Development of a Remotely Controlled Robot and Tool for Maintaining Tasks in Nuclear Facilities

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Abstract: We are developing a remotely controlled mobile robot for maintaining tasks in nuclear facilities, which consists of a mobile platform, a telescopic mast, and a dual arm slave robot with a working tool. As the remote target tasks, we set up a remote manipulation of the manual operation mechanism of the nuclear fuel changer of the heavy water NPP and remote pipe cutting/welding, which may be necessary in the case of an emergency or dismantling of the NPP. To effectively perform remote tasks, we designed the architecture of an integrating program. The integrating program has a system component control module, a virtual guide implementing module, and egocentric remote control algorithms. We also developed tools to perform the target remote tasks.

Keyword: remote control robot, tool for maintaining task, nuclear power plant

1 Introduction

The environment of maintaining tasks in nuclear facilities might be hazardous. Thus, many automation devices are being used to inspect and repair the facilities. However, it is difficult to use the fixed automation devices for non-periodic and infrequent maintenance tasks. Thus, remotely controlled robot systems have been proposed.

If a fuel-handling machine, one of the major components of a PHWR NPP ages, the machine may be stuck to the pressure tube in front of the PHWR calandria. Even though the machine has a troubleshooting measure of a manual drive mechanism, it is still a difficult problem to access the manual drive mechanism. When the machine is stuck, the NPP is being operated so that the radiation level is extremely high and the machine can be located at a high position of up to nine meters. Therefore, a human worker cannot approach the mechanism and the mechanism should be handled remotely. Shin developed an aerial working mobile robot for monitoring a high radiation area and operating a manual drive mechanism of a fuel exchange machine (MADMOFEM)[1].

Mitigation robots of the Fukushima nuclear power plant accident and the dismantling robots for nuclear power plants (NPPs) should find the exact status of the area moving around[2-4]. Because the area of a severe accident of an NPP may be complex with obstacles, the dismantling robot should deal with dismantled parts and may carry out cutting work. Thus, an articulated multi-arm robot system is desirable to use rather than a robot with one task-specific device.

We therefore designed a remote control system for maintaining and repairing tasks in an NPP using an aerial working mobile robot. A dual arm manipulator is going to be installed instead of a single task-specific device. We named the remote control system to be developed as MARTiN (remote control system for Maintaining And Repairing Tasks in NPP). MARTiN can operate the manual drive mechanism of a fuel exchange machine and cut/weld a pipe during an emergency situation.

We designed and made tools for MARTiN to operate the MADMOFEM and cut a pipe. We tested the feasibility of the prototypes.

The dual arm manipulator as a slave robot is controlled by a master device. It is important to reduce the working time and the operator's fatigue as well as to increase the stability and accuracy in the remote work using the haptic device. In the case of complex tasks, visual and haptic virtual guide technology is useful for reducing the work time and the operator fatigue. We tested the efficiency of constraining some degree of freedom (DOF) as a haptic virtual guide[5].

The target tasks and working environment varies from case to case. Thus, it is difficult to make the virtual guide in advance. We used human intuition to generate the virtual guidance. The operator sketches the path on the visual feedback image of the remote environment. Then, the virtual guide is generated based on the sketches [6].

Because the user operates the master device with the limited view of the cameras, he may not understand the situation of the slave robot. Therefore, he may precede the work even though the slave robot approaches a poor kinematic condition such as a singularity position. We designed a master control program to provide helpful information to the operator to feel the singularity information of the slave robot[7].

The aerial working mobile robot can raise the dual arm manipulator to a height of 9 m with a telescopic mast. If the dual arm manipulator is operated at that height, the vibration at the manipulator base can be caused by the flexibility of the telescopic mast. Some researchers proposed a combined control of the manipulator systems on passively compliant bases with the assumption of the fast tracking and slow vibration, which is a superposition of two different tracking and vibration suppression control actions[8-9]. We propose a control scheme utilizing the dynamic decomposition and test the controller using a mockup test bed[10].

It is difficult to quantify the performance of a remote control system intervened by a human. Thus, it is also difficult to evaluate and improve the performance of such a system. We will adapt psychophysical methods to evaluate and improve the performance of MARTiN.

2 Target Tasks

There can be many tasks in a high radiation area such as the operation of valves and switches. First, we are going to have MARTiN remotely operate the MADMOFEM when the machine is stuck. In addition, we are going to develop the remote control technology with which MARTiN cuts/welds a pipe under an emergency situation or in the dismantling process. Fig. 1 shows the example of the target tasks.

Fig. 1 Target tasks.

Fig. 2 shows the concept of a maintenance and repair task in PHWR NPP. A dual arm manipulator on a telescopic mast on a mobile platform manipulates the MADMOFEM. A human worker in the safe area remotely operates the dual arm manipulator as a slave robot through the master device. The worker recognizes the field.

3 Hardware

The mobile platform has four wheels and four flippers. Each flipper has an active small wheel at the end. The platform is able to pass through a gate of 0.9 m in width, to move with loads of 250 kg, and to cross a ditch with a width of 0.75 m and a depth of 0.25 m by using the flippers. The mobile platform changes the direction by the skid steering method, which is easy for the platform with two omni-wheels at the rear side.

The initial height of the robot should be less than 2 m such that the robot can pass through the gate of the shielding aisle. Thus, the telescopic mast is composed of the same shaped frames sliding synchronously with a cable driven mechanism, which can reach up to 9 m including the mobile platform.

The dual arm to be installed on the linear guide on the top of the mast should be light with a high payload capacity and respond to the small external forces such that LBR iiwa 14 R820 is chosen as a dual arm robot. It is a lightweight 7 DOF articulated manipulator, which weighs 29.5 kg with a payload capacity of 14 kg, and is able to move precisely with ±0.1 mm repeatability. It assembles parts delicately and detects the external forces with integrated torque sensors.

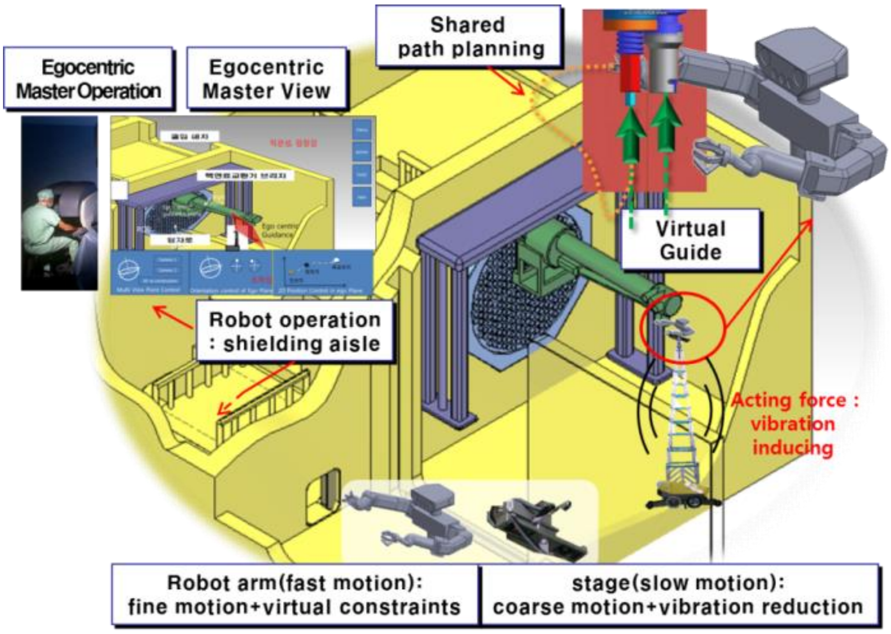

Fig. 2 Concept of maintenance tasks in nuclear facilities.

Fig. 3 Mobile platform, slave and master.

The master device is an Omega 7 of Force Dimension. Omega 7 detects the translational motion of the X/Y/Z directions and the rotational motion of the rx/ry/rz direction. In addition, it supplies the reflection forces, which are 12 N for the translational motion and 8 N for the grasping. Its linear accuracy is 0.01 mm and its rotational accuracy is 0.09 deg. It supplies sufficient stability with an 8 kHz refresh rate. Fig. 3 shows the mobile platform, slave robots, and master devices.

The object to be operated and the work environment are recognized with a depth camera such as a TOF camera and stereo camera. A Kinect v2 (TOF camera) and a ZED camera (stereo camera) were considered as a remote field depth formation gathering device. Embedded boards such as ODROID XU4 for the Kinect v2 and Jetson TX1 for the ZED are used in sending the remote field information to the operating room.

4 Tools

There are three parts to be operated at MADMOFEM: a clutch axis, an engaging helical gear axis, and a RAM driving axis. We made a MADMOFEM mockup to be tested and an operating tool for the slave robot.

The operating tool has three functions: operating the clutch, engaging the helical gear, and driving the RAM. The operating tool is installed at the end of the slave robot. The slave robot can change the pose of the operating tool from the helical gear engaging part to the clutch and the RAM driving tool part so that the slave robot can operate three parts of the MADMOFEM.

We previously developed a tele-RAM operating device driving MADMOFEM as a one task-specific device. The operating tool of 3 kg is very light compared to the tele-RAM operating device of 50 kg. Fig. 4 shows the MADMOFEM mockup, the operating tool, and the previously developed tele-RAM operating device.

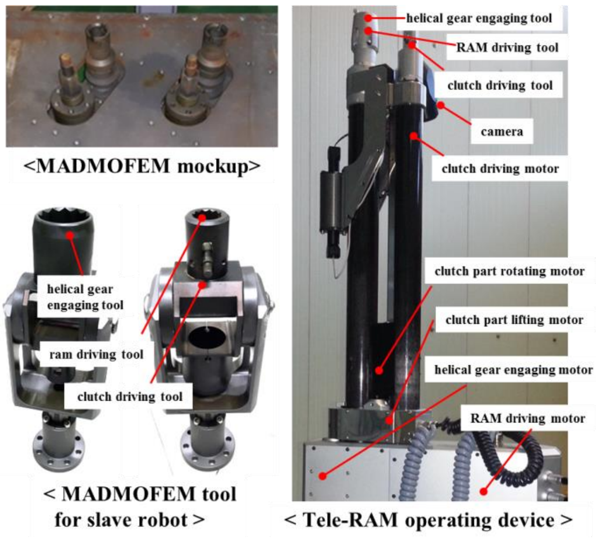

Fig. 4 MADMOFEM mockup and tools.

We developed a pipe cutting tool for the slave robot arm. Since the outer target is a 2 inch pipe with a 5 mm thickness, a 9 inch circular saw was selected. The circular saw of 2 mm thickness can cut the steel and stainless steel pipe with a 5 mm pitch tooth.

The pipe cutting tool has limitations in size and power to be installed at the end of the robot arm so that a low voltage 200 W BLDC motor was chosen as a cutting motor. The rated speed of the motor is high enough to cut the steel pipe. The recommended rotating speed of the saw is 80 rpm. Thus, we attached a reducer to the motor. To achieve an appropriated reduction ratio, we tested several reducers.

To test the cutting ability of the circular saw and the actuator, we built a test bed with a linear guide. If vibration occurs, the saw is caught in the pipe. Therefore, the test bed should be rigid and the backlash of the linear guide should be small.

We controlled the feed rated with a DC servo motor and supplied cutting oil to the cutting spot with a small pump. Fig. 5 shows the cutting tool test bed.

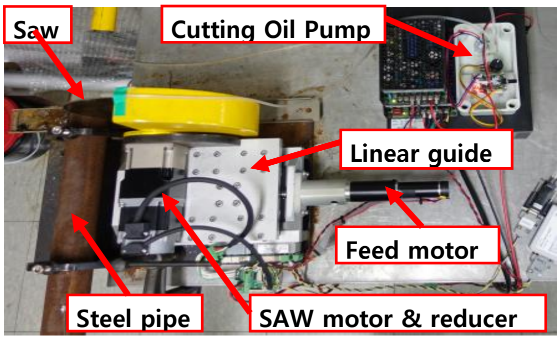

Fig. 5 Cutting tool test bed.

We cut the target steel pipe with the cutting tool test bed. The rotating speed of the saw was controlled as 80 rpm. The current of the saw motor was set 6.4 A. The feed rate of the saw was 0.05 mm/s. If the current of the saw motor went over the setting current, the feed motor stopped and waited until the current went down below the setting current. Fig. 6 shows the control responses of the cutting motor, and Fig. 7 shows the control responses of the feeding motor.

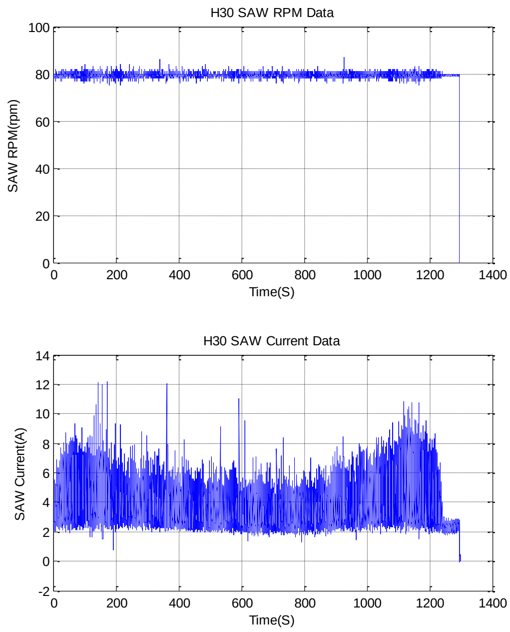

Fig. 6 Control responses of cutting motor.

It took 21 minutes to cut the target pipe. It is noted that the current curve has two picks at which the cutting part is the most thick. In addition, there is a current margin at the mid part.

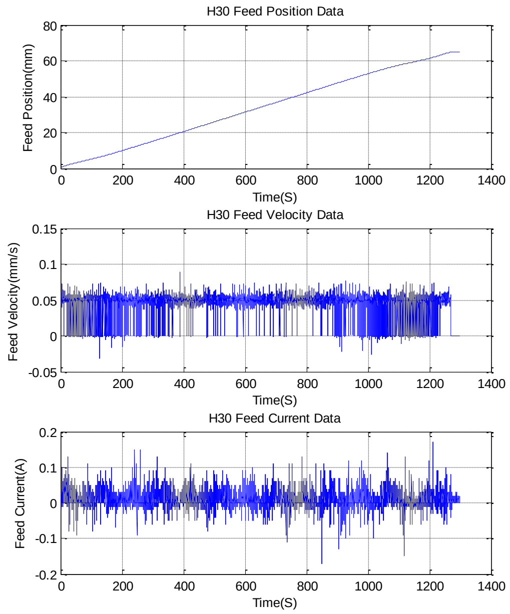

Fig. 7 Control responses of feeding motor.

The cutting time can be shortened if a more effective control algorithm is applied.

5 Software Design

Software will be developed separately for each component of MARTiN: a mobile platform, a telescopic mast, a linear guide, slave robots, master devices, and a depth camera. Virtual guidance, control algorithms, and egocentric remote control programs should also be designed and implemented to effectively control the remote system.

5.1 Real-time virtual guidance and path generation

To reduce the working time and the operator's fatigue, we adopted virtual guide technology. However, because the environment is unstructured, it is difficult to build the virtual guidance in advance. Thus a virtual guide needs to be generated on the spot.

We employ human cognitive abilities to create virtual guidance. A human operator selects features on the computer monitor displaying a 2D/3D image of the spot. The features are lines, circles, ellipses, and smooth curves, which are contour-based features computed using a vision algorithm. The selected features are combined into one. Then the operator defines the target point, target direction and constraint as guidance from the feature.

One of the target tasks of this research is to operate the MADMOFEM in which the slave robot arm should insert the operating tool on the driving axes. This task is one of a peg-in-hole task.

First, we select the representative features of the operating tool as a peg: the center of the contour of the peg and its axis. Second, we select the driving axis as a hole and the normal to its plane. The normal should be aligned with the center of the hole. Then, a guidance fixture is created that will attract the peg to the axis of the hole. Fig. 8 shows the virtual guide for a peg-in-hole.

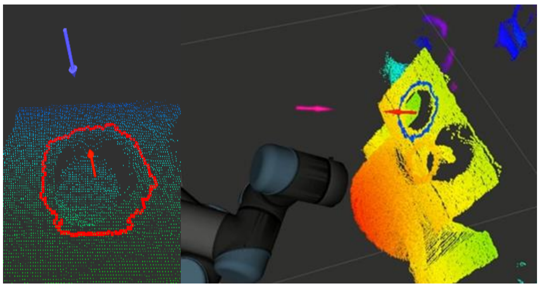

Fig. 8 Virtual guide for a peg-in-hole task.

If the work environment is complex, it is difficult and takes a long time for the robot to approach an object without a collision. Some researchers have been developing automatic path generation technologies. Until now, however, automatic path generation has been difficult and very slow owing

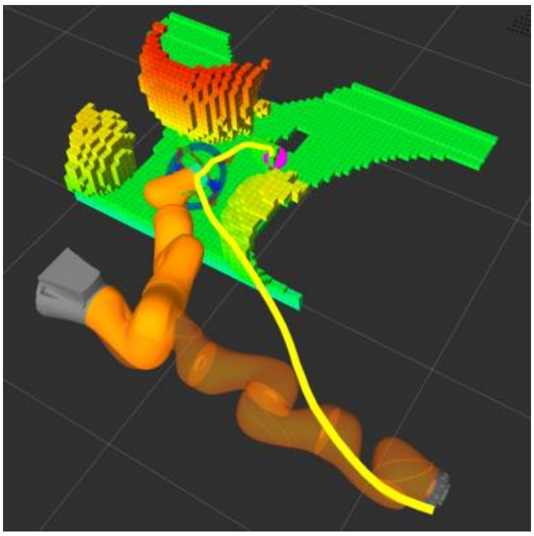

Fig. 9 3D path sketch.

to a lack of cognitive abilities of the working environment and the ability to deal with dynamic obstacles.

We are going to initially sketch the path in the virtual 3D work space with a haptic device. Then the appropriate path will be generated quickly based on the initial sketched path.

5.2 Egocentric remote control

Because the operator is located far from the slave robot and the camera view is limited in the case of remote control, the information of the situation of the spot is limited. To overcome the limitations in the cognitive and manipulation capabilities of the operator, we will provide an exocentric view as well as an egocentric view to the operator. Fig. 10 shows the exocentric and egocentric views. An AR (augmented reality) structure is displayed in the exocentric view and the virtual guide is displayed in the egocentric view.

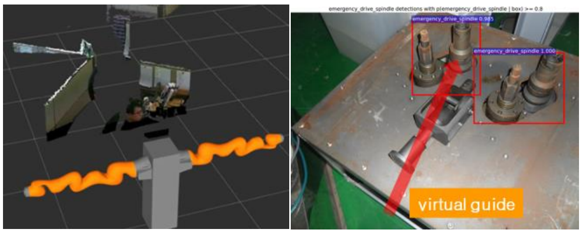

Fig. 10 Exocentric and egocentric views.

We will also provide helpful information for the operator to feel the poor kinematic condition of the slave robot such as the singularity position. To find the singularity direction the manipulability ellipsoid is computed from the Jacobian matrix of the slave robot.

We can apply the ellipsoid of the slave robot to the master device. We provide a force feedback to the master device based on the size and direction of the ellipsoid to result in preventing access to the singularity. Fig. 11 shows the slave-master system, which is composed using PHANTOM Omni as the master device and KINOVA Jaco as the slave robot.

Fig. 12 shows a program in which the GUI gives visual feedback information of a normalized manipulability measure, singularity direction,

Fig. 11 Applying a manipulability ellipsoid from the slave robot to the master device.

and visual feedback of the slave-mater system of Fig. 11. It is noted that when the manipulator is far from the singularity posture, the color of the graph is blue. On the other hand, when the robot approaches the singularity, the color of the graph turns red. In addition, a red arrow in the circle of the GUI implicates the direction of singularity.

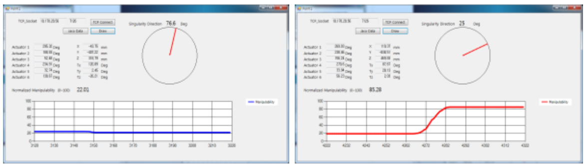

Fig. 12 Singularity information program GUI.

5.3 Shared control of the slave robot

It is very difficult for the tele-operator to control the slave robot by suppressing the vibration subscribed above. For the operator to concentrate on carrying out the target task, we applied the shared control strategy in which and the system suppresses the vibration of the flexible base automatically. We built a test bed to test shared control scheme, as shown in Fig. 13.

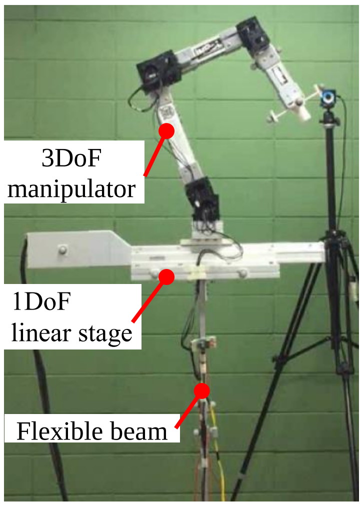

Fig. 13 A shared control test bed of the manipulator on the flexible base.

Before we decompose the system dynamics, we obtain the modeling of the system with the Euler-Bernoulli theory. We can then build an end effector tracking controller and a vibration suppression controller separately. Fig. 14 shows the vibration suppression control response when the 3DoF manipulator moves from a folding position to an erect position.

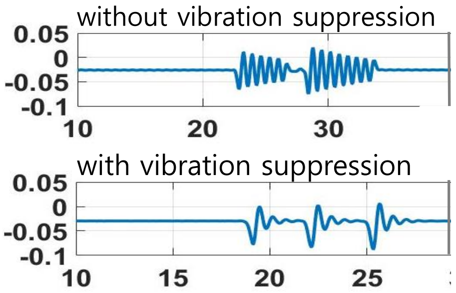

Fig. 14 Vibration suppression control response.

5.4 Integration of the control system

The different software types, developed separately, are connected using TCP and UDP communications and eventually have to be integrated as a single control system. In order to facilitate the integration of such software, we set the development environment uniformly: Windows 7(64bit) OS and VC 2010 for Windows and Ubuntu 14.0.4(64bit) OS and QT4/C++/Python for Linux.

The control frequency or communication frequency is very important in robot control. In addition, when integrating multiple software types, it is especially important to set the priorities of these frequencies. Because the shared control capability of a slave robot and the haptic stability of a master device require a high frequency, the communication frequencies of these components are set to 500 Hz in the developing MARTiN system. The updating rate for rendering the point cloud data of the virtual guide and the location information of the object are set to 10 Hz. In addition, the communication frequency of each joint state and the joint control data are set to 100 Hz. Fig. 11 shows the communication connection and communication periods for the integration of the software described above.

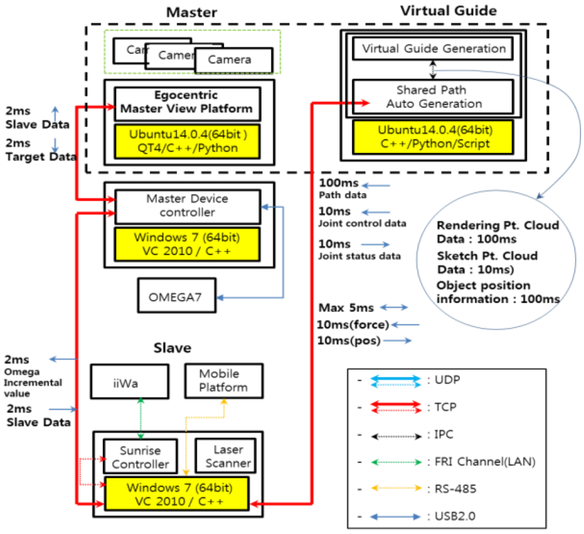

Fig. 11 Software integration diagram

5.5 Evaluation

It is difficult to quantify the performance of a remote control system intervened by a human user. Thus, it is also difficult to evaluate and improve the performance of such a system. We will adopt psychophysical methods to evaluate and improve the performance of the MARTiN system.

For example, we evaluated the usefulness of the virtual guide and the effects of its accuracy through a following psychophysical experiment. We set the peg-in-hole task as the target task, which is a basic manipulation task of operating the MADMOFEM. The virtual guide was generated in the normal direction from the center of the hole, generated an attractive force for the haptic feedback, and had a positional error and angular error with respect to the center of the hole. Quantitative evaluation indicators were defined as the completion time, position tracking error, and attractive/contact/human forces. The experiment was designed to have eight cases, which consisted of a combination of a virtual guide, position and angle errors of 30% and 70%. The subjects were 15 to 20 persons who repeated each case 10 times. The results of the experiment were divided into four sections based on the contact between the peg and hole, and analyzed by ANOVA (Analysis of Variance) using the defined evaluation indexes. Fig. 12 shows the completion time of the results.

It should be noted that the reduction of the completion time is clearly seen in step 1 and step 3 (about 12% in step 1and about 40% in step 3). This is because the haptic guidance reduces the degree-of- freedom of the operating motion of the operator. Meanwhile, the effect of the size of the inaccuracy of the haptic guidance on the completion time is relatively small.

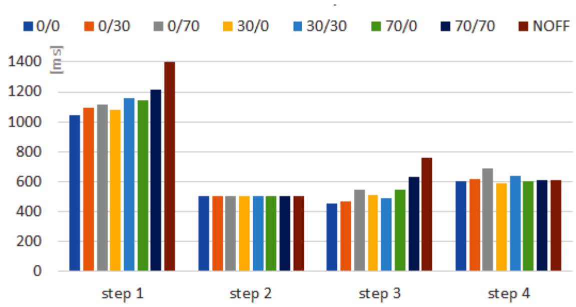

Fig. 12 Completion time

6 Conclusions

We designed a remote control system, MARTiN, for maintaining and repairing tasks in an NPP using an aerial working mobile robot, developed control algorithms and carried out a feasibility test. An LBR iiwa 14 R820 was chosen as the dual arm slave robot and an Omega 7 of Force Dimension as a master device. We made a MADMOFEM operating tool, and a pipe cutting tool for the slave robot were made and tested.

To reduce the working time and the operator's fatigue, as well as increase the stability and accuracy in the remote work, we adopt virtual guidance technology, the exocentric and egocentric view, and the manipulability ellipsoid to prevent the slave robot to access the singularity. The shared controller was developed to automatically suppress the vibration of the flexible base. To integrate individual control algorithms and software, we designed a control architecture and communication flow and update rate.

Evaluation indexes and experiments for the MARTiN system will be designed to evaluate and improve the performance of the technologies. The performance of the MARTiN system will be evaluated through the target tasks.

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