

A mobile robot that removed and disposed ammunition boxes

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We have developed and used a mobile robot for removing ammunition boxes containing explosive fuzes from a storage room to the disposal site at Ordnance Factory Khamaria, Jabalpur. The robot comprises a six-wheeled vehicle carrying an articulated manipulator. It is controlled and monitored remotely through wireless Ethernet from a host workstation. The robot and a pneumatic device for opening the box, have been used to remove and destroy fuze boxes remotely. This note provides a description of the problem that warranted this development. It also describes the hardware and software components of the mobile robot that solved the problem.

About 300 boxes containing more than 13,000 rejected fuzes of anti-tank mines were lying in two storage rooms at Ordnance Factory Khamaria (OFK), Jabalpur for the last 25 years. Because of the peculiar chemical composition of these fuzes, as well as past experience with them, there was a fear that some of these may have become sensitive and may explode at the slightest disturbance. Their presence in the factory premises was a threat to the people, factory and the surroundings. It was clear that these boxes had to be removed and disposed at the earliest. To avoid possible injury or loss of life due to accidents during manual handling of these boxes, it was desired that the boxes be handled remotely by robotic means. Based on a request from the Centre for Fire, Environment and Explosive Safety (CFEES), Delhi, we developed a battery-powered mobile platform with an on-board manipulator for remotely removing the boxes to a disposal site. By end of December 2006, all boxes were removed and disposed. This is a unique indigenous effort in developing a robotic solution for a hazardous operation.

Description of the problem

The site layout is shown in Figure 1a. The fuze boxes containing rejected fuzes were stacked (1.5 m high) in two adjoining rooms, 224 and 225 (Figure 1b). There is an over-bridge running through the centre of this area till the disposal site A. Narrow, cemented pathways connect the over-bridge to the individual storage rooms. There are *traverses* (raised earth wall serving as protection against accidental explosion) separating the rooms from the over-bridge.

There were mainly two types of boxes in the storage rooms: C18A and C374,

measuring 600 mm × 250 mm × 320 mm and 645 mm × 200 mm × 345 mm respectively. They are made up of 1 mm thick steel and each box has a body, lid, spring-clip, hinge, handle-clip, stud and strengthening plate. The lid is retained in position by two spring clips. Maximum weight of a box with its content is 20 kg.

We had to build a robot to remotely remove a box from the stacks, bring it to disposal site A along the road and over-bridge, open the spring-clip of the box and pour its fuzes into a pit for disposal. This had to be done carefully to avoid any possibility of explosion.

Available technologies

Robots for Explosive Ordnance Disposal (EOD)¹ are manufactured and sold all over the world. Of them, the Mark and Andros series of EOD robots from Remotec, USA are well known. These have been extensively used by the US Army during the last decade. Solem and Talon from Foster Miller, USA; HOBOT from Ken-tree, Ireland; TSR from Cybernetix, France; Cyclops from AB Precision, UK, and Teodor and Robert from Telerob, Germany are also well-known EOD robots. Most of these robots are big, heavy and expensive. They are meant to be used in war fronts for de-mining and other similar operations. Smaller EOD robots are also available to detect and defuse Improved Explosive Devices (IED) in airports, aircrafts, auditoria and even under vehicles. They usually have accessories for remote on-line X-ray imaging of the suspected device, and guns (disruptors) for defusing the device using a water-jet or other means. Recently, an EOD robot has been successfully developed by Research and Development Establishment

(Engineers), Pune^{2,3} – a DRDO laboratory – and handed over to the Indian Army for field trial. Although most of these robots have the basic features for remote driving of the vehicle and handling of materials with on-board manipulator, none of them is big enough to have necessary reach and payload, and at the same time small enough to drive on the over-bridge, turn at its corners and enter the storage rooms. A custom design of a robot for this application by any of these manufacturers would have been prohibitively expensive. This prompted us to work towards an indigenous solution.

Robot system for remote operation

As a solution to the problem posed above, we proceeded to build a mobile robot with on-board manipulator for remotely approaching the stacks of fuze boxes in the storage room, grip a box on the stack, lift and place it on a box-holder frame on the vehicle, and then carry the box to the disposal site. The control station was set up at room no. 1103, as it is protected by *traverse* and is sufficiently close to the storage room and disposal pit for uninterrupted wireless communication. Full-scale mock-up facility was set up in room no. 221 to test and qualify the operation of the scheme.

We also developed a pneumatic device for remotely removing the spring-clip and then tilting the box to pour its content into the disposal pit. Both the robot and the unclipping device were to be operated remotely from the control station. The robot was connected to the control room PC through wireless Ethernet. The operator sitting in control room can watch video images received from wireless cameras mounted on the mobile

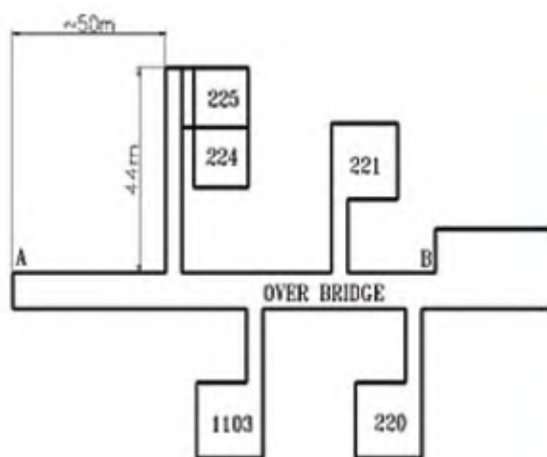


Figure 1. *a*, Site layout. *b*, Stacked boxes in room no. 225.



Figure 2. *a*, SmartROD mobile robot with manipulator. *b*, Control room layout in room no. 1103.

robot and issue motion commands to drive the robot remotely. Figure 2*a* shows the mobile robot, *SmartROD* with on-board manipulator. The box-holder frame on the mobile platform in front of the manipulator holds the fuze box during transit. Figure 2*b* shows the control and monitoring set-up inside the control room.

Design philosophy

As the robot was designed for a specific use over a limited period of operation, we decided to go for a simple design to make it available in a short time. As we had prior experience of building a small indoor mobile robot, *SmartNav*⁴ for testing navigation algorithms in the laboratory, we decided to build a robot with similar control architecture. We decided to drive the robot remotely through a Host Ma-

chine Interface (HMI) program running on a desktop PC in the control room, while looking at video images (on TV monitors), received from on-board cameras. The operator drives the robot following a centre line drawn all along the over-bridge. Some points on this line are marked with symbols indicating actions to be taken, e.g. a left or a right turn. Several cameras were mounted on the wayside to get additional views of the robot in transit. The on-board manipulator was also controlled directly at the joint level by selecting buttons on the HMI.

SmartROD mobile platform

This is a six-wheeled, battery-powered vehicle (Figure 2*a*) with on-board manipulator designed for handling and transportation of ammunition boxes. Its three wheels on one side are coupled together

with a chain and driven by a single motor. When the left and the right set of wheels rotate at the same speed and in the same direction, the vehicle moves straight. If they rotate at the same speed, but in opposite directions, the vehicle turns about itself. However, during turning, the front and the rear wheels skid against the ground, wasting a lot of drive energy in friction. Although energetically inefficient, skid-steered⁵ vehicles are the most common among EOD robots because of their stability and good traction on outdoor terrain, and simplicity of design and control.

Due to counterweights on the manipulator, *SmartROD* was a bit too heavy – close to half a tonne in weight. Skid-steering with this weight is too demanding on the drive motors. Friction due to skid-steer will be less if the wheel base is wide rather than long. However, a wide vehicle is difficult to drive through narrow openings. To overcome this problem, we introduced a middle wheel and mounted it at a lower elevation compared to the front and rear wheels. This forces the middle wheel to take the lion's share of the weight of the vehicle. The front and the rear wheels bearing a minor part of the weight, face proportionately less frictional force. Steering is no longer difficult. We have used four pneumatic wheels at the end and two hard nylon wheels in the middle of the platform. The pneumatic wheels provide necessary traction and cushioning, while driving the platform. Nylon wheels have poor traction because of low friction. This combination of nylon and compressible rubber wheels, we believe, provides *SmartROD* the ability to drive and steer smoothly.

There were bumpers all around the periphery of the robot (not shown in Figure 2 a) to bring it to a halt on inadvertent collision. One Pan-Tilt-Zoom (PTZ) camera was mounted at the front of the vehicle to see the road in front while driving forward. Likewise, one PTZ camera was mounted at the rear for driving the vehicle backward. This was required to bring out the vehicle from the storage room after the fuze box was removed from the stack and placed on the vehicle. One PTZ camera was mounted on the shoulder of the manipulator to monitor the gripper. Each of these cameras had wireless transmitters using separate channels in the 900 MHz band.

Manipulator

SmartROD has an articulated four-axes manipulator for handling ammunition boxes. Although the width and height of the ammunition box is small compared to its length, the stack permits gripping of the box only along its length, which is 600 mm. The manipulator design is such that the gripper is constrained to remain vertical to prevent it from getting tilted during movement. Although the manipulator has a reach of 2 m radius from its base, it can be folded back to be accommodated within the length of the vehicle. The gripper and the joints of the manipulator are actuated by stepper motors.

As the manipulator and vehicle are both controlled wireless with visual feedback, it is possible in principle for the manipulator gripper to approach and hold the container box entirely through remotely conveyed motion commands. However, we thought it would be safer if positioning of the gripper was done with human assistance. An operator can physically bring the gripper close to the gripping position near the box, without even touching any of the container boxes. This ensures accurate positioning of the gripper, which otherwise remains somewhat uncertain when the operation is carried out remotely with the help of video images from stationary cameras installed inside the room. When the operator is inside the room, no motor is activated. The joints are either free or locked. The manipulator and vehicle are powered only when the operator returns to a safe distance from the room. To facilitate easy manual movement of the gripper, manipulator joints were balanced against gravity with counter-

weights. Electromagnetic brakes provided on the joints prevent collapse of the manipulator in case of accidental breakage of motor power supply.

Since the robot was used repeatedly to remove boxes from the same room, the operator was soon comfortable and confident in controlling the manipulator remotely. Thus the option of manual positioning of the gripper was used only in the first few trips to the storage rooms. Later, the entire operation was done remotely.

Remote box opening mechanism

The lids of the fuze boxes were retained in position by a pair of spring-clips. Opening the box involves approaching the clip and applying force on it to overcome spring force and frictional force. A set-up was designed and fabricated for opening the spring-clips and emptying the boxes (Figure 3). The set-up consists of a support frame to receive the box from the manipulator. After receiving the box, it is located and clamped by a set of four pneumatic cylinders. The clip-opening tool removes both the clips provided on the top of the lid. The box is then rotated to pour all the fuzes in the pit provided. All these operations are done remotely from the control station.

Overall control architecture

The overall control architecture of the robot is as shown in Figure 4. The on-board Single Board Computer (SBC) forms the master controller for the system. The high-level application for the control of the robot is executed on this SBC. The SBC has a wireless Ethernet link with the host computer. The host computer executes the application on the SBC via the VNC (Virtual Network Computing)⁶ server installed on the SBC. The SBC issues commands to the vehicle controller as well as the manipulator controller, on two separate serial ports according to instructions received from the HMI program.

The host is a standard desktop computer running Windows XP. The SBC has a standard P-III CPU running Windows 98. It also has two additional serial ports. One of them is used for PTZ controls of the three cameras mounted on the robot. The PTZ movements of the cameras can be controlled individually from

the same HMI used for the operation of the robot. The video signals from the on-board cameras are directly transmitted to the display – a standard television set, through a wireless video link. This display is used for the navigation of the robot throughout the operation.

The fourth serial port on the SBC is connected to the SICK Laser Range Finder (LRF). The LRF generates range data over an angle of 180° in front of the robot. The data may be used to gradually build a line map of the area. Such a map may be made available to the operator on the HMI. It provides accurate information about the distances of the objects from the robot. However, the LRF was not used due to the lack of a reliable mapping program that would work uniformly inside the room as well as outside on the cemented pathways.

Control architecture of *SmartROD*

The mobile platform, *SmartROD* is driven by two DC servo motors. The platform is designed to carry a payload of about 350 kg. The *SmartROD* motions are controlled by a micro-controller based system.

The server program running on the micro-controller carries out the following functions:

1. Establishes and monitors serial communication with the SBC: Serial communication is established between the micro-controller and the SBC by exchanging predefined synchronizing packets. The connection once established is continuously monitored. In case a failure of communication is detected, *SmartROD* is stopped and no further motion commands are executed. Checksum-based data verification is used to detect any corrup-



Figure 3. Set-up for spring-clip opening and unloading of fuze box.

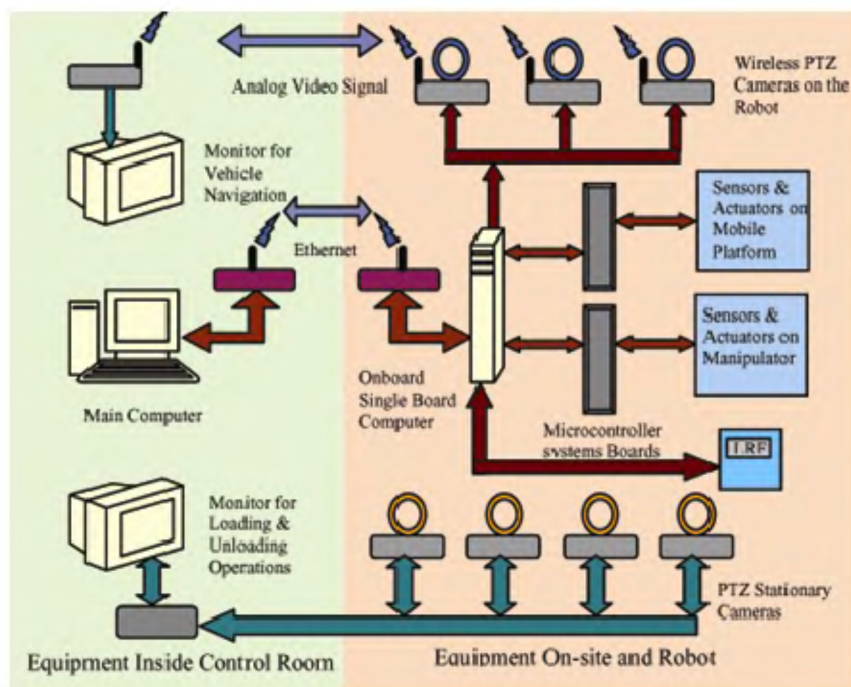


Figure 4. Overall control architecture of the system.

tion in data transmission and reception. Any corrupted command packets received are ignored.

2. Receives, interprets and executes commands: The controller executes commands for parameter setting, translational and rotational motions at desired velocities and motions through desired distances and angles of rotation. The incremental encoder pulses are available as feedback to the controller. The DC motor drives are interfaced to the controller through a DAC.

3. Sends periodic server information packets to the SBC: The controller program sends Server Information Packets (SIP) to the SBC every 100 ms. The SIP contains data regarding the operation status of the mobile platform. These include the current velocities of both sets of wheels, position and orientation of the platform, charging status of battery, bumper status, sonar range data, etc. This information received from the controller is used by HMI application for display and alarm generation.

Control architecture of manipulator

The manipulator has four degrees of freedom and a motorized gripper. All joints are driven by stepper motors. The

manipulator is designed to grip and carry a payload of at most 30 kg weight. It is controlled by a micro-controller-based system similar to the controller of the mobile platform.

The server program for the manipulator is based on similar principles and carries out tasks similar to that of *SmartROD*. The controller executes commands for motion of each joint at specified speeds. Commands are also available for the motion of each joint through desired angles. End-of-travel sensors are provided at all joints for safe operation.

The motions of the manipulator are carried out using video feedback from one on-board camera and a set of fixed cameras in the room. Some joint motions are provided with visual indexing using laser pointers and cross-hair combination. Information received from the microcontroller is used by the HMI window for display and alarm generation.

Host machine interface for control and monitor

Figure 5 a and b shows the graphical interface on the host computer for the remote operation of *SmartROD*. There is a button to connect to *SmartROD* for a session and disconnect at the end of the session. Figure 5 a shows the interface for operating

the mobile platform. The interface provides facilities for driving the platform forward, backward and about itself. There is provision for executing the turn-in-place of the platform by specified angles. In addition, the interface also provides information regarding the charging condition of the battery, position and orientation of the platform as computed from encoder pulses of drive motors, and line map of the area in front of the platform based on LRF data.

The graphical interface is so designed that either the vehicle or the manipulator can be operated at any given time. The vehicle control screen has a button to bring in the manipulator control window. This window provides facilities for control of each joint of the manipulator at different speeds and through different angles. Additionally, this window also provides information on each joint angle of the manipulator and status of the corresponding end-of-travel sensors. The controls are transferred to the vehicle control window on exit from the manipulator control screen.

The *SmartROD* graphical interface also has buttons for the control of PTZ operations of the onboard cameras. These are accessible during both vehicle and manipulator operations. There are emergency stop buttons for both vehicle and manipulator control.



Figure 5. HMI for vehicle operation (a) manipulator operation (b).

Summary

A *SmartRod* mobile robot with on-board manipulator was tested extensively for its designated operation and demonstrated to the Ordnance Factory Task Force members at BARC, Mumbai in January 2006. After shipping the system to OFK Jabalpur in March 2006, and mockup trials at site, the Task Force members slightly modified the procedure for disposal. Earlier it was planned to pour the fuzes into a pit after opening the ammunition box. As there is a potential danger of fuze explosion during pouring, it was decided to dispose (burn) the fuzes within the ammunition box. So in the revised procedure, the ammunition box had to be transported by *SmartROD* to the disposal site after opening its lid. A sloping cemented pathway leading to the disposal site was specially constructed for this purpose.

After many trial runs of the robot from the mock-up room to the disposal site, actual operation was initiated in October 2006. Each cycle of operation of the robot took about an hour. Since burning of fuzes in the pit takes several hours, on an average only three boxes could be disposed in a day. That was rather slow

considering that altogether 300 boxes were to be disposed. As the disposal team gathered confidence after the disposal of a few boxes, multiple boxes were disposed-off together, thus speeding up the operation considerably. As the operations progressed, it became evident that the fuzes were not as sensitive as originally envisaged. Loading of the boxes on the loading tray was carried out manually to further speed-up the operations. The entire operation was over by the end of December 2006. In retrospect we feel that it was the initial fear and uncertainty in handling the fuze boxes that was mainly overcome by the use of the robot. This in itself was the most important contribution that came from the use of the robotic device.

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