UNDERWATER ROBOTIC VEHICLES: LATEST DEVELOPMENT TRENDS AND POTENTIAL CHALLENGES

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ABSTRACT — The treacherous underwater working environment demands state of the art operational technology. Innovation in these technologies has been driven by the need to have a reliable, flexible, productive and reconfigurable machine termed as Remotely Operated Vehicle (ROV) that can work in ever-increasing depths following an optimized strategy. In addition to basic equipment e.g. video camera(s), light sources, water samplers etc, ROVs may be equipped with one or more accessories such as a manipulator arm, SONARs, magnetometers and other instruments for measuring temperature, light and water parameters. Their tasks include operations in sub-sea for structure inspection, repair and placement of underwater manifolds and other applications under the water. This paper is an intensive study of high-tech ROV systems, and supporting tools for this technology. This review is potentially useful to assess the role of ROV as ocean vehicles and can serve as a guide for scientists and engineers working in the area of underwater technologies.

I. INTRODUCTION

Recent era witnessed ever expanding applications of robots. Robots are being used actively in rehabilitation [1-5], motion assistance [6-9], cognition [10, 11], haptics/VR [12] and target detection and tracking [13, 14], nuclear plants [15], Space [16, 17] and numerous other industrial [18-20] and educational [21-29] applications. One important application of robotics lie beneath the ground. Under-water vehicles were initially taken into operation for military applications. Dated back to 1950s, the Royal Navy of Great Britain employed a submersible for recovering torpedoes and removal of undersea mines. In 1960s, a Cable-Controlled Underwater Recovery Vehicle (CURV) intended for rescue and recovery operations in a deep-sea was realized by US Navy that were succeeded by CURV II and CURV III recovery vehicles in early 1970s. With the development and growth of offshore industry in 1980’s and 90’s, that initial trend of military Remotely Operated Vehicles (ROVs) shifted towards the oil & gas, education and ocean science research. A typical ROV implementation showing CURV III in operation is illustrated in Fig. 1.

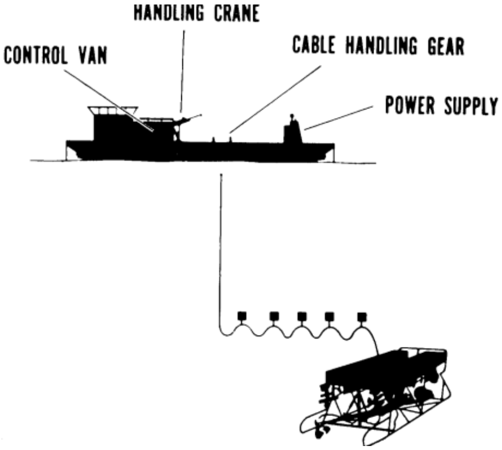


Figure 1. CURV III (Credit: US Navy)

Today, ROVs are considered amongst the most expensive categories of professional service robots. According to International Federation of Robotics (IFR), the unit price for an underwater system was about US$850,000 in 2010. Such systems have seventh highest unit sales in 2010 subsequent to medical, logistic, construction, mobile platforms, cleaning and inspection service robots. Underwater vehicles can be classified as manned and unmanned vehicles. Unmanned vehicles are either tethered which are called ROVs or untethered which are known as Autonomous Underwater Vehicles (AUVs). ROVs are further classified as observation-class, working-class and special use vehicles [30]. ROVs can also be classified depending upon their size, weight, operating depth and operating power.

This paper presents significant early developments of ROVs and in-depth reviews the state of-the-art. Their imperative role has been discussed by highlighting the importance of these vehicles. Based on different performance metrics (e.g. operational depth, max. velocity, manipulation capacity, sensing and auto-pilot capabilities, maneuvering, weight, application areas etc), ROVs reported in the literature have been appraised. The paper is arranged as follows: Section II sheds light on ROV from historical point of view. Section III lists popular ROVs reported in the literature. Section IV discusses system simulators and professional bodies about ROV. Finally, Section V comments on conclusion and highlights the key challenges and future directions.

II. ROVS – HUMAN’S HISTORICAL OCEANIC DELEGATE

ROV has substantial occupation in service to the human beings for exploring oceanic world and dealing with underwater deployments. Scientific literature does not pin point the first ROV developed historically. The CUTLET ROV (illustrated in Fig. 2) has been categorically highlighted as a pioneer remotely operated oceanic fellow that was developed and introduced by the Royal Navy in 1950’s to recover practice torpedoes [31]. The ROV was designed to work at the depth of the seabed. Main frame of the CUTLET was of aluminum equipped with lights and camera. An electric motor was used for its manipulation. To grip the target objects, a metal claw was mounted on the arms attached to the main frame. This vehicle was remained operational till 1980s.

Figure 2. CUTLET
(Credit: Jerry W. Saveriano, Innovational Musings)

Later on, in 1953, a Frenchman Dimitri Rebikoff conceived RP-32 Poodle [32]. XN-3 underwater vehicle of US Navy is also considered amongst the early developments, which were further modified in 1960s as CURV – a work class ROV shown in Fig. 3. It was first time that ROVs gained significant recognition [32] which was due to role of CURV in recovery operations in Mediterranean Sea [31]. In 1966, a B-52 bomber collided with a tanker aircraft during refueling and both were crashed into waters near Polamares in southern Spain. US deployed CURV to recover a hydrogen bomb at the depth of 2850ft. For this, CURV was modified to work at a depth which was beyond its designed operational capability. Later, the CURV was tailored to develop CURV II (Fig. 4) and a series of advanced ROVs including CURV II-B, CURV II-C, and CURV III.

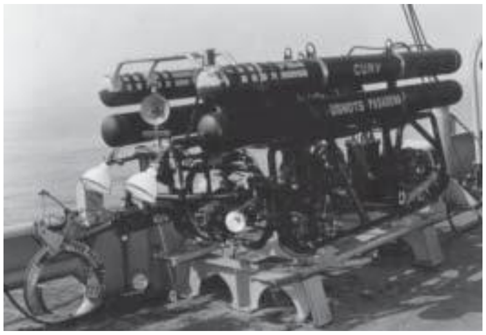


Figure 3. CURV (Credit: Sandia National Labs.)

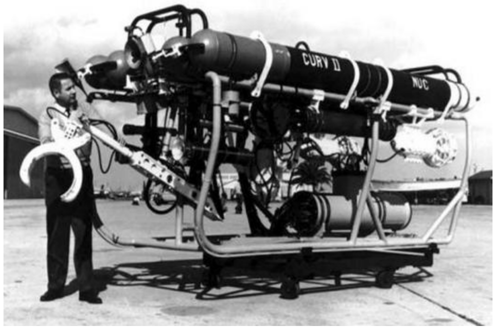


Figure 4. CURV II (Credit: R. D. Christ and R. L. Wernli)

CURV III (Fig. 5) was the most sophisticated ROV of CURV series. It was designed to operate at 6000 feet underwater with a weight of 5.85 tons employing fiber-optic tether. The vehicle was facilitated with onboard hydraulic power system, generator, operations and maintenance van, and acoustic tracking system for navigation. Electrical power for the system was provided through a diesel generator or through compatible auxiliary power sources. The vehicle offered remote maneuvering with six Degrees Of Freedom (DOF) for depth, altitude and heading using altimeter and depth-meter sensors. To interact with the target spots, it was equipped with Continuous Transmission Frequency Modulated (CTFM) sonar sensors, TV cameras, digital cameras and two manipulators. It was primarily used in a major overhaul activity in Azores Fixed Acoustic Range (AFAR) at the depth of 7000 feet with sonar system, CCTV and documentary camera systems, undersea lighting system, electro-hydraulic manipulation system and other application specific tools. The most prominent operation conducted by CURV III was retrieval of a manned underwater vehicle from Irish sea near Cork in 1973 saving the pilots of Pisces [32].

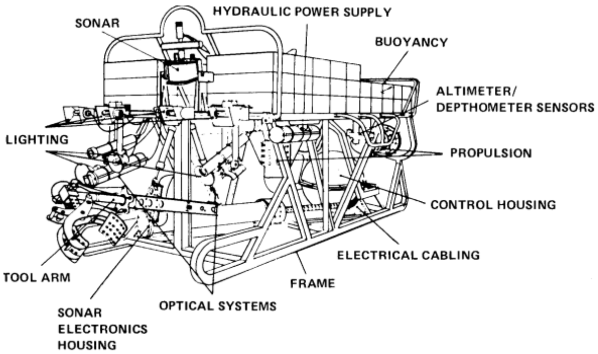


Figure 5. CURV III (Credit: US Navy)

In offshore oil and gas industry, first ROV for a well operation was the Manipulator Operated roBOT (MOBOT) developed by H. L. Shatto and Shell in 1962. MOBOT was a modified version of a ground vehicle [31]. The opening of research in ROVs in education and science, which was actually shift from military to commercial ROVs, evolved in 1980's and progressed onwards due to the potential commercial benefits in oil and gas and sea exploration industry. The second annual conference and exhibition on ROVs in 1984 held in San Diego US witnessed demonstration of more than 400 vehicles, most of which were intended for oil rig services. At that time, the ROV technology made it possible for human beings to explore the oceans at the depth of 8000feet with a prospect to discover 98% oceanic world in the subsequent years.

III. ROVs – An Exclusive Appraisal

Research in ROV technology triggered extensive developments in allied technologies like stereo vision, sonar and acoustic systems, tether systems, navigation and positioning tools, pipelines and structures inspection techniques, robotics and automatic control systems. Such developments resulted in realization of many ROVs. Some popular systems are presented below:

A. TIBURON

MBARI developed its first ROV, Ventana with an operational depth of 1850m in 1991 to capture underwater photographs and to collect data samples at Monterey Bay. Tiburon (Fig. 6), an ocean science research ROV, was the modified and extended version of Ventana. First prototype of Tiburon was developed and tested in 1993-94. It was launched in 1997 to explore the undersea world to its designed depth of 4000m. The vehicle was provided with 1600V and 400Hz three phase AC power through a 17.3mm steel tether. Six thruster motors of 5HP were installed for vehicle movements. The vehicle was equipped with four toolsleds for underwater investigation including Mid-water toolsled for fauna observation with lights and imaging capability, Benthic sampling toolsled for sample collections, Geotechnical toolsled equipped with tools for drilling and sensors (temperature and resistivity) and the Survey toolsled equipped with stereo video and side-scan sonar for imaging and 3D data representation.

The vehicle was able to move at 23.4m/minute in forward direction with full system deployed. Neglecting tether drag, the lateral velocity was 24.6m/minute and the vertical natural buoyant speed was 30.48m/minute. GUI for remote control was on HP Unix workstation with a joystick support. Customized software for manipulation, velocity control and power management was employed. Payload capacity of the vehicle was around 340Kg with 68Kg variable buoyancy capability.

Figure 6. Tiburon (Credit: MBARI)

The vehicle was used for collecting animals and species for Monterey bay aquarium and science research, analysis of deep water sequestering CO_2 effects and residue carriage and erosion in submarine canyons, identification of lava flows, installation of the seafloor cables and spectrometer and biological research in the Monterey bay area.

B. SEAPUP

Sealion is a series of ROVs developed by Techno-Transfer Industries. Seaup, a work class ROV, is one of the Sealion family members developed in 1997-98 with 95% electronics compatibility within the Sealion family making it low cost in the ROV market. Seaup was designed for a depth of 600m with five thrusters providing 20HP for forward, lateral and vertical movements. The vehicle was capable of auto heading (±1.5 degree), auto depth (±100mm), auto altitude (±100mm) and auto turn (.1turn) controlled by vehicle control unit using a microprocessor based SCADA system. It was equipped with a compass, depth sensor, echo sounder, 3 cameras with pan, tilt and focus functions, variable intensity light, one 3-function manipulator, and support for sonar. All of this equipment was manipulated through vehicle control unit. Surface control unit was a Windows based PC which was linked with the vehicle control unit through a telemetry system.

C. VICTOR 6000

French research organization IFREMER developed Victor 6000, a member of Nautile, SAR, and Cyana ROVs. The project was started in 1992 and accomplished in 1997. As the name indicates, the ROV (Fig. 7) was a 6000m underwater vehicle with 0.77m/s speed. It was a 4ton vehicle with six thrusters and 8000m tether with 6 optical fiber cables. Real time system was employed for the vehicle control system with 2 VEM computers, one each in the vehicle and on the surface unit. Vehicle was equipped with 2 pilot cameras, 3CCD camera, Sonar, altitude and pressure depth sensors, a 7-function arm for manipulation with a 5-function arm for grasping applications. Its modular design allowed carrying application specific toolsled. Major operations involved German icebreaking research vessel polarstern, investigating significant reasons for functional benthic biodiversity in polar deep sea, geological, optical and mid ocean rift survey, West African continental margin ecosystems, hydro-thermal vents inspection and local area investigation.

Figure 7. Victor (Credit: ASIMO. PL)

D. PEMEX's ROV

For visual analysis of underwater structures, an observation class ROV design was proposed in 2010. The system (Fig. 8) was devised for Federal Mexican Oil Company to inspect pipelines, oil production units and other structures in deep waters [33]. The proposed system consisted of surface unit, launching unit, tether management unit and the vehicle. The vehicle was designed to operate at the depth of 2000m with six thrusters, 5-function hydraulic manipulator and a 3-phase power supply for 440VAC. The manipulator was operated from the surface unit using a joystick.

The vehicle was equipped with depth sensor, compass, altimeter, rate gyros, sonar, 3 cameras and 4 lights. The velocity of the vehicle was 0.55m/s vertically, 1.25m/s in forward and 1m/s in reverse direction. Additionally, the sensory system consisted of sensors for measuring internal temperature and humidity, voltage and current.

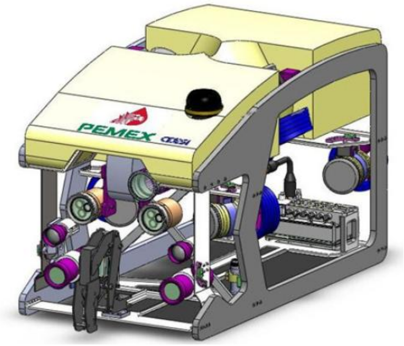


Figure 8. PEMEX ROV design [33]

E. Human-Sized ROV with Dual-Arm

As the name suggested, this ROV is capable of working like a diver by performing its tasks with two hands. It has been tested at the depth of 10-20meters in Biwa Lake, Japan [34]. Key features of this design are dual manipulator system (Fig. 9) and the attitude control system which makes it capable of controlling the attitude angle and keeping the vehicle in horizontal plane. With 56Kg weight, the ROV has six thrusters for driving force. It has been equipped with a camera, light, pressure sensor, accelerometer and angle rate gyro and magnetometer sensors. Each of the manipulator, with 3.6Kg weight underwater, has 5 DOF, four for the arm joints and a gripper hand. Harmonic motors have been used for these joints motions.

To control the multi-DOF of this vehicle, a purpose-designed master-slave control system has been implemented. To control the vehicle movements, two joysticks have been mounted on the controller, each of which has push button for pitch angle control. The system offers an operator the control over vehicle attitude and dual manipulator.

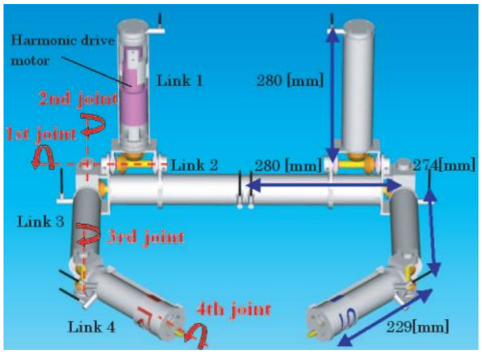


Figure 9. Dual arm manipulator of human-sized ROV [34]

F. The Eyeball ROV

To get the required video image in a narrow workspace like pipelines, with requisite capability of camera orientation, a small spherical ROV design illustrated in Fig. 10 has been proposed by researchers at MIT [35]. The ROV can revolve and reorient itself like an eyeball without altering the position acquired by the ROV body. The vehicle can execute this motion using the gimbal mechanism employing a pair of thrusters with non-holonomic constraints. Gimbaled mechanism is being employed for the first time in underwater vehicles.

Pan, tilt and forward motions are required to execute the eyeball designed motion. Yaw motion is especially complex to execute and control using the moments about roll and pitch axes. An array of two thrusters has been employed to create a moment combined with that of eccentric mass to control the three required motions. The eyeball ROV design offers passive collision avoidance with its spherical shape, increased robustness due to less number of actuators and application specific scalable structure.

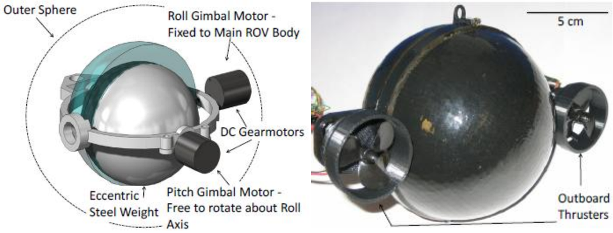


Figure 10. Eyeball mechanism and prototype [35]

G. HYBRID-ROV

Marine Environmental Sciences MARUM (University of Bremen, Germany) is working on a design ROV/Autonomous Underwater Vehicle (AUV) for high-risk zones like under-ice operations, hydrothermal vents and harsh topography near the seabed. The proposed system is aimed at reaching and balancing itself at the depth of 4000m with and/or without the tether [36]. The designed ROV (Fig. 11) has large front size and appropriate distance between centers of buoyancy and mass which makes it slow and stable with an additional support from tether. In contrast to this, AUV with torpedo shape will make it faster and less stable at low speeds. The design has 7 thrusters: two tunnel thrusters for yaw and hovering, three thrusters for vertical axis and two ring-thrusters for forward speed. Digital Telemetry Subsea nodes are to be used for power transmission, information routing and signal transmission. The vehicle is planned to be furnished with general ROV equipment like cameras, lights, pan tilt unit, drawer box and the manipulator. The intended tether is re-enforced fibers of 2mm dia with an operational range of 4 to 5Km. The vehicle will work as an AUV to perform the required tasks in case the tether is snapped or detached.

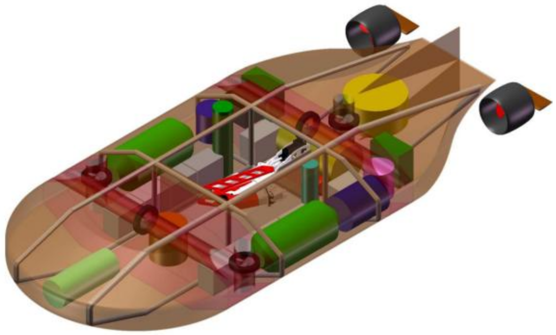


Figure 11. Proposed design by MARUM [36]

IV. ROVs – SIMULATORS AND PROFESSIONAL BODIES

Scientific literature reports simulators for facilitating understanding of ROVs functionality and various related professional bodies.

A. ROV System Simulators

SeaMaster is a purpose-designed simulation platform for education and training of ROV manipulator's tele-operations [37]. The simulator regulates the actual arm through a GUI employing a master control arm. Surrounding environment is simulated in a 3D view. Both Manipulator and ROV can be controlled using additional devices connected to the computer. Block diagram of SeaMaster simulator is illustrated in Fig. 12.

The simulator offered three control modes which include rate-mode for joint manipulation, master-slave for coordinated operations and data-driven for repetitive tasks. It also offered manipulator operations in fixed-base or moving-base modes employing underwater dynamics.

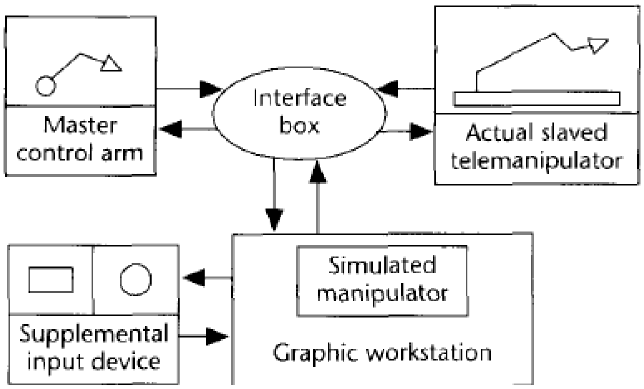
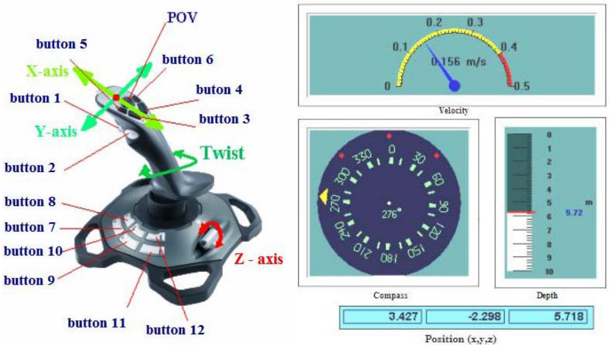


Figure 12. SeaMaster simulator [37]

Another platform, *Micro ROV Simulator* has been designed for micro ROVs using modular approach to accommodate additional functions. The simulator [38] offered environment to develop 3D view of the ROV and its manipulator. Additional functions include camera manipulation, gripper management and factual lightening. Two user interfaces have been provided. The control user interface (Fig. 13a) offered joystick console for axes control, gripper control, light control and zooming capability while the visual user interface (Fig. 13b) provided information about the position and orientation of the ROV, its velocity, depth and the compass value.



(a) (b)

Figure 13. Micro ROV Simulator [38]
(a) Control user interface (b) Visual user interface

Office of naval research USA sponsored virtual environment training for the ROV pilots under the program of *Training for Remote Sensing and Manipulation (TRANSoM)* [39]. The vehicle simulations were generated in the simulator employing virtual environment technology. For trainee guidance especially in case of critical tasks, Intelligent Tutoring System (ITS) has been built in the simulator. Employing ITS, users were able to interact with sensory data, virtual environment and virtual vehicle through a tracking display and interface box. System components of TRANSoM are shown in Fig. 14.

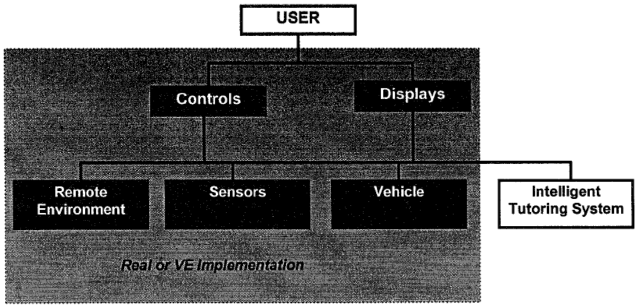


Figure 14. System Components of TRANSoM [39]

B. Professional ROV Organizations and Societies

A number of diversified specialized societies exist dealing with various aspects of ROV. These organizations either offer direct assistance or provide collaboration in research and development, education and training, scholarship awards, international and national competitions and conferences and database services. To name active organizations: Monterey Bay Aquarium Research Institute, Marine Technology Society, National Oceanic and Atmospheric Administration USA, National Oceanography Centre Southampton, Marine Advanced Technology Education Centre, Association for Unmanned Vehicle Systems International, NPS Submerged Resource Center, Woods Hole Oceanographic Institution, Institute of Ocean Science Canada, IFREMER France, Korea Research Institute of Ships and Ocean Engineering, Association of Diving Contractors International etc.

V. CONCLUSION

Exploration of undersea natural world and human deployments in a safe and productive manner can be considered as the key challenge in developing ROVs. Another vital concern is to provide cost effective and less expensive ROV solutions for educational and training purposes. These rationales present a whole range of dares and defies such as the development of cheap yet high quality underwater imaging technology, better power management techniques, improved tethering techniques for power supply and signal transformation etc.

With the increase in the cost effectiveness of these vehicles, the application intensity and areas will definitely expand replacing the human divers and manned vehicles. A near future direction that is to develop hybrid underwater vehicles has already been taken up by MARUM Germany. The difficulty for hybrid structures is to ensure robustness and stability at the same time. A far future move is to transfer from ROVs to AUGs. The most prominent advantage of this direction will be to have vehicles that are umbilical independent thus making them more dynamic. In that case, with more dynamic capability, improved communication techniques and underwater technologies would be required.

Additionally, the other aspect of this future direction would be to design more stable structures for AUVs which can hover themselves at a required sea depth to accomplish a task.

Keeping man in the loop, major applications of ROVs include activities like rescue and recovery operations, science research operations for undersea world, technology testing engagements etc. Improvement in the quality of associated technologies and their readily availability will further widen their application domains.

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