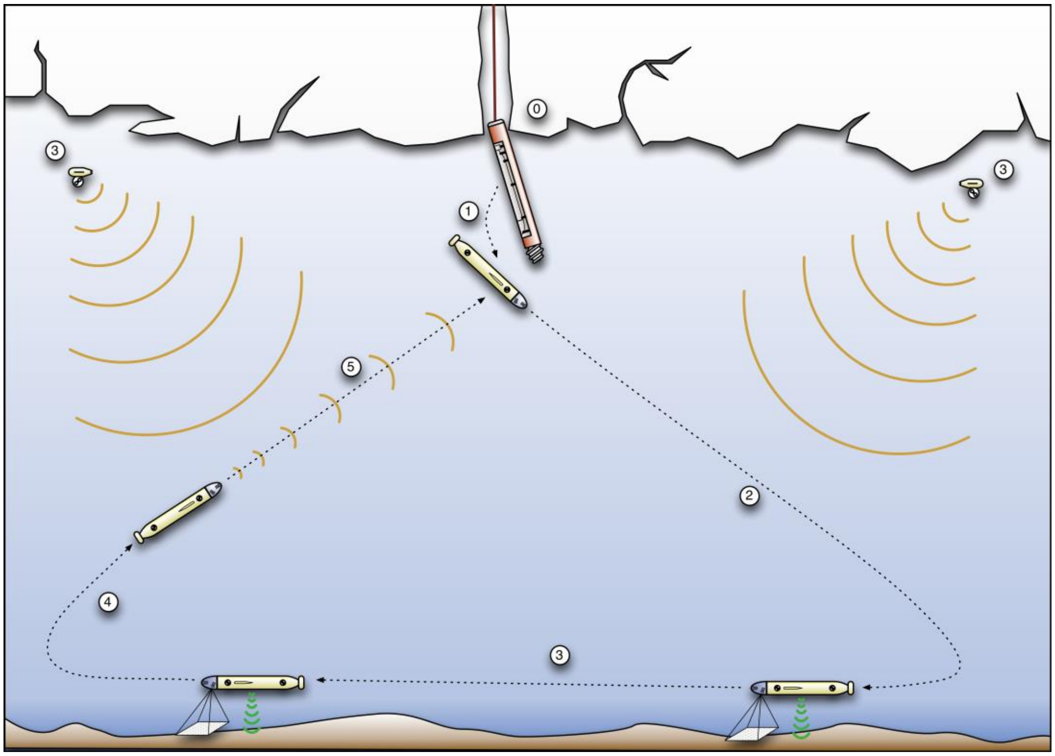

Figure 12: Schematic overview of a possible mission scenario. With a Leng/Teredo type system.

Process optimization for future mining activities cannot be achieved by the enhancement of single machines or assets alone, though. Another key component to handle the full chain of future mining processes will be to tackle the coordinated operation of multiple complex systems in space and time. Here, manual planning will reach its limits, but artificial intelligence techniques like autonomous spatio-temporal planning can be applied to achieve coordination of all actors for productive and safe long-term operation as described for example in [20,21].

Proposition of a minimally invasive mining platform

Based on the insights from projects using legged locomotion and the technologies presented in the previous sections, a robotic platform is proposed that is meant to have only minimal ground contact in order to avoid the generation of plumes based on locomotion. An illustrative drawing of the robot is depicted in Figure 13. At the front, there is a phalanx of high-speed gripper systems that select manganese nodules individually based on multimodal sensor input like camera data and laser-scans. The nodules itself are transported inside the carrier of such a system. Additional sediment that is carried along with the nodules inside the robot is collected, compacted and deployed on the sea-floor. Besides the minimum ground contact, such a system is also cabaple of adapting to changing terrain conditions. The individual selection of nodules allows the parametrization of the nodule selection, preserving nodules on the sea floor as a habitat for marine life.

This approach and its benefits need to be validated on laboratory and field tests, which need to be performed in the future. Combining this idea with the technologies presented in the previous sections, that is: using multiple instances of these robots that are equipped with fine-manipulation technology and a variety of inspection sensors while the fleet of robots is maintained and monitored by subsea-resident autonomous underwater vehicles has the potential for an interesting alternative solution compared to existing approaches.

Figure 13 Illustrative drawing for robotic platform with minimal-invasive ground contact and individual handling of manganese nodules

Summary

Marine Mining operations require the appliance of various equipment in order to operate safely and with minimal interference of the marine environment. Robotic solutions ranging from vehicle technology and operation, inspection, manipulation as well as autonomous capabilities combined with attempts from artificial intelligence can support these operations in the areas of maintenance and repair. Based on robotic approaches regarding a minimal invasive mining solution, we propose a robotic design that ideally has minimum impact on the sea floor and reduces the risk of plumes during the collection of manganese nodules.

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