From Space Robotics to Underwater Mining

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Abstract

Exploration of mineral resources on ocean floor calls for unmanned systems and machines controlled from the surface. Removing operators from the vicinity of worksites introduces many technical challenges: low situational awareness in unknown environments, complexity of operated machines, and the need for high bandwidth real-time communication. Precise maps of the worksites underwater do not exist and accurate localization of remote machines at the end of several kilometer long tethers is not straightforward. Additionally, the cost of teleoperation is high - it requires highly skilled operators as the cost of an error is extremely high. These factors make it difficult to exploit the underwater resources economically and with minimum environmental damage.

Challenges of operating underwater mining machinery are similar to those of robotic systems on-orbit or during planetary exploration. For space systems a combination of two approaches is used to address the difficulty of teleoperation: a) presenting virtual models of worksites and controlled hardware to operators and b) increasing the remote systems' autonomy. Immersing the operators in virtual environments increases their situational awareness. Autonomy enables the remote systems to perform some of their tasks using on-board sensors and intelligence, control certain degrees of freedom and to operate safely with minimum operator involvement. Planning space missions and developing necessary technologies includes various structured processes, e.g., phased development, assessment of maturity and difficulty of required technologies, and analysis and management of project risks. Technologies and expertise gained in developing systems for space may be useful for autonomous seabed mining systems.

Keywords: Underwater mining, space robotics, tele-operation, autonomy, 3D imaging,

1 Underwater mining operations

Deep sea mining poses a very significant challenge, as it is not possible to have mining staff on site at such depths. Thus, all operations need to be performed by automated or semi-automated craft and robotic equipment specially designed to withstand pressure and capable of performing their tasks. These systems must either be controlled remotely via teleoperation or endowed with a certain degree of autonomy.

Removing operators from the equipment or even from the vicinity of the worksite restricts their situational awareness as they have to rely on camera views, real time telemetry, estimated locations and prior maps of the worksites [Whitcomb 2000]. Autonomy requires real-time perception that enables the underwater craft to position themselves with respect to local features and in a global sense, allowing them to perform the mining tasks. Challenges of underwater mining using remote mining equipment include

- Low situational awareness of the operators due to restricted camera views, unnatural illumination conditions, lack of 3D perception and non-visual sensory perception.
- Potentially poor visibility underwater especially when close to active mining areas.

- The need for real time and wide bandwidth of communication links to the surface transmitting images and telemetry.
- Complexity of the teleoperation tasks that need to be performed, e.g., navigation of a Remotely Operated Vehicle (ROV), which is performed in all six degrees of freedom; operation of mining tools during precise mining.
- The presence of long tethers connecting to the surface (directly or indirectly).
- The lack of accurate, detailed and current maps of the seabed at the mining worksite.
- The need to maintain a positioning system infrastructure enabling accurate localization.
- The need for underwater infrastructure in support of the mining operations and craft.
- The cost of retrieving craft due to failure, operator error or for maintenance.

Similar challenges exist in tele-operating robotic systems in space: on orbit and in systems deployed on the moon or planets. Expertise gained from the space missions will be invaluable in underwater mining systems. An earlier version of this paper has been presented here [Jasiobedzki et al. 2007]

2 Space exploration and underwater mining

Similar challenges to the underwater teleoperation of complex equipment in partially known environments and with restricted situational awareness are faced by the space community in space exploration, and spacecraft and robotics operations on orbit. Limited camera views, harsh lighting conditions, limited communication bandwidth and latency, and significant cost of operator errors require highly skilled and trained tele-operators. Indeed, in outer space some operations cannot be performed using teleoperation at all, due the communication latency, windows and low bandwidth available. For space systems solutions are sought by increasing the remote systems' autonomy in such a way that these systems can perform some of their tasks autonomously using on-board sensors and intelligence, control certain degrees of freedom and operate safely without operator involvement.

MDA is actively involved in development of novel robotic technologies for space exploration, servicing and operations. These technologies include the robotic hardware (manipulators, planetary rovers, tools, control systems), sensors and vision systems (image analysis), vision guided operations (visual servoing, navigation, localization and mapping), operations planning, and autonomous monitoring of robotic operations.

Selected technologies are being currently adapted now for underground mining in order to reduce the workload of teleoperation, and increase the productivity and safety of the ore transfer underground. The creation of virtual models of underground mines and integration with mine management software allows monitoring of mine advancement without the need for highly trained staff to visit the active mines faces. Developing such mining tools requires technical solutions in a range of technologies including autonomous navigation, modeling and monitoring, and sensor guided operations, as described below.

2.1 *Sensing and autonomous navigation*

Sensor-guided autonomous navigation is an enabling technology that has been used to great success in outer space. The MDA Spaceborne Scanning Lidar System (SSLS) [Nimelman 2005], deployed on board of the AFRL XSS-11 satellite and launched in 2005, was used to detect and track position of a target spacecraft, and to guide the servicer from a distance of several km to 10m (Figure 1). SSLS could also create high resolution 3D models for spacecraft inspection, 3D modeling and measurements.

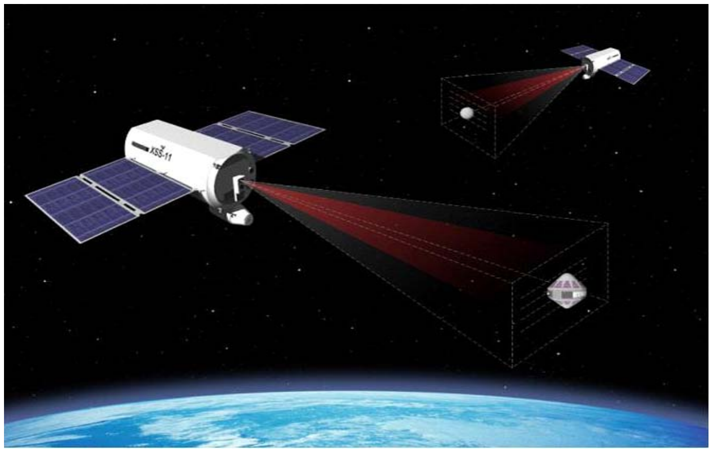

Figure 1 XSS-11 spacecraft equipped with the MDA Space borne Scanning Lidar System

Sensor based vehicle navigation systems developed by MDA enable shared control, “auto-tramming”, of Load Haul and Dump (LHD) vehicles transporting the ore underground. The operator on the surface tele-operates the vehicle during loading only and the vehicle operates fully autonomously during traverses and dumping into ore passes. The guidance systems do not require any infrastructure to be installed in the mine and use on-board LIDAR and sensors to localize the vehicle and follow paths “learned” by the vehicles during a training phase (Figure 2).

Figure 2 Underground Load Haul Dump (LHD) vehicle driving autonomously with no infrastructure (right)

2.2 *3D modeling and monitoring*

3D photorealistic models created using devices such as the MDA instant Scene Modeler (iSM) [Se and Jasiobedzki 2007] and the AQUA Sensor [Dudek et al 2007] bring the remote environment to operators’ workstations enabling virtual presence (Figure 3). The iSM system, initially developed for planetary exploration, is currently used in underground mining to assess ore distribution in 3D on active faces and to monitor mine advancement. iSM creates 3D models from sequences of stereo cameras images. The models are annotated by a technician operating the system underground to indicate ore concentration; samples are taken and their location and concentration are recorded within the model. As the models are registered in the mine coordinate system the data is entered into the mine management system and combined with other mine information (borehole samples, geo-seismic models) to approximate ore distribution in 3D, and to plan and monitor mining operations. A similar 3D modeling system has been developed by York University and has already been deployed on an aquatic robot AQUA [Dudek et al 2007]. The AQUA sensor records sequences of stereo images and automatically estimates the relative motion and creates 3D models of the seabed, coral reefs and submerged vessels. The system is equipped with inertial sensors, which help in estimating motion in the aquatic environment. The on-going research focuses on monitoring growth of coral reefs using automatic change detection in 3D and by analyzing 2D images.

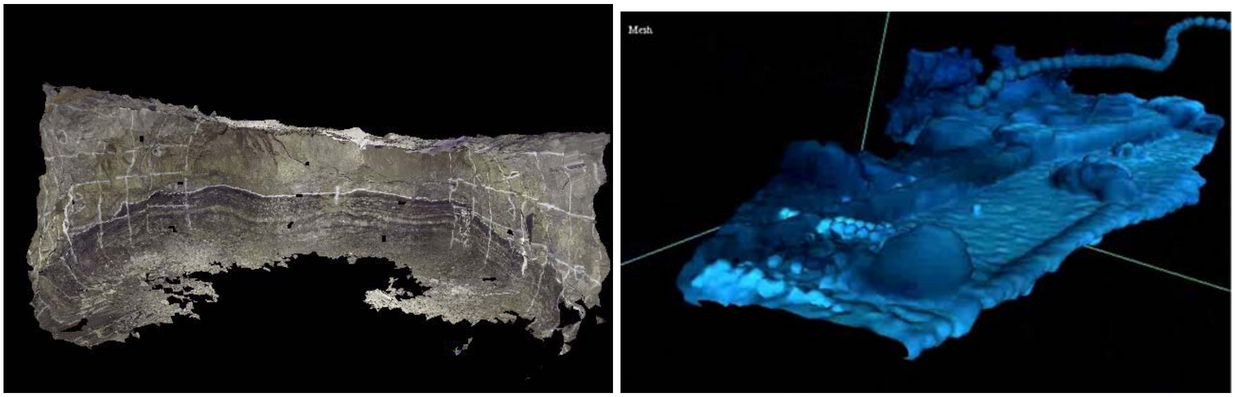

Figure 3 Examples of 3D models created using the MDA iSM underground (left) and York AQUA sensor underwater (right).

2.3 *Sensor guided precision operations*

Access to accurate real world data in real time enables sophisticated robotic operations to be performed autonomously. For example, the Orbital Express Demonstration Mission uses an MDA system consisting of a robotic arm guided by a vision system to capture autonomously a free floating satellite. The vision system detects location of a robotic interface on the target and commands the robotic end-effector to close on the interface [Ogilvie 2008], see Figure 4. The same arm and vision system are used for inspection and for servicing of the target spacecraft.

Performing unplanned precision tasks, especially on satellites not designed for robotic servicing, still requires human operator, his perception skills, understanding of the task and dexterity. Vision systems sensing the environment in 3D endow the operator with virtual presence by displaying the worksite models in synthetic (immersive) environments. Such environments include photorealistic models created from images or range data, models of known structures, and kinematic models of robots and tools. The operator uses these models to plan and rehearse the operations in virtual environments first; later the operation sequence is transmitted to the remote site for autonomous execution. On-board sensors and processing system are used to sense the real environment providing feedback (position, force, movement) to remote robots and tools ensuring correct and safe operation.

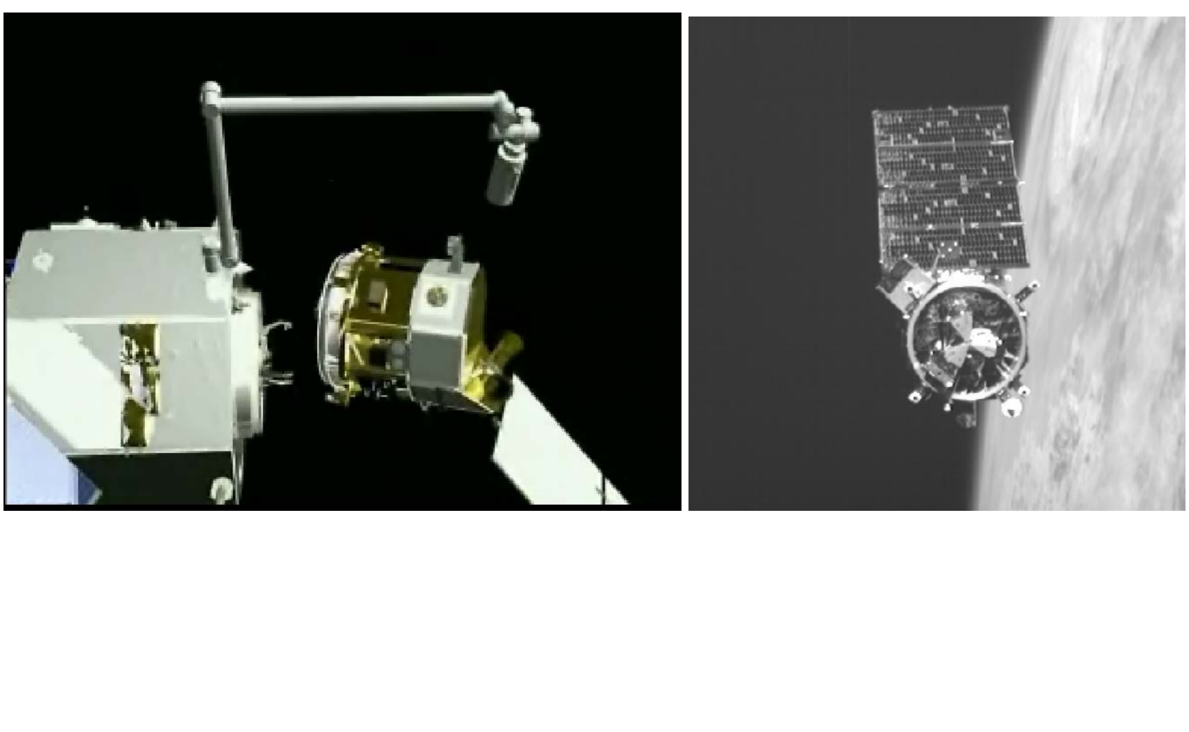

Figure 4 Autonomous robotic capture on orbit (left) and an image from space (right)

3 Autonomous Underwater Mining

Given the ability to sense and reason based on those complex sensor representations, autonomous systems can be built to support autonomous mining at depth. Although developed for outer space, suitably modified these technologies can be used to enable deep sea mining. MDA is currently such exploring technologies and is focusing on the following tasks:

- Modeling and monitoring of underwater environments
- Shared control of underwater craft and machinery for precision operations and mining.

3.1 *Modeling and monitoring of underwater environments*

Recent years have seen the rise of a number of light-based sensing technologies for ROV/UUVs. Laser based ranging systems (e.g., Moore et al., 2000) adapt surface-based laser systems to the underwater domain. In adapting laser-based technologies to the underwater domain critical issues related to backscatter of the laser beam due to suspended particulate matter and absorption of the laser energy by the water column must be addressed. The effects of absorption can be reduced via an appropriate choice of laser wavelength (ideally in the blue-green range). Once the details of the unique aquatic environment have been addressed, traditional terrestrial- and space-based laser technologies find direct application in the aquatic domain.

An alternative to laser-based technologies is the use of multiple cameras (in stereo configuration) sensing technologies to obtain 3D surface structure representations which can later be used for localization tasks. Devices such as iSM and AQUASensor, discussed earlier, can be used to obtain 3D representations of the environment for navigation, obstackle detection and for vehicle localization. Recent advances in 3D imaging sonars will offer a similar 3D sensing and modeling capabilities that will operate reliably underwater; albeit currently at lower resolutions than camera based systems [CodaOctopus, Zimmerman].

Near real time access to 3D models will significantly increase situational awareness of operators of the remote craft or underwater mining machines by effectively immersing them in the environment. This will provide them with virtual views the scene in 3D and optimum viewing angles and distances for precision operations.

Scanning the same environment multiple times and registering the 3D models will enable change detection over time. This will allow monitoring of the mining operations and assessment of the environment impact by directly comparing the same locations in photorealistic 3D using data collected over extended periods of time.

3.2 *Shared control of underwater craft and machinery for precision operations and mining*

Shared control of underwater craft and mining machinery will alleviate some of the limitations of teleoperation by autonomous execution of mundane operations (e.g., traversals between sites), retaining operators' involvement in tasks requiring their skills and reducing their fatigue. Reducing the operators' load per craft will allow them to control multiple systems reducing thus the cost.

The need to navigate around sub sea features, to minimize environmental impact, and to maximize the value of the ore which is extracted, motivates the need for precision mining capabilities. Assigning some of the control functions to the autonomous controller will allow the operator to concentrate on tasks that require his high level skills. For example, precise automatic control of the ROV with respect to the mooring ensures the ROV hovers automatically with respect to the mooring and the pilot is free to focus only on the manipulation tasks [Plotnik 2005]. Similarly, tasks such as visual homing to a target designed by the operator, maintaining safe distance and obstacle avoidance can be performed autonomously.

4 Technical management of space projects

Space systems, such as network of satellites of the Global Positioning System (GPS), International Space Station (ISS) or missions to Mars, are necessarily complex system. This complexity is brought by many factors: the number of sub-systems and components, their interactions and dependencies, and required extremely high reliability. Testing of the complete systems on the ground is often impossible, and very limited capabilities to perform repairs after the launch exist. Space programs typically take 7 – 15 years and involve large multi-disciplinary teams working in different geographic locations. At the start of a project many of the required technologies may not exist at all, exist only as laboratory prototypes or require re-engineering to operate in space environment. Mission planners are faced with alternative solutions offering different performance and at different maturity level. It has been necessary to develop structured processes for phased development, assessment of maturity of proposed technologies and difficulty of developing new technologies, and analysis and management of risks, uncertainty and cost.

4.1 *Life-cycle of space projects*

The NASA life-cycle of formulation and implementation of space projects is divided into incremental phases that allow assessing management and technical progress [NPR 7120.5D]. Major reviews are carried out between the phases and their outcome determines if the project is continued in the next phase. Projects typically start from concept studies (Pre-Phase A) and are followed by project formulation, which consists of: Phase A (concept & technology development) and Phase B (preliminary design). Project implementation consists of Phases C-F, which involve: final design (C), integration and test (D), operations (E), and closeout (F). The objectives and scope of the major reviews between the phases, as well as, reviews during each phase are clearly defined and include progress to date against the approved baseline, the implementation plans for current and upcoming work, budget, schedule, and all risks and their mitigation plans. Reviews during Phases A and B focus on the readiness of the program to proceed into implementation: proposed program's objectives and the concept for meeting those objectives are assessed, and key technologies and other risks are identified. During the implementation phases the reviews focus on readiness for the fabrication, integration and testing of components, readiness of the overall system for testing, development of operational procedures and readiness for launch.

This project life-cycle is used for all of the projects; however, only a minority of the projects considered in Pre-Phase A concept studies are launched and operated in space. This happens for a variety of reasons but mostly because of inadequate performance of technologies and change of priorities. Some of technologies required for the mission may carry high risks due to their technical immaturity or require a significant and costly development that exceeds the project budget or schedule. Change of priorities relates to modification of the scientific objectives of the proposed mission or redirection of the funding. Selecting technologies for a mission requires measures that can be used to assess maturity of existing technologies and difficulty of advancing them to a level when it becomes suitable for the mission. The same measures should allow comparison of alternative technologies. Two such metrics have been used: TRL and R&D3, and they are described below.

4.2 *Technology Readiness Level*

Technology Readiness Level (TRL) [Mankins 95], has been originally developed by NASA for space programs, and is currently used in military and civilian industries, measures maturity of technologies on a scale from TRL 1 to 9. The following definitions are used:

- TRL-1 - Basic principles observed and reported
- TRL-2 - Technology concept and/or application formulated
- TRL-3 - Analytical and experimental critical function and/or characteristic proof-of concept
- TRL-4 - Component and/or breadboard validation in laboratory environment
- TRL-5 - Component and/or breadboard validation in relevant environment
- TRL-6 - System/subsystem model or prototype demonstration in a relevant environment (ground or space)
- TRL-7 - System prototype demonstration in a space environment
- TRL-8 - Actual system completed and “flight qualified” through test and demonstration (ground or space)
- TRL-9 - Actual system “flight proven” through successful mission operations

For example, if a novel 3D imaging system assembled on a laboratory bench produces first 3D images at low rates, it will be rated as TRL-3. If it is launched and operates successfully under space conditions it will be rated as TRL-7. It will reach TRL-9 when it is used as a guidance system during space rendezvous.

4.3 *Research and Development Degree of Difficulty*

TRL is a measure allowing to assess maturity of a specific technology and to compare alternatives; however, it does not provide any information about technical difficulty and cost of maturing the technology to the next level. Research and Development Degree of Difficulty (R&D3) provides such a measure [Mankins 98]:

- R&D3 - I - A very low degree of difficulty is anticipated in achieving research and development objectives for this technology. Probability of Success in “Normal” R&D Effort 99%
- R&D3 - II - A moderate degree of difficulty should be anticipated in achieving R&D objectives for this technology. Probability of Success in “Normal” R&D Effort 90%
- R&D3 - III - A high degree of difficulty anticipated in achieving R&D objectives for this technology. Probability of Success in “Normal” R&D Effort 80%
- R&D3 - IV - A very high degree of difficulty anticipated in achieving R&D objectives for this technology. Probability of Success in “Normal” R&D Effort 50%
- R&D3 - V - The degree of difficulty anticipated in achieving R&D objectives for this technology is so high that a fundamental breakthrough is required. Probability of Success in “Normal” R&D Effort 20%

Continuing with the previous example of the 3D imaging system for space rendezvous - advancing it from a proof-of-concept system (TRL-3) to a prototype suitable for laboratory testing (TRL-4) may require increasing the processing speed tenfold. Difficulty of this task may be rated only as R&D3-I, if it involves porting the software from a prototyping language to C, and if such an improvement was achieved before in a similar project. However, if this change requires developing a new high performance computing platform and such an improvement has never been achieved before, it might be even rated as R&D3 - IV. In order to achieve the success, multiple approaches (e.g., using general purpose computing platforms or dedicated hardware processors) may have to be investigated.

4.4 *Risk management*

Space and other projects relying on novel technologies carry significant risks. These risks may involve unplanned development costs and schedule delay, or failures during operation and considerable losses. It is therefore essential to identify and manage the development and operational risks. NASA and their contractors use Continuous Risk Management (CRM) process [SP-610S]. CRM is an iterative and adaptive process used during the full life cycle of a project to help with its successful execution. CRM includes the following iterative steps (see Figure 5):

Identify – Identify program risk by identifying scenarios with adverse consequences

Analyze – Estimate the probability and consequence of identified risks

Plan - Plan the Track and Control actions. Decide what will be tracked, define decision thresholds for corrective actions, and proposed risk control actions

Track – Track program performance as compared to its plan

Control – Given an emerging risk issue, execute the appropriate control action, and verify its effectiveness.

Communicate and Document – These are elements of each of the previous steps. Focus on understanding and communicating all risk information throughout each program phase.

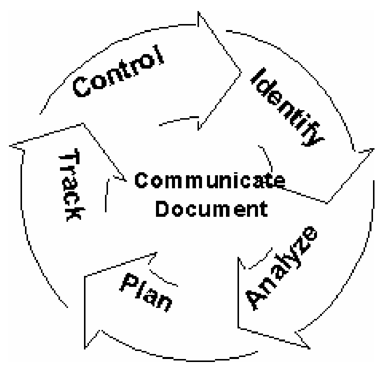

Figure 5 NASA Continuous Risk Management process [SP-610S]

5 Concluding remarks

Deep sea mining is the next frontier of mineral development. Operating underwater craft and machinery remotely from the surface to depths of several thousand meters can be as much of a challenge as working in Earth orbit or on the surface of Mars. A range of robotic and sensing technologies recently developed for space and other difficult terrestrial applications can be adopted for underwater mining. Specifically, developed technologies can be applicable for tasks such as: mapping and monitoring of underwater deposits, increasing situational awareness of tele-operators and reducing their workload by providing shared autonomy, and allowing for precision mining with minimum environmental impact.

Development of unmanned semi-autonomous underwater mining systems that will operate reliably and efficiently is a technically complex endeavor. Additionally, this must be achieved at an acceptable cost and schedule to ensure commercial success. Some of the systems engineering processes and project management methodologies developed for space programs may help to achieve these objectives.

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