Design of an Amphibian Exploring Robot

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Abstract. To design and develop an amphibian exploring robot capable of operation in constrained mine environment puts a tremendous challenge to the system developers from both scientific and engineering perspective. Very few attempts have been made to fulfil these criteria of versatility in design, communication and control. The CSIR-CMERI developed amphibian subterranean robotic explorer (SR) is capable of moving over fairly rough terrain. It can swim as well as crawl over basin floor effortlessly. It is capable of operating at a maximum depth of 10m and can swim at 1 knot. A number of field trials have been carried out for performance testing of the system to ascertain its capability in underground flooded mine tunnels. This paper presents the insight on the design of an amphibian exploring robot for mine safety and disaster mitigation with special features of low power consumption vis-à-vis high mission time.

1. Introduction

A few mobile robots have been developed and applied to support the monitoring and mapping of active mine environments. Notable among these are ‘Numbat’ [1] - mine emergency recovery vehicle developed at Commonwealth Scientific and Industrial Research Organization (CSIRO) which is equipped with gas detection sensors, thermocouples etc. The mapping of 3-D mine tunnel was also investigated by Carnegie Mellon University [2]. Robotic mine mapping systems ‘Groundhog’ and ‘Cave crawler’ developed at CMU can recognize topological features of mine tunnels [3, 4, 5]. Besides, a few attempts have been made to introduce robotics for other mining related activities, e.g. a robotic system for underground coal mining has also been developed by CMU which can maneuver in highly constrained environments and cut coal without human operator onboard [6]. Researchers of Monash University - Gippsland Campus, are carrying out a project which aims to provide a computer assisted remote operation of mining machines and services [7]. This research also aims at developing an intelligent unmanned mining system using robotics technology for coal harvesting at a major Australian open cast mine. Forster & Schraft [8] have described a semi-automated coal extraction system with longwall drum ranging shearer. Another class of specially designed underwater robots developed and deployed in various tasks related to undersea applications. These robots are called Remotely Operated Vehicles (ROV). The un-tethered version of such robots with very limited payload, endurance and capability but self contained power and communication capability is called Autonomous Underwater Vehicle (AUV). Both ROVs and AUVs are used in deep sea activities rather than shallow turbid waters of underground coal mines.

This clearly shows that only a limited number of research works have been reported in literature for development of robotic system capable of exploring both dry and underwater environments. In general, chances of flooding is a serious threat to Indian coal mines because of higher groundwater...
table as well as the presence of flowing stream in the vicinity of coal-rich areas. Several accidents have been reported in the recent past [9]. Comprehensive accounts of mine inundation have been presented in [13] and [14] for Indian as well as international scenario. It is therefore essential for developing a robotic system which can be deployed within shortest possible notice to gather most recent information of the flooded mine galleries so as to plan and launch any emergency intervention in post flooding scenario. The SR, as depicted in figure 1 is an amphibian explorer which is capable of moving over both dry land and partially or fully submerged mine tunnels and simultaneously can collect data from the surroundings. While under water it is similar to an AUV and does not have any physical link with the control station. It is not designed to carry heavy payload and sole purpose of this system is to explore and gather data. The gathered data are stored in local storage for further analysis. A part of which with very low bandwidth-overhead is transmitted back online to assist navigation. Though most of the navigational parameters are locally handled at client-end, it can be manually intervened for failsafe operation.

![Figure 1. The CSIR-CMERI Subterranean Robot (SR).](image1)

![Figure 2. Layout showing relative positioning of major equipments.](image2)

2. System Design
The proposed system is aimed towards operation in partially or fully flooded mine tunnels and this calls for special considerations to be undertaken in its design so that the system can effortlessly move over a variety of terrain surfaces under varying conditions. Another interesting behavior is that the proposed system should exhibit swimming capability against moderate current. Foregoing discussion clearly shows that a variety of issues need to be considered critically to arrive at an acceptable system design. In view of above the following wish list has been created. It is desired that the system design must satisfy the above features and capabilities to a large extent.

2.1. Shape and Size
The key issues that influence the shape and size of the amphibian explorer is the equipments that need to be mounted on it, depth of operation, mission time and power requirement. A major share of the total power is consumed by the propulsion system, such as, motors and thrusters. Various equipments and sensors such as acoustic modem, forward looking sonar, camera with light, drive system, radio modem etc. are packed within a very limited space. The hull made up of two watertight compartments enclosing various equipments like motors, Controllers, on-board battery banks, single board computer (SBC), necessary electronics and cabling. The system is provided with two modular track-wheel arrangements on both of its sides. The track modules are driven by two different motors from within the hull, the shafts of which are extended to two drive-wheels outside the hull. In addition to an underwater camera the SR is mounted with short range pencil beam sonar for obstacle avoidance and safe navigation through turbid water.
2.2. Equipment Layout
Arrangement of various equipments and placements of sensors were determined based on their field of view and beam angle and are shown in figure 2, 3 and 4. The underwater camera used has a built in light and having field of view 54ºx30º. The sonar has a maximum scanning field of 360º and the acoustic modem with 17.8 kbps acoustic link has a range of 1.5km in narrow beam mode which is a 60º cone. Lower cavity of the hull is comparatively larger and houses most of the heavier equipments.

![Figure 3. Field of view of acoustic modem, forward looking sonar and camera [15].](image)

2.3. Propulsion
It is imperative that an ideal system should necessarily be designed under consideration of effective traction mechanism together with efficient drag reduction objective. Tracked wheel configuration makes the system capable of moving over fairly rough terrain when exploring over dry land, whereas, the thrusters come into action when it is underwater. Besides, chances of sinkage of the robotic system while operating on muddy or soft soil condition also needs to be evaluated.

2.4. Buoyancy Management
Wherever possible the heavy equipments were kept at lower cavity of the Hull (as depicted in figure 5) to achieve a considerable gap between the centre of gravity (CG) and centre of buoyancy (CB). More the separation the better is the stability and as a result the sway tends to stabilize faster. Figure 5 shows the restoring couple for roll stabilization generated due to such positing of CG and CB. Overall weight of the system is 41.5 Kg whereas buoyancy was measured 49.7 Kg. With dimensional parameters, the roll restoring couple-arm was measured to be 50 mm/30º tilt. The overall system was designed slightly over-buoyant. However, buoyancy packs and dead weights were provided to fine-tune overall buoyancy. The system can be deployed neutrally-buoyant, over-buoyant or under-buoyant depending upon the mission requirement. This enables to adjust the weight of the system to crawl on the mine bed of fully flooded mine galleries/tunnels or float on the surface of water in partially flooded tunnels.

2.5. Design Specification
The system was designed to be remotely deployable and tether less. This enables the robot to explore through several bends in the mine gallery. However, this drastically reduces the mission time as the system solely relies on limited onboard battery power. Considering its scope of usage, the system was designed to operate up to a depth of 10 meter and was properly sealed and pressure-tested to eliminate any possibility of water leakage.
The bearings mounted on these drive-shafts are adequately sealed to eliminate any possibility of water leakage. Also the system was provided with several moisture sensors to raise an alarm in the event of any water leakage into the cavity.

Table 2. Design Specification

| Specification          | Details                                      |
|------------------------|----------------------------------------------|
| Basic Dimension        | 550 x 270 x 250 mm                          |
| Weight                 | 41.5 kg                                      |
| Max. Depth             | 10 m                                         |
| Speed                  | 0.5 m/s                                      |
| Drive                  | Separate differential drive with two motors and two thrusters |
|                        | Motor: Graphite brushed servo motors          |
|                        | Thruster: DC brushless thrusters              |
| Power Supply           | Onboard Li-Ion battery banks                 |
| Processors             | PC104+ based Single Board Computer (SBC)     |
| Communication          | Acoustic and RF based network                |
| Architecture           | Multiagent based Client-Server using TCP/IP   |
| Sensors                | Encoder, Sonar, Camera, Compass              |

3. Drag Analysis
To minimize propulsive power requirement, the shape of such a system should be as streamlined as possible. However, system requirement dictates that many equipments and sensors are to be packed within a small volume. For this reason it is not only difficult to achieve a good streamlined shape but also it is not an absolute necessity considering its slow operational speed. The hull of the robot was judiciously designed to achieve optimal shape. To estimate the hydrodynamic properties and to optimize drag, studies were carried out with the help of CFD tools. The 3D computational fluid dynamic (CFD) simulation of the robot was carried out to study hydrodynamic properties of the system. Based on these results, several improvements in design of the robot were done. Figure 6 shows the pressure distribution of flow past the SR explorer body for two different designs.

Formation of vortex vis-à-vis low pressure zone at the rear end of the SR contributes to drag. Thruster Power requirement is dictated by Total Drag ($R_t$) that an underwater body experiences while in motion and can be estimated as:
\[ R_i = R_f + R_d \]  

(1)

Where, \( R_f \) and \( R_d \) are friction drag and pressure drag respectively.

Again,

\[ R_f = \frac{1}{2} \rho A_w V^2 C_f \]  

(2)

\[ R_d = \frac{1}{2} \rho A_f V^2 C_d \]  

(3)

Flow separation causing higher pressure drag is a major phenomenon that hinders smooth propulsion when it is in motion under water. To minimize this, modifications in the shape of the SR were done as well as through vents were provided in the rear end of the casing. Vents allow smooth passage of the flow and alone helped to reduce drag by 30%. CFD analysis was done at different speed of the robotic vehicle and a typical \( C_d \) for the system was estimated to be 0.53, which is acceptable for such slow moving underwater system.

**Figure 6.** Pressure Plots are compared on the same scale. Vents were introduced on the body cover and the analysis result is shown in (b). The low pressure zone at trailing end is considerably reduced due to introduction of vents.

4. Manoeuvring

The two tracks are powered by two different motors. While moving over land, the steering action is achieved by differential drive of the track motors. Steering of the SR having Track \((d)\) was achieved by differential drive of the individual track belts. If an equal differential speed \((v)\) is applied on both tracks having initial speed \((V)\),

\[ V + v = \omega(R + \frac{d}{2}) \]  

(4)

\[ V - v = \omega(R - \frac{d}{2}) \]  

(5)
The radius of curvature \((R)\) of the robot path can be formulated as:

\[
R = \frac{Vd}{2v}
\]  

(6)

From this equation, the following few inference can be drawn,

For \(v = 0\), \(R = \infty\), the robot moves on a straight line.

For \(v = V\), \(R = d/2\), the robot turns centering on one track.

For \(V = 0\), \(R = 0\), the robot performs in-place turning.

Similarly Right and left thrusters are powered separately. While moving in water steering is achieved by differential action of the thrusters. Again the two thrusters are mounted on a common swivel rod which can be tilted. Pitching up or down is achieved by suitably selecting the thruster tilt angle.

![Differential drive of SR while moving over land.](image1)

![Thrusters are mounted on a common shaft and are tilted to pitch up or down while manoeuvring under water.](image2)

5. System Architecture

All the on-board equipments and accessories are connected to an on-board Single Board Computer (SBC) for control, communication and system operation. The sensors and other devices communicate with the SBC through multiple signal transmission and communication protocol ranging from pure analog to serial data transmission mode depending upon the specific sensor and device used. A block diagram depicting the system architecture is shown in figure 9.

6. Limited Field Trial and Deployment

Before actual deployment, several trial runs were carried out in simulated environment (figure 10) to ensure sealing and proper functioning of the equipments. Actual field testing at underground coal mine was carried out at Satgram Project under Eastern Coalfields Limited [10]. The mine shaft is approximately 211 m deep and a gassy-2 mine [11]. The location designated as ‘Drift-3’ was identified for field trial (figure 11). This drift is approximately 25 m long with slope of 1:6. The surface control station was set up above the mine shaft in order to demonstrate the capability of the robot to work in partially or fully flooded mine tunnels. Raw data obtained during the field trials were logged into the onboard SBC of the SR. Sonar and camera data (besides logging into the hard disk of SBC) was processed locally for obstacle avoidance and safe navigation.

Portability and remote deployment capability of the current system eliminates the need for expensive launching mechanism which is always an essential part of many underwater robotic systems such as ROVs and AUVs.
Although the main emphasis of this work was to develop a robotic system to locate entrapped miners, its potential was found to be far more extended. Apart from flooding, other disasters like subsidence, roof collapse, fire and explosion are a few common examples of mine accident. Work is also in progress to enhance the operational capability of the system to cater the need at time of such disasters.

Figure 9. System Architecture of the robot together with the command station.

Figure 10. Field testing of free swimming of the SR at CSIR-CMERI test facility.

Figure 11. The SR deployed in an inundated and submerged mine tunnel of Satgram Project.

The present system can be equipped with other mission specific sensors for disaster mitigation, surveillance, mapping of coal mines. Moreover, the amphibian subterranean robot can also be used for the purpose of autonomous mode of exploration in many shallow water bodies like pools, tunnels and lakes. In narrow mine tunnels, the performance of acoustic mode of communication reduces drastically due to noise caused by reflection even though suitable filter was used. However, the SR successfully achieved the objectives as envisaged.
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