DEVELOPMENT OF TELE-ROBOTIC INTERFACE SYSTEM FOR THE HOT-LINE MAINTENANCE

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Abstract: This paper describes the development of the tele-robotic interface for a hot-line maintenance robot system. One of the main issues in designing human-robot interface is to plan the control procedure for each part of the robotic system. Another issue is that the actual degree of freedom (DOF) in the hot-line maintenance robot system is much greater than that of available control devices such as joysticks and gloves in the remote-cabin. To design and test the interface, a virtual simulator which includes the virtual hot-line maintenance robot system and the environment is developed in the 3D environment using CAD data. It is assumed that the control operation is done in the remote cabin and the overall work processes are observed using the main-camera with 2 DOFs. Two joysticks, two data gloves, one pedal, and a Head Mounted Display (HMD) with tracker sensor were used as input devices. Designed human-interface system is operated using high-level control commands which are intuitive and easy to understand without any special training. *Copyright ©2005 IFAC*

Keywords: Telerobotics, Virtual reality, Redundant manipulators, Human supervisory control, Maintenance engineering.

1. INTRODUCTION

In the modern life, the electricity is used everywhere and the electricity becomes the most important daily life commodity in the society. To avoid any interruption of the power supply, the electric power companies are trying to develop hot(live)-line maintenance systems for providing stable power supply. However, hot-line maintenance is risky and dangerous and there are many accident reports about the injury or the death of workers during hot-line maintenance. For this reason, in several countries, hot-line maintenance robot systems have been developed for cost reduction, work efficiency, labor savings. One of the most representative work on this field may be the Phase series from the KEPCO Kyushu Electric Power Company) in Japan (Tanaka, *et. al*, 1996; Takaoka, *et. al*, 2001). Another example of hot-line work robot is the ROBTET in Spain (Penin, *et. al*, 1998).

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Since the work environment for the live-line maintenance is complex and complicated, which makes it hard to make the robot work fully autonomously, semi-autonomous or tele-robotic system is developed for the hot-line work robot system (Faucher, *et. al*, 1996; Nio, *et. al*, 1993). One of the main differences between automatic and tele-robotic system is the inclusion of a human operator in the control loop. With tele-robotic system, high work efficiency can be achieved for the complex and non-structured environment while not exposing the human operator in the danger situation.

The robotic manipulator with a redundant degree of freedom (DOF) is used in the hot-line maintenance robot system, because it has advantages especially in the obstacle avoidance. But, the motion planning of a redundant robot manipulator is difficult, because the inverse kinematics solution for the redundant robot is not unique without extra design criteria. Therefore, several design objectives, such as obstacle avoidance, singularity avoidance, torque minimization, energy minimization, etc. are used to get an appropriate solution. The problem can be also solved with an iterative method.

The objective of this paper is to describe the design and development process of tele-robotic system for the hot-line work robot system. Also, the motion planning using the neural networks of the robotic manipulators is developed. The virtual simulator model for the hot-line work robot system and its environment is developed first. For the developed model, various interface techniques are suggested using the devices such as Head Mounted Display (HMD), gyro sensors, data glove and joysticks. Since the overall system is not developed yet, the experiments with only the manipulators and the camera were carried out.

This article is organized as follows. In section 2, description about the developed virtual hot-line work robot model and its environment will be given. In section 3, various interface devices are introduced and their application to tele-robotic system of the hot-line work robot is discussed. Section 4 concludes the paper.

2. CONFIGURATION OF THE HOT LINE MAINTENANCE ROBOT SYSTEM MODEL

Based upon the observation on previous hot-line work robot model such as Phase III and ROBTET, the necessary components of the hot-line maintenance robot system are determined. The first component of the robot system is two robotic arms for performing various tasks. Since the cabin where the human operator should control the robotic parts is distant from the working environment, there should be at least one camera to see the robot system and working area. Besides this, there can be many other kinds of devices which are useful to perform live-line maintenance. However, in this paper, the simplest prototype of the robot system is considered. Every part of the system is modeled with the 3D CAD software and converted to VRML files to rebuild the whole robot system in the 3D programming environment.

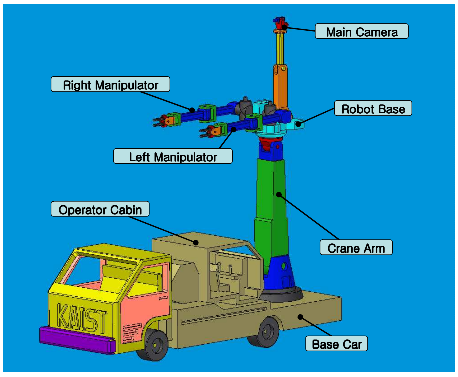


Fig. 1. Developed hot line maintenance robot model

The developed hot line maintenance robot model is shown in Fig. 1. On the vehicle, there is a operator's cabin. The actual robot part is connected to the base car through crane arm, which can adjust the height and orientation of the robot base which has two robotic manipulators and one main camera. Using this robot model, the work environment is rebuild by adding the road, electric lines, and the electric poles in the 3D environment.

The main camera is able to perform pan/tilt operation so that the desired working area can be viewed.

The most important part of the robot system may be the manipulator and, in this paper, the redundant robot manipulator which has 7 DOF is considered. Since in the complex/complicated mode, the robot manipulator should be able to move with the various pose to avoid obstacles or to achieve more efficient performance. Since the recent report about the hot-line maintenance work tells that the most frequent task necessary in the hot-line maintenance gripping and cutting, gripper type of end effector adopted in the manipulator.

Using this kind of simulated environment, various types of the hot-line work robot system can be tested to find the most acceptable structure for the hot-line work robot system for each electric environment, which varies from countries to countries. Also based upon the developed model, various interfacing technique to achieve the tele-robotic system is verified for its usefulness.

3. DEVELOPMENT OF TELEOPERATION SYSTEM

3.1 General Description

In this section, interfacing devices are described and corresponding roles of those devices is explained. Used devices are as follows: HMD, gyro tracking sensors (Intersense Company), 2 data gloves with 5 finger sensors, 2 joysticks and a pedal. Especially, HMD and gyro tracking sensors is used to implement the interface for the main camera. The rest devices are used to control 2 manipulators, the crane arm. All devices are connected to the main PC as shown in Fig. 2 and using the input values given from those devices, various tasks are tested. Fig. 3 shows the scene when a user wears all devices and operates the system.

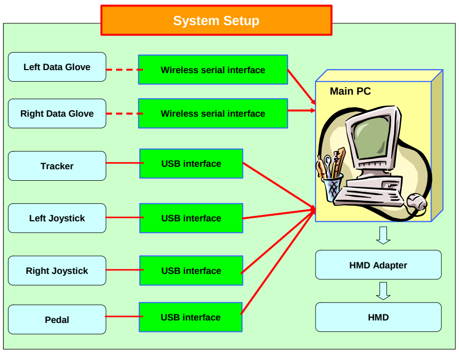


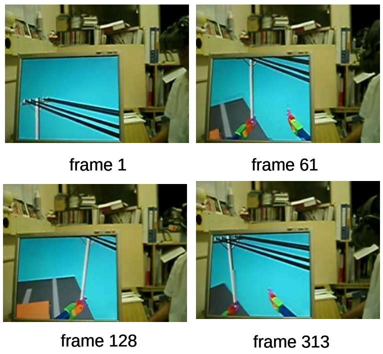
Fig. 2. Interface system configuration

Fig. 3. System operation

3.2 Interface for the Main Camera

To make the user feel as if he is actually in the cabin of the simulated environment, HMD is adopted. The developed software environment can produce stereo scene, which is directly displayed on the HMD so that the user can feel the 3D environment. In this paper, the user can watch the simulated environment in two modes. The first is the main camera view and the second is the bird's eye view. In the main camera view, the scene which is viewed from the main camera is reconstructed. In the real environment, there is a specific panel displaying the working area seen through the main camera. To achieve the main camera view, the camera position in the 3D Cartesian space is calculated by solving forward kinematics from the world's origin to the camera position.

Controlling the pan/tilt motion of the main camera is achieved by attaching gyro sensor on the HMD. As the user turns his head, the gyro sensor generates the angle information and sends it via USB connection to the main PC. According to this angle information, pan/tilt part of the main camera is activated. Example of changing scene captured by the main camera view when the user turns his head is shown in Fig. 4.



frame 1 frame 61
frame 128 frame 313

Fig. 4. Main camera view

In this way, the user can watch the interested working area by moving his head only. This kind of interfacing for the watching working area can be easily applied to the real system by simply showing the scene from camera and may prove useful in controlling the complex hot-line maintenance robot system.

3.3 Interface for the Crane Arm

Since, only 3 DOF control inputs (x/y transition and twist of the lever) are available with the our joystick, the whole task is divided into the several working modes including crane control mode, robotic arm control mode, end effector relative/absolute control mode and so on. In each working mode, the input from the user can move each part of the robot system. The crane arm is usually operated first before performing the real live-line maintenance job. Since, it is desirable to maintain the robot base at the height of electric lines; two rotational axes in the car base and the robot base are operated in opposite direction as shown in Fig. 5. The crane arm is controlled with 2 joysticks and a pedal as shown in Fig. 3.

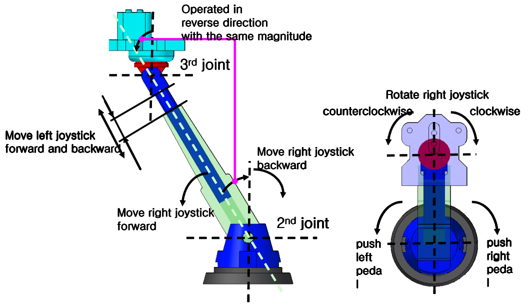


Fig. 5. Interface details for the crane arm

3.4 Interface for the Robot Manipulator

The robot manipulator used in this paper is redundant type. The control of robot manipulator can be further divided into the upper arm and the end effector. In this section, the control strategy for the upper 4 DOF part of the robot manipulator is discussed. It is desirable that the control method is intuitive and easy to understand. Control of the robot manipulator is achieved with a joystick. The motion command for the upper manipulator is defined as shown in Table 1.

Table 1. Commands for upper arm

Joystick input	Motion of the robot arm
forward/backward	±y position
left/right	±x position
rotate clockwise/ counterclockwise	±z position

Actual joint commands for the robot manipulator should be generated to fulfill the motion command defined in Table 1. The user can change the target position in discrete manner by handling the joystick. The motion planning to the desired target position is carried out by the method in the following subsection.

3.4.1. Motion Planning Because the redundant manipulator is used, there can be many configurations of the joints for the same position in the task space. To decide the desired trajectory, the additional measures or constraints are needed to choosing one configuration among the candidates. For this purpose, we introduce two criteria for the minimization of the moving energy and the tracking error (Kim, *et. al*, 2003). After introducing the criteria, the motion planning problem of a redundant robot can be formulated as an optimization problem. Then, the dynamic programming procedure is used to solve this optimization problem.

To approximate the inverse kinematics of the manipulator, the neural network is used. Because the manipulator is a redundant one, there can be several solutions for the same position. So, the inverse kinematics can not be learned by one neural network. To handle this problem, we fix some joint variables so that the other joint variables can be obtained uniquely. For example, if we use 4DOF manipulator, we fix 1 joint angle. In this case, the inverse kinematics with that fixed joint value can be trained using one neural network and therefore, we require as many number of neural networks as the number of joint angle configurations we choose. In Fig. 6, the structure of the proposed motion planner is shown. Each neural network is in charge of the inverse kinematics for the each configuration.

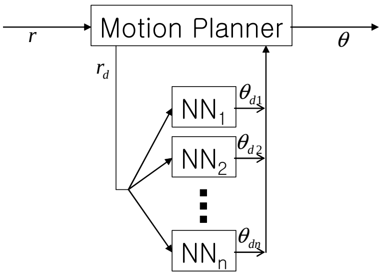


Fig. 6. Structure of motion planner

We gather the training data for the predetermined fixed joint angles having several different values. For each value, we construct motion training data at various target positions that are spaced regularly in the task space. Then, the neural network is trained. The inputs of the neural network are the desired positions in the task coordinate, i.e., x-, y-coordinates, etc., and the outputs are each joint angle. Finally, we can get the multiple models with several different configuration of the joint angles.

Next, we have to select the joint configuration among multiple models at each time step. The desired trajectories are generated as close to the line connecting the initial and final target position as possible. We apply the dynamic programming procedure to obtain the optimal solution for the problem. With the given weights and time steps, we can get the optimal joint configurations following the trajectories that minimize the objective function.

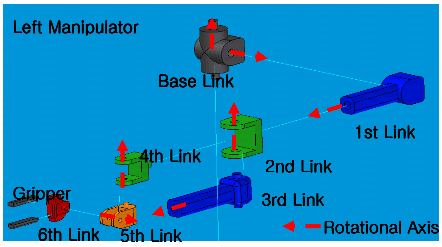


Fig. 7. Redundant manipulator

3.4.2. Experiment The line configuration of the manipulator is as shown in Fig. 7. We choose the third joint as fixing joint because it is a counterpart of the human's elbow and it can play an important role in obstacle avoidance. The neural network used was a feed-forward multilayer perceptron which has one input, two hidden layers, and one output layer. The inputs are the coordinates in Cartesian space and the outputs are the 3 joint angles. These layers have 3, 20, 20 and 4 nodes respectively, and a bipolar sigmoid function was used. We varied the third joint angle every 5 degrees from -45 to 45 degrees. For each configuration, the 343 training data which are regularly distributed in Cartesian space were obtained. Note that the training data are collected within the range which the manipulator can reach. And with this approach, we could move the manipulator even when new target point, which was originally not in the training data set, was given.

Also, we tested the motion planner. In Fig. 8 and Fig. 9, we show the results with the energy minimization criteria only. In this figure, we note that the angle of third joint was not changing during the experiment and this means that the only one neural network model was chosen during the experiment.

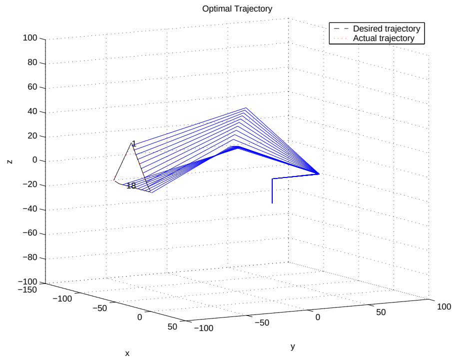


Fig. 8. Result with energy minimization criteria

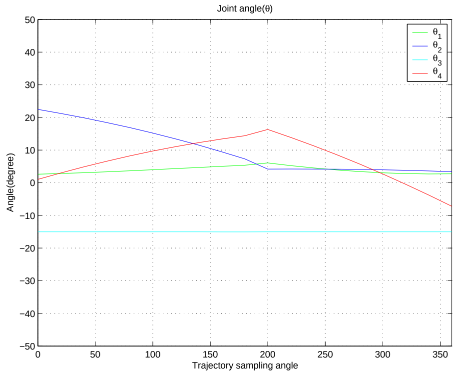


Fig. 9. Joint angle with energy minimization criteria

Next, the results with both energy minimization and tracking error criteria are shown in Fig. 10 and Fig. 11. In this case, the different configurations of the joint angle are selected. The angles of the third joint is 0 and 5 degrees and this means that the robot arm is almost unfolded.

From the graphs, the planner generated the optimal path and joint angles and showed good performances. We can adjust the weights as desired performance property. By matching the range of the joystick inputs to the desired amount of Cartesian motion of the robot manipulator, a user can easily operates the robot arm.

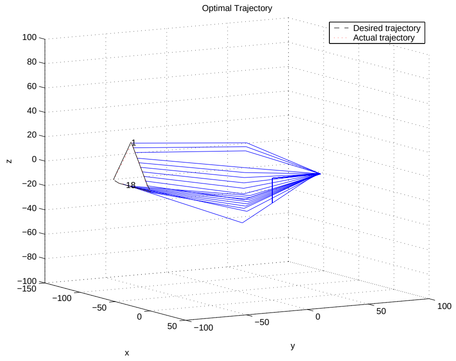


Fig. 10. Result with energy minimization and tracking error criteria

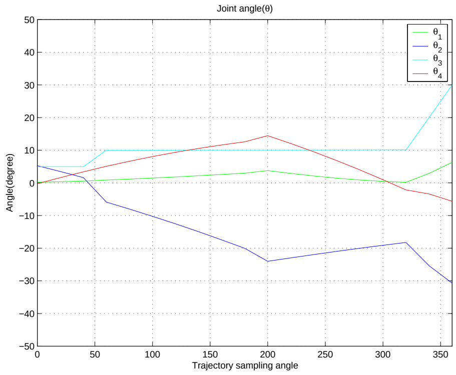


Fig. 11. Joint angle with energy minimization and tracking error criteria

3.5 Interface for the End Effector

The end effector adopted in this paper has 3 DOF shown in Fig. 12. Also gripper is attached to the end effector. The end effectors are also operated by two joysticks: one joystick for each end effector. The orientation of the end effector is adjusted via joystick. The gripping motion of the end effector is controlled by data gloves. Because the data extracted from the finger sensor of data gloves shows much fluctuation, a single fuzzy model is built to filtering the sensor value and to produce the single output using 5 finger sensors. The value of 5 finger sensors and the corresponding commands for the tooltip are shown in Fig. 13. The example motion is shown in Fig. 14.

3.6 Experiment for real robot manipulator

For the experimental purpose, two robot manipulators are designed and constructed. However, the robot base and the crane are not developed. The developed robot manipulator system consists of

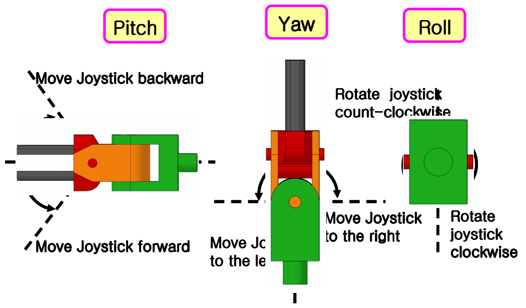


Fig. 12. Interface details for the end effector

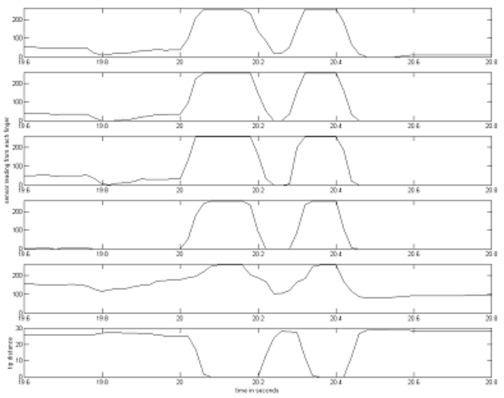


Fig. 13. Finger sensors' value and the tooltip distance

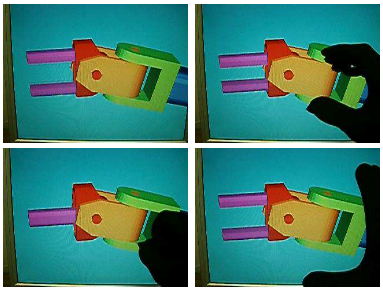


Fig. 14. Experiment results for gripping

17 joints totally and the motor control modules, which control the motor effectively, are also developed using the motor control ICs (LM629) and the motor driver ICs (LMD18200). The interface system with various input devices are programmed using Microsoft DirectX Software Development Kit (SDK).

In Fig. 15, the end effector operation followed by the robot arm operation with the right manipulator. The motion planning described in previous section can be also tested.

Finally, the robotic manipulators are controlled to perform the basic hot-line maintenance work. The work under consideration are gripping an wire, moving an wire to the target position and the cooperative work of two arms. With the proposed interface system, we can control the robotic manipulator in easy manners.

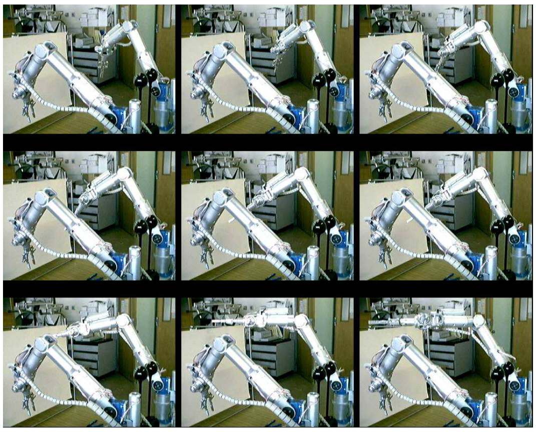


Fig. 15. Experiment results for right arm

4. CONCLUSION

In this paper, the development of tele-robotic interface for the hot-line maintenance robot system is described. Virtual hot line work robot system and its environments are developed on the 3D environments, which makes it possible to test various types of the robotic platforms and to test various interface techniques.

The operations of the hot line work robot are divided into several working modes. Interface algorithm for each mode was developed with the limited input devices. The developed operating methods are intuitive and simple while the low level control algorithms are hidden to the users. We can verify the ease of the proposed control method with the actual robot manipulators.

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