Proceedings of the 2004 IEEE
International Conference on Robotics & Automation
New Orleans, LA • April 2004

Teleoperated Manipulator for Leak Detection of Sealed Radioactive Sources

WANG Wei, YUAN Kui
Institute of Automation, Chinese Academy of Sciences
95 Zhongguancun Donglu Road, Beijing 100080 China
E-mail: {wei.wang, kui.yuan}@mail.ia.ac.cn

Abstract

This paper introduces a practical teleoperated manipulator under nuclear radioactive environments. The system, called *RoboSource* herein, is designed to perform the leak detection of sealed gamma and neutron radioactive sources used for oil well logging in oilfields. *RoboSource* includes two stations connected via RS-485 and with a distance of up to 1.2Km. The base station (safe zone), with an industrial PC as the master controller, provides the operator console and performs the high-level control of the manipulator, and the field station (hazardous zone), with a programmable logic controller as the cell controller, is responsible for the motion control of the manipulator and radiation contamination detection. Two manipulator arms with pneumatic actuators and electric motors, two cameras, and a radiation contamination detector are deployed to the field station. With the intuitive Windows style graphic user interface and the live video from the field station, the human operator can effectively control and monitor the manipulator at the base station. *RoboSource* has been employed to perform the leak detection of sealed radioactive sources, which was completed manually by human workers before, in the Shengli Oilfield, the second largest oilfield in China.

1 Background

Our work is motivated by the observation that the leak detection of sealed gamma and neutron radioactive sources used for oil well logging or natural gas well logging is currently performed manually by human workers, so this necessitates the automatic teleoperated leak detection to protect the human workers from ionizing radiation exposures. On the other hand, the automatic operation can improve the detection reliability and quality.

The radioactive source used for oil well logging is a cylinder with a steel shell and radioactive substances sealed inside. Generally, a radioactive source has a handle for grasp at its one end. Figure 1 shows the gamma source (^{137}Cs) and the neutron source (^{241}Am-Be), which are being grasped by the manipulator gripper of *RoboSource*.

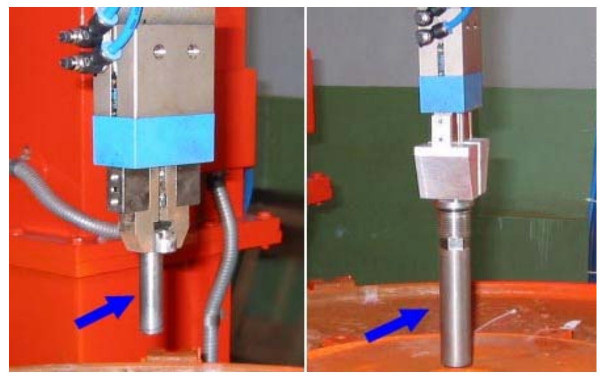

Figure 1: Gamma source (left) and neutron source (right) used for oil well logging

Usually, the radioactive sources are stored in the special warehouse under strict safeguard. If needed for oil well logging, the source will be transported to the oil well field by the special truck, and returned to the warehouse after finishing the oil well logging. The rigorous environment inside the oil well and other factors in the process may cause slight or bad damages of the radioactive source, which will induce the likelihood of radioactive substances leaking from the steel shell of the source. The leak of radioactive sources is the awful accident, which can result in tragedies for human health and environments. Consequentially, the damaged radioactive source cannot work effectively for oil well logging anymore.

The regular leak detection becomes essential for radioactive sources stored in the warehouse. Such detections are performed two or three times every year in the Shengli Oilfield. Unfortunately, to date, the leak detection is still completed manually by human workers in many oilfields and natural gas fields. Standing behind concrete or lead shields, the human worker grips the radioactive source with simple tools, such as clamps, and wipes the source's surface with the special fabric, then detects the contamination of the fabric with the detector. This manual operation is cumbersome and dangerous for human workers. In any wise, safe operation is always prerequisite. Obviously, the manual operation by human workers is problematic. On one hand, it is inevitable for the human operator to be directly exposed to dangers to suffer from ionizing radiation. On the other hand, the operation is limited by the operator's skills and abilities, and fatigue and lack of concentration contribute to reduced detection quality. The improper operation of the human worker can lead to the neglect of a damaged radioactive source. The further usage of a leaking source will induce the spread of radiation contamination.

The objective of our work is to provide a substantial teleoperated system to perform the leak detection of sealed gamma and neutron radioactive sources, in place of human workers. This paper will present our system *RoboSource* intended for such purpose. In the following sections, we begin by describing the overall architecture of *RoboSource*. We then introduce devices at the field station, the communication between the base station and the field station, as well as the operator interface. Finally, we give conclusions and some issues on potential for technological improvement.

2 Overall Architecture

Many telerobotic systems have been used successfully to complete hazardous works to some extent, but state-of-the-art remote robotic technology is not as mature as many might expect. To date, a great number of hazardous works are stilled performed manually by human workers, who are in simple protective suits and enter into the hazardous environments to complete activities manually. Furthermore, humans cannot be used directly for most of the more hazardous work, but remote robotic technology available today cannot well be suited to the needs. The key factor is that current remote robotic systems are too costly in terms of procurement, facility burden, and the requirement for highly skilled operators. Remote robotic systems are typically regarded as too slow in task completion and not capable of matching human dexterity. Many researchers [1-5] have been making significant efforts to improve remote robotic technology and make it capable and cost effective in support of tasks in hazardous environments.

For tasks in high radiation level zones, the primary attention should be paid to the human worker's safety. The application of remote robotic technology in the nuclear radiation environment has been driven by the need to reduce personnel radiation exposure. In particular, for leak detection of radioactive sources, the human workers have to be close to the radioactive source at the risk of radiation and contamination. Remote robotic system is highly desirable to reduce personnel radiation exposure in such case. In order to develop a practical system as soon as possible, we designed *RoboSource* based on the as low as reasonably achievable (ALARA)[1] principle and tried to make it reliable, simple and easy to use. Figure 2 shows the overall system architecture.

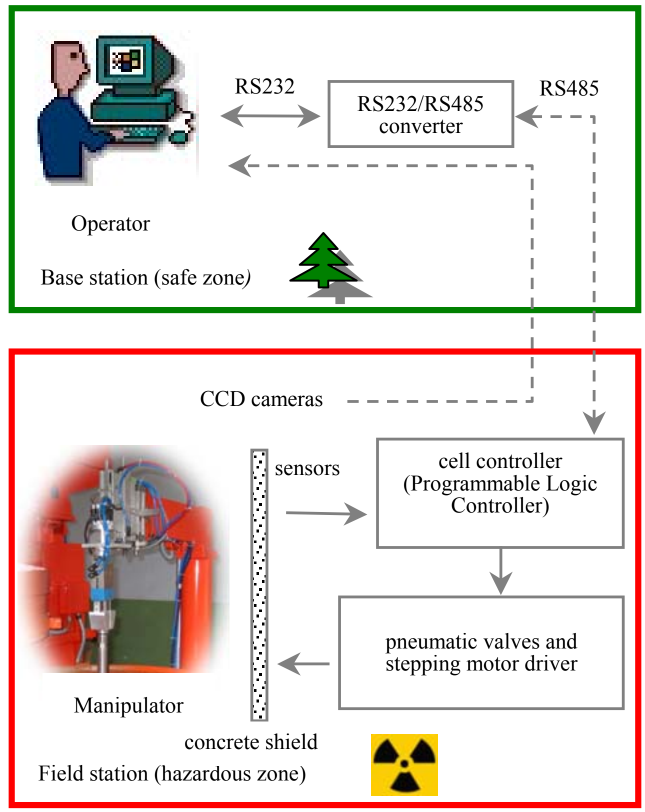

Figure 2: RobSource system architecture

The system is composed of two stations connected via RS-485: the base station and the field station, which are respectively situated in two isolated rooms. The field station is the potential radiation zone, where the manipulator performs the leak detection of radioactive sources. As the control and monitor room, the base station is the radiation free zone. As for as the sealed radioactive source for oil well logging, the distance of 50 meters between the two stations is enough for radiation protection. Indeed, the distance of 1.2Km is available with a signal repeater. The transmission delay is slight and tolerable for this system.

The field station is an automatic work cell mounted on a steel base, which involves the manipulator, cell controller, video system, contamination detector, sensors and pneumatic power supply, etc.. To simplify the control, a programmable logic controller is used as the cell controller, to which stepping motor control modules are attached. The cell controller transmits the sensor information and the contamination detection data to the base station, and also receives the commands from the base station. Two cameras are deployed, one used to provide the panoramic view of the field station, another used to record the video of the source code.

The master control and monitor console locates at the base station. The base station is responsible for the operator interface, image processing, and high-level manipulator control. It manages the communication between the operator interface and the manipulator. The master controller is based on the popular PC/Windows in terms of the easy use for the end user. The console provides multiple operation modes, such as automatic operation and semi-automatic operation, and allows the operator to determine and set the current mode. With the sensors feedback and the intuitive video feedback of the field station, the operator is able to have sufficient surveillance to observe the status of the field station and make appropriate decisions.

3 Field Station

The *RoboSource* manipulation capability primarily consists of two pneumatically powered manipulator arms, the conveying vehicle and the wiping device. A 4KW/0.1-1Mpa air pump is employed to power the manipulators. The air pump supplies power to the system through the high-pressure hoses, valves and filters. To ensure the effective source-wiping operation, a stepping motor is used to rotate the gripper responsible for grasping the source. Figure 3 is the picture of the manipulator.

In Figure 3, the primary components of the manipulator are denoted in uppercase letters, but this picture does not involve the panoramic camera for the limited view angle of this picture, as well as the air pump and the cell controller for their spatial isolation from the manipulator. The detailed description is given below alphabetically.

A: barrelhead-handling manipulator arm

This manipulator arm performs the barrelhead (*C1*) handling operation, which is a simple operation. The arm, however, needs high payload capacity of over 200Kg, and precision enough to pick up the barrelhead and drop it on the barrel (*C*) correctly. Only the barrelhead removed, it is available for the source-handling manipulator arm (*B*) to handle the source. The arm has 3 degrees of freedom (DOF), one driven by an electric motor, two by pneumatic cylinders. Particularly, a large power pneumatic cylinder actuates the elevation of the barrelhead and can keep the barrelhead of 200Kg suspended in the air. Because of the high payload, once grasped, the motion of the barrelhead must be safe and steady. Especially in case of malfunction, such as unexpected halt of pneumatic supply, the barrelhead must be kept grasped and held securely in the air, instead of loosened and downfall. Our mechanism design has guaranteed the safety and reliability.

Figure 3: Detecting field and the manipulator

B: source-handling manipulator arm

With 4 DOF, the manipulator arm has enough flexibility to perform source-handling operations, such as grasping the source, picking up and dropping the source from/into the barrel, rotating the source for wipe, etc.. With a harmonic drive of 60:1 reduction ratio, a 2-phase stepping motor is used to drive the rotation of the gripper. Other motions of the arm are pneumatic drive. To wipe the source's surface clean, firstly the special fabric attached to a bracket (*F*) touches the source, and then the gripper rotates the source slowly. The source should be dropped into the barrel and covered by the barrelhead before the contamination detection of the fabric. Figure 4 illustrates the wiping operation and the contamination detection of the fabric.

C: barrel, and C1: barrelhead

The barrel, equipped with a removable barrelhead (*C1*), is used to hold the radioactive source. The barrel for the neutron source is deployed with paraffin wax shields, and the barrel for the gamma source with lead shields.

D: conveying vehicle, and E: slide way

The vehicle is used to move the barrel from the site of the barrelhead-handling arm to the site of the source-handling arm, and vice versa. It only requires straight-line motion alone the slide way (*E*).

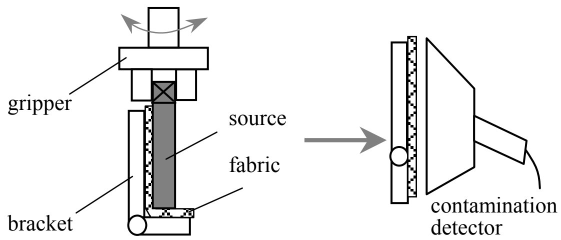

Figure 4: Wiping the source clean (left) and detecting contamination of the fabric (right)

F: source-wiping fabric and bracket

Used for wiping the source's surface, see *B: source-handling manipulator arm*

G: camera for recording video of the source code

Every source has an exclusive code marked on its surface by the vendor. It is required for the operator to verify the code. When wiping finished, the master controller records the video while the gripper slowly rotates the source for 360 degree, the video is saved and can be replayed online or offline.

H: contamination detector

An instrument used to measure alpha, beta and gamma particulates, its counting yield (pulses) is input to the cell controller and transmitted to the master controller.

I: base

A 2.6x1.6x0.1meters steel base is designed to facilitate the mount of the work cell.

The gripper is picking up a neutron source (*J*) from the barrel in Figure 3. To avoid interference and enable the work cell harmonious in performing the operation, it is necessary to provide interlock motion between the manipulator arms. Otherwise, the operator's inadvertent command would make the manipulator arms generate improper actions, lose their grasps and drop their payloads, or cause collision. To reduce the operator error and ensure the safe operation, the software design of the cell controller has guaranteed the interlock of manipulator arms motions. The operator's error command would be ignored and the inadvertent motion would be essentially eliminated.

As mentioned previously, the contamination detector produces counting yield (pulses). For every source, its wiping fabric would be measured for 6 periods, and every measuring period needs 60 seconds. The cell controller transmits the counting data (pulses per minute) of 6 measuring periods to the base station. The master controller would evaluate the counting data and give the conclusion, i.e. whether contaminated or not. We will not give the detailed computation of contamination because of the limited space of this paper.

4 Communication

The industrial computer has standard RS-232 serial ports, but RS-232 system is not appropriate for long distance communication for its limited transmission speed, range and networking capabilities. In our system, RS-485 system is used for the communication between the base station and the field station. RS-485 data transmission system uses balanced differential signals, and supports half-duplex communication. Furthermore, only two wires are needed to both transmit and receive data.

We selected the ADAM-4520 module (from Advantech Inc.) as the RS232/RS485 converter. The ADAM-4520 isolated converter transparently converts RS-232 signals into isolated RS-485 or RS-422 signals. A special I/O circuit in ADAM-4520 automatically senses the direction of the data flow and switches the transmission direction, so no handshaking signals are necessary. The user can build an industrial grade, long distance communication system with standard PC hardware.

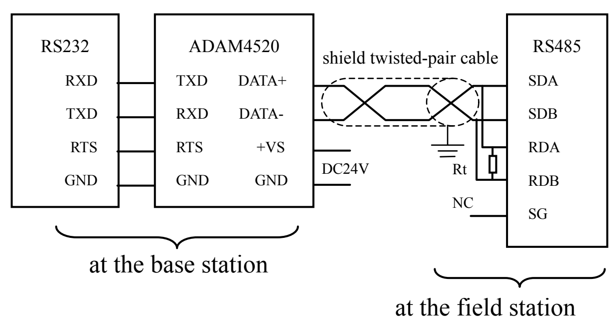

Figure 5: Circuitry connection of RS232/RS485

At the field station, the RS-485 communication board FX2N-485-BD (from Mitsubish Electric), inserted into the PLC's communication port, is used to provide the RS-485 interface. Figure 5 shows the circuitry connection between the industrial PC (RS-232) and the cell controller (PLC with RS-485 interface). The connection between ADAM-4520 and FX2N-485-BD uses shielded twisted-pair cable complying with the EIA RS-485 standard to reduce interference. The communication distance is 50 meters and can be extended to 1.2Km with a signal repeater. In Figure 5, the term Rt is the terminal resister (110 Ohm, 1/2W) between terminals RDA and RDB.

As discussed above, the computer uses a standard RS-232 serial port, and the cell controller has the RS-485 interface. So the communication protocols are standard RS-232 protocol for the computer, and typical RS-485 two-wire-link communication protocol for the cell controller. The baud rate 19,200bps is available, but 9600bps is enough for our system.

Data to be transmitted are packet with no gaps between bytes [6]. Each data packet consists of multiple bytes, and the number of the bytes differs in the command type and the transmitted data. Figure 6 illustrates one example of the data packets. In this example, the computer sends the hexadecimal digit b7b6b5b4b3b2b1b0H(32bits) to the specified registers D0204(16bits) and D0205(16bits) of the PLC. The PLC responses back the data packet "ACK00FF" to the computer to acknowledge the success of the data reception. Where, "ENQ" is the preamble of the data packet, "00" and "FF" specify the station number and the PLC number respectively, "WW" means the command "write word", the following "0" is the message wait time, and "XX" is the sum check code.

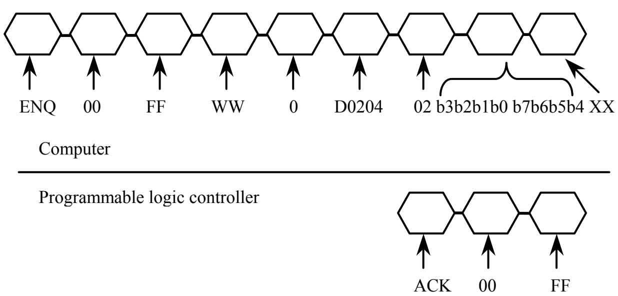

Figure 6: Data packet frame

5 Operator Interface

The interface console involves the control, surveillance and data management. *RoboSource* offers a PC/Windows based "point and click" interface. This allows the operator to quickly master the operation without expertise. Figure 7 shows the operator interface, which is developed in Visual C++ under Chinese environment with a view to the Chinese-speaking operators in the oilfield in China. Herein, we append English comments to Figure 7. The interface contains three primary functional sections: the *command and data management* (left), the *feedback information display* (bottom) and the *live image* (central). Below is the detailed description.

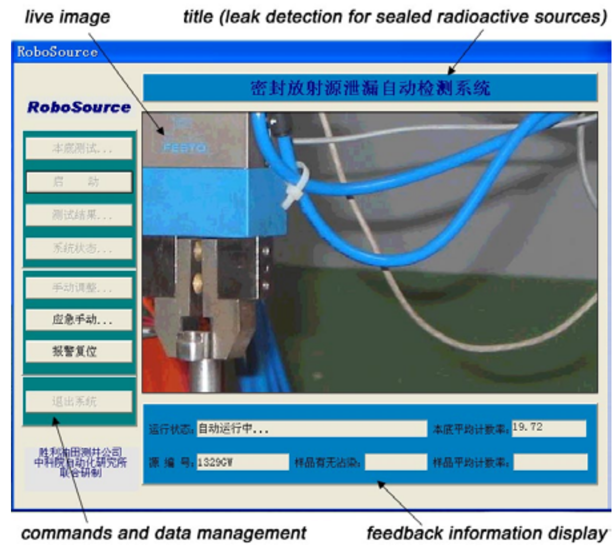

Figure 7: Operator interface of RoboSource

(a) command and data management

These command buttons accept user commands or provide continuous feedback from the manipulator's sensors. Clicking some buttons can activate the next level pop-up dialogue forms. The operator can perform the following functions:

- *Background radiation detection:* the command will be transmitted to the cell controller and invoke a subroutine to detect the ambient radiation at the field station. The detecting result will be transmitted to the master controller and displayed on the bottom of the operator interface.
- *Automatic run:* to give a command to the cell controller to execute the automatic run subroutine. The manipulator will perform the leak detection automatically.
- *Manual jogging:* this command will activate a next level pop-up dialogue form, in which the operator can specify the manipulator's individual joint motion (locomotion, rotation, etc.) to move the manipulator into fixed configurations.
- *Emergency operation:* in case of a malfunction that the manipulator sensor cannot work, the authorized operator can enter the password-protected dialogue form to perform necessary commands to drop the radioactive source into the barrel and cover the barrel with the barrelhead. Consequently, human workers are able to enter the field station to check and remove the malfunction without suffering from the ionizing radiation.
- *System status:* to pop up a dialogue form to display the manipulator's current position information, which is from the cell controller and updated every

1.5 seconds. Additionally, the live image, to be mentioned below, is an intuitive alternative to observe the system status.

- *Data management:* to manage the contamination detection data, including searching, printing, etc..

(b) live image

It will excessively consume the master controller's resource to continually display the live image from the field station. To guarantee real time of communication and control, the live image window on the master controller is active only at the time for recording the source code, and inactive at other time. To supervise the panorama of the manipulator, we deploy an overhead CCD camera at the field station, and a separate monitor at the base station to display the scene of the field station in real time.

(c) feedback information display

The displayed information involves:

- Current operation of the manipulator;
- Background radiation data;
- Current radioactive source code;
- Radiation data of the current wiping fabric;
- Whether current wiping fabric contaminated or not.

6 Conclusions and Future Work

The end user has benefited from the use of the system. *RoboSource* has been proved to be a practical system for performing leak detection of gamma and neutron radioactive sources. This system enables the human worker to keep away from the ionizing radiation and have a comfortable operation environment. Moreover, the high detection quality superior to human manual operation is attainable.

As a preliminary research, our system is still in need of improvements and evolution into a more robust system. The end user returned us some constructive suggestions, and experiences gained during the development give us some ideas for the further work.

One key issue is the radiation protection of the devices. Because of the close proximity to the radioactive source, the lens of the camera used for recording the source code tends to become dim after a long time radiation. The camera's radiation protection or other type camera is necessary for the high quality image. Video is the important intuitive feedback for a teleoperated system. Although the master control computer can provide the accurate status of the remote manipulator by sensors, the live video from the field camera is preferable for the operator. Wide enough fields of view and more views from different angles are desired. One overhead camera is currently deployed at the field station, which only provides the front view of the manipulator. To observe the status of the manipulator in the round, a commercial panoramic surveillance system is being schemed.

To guarantee the safety and reliability in case of malfunction, we have developed a semi-autonomous mobile robot, which is supposed to be incorporated into the field station for dealing with unexpected events. With a joystick, the mobile platform can be teleoperated via RF (Radio Frequency) modem. A 4 DOF manipulator is being designed, and expected to be mounted on the mobile platform to perform tasks for emergency, e.g. picking up the radioactive source, dropped on the ground by accident, and laying it in the specified location.

It is difficult to make a tradeoff between the low system cost and the tight performance requirements of components. If cost-efficient, we would use high quality components in the system and devise dexterous manipulator arms in place of current arms which look hulking. Our ongoing work is aimed at offering a more robust and lower cost solution to the leak detection of radioactive sources.

Acknowledgments

The work presented in this paper was performed in the Shengli Oilfield China, and funded by The National High Technology Research and Development Program of China (863 Program) under grant 2003AA421030.

References

[1] Michael Catalan, Sharon Bailey. "Lessons Learned from Pit Viper Integration into Hanford Tank Farm Reality." Proceedings of the 2002 IEEE International Conference on Robot and Automation, Pages3479-3484, May 2002.

[2] William R. Hamel, Pamela Murray. "Observations Concerning Internet-based Teleoperations For Hazardous Environments." Proceedings of the 2001 IEEE International Conference on Robot and Automation, Pages638-643, May 2001.

[3] K. A. Manocha1, N. Pernalete and R. V. Dubey. "Variable Position Mapping Based Assistance in Teleoperation for Nuclear Cleanup." Proceedings of the 2001 IEEE International Conference on Robot and Automation, Pages 374-379, May 2001.

[4] M. W. Noakes, L. J. Love and P. D. Lloyd. "Telerobotic Planning and Control for DOE D&D Operations." Proceedings of the 2002 IEEE International Conference on Robot and Automation, Pages3485-3492, May 2002.

[5] http://www.hwm.com

[6] FX Communication, User's manual. Mitsubish Electric.