**Executive Summary**

Mechanically efficient and innovatively designed robots equipped with reliable sensing and detection techniques can not only help in greatly reducing the time needed to clear an area inflicted with landmines but also reduce the life threats to individual deminers. Our team at LUMS-SSE proposes a new direction. Instead of having a single expensive and mechanically complex robot with a high probability of total failure, we propose a coordinating team of affordable, simple and robust robots that compete with or outperform a single robot. We rely on developing simple robots that can be assembled, deployed and maintained with ease in a third-world small-town environment. The underpinning concept is to exchange the mechanical complexity with computational sophistication. Even the computational resources are envisioned to be based on commercial off the shelf technology. We use NI’s rapid prototyping philosophy to quickly produce a proof or concept design. A major design challenge will be to keep the human intervention to a minimum, although it is almost impossible to eliminate this need completely.

We start with an economic justification of using a robotic swarm. We then move on to the design of the robots and their coordination architecture. Finally, we give some background on our design team and task distribution.
Objectives
The objectives of this project are as follows.

1. **Affordability.** To prototype an affordable robotic system for mine detection so that it can be used by smaller/poorer governmental and private organizations.
2. **Simplicity.** To produce a design that is easily replicable using the simplest commercial off-the-shelf (COTS) technology so that it can be indigenously produced, deployed and maintained in a third world country by small budget organizations.
3. **Scalability.** To keep the system reconfigurable and its performance scalable, so that the same low-budget design can be re-scaled to a large-scale mine-clearing operation.
4. **Light-weight.** To keep the design light-weight for rapid deployment and transportation.
5. **Friendly HRI.** To keep the human robot interaction as friendly and simple as possible so that it can be operated with minimal training.
6. **Rule Compliance.** To keep the design consistent with ALL the rules of contest (See Page 10 of the rulebook document.)

The Economic Case for a Robotic Swarm
The entire concept of humanitarian demining rests on whether it can be made affordable. Robotic solutions to demining efforts have been proposed and researched for almost two decades now. However, prohibitive costs and reliability issues have thus far been hindering the wide scale deployment of robotic technologies in this area. Affordability, reliability, scalability and technological complexity are pivotal issues for the deployment of demining robots in the poor countries of the world.

Market and Performance Constraints
To prove the economic justification of a robotic technology for replacing human demining experts, the following rough estimates can be a useful start.

1. It is possible to hire human experts under $2000 dollars / year for mine detection and clearing operations in a South Asian / African country. Additionally, they work without life-insurance or disability support from the parent organization.
2. The entry barrier to a small organization for conducting a small-medium scale operation for clearing/detecting mines stands at roughly $10,000 / year / km² including all overheads.
3. Current robotic technology, capable of navigating rough terrains and delivering similar performance and reliability stands at $10,000 or above for platform only. Operation, maintenance and deployment costs are not included. These overheads can easily swing the number to over $100,000/year.
4. Going for a sophisticated technology solution will not lower the barrier for robotic demining solutions, unless the costs of both the platform and its maintenance are reduced drastically.
5. Any attempt at reducing the cost of a robotic platform results in a significant increase of failures and degrading of performance.
Solution: A Cheap Platform Replicated Many Times Over
One can confidently estimate from these constraints that it is *not possible* to produce a single reliable and cost effective robotic system that can compete with human experts using the current technology. In this project, we propose that we can still solve the economic issue of cost vs. reliability by the following.

1. A mechanical platform with mechanical complexity comparable to a wheelchair or bicycle, so that it can be built, reproduced, maintained and deployed from a small town auto-mechanic or electrician’s workshop.

2. Where possible, exchange the *hard* mechanical complexity of the system with maintenance free, easily replicable and *soft* computational solutions.

3. (1) and (2) together bring the platform cost drastically down to $2000 or less (See an example budget in Table 1 below). However, there is a significant degradation of performance.

4. To overcome the reliability barrier for such a simple design, we deploy a team of such robots, instead of one, thus increasing the redundancy of the system and make the performance completely scalable.

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<tr>
<th>Item</th>
<th>Cost (USD)</th>
<th>Weight</th>
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<tbody>
<tr>
<td>Embedded controller [production model]</td>
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<td>Negligible</td>
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<tr>
<td>Sensors (Metal detectors, cameras)</td>
<td>$400</td>
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<tr>
<td>Video link/Radios/Comm. Modules</td>
<td>$150</td>
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<td>Motors, drive, power electronics</td>
<td>$500</td>
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</tr>
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<td>Steel frame, tires, assembly</td>
<td>$300</td>
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</tr>
<tr>
<td>Battery</td>
<td>$300</td>
<td>5 Kg</td>
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<tr>
<td>Laptop for teleoperation [One per robot team]</td>
<td>$600</td>
<td>N/A</td>
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</tbody>
</table>

| Total Cost: | $1800/robot+$600 | Total Weight: | 30 Kg | Payload: | 12 Kg |

Table 1. System cost budgets for a production model. (Prototyping cost not included)

In the graph below, we explain how we satisfy these cost and reliability constraints. A team of 5-6 robots beats the human expert cost barrier of $10k while also satisfying a total reliability of 1% failure rate or less for the total system. An overhead of $600 for the total system is added to indicate a common tele-operation for all robots in the team. The reliability calculations have been done using very crude models. However, we see in the graph that a design of 5-6 robots beats this barrier for several pessimistic choices of failure probability.
Why a Robotic Swarm?
The last point deserves some more elaboration. The idea of deploying a robotic technology made up of a large number of less reliable cooperating agents instead of a single sophisticated but expensive robot is not new. In fact, it has become one of the most seriously investigated topics in robotics and systems engineering today. This swarming solution to solving complex problems is directly inspired from nature where there is a demonstrated strength in problem solving by using large numbers of individual agents. Examples include ant colonies, bird flocks, fish schools, mammalian herds etc. The cost we pay for such a solution is to devise some ingenious communication and coordination mechanism. In our case, we argue that such a coordination scheme is possible and can be implemented completely in a soft compute and communicate solution.

We also reemphasize that we attempt to do this while obeying all the rules of the contest. Our system will be operated by a single user only. The robot team members will coordinate autonomously.

Redundancy Vs. Coordinated Problem Solving
It is also important to clarify that we are not just proposing multiple redundancy but a cooperative and parallel problem solving strategy. Redundancy would just mean that multiple robots are kept as a backup to replace other malfunctioning robots. What we propose is a coordinated, autonomous and verifiable effort to sweep the entire area using robots working in parallel. Redundancy is only a by-product of this. Another major advantage of this design is that it is completely scalable. By adding more robots, we can get faster coverage of the hazardous area, more reliability and decreased cost/unit.

Design Overview
The total system is made up of many robots of the same design, linked together by a communication network and operated remotely by a single user (as required by the rulebook). Each robot is semi-autonomous with no mechanical coupling to others. All robots are connected to base station which serves both as a communication hub and a terminal for human operator control.
In this section, we give an overview of our design at four planes.

1. Mechanical design of robotic platform
2. Sensors, drive and control hardware
3. Software architecture and supervisory control
4. Multi-robot coordination and HRI (Human-Robot Interaction)

In Section 4, we will give details on important sub-components at each level of overall design.

1. Mechanical Design of Robotic Platform

In keeping with the spirit of the contest, we explain here the mechanical design of our atomic robot.

The robot is a four wheeled cart, with steering at the front. The wheels are driven in the front by DC motors. The wheels support the main body via a suspension. In front of the robot, there is a two degree of freedom arm on which an array of mine detection sensors is mounted. The sensory arm is capable of being adjusted automatically according to the ground profile. The platform is simple, stable and capable of traversing rough terrains at reasonable speeds.

Please note again, that the mechanical design complexity has been deliberately kept to a minimum. We give below several images that explain the design and its mechanisms.
Figure 1. Front wheel, shock and motor

Figure 2. Sensor arm details.

Figure 3. Steering and sensory arm.

Figure 4. Steering.

Figure 5. Steering motor.

Figure 6. Top view.
2. Sensors, Drive and Control Hardware

A host of sensors are mounted on the sensory arm for carrying out mine detection close to the ground. The sensory arm keeps an appropriate height from ground by visual servoing aided by ultrasonic distance finders and on board robot pose estimators. This is enabled by a set of cameras (for stereo vision) mounted on the main platform. Moreover, a host of sensors are mounted on the main body for navigation, obstacle avoidance, path planning and communication. The sensors and communication modules are connected to the main computational unit (depicted by a computer in the mechanical design figures). The system architecture is shown in Figure 7 (below).

The sensors include

1. Cameras/Vision. One pair tilted downwards for visual servoing of detector arm and one forward looking pair for navigation/obstacle avoidance and mine detection. Both pairs provide stereo vision for accurate depth estimation.

2. Ultrasonic distance sensors. One set mounted on arm for ground distance estimation to aid visual servoing and one on main body for robot navigation/obstacle avoidance.


4. GPS and electronic compass for reporting ground position and orientation of robot.

5. IMU sensor suite (accelerometer, gyro) for reporting 6 DOF robot pose. Critical for adjusting arm properly in a rugged terrain.

The drive system includes

1. Battery unit and energy management interface (for reporting battery life)

2. Power electronics and drive interface

3. Standard automotive grade high-torque DC motors for steering main robot and mechanical arm.
The computational/control hardware include:

1. NI sbRIO-9642 for low-level real-time control loops, sensor/drive interfaces.

2. High performance embedded PC platform (Beagleboard) for supervisory control, communication and high-end vision algorithms.

In this project, we also use an embedded PC platform as a supervisory controller for non-critical real time tasks such as wireless communication, map building, data logging, high level path planning and possibly some intensive computer vision algorithms that cannot be handled by sbRIO. We give details of this mapping in the next subsection.

BeagleBoard has been chosen as the embedded computer for this project because of its high processing power, wide peripheral base, extremely low power consumption and strikingly small size. The BeagleBoard has at its core a System On A Chip (SOC) by Texas Instruments (TI) called OMAP 3530. It consists of a DSP+ARM A8-Cortex processor, with 256MB each of NAND and FLASH memory. The BeagleBoard also has provisions for attaching external memory in the form of MMC/SD cards.
sbRIO-9642 has been chosen as the platform for low-level time-critical signal processing, feedback control and sensing tasks. sbRIO has been chosen due to its rapid prototyping environment and ease of interfacing with hardware devices, sensors and actuators. It runs as a slave under Beagleboard with which it communicates using a 10/100 Mbits/s Ethernet port available on this model of sbRIO.

3. Software Architecture and Supervisory Control

The software architecture (for each robot unit) is inspired by the DARPA Grand Challenge winner design of Stanford University’s entry Stanley. It has a clear emphasis on modularity, robustness and on-board system diagnosis. The modularity allows transparent mapping on appropriate hardware resources (e.g. sbRIO or Beagleboard). All software modules meet real-time constraints using support provided by real-time LabVIEW on sbRIO and Ubuntu’s Karmic (a variant of Linux) on Beagleboard. The various software modules along with information flow has been given in the figure below. The various data pathways are either internal (e.g. via a shared memory and real-time process scheduler when on the same board) or via Ethernet ports (when on different boards).

The various software modules/blocks are

1. Vehicle Navigation and Map Building [Beagleboard+Linux]
   a. Obstacle detection (stereo depth estimation, sensor fusion with ultrasound data)
   b. Localization and map building (SLAM algorithms)
   c. Navigation / High-level path planner (AI planning algorithms)

2. Vehicle and Arm Movement Control [sbRIO+Real-time LabVIEW]
   a. Depth estimation (near field stereo vision, sensor fusion with ultrasound)
   b. Surface mine/cluster bomb detector (vision based pattern recognition)
   c. Robot self-pose estimation (Kalman filtering of IMU data)
   d. Mine detecting arm control (Feedback control algorithms for motor position control)
   e. Vehicles low level control (Control commands for power electronics+drive)

3. System Health Monitoring+Data Logger (Emergency shut down+data dumps) [Beagleboard+Linux]

4. Top Level Control (Arbitrator; system state machine; bootup/shutdown) [Beagleboard+Linux]

5. Communication (Wireless, 802.11/Zigbee) [Beagleboard+Linux]
4. Multi-Robot Coordination and HRI

The total system will consist of a team of 5-6 networked robots for coordinated search of mines in a given area. The coordination will be done using a backbone of standard 802.11n wireless communication between robots and a base-station. Our assumption is that a single robot will cover a 100m x 100m area. By this assumption, robot can be maximally apart by 250m, which is less than the max. range of 802.11n. The base-station is a standard notebook computer running a standard operating system such as Windows or Linux.

A number of coordination and HRI (Human Robot Interaction) tasks will run at the base-station. These include:
1. High level mission planning and task assignment. [startup; non real-time]
2. Area coverage verification. [mission duration; near real-time]
3. Network connectivity by proximity maintenance. [mission duration; near real-time]
4. Timely intervention by human operator for recovery and maintenance. [mission duration; near real-time]
5. Sensory data exchange between robots. [mission duration; near real-time]
6. Recovery and wrap-up [shutdown; non real-time]

Some Preliminary Results and Experiments
Extensive work has already been carried out by our group during the past few months in preparation of the contest at various levels. Below is a brief summary/status report.

1. The mechanical design of the robot has been finalized. The robot is currently being manufactured at a local machine shop. We expect to receive our first robot in late August.
2. Feedback controllers for mechanical arm were designed and tested by a student group as a course project for CMPE-432: Feedback control design at LUMS.
3. Visual servoing was studied by another student group during CMPE-432 and subsequently in a summer internship program at CYPHYNETS Lab at LUMS. Ultrasound and vision sensor data has been successfully interfaced and fused.
4. Extensive work was done by two student groups this summer on depth estimation by stereo vision. Both groups reported preliminary success in simulation and are currently working on real time aspects for implementation.
5. An undergraduate student team worked on making a low cost metal detector to further reduce the cost of sensors. This team achieved a limited success. However work is still underway on improving the design.
6. A senior thesis project by computer engineering students worked extensively on the issue of communication between robots. For this study the students worked on a group of four iRobot Create robots. However, the software and hardware control was independent of platform. The students demonstrated network maintenance, and real-time coordination capabilities. We expect this work will be ported seamlessly onto the new demining application.
7. The same student group worked out a robotics embedded system architecture and successfully used Beagleboard with Ubuntu (Linux) as a supervisory controller for robotic systems.
8. Another student group studied the problem of multi-robot coverage and pointed out various issues in implementation.

Some snapshots from these preliminary results are given below. More details on these projects are available as technical reports.
The LUMS team is an interdisciplinary group of electrical, computer and mechatronics engineers and computer scientists from two departments within SSE. The team organization is as below:

Dr. Abubakr Muhammad, Assistant Professor of Electrical Engineering
[team lead. system engineering, multi-robot architecture, project management]

Dr. Mian Muhammad Awais, Associate Professor of Computer Science
Mr. Umar Suleman, PhD Candidate in Computer Science
[HRI, high-level planning, AI]

Mr. Ali Abbas, PhD Candidate in Computer Science
[robot simulation, image classification, machine learning]

Mr. Suleman Sami Qazi, MS EE, Lab Engineer, Electrical Engineering
[reliability engineering, technical communication, LabView/NI tools]
Mr. Mhequb Hayat, MS student, Computer Engineering
[mechatronics, robot motion planning, SLAM]

Mr. Hasan Arshad Nasir, MS student, Computer Engineering
[embedded controller/sbRIO, sensors and electronics, control systems design]

Mr. Ali Ahmad Khan, BS student, Electrical Engineering
[real-time operating systems, software architecture]

Past Experiences
The LUMS team has extensive research and development experience in
1. NI LabView/DAQ Solutions. We currently have numerous NI DAQ cards in use in different labs at LUMS SSE. All our freshman students are introduced to LabView environment.
2. Robot design, AI and mechatronics.
3. Control system design
4. AI, vision, machine learning
5. Multi-agent robotics architectures, analysis and design.

National Instruments Equipment Required

1. NI sbRIO-9642/9642XT Embedded Devices with DIO, AI/AO, 24 V DI/DO, 2M Gate FPGA (x2)
2. NI Single-Board RT and FPGA Developer Suite
3. 24 VDC power supplies for NI Single-Board RIO, NI Smart Cameras (NI PS-17/PS-16/PS-15)
4. NI 9215E 4 channel simultaneous sampling AI.
5. NI 9219E Universal analog I/O. (x2)
6. NI 9481E 4 channel relay. (x2)
7. LabVIEW Robotics sbRIO Starter Kit.
8. LabVIEW Robotics Software Bundle.
9. NI vision guided robotics Bundle.
10. NI 1744 Smart Camera (x4).

**Budget**

**Summary:**

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<td>2</td>
<td>Faculty Startup Research Grant</td>
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**Equipments costs:**

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### Major Equipment

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**Sub Total:** $5,000.00

### Special Equipment

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<td>Equipment 4</td>
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**Sub Total:** $24,125.00

### Other Equipment

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**Sub Total:** $6,812.50

### Total Equipment Cost:

$35,937.50

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**Project Director (PD)**  
**Joint Project Director (JPD)**  
**Professional Researchers / Developers**  
**Research Assistants (Students)**  
**(MS)**  
**(PhD)**

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Total Technical HR Cost : $ 24,937.50

References


