Teleoperated Buggy Vehicle and Weight Balanced Arm for Mechanization of Mine Detection and Clearance Tasks

Edwardo F. FUKUSHIMA[a*], Paulo DEBENEST[a], Yuki TOJO[a]

Kensuke TAKITA[a], Marc FREESE[a], Helmuth RADRICH[a] and Shigeo HIROSE[a]

[a] Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8552, JAPAN

ABSTRACT

The development of a practical mobile robot system for mechanization of humanitarian demining tasks such as sensing/verification and/or clearance of anti-personnel landmines is close to be completed. The system proposed by Hirose group at Tokyo Tech is a simple but effective solution that consists of a pantographic weight-balanced manipulator mounted on top of a mobile platform. A practical and versatile mobile platform has been successfully realized by converting a commercial 4-wheel buggy for remote-operation. Nonetheless, it still preserves the characteristics of the original buggy, and can conveniently serve as a commuting vehicle for the human worker as well. On the other hand, the manipulator mounted on the buggy is a complete new type of manipulator especially designed for the landmine detection and removal tasks. It adopts a new weight-compensated configuration consisting of 4 links and 5 nodes pantographic linkage. This manipulator can be equipped with many types of sensors to detect landmines and also has the capability to equip grass cutter, prodders and other tools if so required. For the short term in particular, this research is focused on the sensing tasks. For this purpose, mine sensors composed of metal detector and ground penetrating radar has been tested. Furthermore, automatic topographical mapping generation and scanning of the terrain has also been implemented using stereo-vision cameras mounted on the manipulator link. This automation relieves the human-operators from the burden of watching all the scanning process which can be long and demanding. Nonetheless, the operator can switch to manual scanning and teleoperate the manipulator whenever it is necessary. In this paper the authors explain the system main concepts and give details of its main composing parts. The validity and usefulness of the proposed system are demonstrated by real experimental results.

Keywords: Mobile Robot, Manipulator, Gravity Compensation, Energy Generation, Metal Detector, Ground Penetrating Radar

1. INTRODUCTION

The consequences of nations irresponsibly burying anti-personnel landmines in war time without considering their posterior safe removal are felt even long after war and conflicts are over. Most of the victims are civilians who remain and live in the affected areas, which are urged to be inspected and cleared as soon as possible in order to restore normal life.

Mechanization and automation of humanitarian demining tasks have been active topics of research by many robotics researchers around the world during the last decade. However, few or none practical robotic solutions has been successfully implemented and widely used in real mine fields to date, as far as the authors' knowledge. On the other hand, the use of heavy machines such as flails has gained wide acceptance for the mine clearance stage known as mechanized detonation. However, although mechanized detonation can cover wide areas in a short time, it is not 100% reliable. So one last stage to verify the clearance of landmines is still needed for final inspection and removal of the mines that remain in the ground. At present, as depicted in Fig. 1, this last stage is mainly performed by human deminers who are almost at direct contact with the landmines, thus exposed to great danger.

Our research group aims to develop a new teleoperated robotic system that can be effectively and reliably used to carry sensors/equipments to the mine-field to detect and if required also to remove/neutralize the landmines at a safe distance away from the mine field. This will assure maximum security for human deminers who remote-operate the system. Furthermore, the introduced robotic system can be easily operated after a short training period, so that human deminers that are now working on the verification and clearance operations and possess high expertise on manual demining tasks, could become operators of the new robotic system soon it is available.

Fig. 1. Illustration of a deminer working on verification and clearance of landmines. Deminers are exposed to great danger and potential accidents.

1.1 System Concept

The proposed system, which has already been tested under several operation conditions in prepared test fields, is illustrated in Fig. 2. It consists of a manipulator arm mounted on a mobile platform. The total system is

* fukusima@mes.titech.ac.jp; phone +81 3 5734-3175; fax +81 3 5734-3175

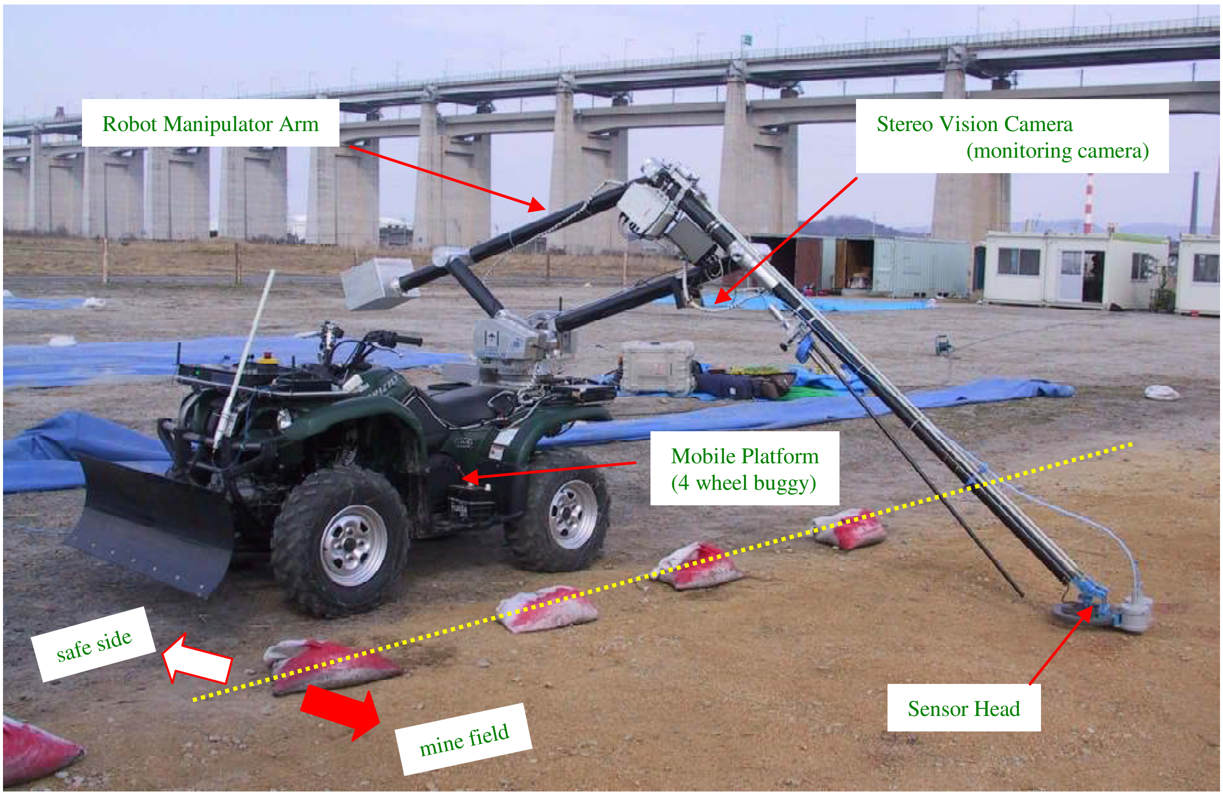

Fig. 2. The teleoperated buggy vehicle and weight balanced arm "Gryphon-IV" during field tests at Kagawa. The mobile platform is based on the Yamaha GRIZZLY 660. It can be both manually driven and/or teleoperated. The arm is equipped with a commercial metal detector CEIA MIL-D1, which is presently the most widely used manual mine detector in Afghanistan. A GPR (ground penetrating radar) can also be integrated to the system. This photo illustrates the system performing an automatic scanning of the prepared mine field with uneven ground surface, during the "Test and Evaluation on Mine Detection Sensor Systems (prototype)" promoted by the Japan Science and Technology Agency (JST) last March 16, 2005, at Bannosu Industrial Park, Sakaide City, Kagawa Prefecture, Japan.

Fig. 3. Gryphon mobile platform can be either manually driven and teleoperated. It can server as a commuting vehicle for the human worker.

Fig. 4. The remote controller is equipped with two joysticks and few switches. The display panel is in fact a panel computer

equipped with metal detector and GPR for efficient and effective mine detection, and also has a mine location marking apparatus to visually mark the ground where the mine has been detected. Nonetheless, the position of the mine is also registered in the on-board computer for future references. The manipulator arm can be manually controlled, but a high degree of automation of the scanning process has been successfully accomplished by using a stereo vision camera to automatically map and scan the terrain. The human operator supervises and operate the system from a safe place using a wireless remote controller (see Fig. 4).

1.2 Design Specifications

The main specifications and goals that have been seriously considered throughout the design/development stages of the total system are:

- High level of protection against dust and water (IP65).
- Wide operational temperature range (-10 to +60 ^{o}C).
- Protection and resistance against humidity.
- Protection and resistance against vibration and mechanical shocks.
- Long and continuous operation time. The system should not be constantly interrupted for battery charging/changing or refueling.
- Wireless communication range more than 100 meters.
- Low cost, affordable prices. Use of off-the-shelf components.
- High reliability, fail-safeness, easy maintenance, easy to use.
- Short development time, application of matured technology.

In a great extent, most of these specifications have been realized and the developed system fulfills the demands for a practical system to be used even under severe environmental conditions encountered in such countries affected by landmines.

As shown in Fig. 2, the system can be divided and discussed in 4 main components, say: (i) mobile platform; (ii) manipulator arm; .(iii) mine sensor; and (iv) stereo vision system. The following sections will explain in some detail the concept of each part. For more detailed technical explanations, please refer to the published literature [1]-[5].

2. MOBILE PLATFORM

The main purpose of the mobile platform is to carry and move sensors and equipments to and from the minefields, in order to accomplish tasks such as verification/detection and/or clearance/neutralization of landmines. A high payload capacity is desirable in order to mount a robotic manipulator, sensors and tools. Moreover, high mobility on uneven terrain is also demanded, because the system should operate not only on the flat terrain but on uneven terrain such as minefields after heavy machines already revolved the soil.

Taking in account limited time for the development, costs, and all the above design specifications, the use of a commercially available buggy has been decided. Actually, the development of an autonomous buggy type vehicle for field works has been addressed in earlier works [2]. Thus, knowledge about mechanical and electronic implementation for automation of the main functions such as throttle, brakes, gear shift and steering had been already accumulated by the time the humanitarian demining project by the Japanese Science and Technology Agency (JST) started. Furthermore, 4 wheel buggies or ATVs (All Terrain Vehicles) are known to possess high mobility in many kind of terrain and operate under severe conditions. All these potential features are inherited by the autonomous buggy.

Other important feature of the mobile platform proposed by our research, is the electrical energy generation using the on-board combustion engine and alternator.

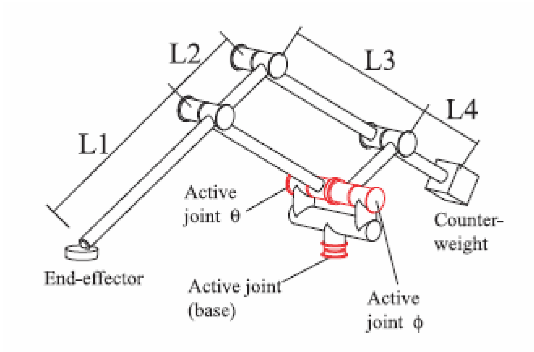

Fig. 5. Pantograph manipulator with 4 links and 5 nodes. The three active joints, i.e. equipped with motors, are placed on the base of the manipulator. The counter-weight when properly dimensioned balances the whole structure in any given posture, hence the manipulator can efficiently actuated with very low power and energy consumption

Fig. 6. Gryphon-IV demonstrating the manipulator long-reach capability and the possible aplication for scanning operation in steep slopes.

The electric energy is supplied to the manipulator arm and other contollers. Test results indicate that the system can operate continuously for about 8 hours consuming less than 20 litters of gasoline (about 3/4 of the fuel tank). So in most cases a full tank of fuel is enough for one day operation including commuting from the base camp to the minefield. Nonetheless, refueling the buggy is done in the same way as for the original vehicle.

3. MANIPULATOR ARM

Fig. 5 shows the configuration and placement of active joints, i.e., equipped with electric motors, for the weight balanced arm mounted on the mobile platform. It has a pantograph-similar construction that, through the action of a counterweight, keep the total center of mass at a fixed position near the active joints, independently from the posture of the arm and inclination of the base. This guarantees a low power requirement and very low energy consumption for the actuators and at the same time generates very stable motion because of good weight balancing. For instance, the arm can reach lower places than the level, still maintaining good stability, as shown in Fig. 6.

The manipulator arm can be equipped with many different types of tools, e.g. grass cutter, prodder and sensors. The example on Fig. 7 shows a prodding device developed in an earlier stage of this research. However, lately the development of a system for detection of landmines has been set as priority, so recent attention has been paid to effectively integrate mine sensors to the manipulator tip instead of digging/prodding. Nonetheless, in the near future the authors plan to finish the development of other types of tools as well.

Fig. 7. Former model Gryphon-III equipped with prodder capable of digging the ground. Note that although this is a smaller buggy than the used in Gryphon-IV, the basic automation functions are the same.

Fig. 8. Sensor head. The left cylinders are the GPR transmitter and receiver antennas, and the right circular sensor is the metal detector CEIA MIL-D1.

3.1 Mine Sensors

The sensor head used in the preliminary field experiments is shown in Fig. 8. It is composed by a metal detector (MD) and a ground penetrating radar (GPR). Its orientation can be controlled by a two degrees of freedom wrist mechanism.

It is crucial for reliable detection of mines to keep the sensor head as close to the ground as possible. Using a remote controller, Gryphon can be entirely remote-operated manually. However, the task is extremely difficult because a human operator has to deal with five degrees of freedom at the same time, which is too much to handle and prone to errors. For this reason, we propose to operate the system through a control system that has some knowledge about its surrounding topographical environment thus allowing the system to automatically scan the terrain to be inspected. The detail of the automatic scanning is explained in the next section.

4. STEREO VISION SYSTEM

Proximity sensors attached directly to the sensor head can be a very simple solution for a reflexive control scheme to automatically adjust the vertical distance of the sensor head to the terrain. However, although technically more complex and expensive, in order to make possible a more efficient mapping and scanning of wider areas in a minimal time, our work focused in using sensory systems that allow topographical map building. Examples of potential sensors that can be used for this purpose are listed below.

Table1 Types of topographical map acquisition systems

Feature / Sensor type	Cost	Accuracy	Acquisition speed
Active stereo vision	expensive	very good	Fast
Passive stereo vision	affordable	good	Fast
1D Laser range finder	affordable	very good	slow*
2D/3D Laser scanner	expensive	very good	Fast

* A laser range finder attached to the arm would require driving it back and forth to acquire enough topographical points.

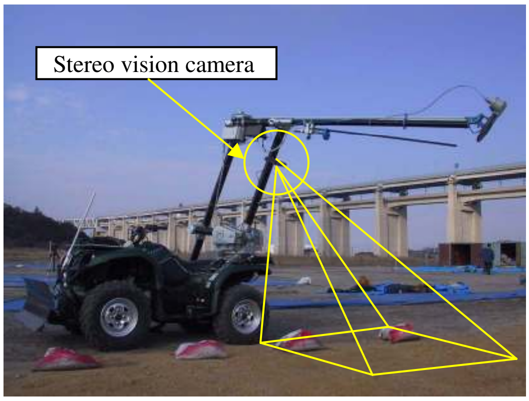

Fig. 7. The arm can be lifted up and controlled to different postures for effective topographical map acquisition.

A passive stereo vision system has been selected for its good cost/performance ratio and ease of use. For our first prototype in particular, a stereo vision camera with a resolution of 1024x768 pixels from Point Grey Research (Bumblebee^{TM}) was used. This camera is pre-calibrated and has an easy-to-use library for disparity calculations and depth map extractions. Performance in a natural outdoor environment, naturally containing highly textured surfaces, is very good, justifying a passive stereo vision system for our application over an active one (an active stereo vision system artificially textures its environment by projecting light patterns onto it).

The camera was mounted on one link of the manipulator arm (Fig. 7) and inherits two degrees of freedom from the manipulator motion. An additional extra degree of freedom is optionally added to the camera supporting mechanism, which allows for more flexible operation (and additionally allowing using the stereo vision camera also as a simple 2D-monitoring camera).

4.1 Autonomous Scanning

Autonomous stereo vision assisted scanning is divided into two sub-tasks: topographical environment acquisition and scanning itself.

(a) Topgraphical Environment Acquisition

A precise positioning of the camera relative to the manipulator arm base (yaw joint) which is chosen as the reference system of Gryphon is extremely important. The topographical environment is generated by merging a set of smaller topographical maps taken from various stereo vision camera locations to cover the region of interest as extensively as possible. For that operation the yaw-axis of the arm is rotated at fixed intervals while a sequence of vertical camera supporting motor positions are selected to acquire portions of the terrain. The obtained topographical maps are partially overlapping.

(b) Scanning

Scanning itself is preceded by a series of operations on the acquired topographical map:

1. Generation of a regular grid from the topographical map.
2. Filling of missing parts in the grid by linear interpolation (sometimes needed when texture level is not high enough or in case of bad illumination conditions)
3. Low-pass filtering of the grid
4. Vertical shifting of the grid about the desired scanning height above the terrain

The result is a smooth grid (Fig. 8) that is used to guide the sensor head over the terrain. While the orientation of the sensor head follows the curvature of the grid, the described trajectory is a series of arcs concentric to the manipulator arm's yaw axis, effectively minimizing power consumption, reducing jitters and allowing for better MD/GPR detection performance.

5. OVERALL EXPERIMENTAL RESULTS

Gryphon-IV has been operated for about 200 hours during a three weeks of extensive tests organized by JST, "Test and Evaluation on Mine Detection Sensor Systems" (2005) at Kagawa prefecture, Japan. The test lanes consisted of various prepared lanes containing buried surrogate landmines at different depths.

5.1 Autonomous Scanning of the Terrain

One of the lanes contained numerous 10-20 cm high bumps, which can be expected in real minefields. These tests showed how good the autonomous scanning accuracy using the stereo vision camera was. One example of terrain curve following performance of the sensor head is shown in Fig. 9. The system performed well as expected and, given a safety distance of 5 cm above the ground, was able to perform a total of about 200m^2 (2m^2 for each scan) in 10 days of tests. The average scanning speed was about 8 min/m^2, limited by the specification of the GPR sensor. The arm itself can move about three times faster and considering the response of the metal detector, this system would perform much faster than a human deminer when comparing sensing using metal detector only. The metal detector response can be visualized in real-time, as shown in Fig.10.

5.2 Autonomous Maneauvering of the Vehicle

Fail-safeness is of major importance for an autonomous mobile robot that will operate near humans workers. It is not acceptable that the system loose control in any circumstances because it can injure people around. For this reason, software and hardware has been implemented with fail-safeness in mind [5]. In order to test the reliability of the system, errors were intentionally simulated by unplugging the communication cables, turning off the controller, disconnecting the wireless antenna, turning off and resetting the control circuitry and driving the vehicle out of the wireless modems maximum range. The overall system behaved as expected and was always correctly halted (stopped in a safe state) when any malfunction was detected. One unmanned remote-operation experiment is shown in Fig. 10.

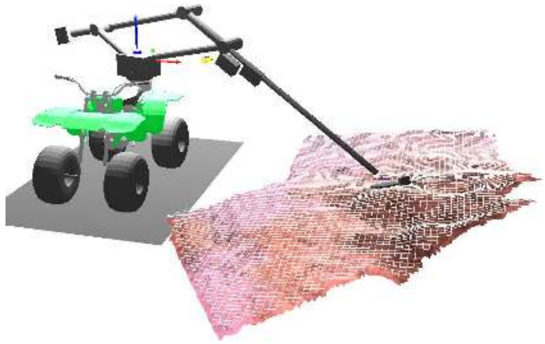

Fig. 8 Illustration of internal 3-D model and mapping of terrain. The computer generated model and grid is overlapped to the real terrain image and can be displayed to the remote controller panel shown in Fig.4

Fig. 9. The sensor head closely follows the contour of the terrain.

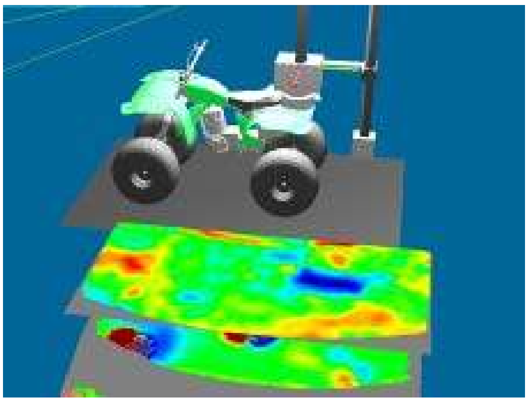

Fig. 10. An example of graphical illustration of the locations where buried objects has been detected. Upper layer show GPR reading, and the bottom layer the metal detector reading.

Fig.10. Gryphon-IV remote maneuvering experiment. The system can be remote-controlled in a range of about 150meters.

6. CONCLUSIONS

The overall performance of the proposed system is very satisfactory. Evaluation results from many experiments show that Gryphon scores as well as human deminers when considering the performance of anti-personnel land-mine detection using off-the-shelf metal detectors (e.g. CEIA MIL-D1). For this reason, this system should already be seriously considered to replace human deminers from the dangerous task of sensing/verification. Moreover, combination of metal-detector and GPR has also been evalutated in our system, and despites it takes some time for post-processing the detection results are even better than metal-detector only.

Two new complete "Gryphon" system is under development now, and they will be available for tests in real minefields this year.

ACKNOWLEDGEMENT

The authors would like to thank JST (Japan Science and Technology Agency) for sponsoring this research.

REFERENCES

[1] E. F. Fukushima, P. Debenest and S. Hirose, "Autonomous Control of an Engine-Driven Mobile Platform for Field Robotic Systems," *Proc. of IROS'01*, pp. 84－89, 2001.

[2] P. Debenest, E. F. Fukushima, Y. Tojo, S. Hirose, "A New Approach to Humanitarian Demining. Part 1: Mobile Platform for Operation on Unstructured Terrain," Autonomous Robots, vol. 18, no. 3 (May 2005), pp. 303－321, 2005.

[3] P. Debenest, E. F. Fukushima, Y. Tojo, S. Hirose, "A New Approach to Humanitarian Demining. Part 2: Development and Analysis of Pantographic Manipulator," Autonomous Robots, vol. 18, no. 3 (May 2005), pp. 323－336, 2005.

[4] M. Freese, Y. Tojo, E. F. Fukushima and S. Hirose, "Teleoperated Buggy Vehicle and Weight Balanced Arm System for Mechanization of Mine Detection Tasks - Automatic Scanning of Mine Fields based on Stereo Vision -," Proc. Of Robotics and Mechatronics Conference 2005, 1P1-N-047, 2005.

[5] H. Radrich, P. Debenest, E. F. Fukushima and S. Hirose, "Teleoperated Buggy Vehicle and Weight Balanced Arm System for Mechanization of Mine Detection Tasks - Fault-tolerant and Fail-safe Distributed Control -," Proc. Of Robotics and Mechatronics Conference 2005, 1P1-N-047, 2005.