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# Preliminary Design and Feasibility Study of a 6-Degree of Freedom Robot for Excavation of Unexploded Landmine

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**Abstract.** At present, the Sensing and Access Control R&D for Humanitarian Mine Action project has been carrying out by the Japan Science and Technology Agency (JST). Chiba University's group join to this project. Our effort is to develop a small vehicle for mine detection and clearance. Specifically we are concerned with the development of a 6 degree-of-freedom robot arm for exposing buried anti-personnel mines, with plans of field-testing in Afghanistan in 2005. This paper describes the current state of development in the anti-personnel mine exposure and clearance system, focusing on the robot arm.

## 1. Introduction

Since 1999, our group has been involved in the research and development (Nonami et al., 2003) of landmine detection and clearance technology with the aim of maximizing safety and increasing the overall speed in humanitarian demining.

Currently our group is participating in the Japan Science and Technology Agency's (JST) Sensing and Access Control R&D for Humanitarian Mine Action project[1] with our effort to develop a small vehicle for mine detection and clearance. Specifically we are concerned with the development of a 6 degree-of-freedom robot arm for exposing buried anti-personnel mines, with plans of field-testing in Afghanistan sometime around the middle of 2005. We must therefore produce results in a relatively short period of time, and so we have divided the project into several tasks to be tackled.

Other groups participating in the JST project are Hirose's group from Tokyo Institute of Technology and Fukuda's group from Nagoya University including Tadano Ltd except advanced sensor R&D groups.[2,3] The three groups have the same ultimate goal, but are taking different approaches. Hirose's group has put a lot of effort into its Mine hand device and a buggy vehicle with metal detector. It is low cost and structurally simple. Fukuda's group is developing a huge crane based on existing technology for GPR based mine detection. Our team, in cooperation with Fuji Heavy Industries and Sato's group from Tohoku University, and Arai's group from University of Electro-Communications has proposed a small remote controlled vehicle-based system. The system is still in development, and we believe that when it is complete it will be effective in a practical setting.

This paper describes the current state of development in the anti-personnel mine exposure and clearance system, focusing on the robot arm. In particular, we have achieved the reasonable performance of a 6-degree of freedom robot with multi-function tool by means of nonlinear control based on "LOOK AT TABLE" scheme.

## 2. Project Outline

The tasks prescribed to our group concerning the JST project are as follows.

(1) Anti-personnel mine detection
(2) Anti-personnel mine exposure

The task of landmine detection is being undertaken by Sato's group at Tohoku University, who are developing an array-style ground penetrating radar (SAR-GPR) (Sato et al., 2003). Fuji Heavy Industries and a member of our group are responsible for the development and control of an arm that the sensor will be mounted on. The rest of our group is focused on the task of anti-personnel mines exposure. After a mine is exposed, its disposal will be carried out in a usual manner, for example the mine may be exploded by placing a charge next to it. The disposal of anti-personnel mines lies outside the requirements laid out for our project, however we aim to complete a system capable of removing them.

## 3. The Controlled Object

### 3.1. The Hydraulic Robot Arm

The controlled object, the multifunction robot arm (Fig. 1), has six joints and an end effector consisting of a gripper, electromagnet, drill, and air jet (Figs. 2 and 3). The sixth joint is a tool changer that allows for switching between end effector tools as needed by the application. The arm is to be mounted on a mine detection vehicle that is being manufactured by Fuji Heavy Industries. The arm's primary specifications are listed in Table 1.

Hydraulic cylinders with proportional electromagnetic valves actuate the six joints. The speeds at which the cylinders extend and retract are proportional to the voltages applied to the valves. The gripper on the end effector is also hydraulically driven, but it employs an ON/OFF valve. The electromagnet, drill, and air jet are all activated by switch.

The arm's link configuration and joint ranges are shown in Fig. 4. Each joint, with the exception of the base joint (Joint 1), has an absolute value encoder to measure the joint angle and eliminate noise. Joint 1 currently uses a potentiometer to measure the angle, but it will also be switched to an encoder in the near future. The main problem encountered with potentiometers is one of noise, and the coping method currently being used is to calculate a moving average of data over the last five samples. Strictly speaking this method produces a delay, but considering the desired rotational speed of the arm, this delay is not perceived as a problem.


*Figure 1.* Multifunction robot arm.

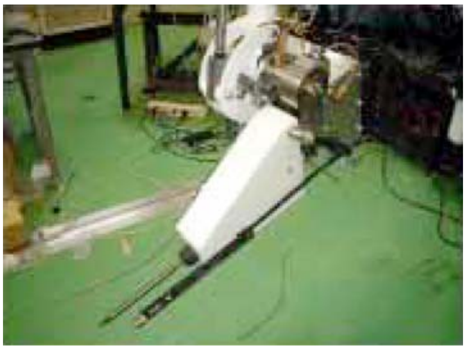


*Figure 2.* Drill and air jet nozzle.

### 3.2. Control System

The control system is currently being developed for the MATLAB/Simulink xPC Target operating system. xPC Target is a real-time operating system for ×86

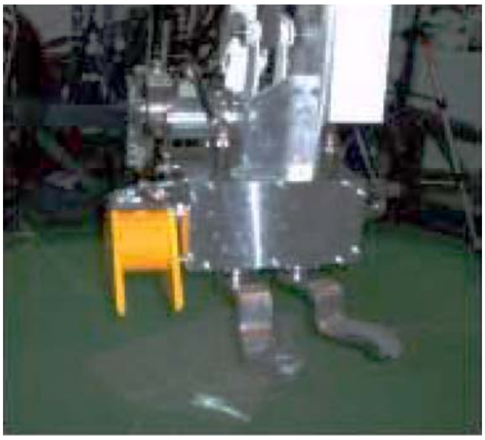


*Figure 3.* Gripper and electromagnet.

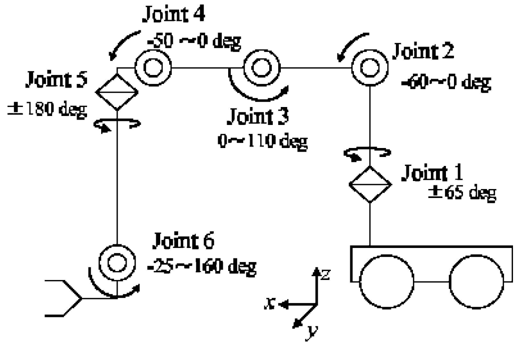


*Figure 4.* Configuration of multifunction robot arm.

processors that allows rapid prototyping using Simulink models. The target PC is a PC/104 system from Diamond Systems. The controller is developed in Simulink on a host PC and uploaded to the target PC for execution. Communication between the host PC and target PC is via RS232, and while the controller is running, the operator can manage the target PC and issue commands from the host PC. We have found xPC Target to be an extremely useful tool for prototyping, but in the future we will have to move to an embedded system. Realtime Workshop converts a program composed in Simulink to C code. These tools along with Stateflow are very effective for developing large-scale systems in a short time. In the future we are considering using this C code and developing an embedded system.

*Table 1.* Specifications of the multifunction robot arm.

| | |
|---|---|
| Length/heigth /width | 2112 mm × 1536 mm × 307 mm |
| Degrees of freedom | 6 |
| Drive system | Hydraulic pressure (13.7 MPa, 10 L/min) |
| Position sensors | 5 Absolute value encoders, 1 potentiometer |
| Range of motion | 2-meter radius, 130-degree fan-shaped region |
| Mass | 200 kg |
| Onboard tools | Drill, high-pressure air jet, electromagnet, gripper |
| 2-finger gripper strength | 10 kgf |
| Tool changer range of motion | 180° |
| Position encoder precision | Horizontal direction: +−10 mm,<br>Vertical direction: +−10 mm |
| High-pressure air jet | Tank capacity: 24 $m^3$, Pressure: 10 Mpa, 1 tank lasts 200 times |
| Control methods | Vision-based, Joystick, etc. |

## 4. Implementation Tasks

The tasks currently being worked on are described here. They will be combined with the aim of constructing the anti-personnel mine exposure system described in Section 6. These tasks are the core of our research and are currently under development.

### 4.1. *Environment Recognition with Stereovision*

Mine detectors can be used to determine the position of buried anti-personnel mines, but they cannot identify obstacles on the terrain surface that may hinder the robot arm. Stereovision can be used to generate a 3D map of the terrain and detect obstacles. The 3D terrain map and sensor data can be combined into a virtual reality scene to assist the operator in target selection. Terrain data and obstacle position data will also be transmitted to the arm's controller and used in trajectory generation.

### 4.2. *Reference Generation with Online Inverse Kinematics*

When the positions of obstacles and buried mines are known, the various joints of the robot arm must be controlled to achieve target positions. In practice the positions of obstacles and mines will always be different, so arm positioning cannot be solved offline in advance. Therefore this system will always use reference

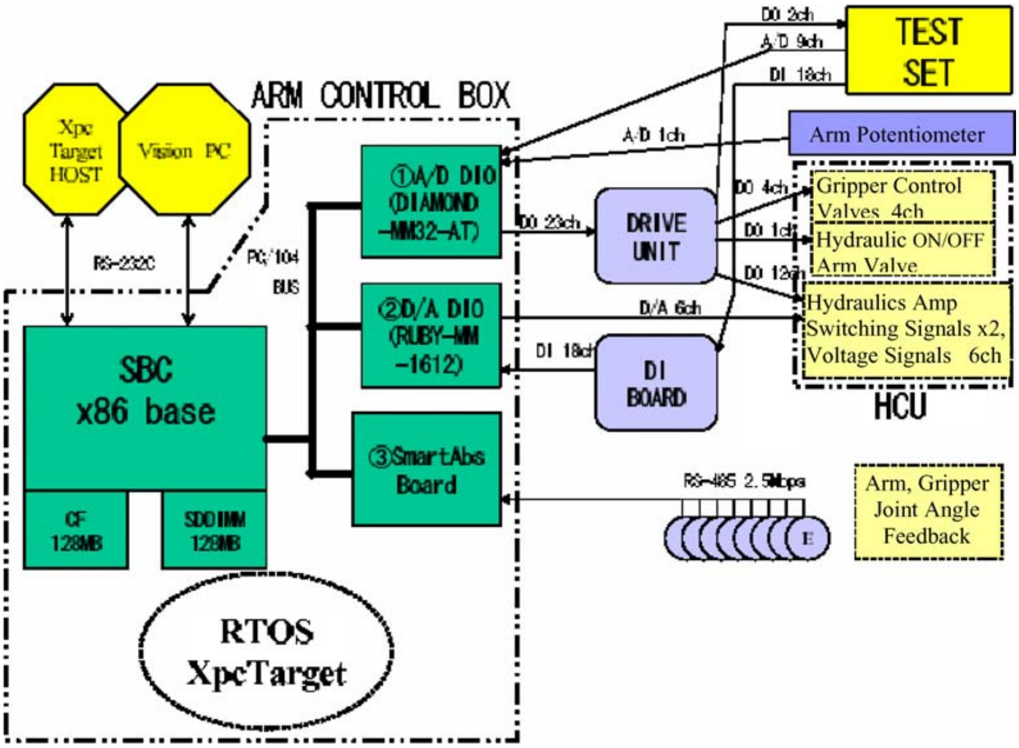


*Figure 5*. Control system.

*Figure 6*. PC/104.

generation with online inverse kinematics to solve the positioning problem.

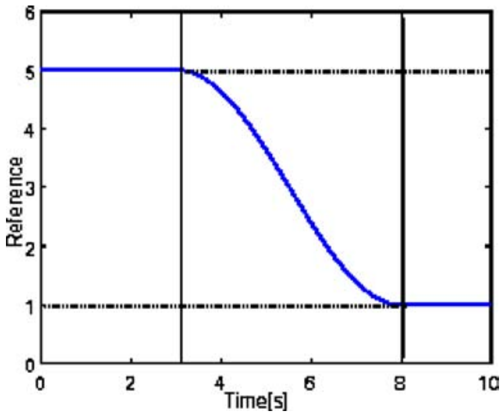


*Figure 7*. Online trajectory planning.

### 4.3. Online Trajectory Generation

Vibration and jerky behavior in the arm is minimized by generating a smooth trajectory reference between the current position and the reference position. The trajectory is calculated according to Eq. (1)

$$y = \frac{x^p - x^n}{2} \cos\left\{\frac{2\pi}{T}(t - t_n)\right\} + \frac{x^p + x^n}{2} \qquad (1)$$

Here, $x_p$ is the initial reference position, $x_n$ is the next reference position, $T$ is the period in seconds, and $t_n$ is the predefined time at which $x_n$ is achieved. $y$ is an intermediate reference point along the smooth trajectory. And, $t$ is the present time, $t$ should be satisfied the following condition as $t_n \leq t \leq t_n + \frac{T}{2}$.

### 4.4. *Proportional Control with Input Compensation Using Table-Lookup*

A traditional analytical approach to controller design was difficult due to time constraints and strong nonlinearities inherent in the system. As an alternative, a tuning-based algorithm was developed that worked around the nonlinear elements and yet proved to have reasonable performance. Section 5 discusses the algorithm.

## 5. Control Technique

The hydraulic manipulator has various nonlinearities such as valve dead zones, hydraulic cylinder stick-slip, and inertial changes depending on the posture of the arm (Yamada et al., 2002).[4] These nonlinearities make theoretical modeling and modeling from system identification very difficult, and development of a model-based control system would be very time-consuming. Due to limited time constraints within the project, we had to sidestep some common practices for improving control performance.

### 5.1. *Creating the Input Compensation Table*

The two primary factors contributing to nonlinear behavior in the control subject are the hydraulic elements and changes in arm posture. To determine the real system response with these nonlinear elements, we took experimental measurements of the cylinder velocities and joint angles for a range of input voltages to the valves (Fig. 8). The measurements were used to construct reference tables for the voltage-velocity-angle relationship of every valve. Examples of voltage-velocity-angle relations are given in Fig. 9. The plots show the measurement results for joint 2.

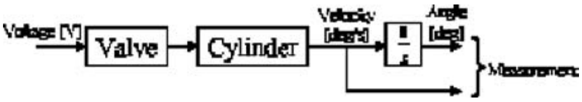
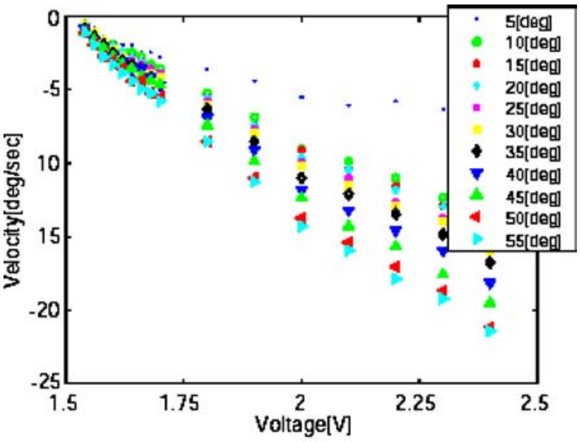
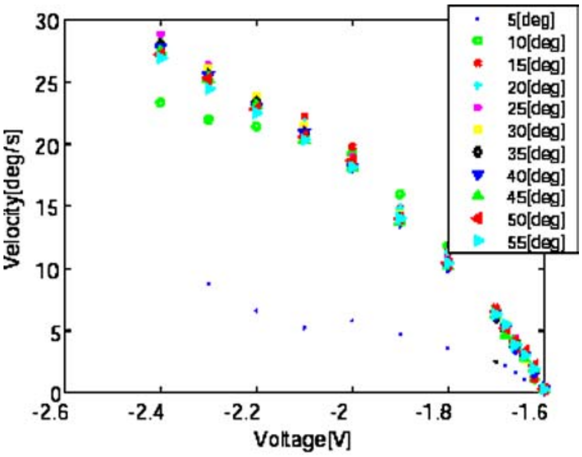


*Figure 8.* Measurement of velocity-voltage-angle relations.



(a) Link 2 up

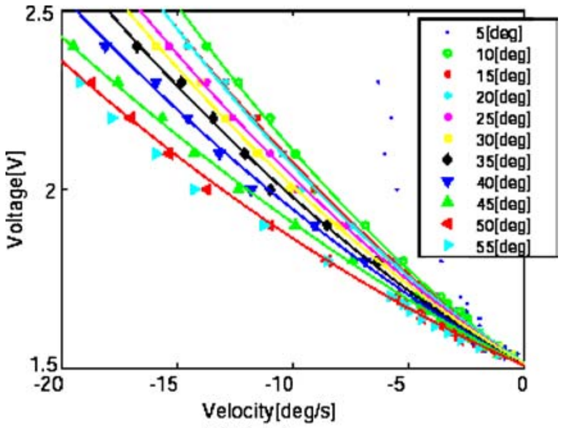


(b) Link 2 down

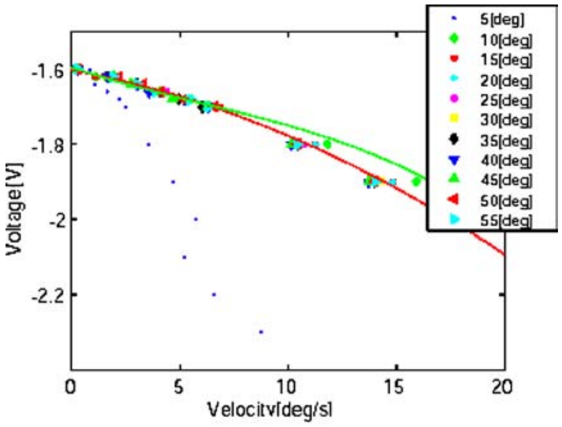
*Figure 9.* Velocity-voltage-angle relations.

Sample data for the tables was collected and averaged for 20 sampling cycles, each lasting 1 minute. Averaging over a large number of sample sets increases the reliability of the data.

While the data was being collected, the hydraulic cylinders exhibited some small intermittent movements causing some data points to be unreliable. The voltage-velocity data sets were approximated by first and second order curves to smooth over the irregularities, as shown in Fig. 10. The tables then allow an input voltage to be calculated for a desired rotational velocity. It is not necessary to change the compensation table, if the tool on end-effector is changed. Because the total



(a) Link 2 up



(b) Link 2 down

*Figure 10*. Reference table curves for Link 2.

dynamics does not change comparing with the changes in arm posture.

## 5.2. Experimentation

Experimentation was carried out to compare the performance two control strategies - a proportional controller with dead zone compensation and a new controller with the input compensation tables added. Figure 11 shows a block diagram of the proposed new controller. Tuning was introduced for the dead zone compensation controller while observing the arm's response to prevent abrupt motion.

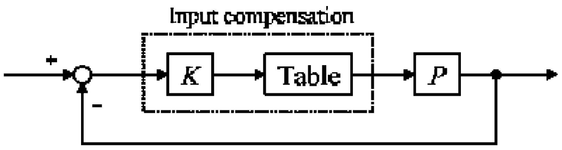


*Figure 11*. Block diagram of proportional control using input compensation.

### 5.2.1. Performance Comparison for a Single Joint.

The step response and sine wave response of the system with both the proportional controller and input-compensated proportional controller are displayed in Figs. 12–14. As before, these are the results for link 2. The figures show the reduction of dead zone effects and the lag of the arm's motion behind the reference signal. The proposed controller was able to compensate for dead zone effects without abrupt motion in the system response.

### 5.2.2. Trajectory Following.

In practice several joints will move at the same time, and not just one, so the input-compensated proportional controller was tested

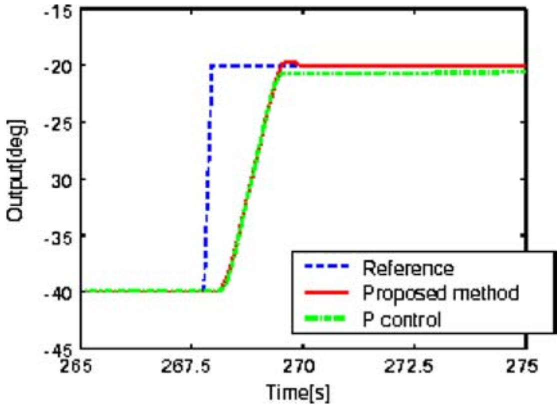


*Figure 12*. Rising step response.

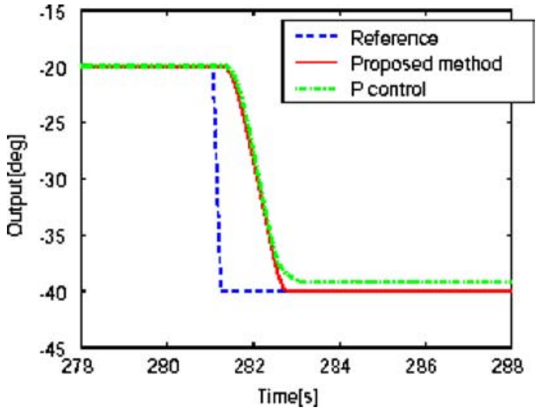


*Figure 13*. Falling step response.

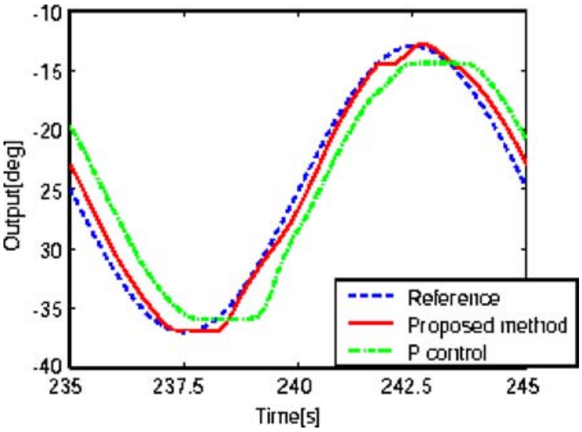


*Figure 14*. Sine wave response.

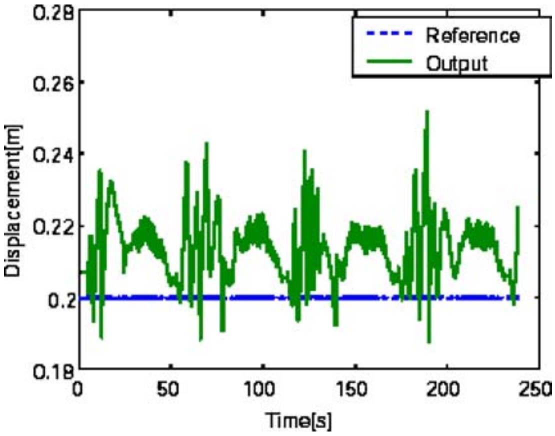


*Figure 16*. Response along $z$-axis.

for the case of multiple joints moving. Specifically, a trajectory was planned to move the arm's end effector forward 20 cm along the $x$-axis at a constant height of 20 cm by actuating joints 2 through 4. Figures 15 and 16 show the results. It can be seen that compliance with the reference deteriorates when multiple joints are actuated, compared to single joint motion. This is likely due to a drop in hydraulic pressure to the cylinders because there is only one pump. From a practical standpoint it is unrealistic for each joint to have its own pump. Trajectory following has become an essential task because joystick operation is planned for the robot arm. Improving the performance has become a primary focus.

Because of the poor trajectory following performance, when a reference point is supplied, the present algorithm moves the joints one at a time in sequence, rather than all at once, and forces the control input to zero when the error reduces to within an acceptable level.

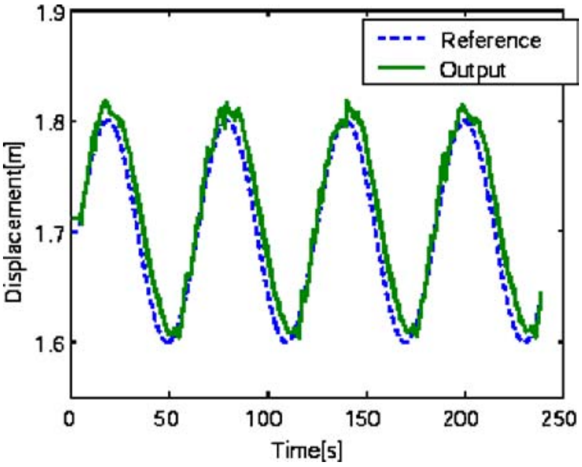


*Figure 15*. Response along $x$-axis.

## 6. The Anti-Personnel Mine Exposure and Clearance System

The tasks described in the previous sections are being joined together to construct part of a comprehensive anti-personnel mine exposure and clearance system to meet a set of functional requirements laid out by JST. The requirements are listed as follows:

(1) Removal of rocks and other obstacles from the mine detection area.
(2) Removal of spent ammunition and other small metal objects from the mine detection area.
(3) Identification of the position of buried mines using SAR-GPR.
(4) Breaking up of bedrock or loosening of hard soil surrounding buried mines.
(5) Clearing of rocks and soil from the surfaces of buried mines, thereby exposing them.

The goal is to meet these functional requirements, though the means of implementing them are not explicitly specified. Our research is directed toward achieving all of these tasks except the third and we have decided on a suitable approach for each. The gripper will be used for grasping objects in Task 1. The electromagnet will be used to collect metal objects in Task 2. The drill will be used to loosen soil in Task 4. Finally, the

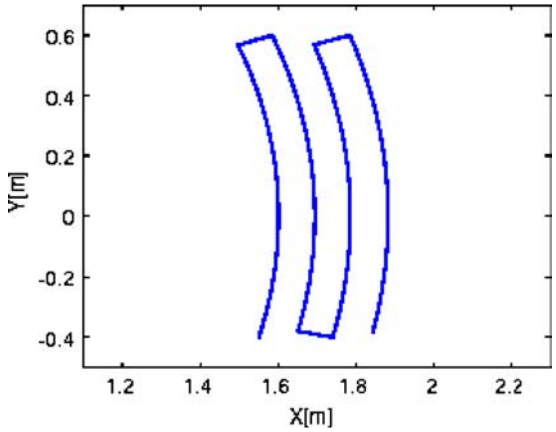


*Figure 17.* Orbit of electromagnet (X-Y plane).

high-pressure air jet will be used to clear away soil in Task 5.

The prototype of air spade have been deployed to Afghanistan and Cambodia.[4] Its objective is to provide a safe standoff capability to rapidly excavate anti-personnel mines and anti-tank mines, doing so at a faster rate than any other current method. The air spade is simple to operate and transport. It is not intended for use in heavily vegetated areas. This air spade is operated by deminer. Our prototype is completely different from the prototype of air spade because our air jet nozzle positioning and posture is a full autonomous or a tele-operated control based on stereovision technology.

For electromagnet action, the end effector follows the orbital trajectory shown in Figs. 17 and 18. For other actions, data from stereovision is used. The operating procedure we are following to expose anti-personnel mine is outlined below.

(1) The terrain and obstacles are detected using stereovision.
(2) The gripper is moved to a position 15 cm in front of the obstacle and then approaches the target point along a straight-line path.
(3) The gripper grasps the object and sets it down outside the scan area.
(4) The electromagnet sweeps over the scan area collecting spent ammunition and other light metal objects.
(5) The metal objects are set down outside the scan area.
(6) Stereovision is used to determine the position of a visual marker that has been placed over a buried mine (we are temporarily using visual markers to mark the location of mines in experiments because the detection sensor has not been completed yet).
(7) The air jet nozzle is positioned near the marker and releases a blast of air that blows away gravel and soil, exposing the mine.

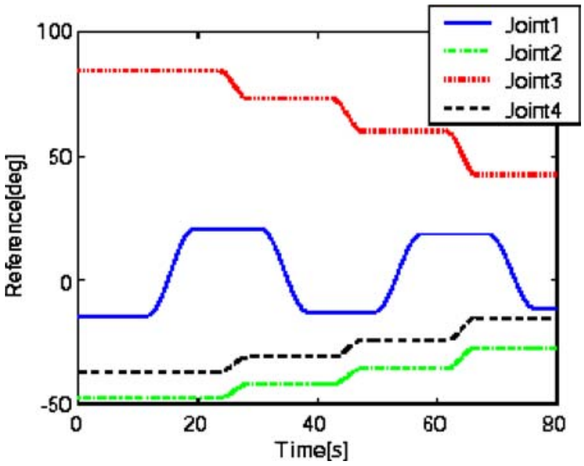


*Figure 18.* Orbit of electromagnet (reference for each joint).

## 7. Conclusion

We have discussed the current state of development of a anti-personnel mine exposure and clearance system, with emphasis on multi-joint control of a robot arm. We have achieved the reasonable performance of 6-degree of freedom robot with multi-function tool by means of nonlinear control based on "LOOK AT TABLE" scheme. The focus of the next stage of development will be devising a means of joystick operation for the arm and tools. Research in the field of hydraulic robot arm control is extensive, but there is still plenty of room for improving performance. Our group is addressing a number of elements within the system at the same time with the aim of improving the system as a whole.

Currently the arm can only be operated by command instructions from the operator. For the future, various other command methods are being considered, such as joystick control, master-slave control, and other new human interface control ideas. We are also considering problems that may arise when the arm is mounted on the small vehicle. Presently the multifunction arm weighs 200 kg and the sensor arm weighs 150 kg. The multifunction arm may need to be lightened to maintain a good balance. We will continue to develop the multi-function robot arm and work to improve performance in time for the planned field-test in Afghanistan.

## Notes

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2. http://www.jst.go.jp/kisoken/jirai/kadai-frameset.html
3. http://www.jst.go.jp/pr/jst-news/2004/2004-07/page16.html
4. Humanitarian Demining-Developmental Technologies. 2000–2001. DoD Humanitarian Demining R&D Program.

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Yamada, H. Takeichi, K., and Muto, T. 2002. *Sliding Mode Control of Hydraulic Power Shovel, Trans of the Japan Society of Mechanical Engineers*, 68(670): 1768–1774.

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