An Impedance-Control Based Teleoperation System for Live-Line Maintenance Robot

Yang Wang, Hui Wu and Xiaoming Mai

Electric Power Research Institute of Guangdong Power Grid Corporation, Guangzhou 510000, China

Abstract. Robotic operation is an effective way to upgrade the live-line maintenance safety, efficiency, and quality. This paper proposes an impedance control-based teleoperation system to improve the adaptability of live-line maintenance robot in outdoors environment. The key technology of this system is utilizing three virtual spring-damper systems to model the elastic connection between the end-effector of slave manipulator and the environment, between the end-effector of slave manipulator and the counterpart of master haptic device, and between the end-effector of master haptic device and its base, respectively. Experiment results show that, under control of our proposed teleoperation system, the slave manipulator is able to track the motion of master haptic device and the robot is able to complete a set of complex action to peel the coat off the cable.

Keywords. Impedance control; teleoperation; live-line maintenance robot.

1. Introduction

In today’s highly electricity dependent society, outage-free power supply has become an obligation for electrical companies [1]. As a result, live-line maintenance techniques in overhead distribution lines have been developed and widely used around the world. The maintenance tasks consist of relocating a conductor to a higher pole, installing switch gears, peeling the coating off cables and so on [2]. These maintenance tasks have been all conducted by human workers, who are required to work in unsafe circumstances such as in high places and near high-voltage lines [3], as shown in figure 1.

In the goal of risk reduction, labor savings, and work quality upgrading, operation-type robot for live-line maintenance were developed [4], as shown in figure 2. At the very beginning, the robot system is merely a master-slave teleoperation system [5]. The operator must keep eyes on the target object, measure its relative distance from the robot very carefully, and use the master arm or joystick to control the slave manipulator conducting the live-line work in a low efficiency [6]. The experience of teleoperating is not good in practice. In recent years, with the developing of robotics sensing and control technologies, researchers attempted to realize a fully autonomous maintenance operation [7]. However, the outdoors environment for live-line maintenance is highly unstructured because of the significant difference of maintenance tasks, target objects, distribution line structures, light conditions, and wind intensities. The reliability and adaptability of a robot to accomplish a maintenance task with a fully autonomous control system is hard to meet the electrical companies’ requirements.
Inspired by the latest success of novel haptic device applied on surgical robot, the master-slave teleoperation system re-attracts the attention of operation-type robot researchers [8]. With these haptic devices, the operator could control a slave manipulator with six or more degrees of freedom (DOF) by moving his wrist merely. Furthermore, by integrating a force sensor mounted on the end-effector of slave manipulator into the teleoperation system, both the magnitude and direction of the external force acting on it can be reflected on the counterpart of the master device with a high resolution. And then the operator could feel the robot-environment interaction with a immerse experience and manipulate the robot easily to conduct a proper operation on the target object.

To combine the both advantages of autonomous control system in high regulating precision and fast dynamic response and the teleoperation system in adaptability of environmental variety [9], in this paper, we propose a novel an impedance control-based teleoperation system for the robotic live-line maintenance. First, a velocity-based impedance control method is applied on the motion control of the end-effector of manipulator to realize a safe and precise interaction between the line and robot. Second, two spring-damping models are established and used to eliminate the tracking error of master-slave teleoperation. Finally, a physical experiment of a duo-arm robot peeling the coating off cables with its two arms cooperating under control of we proposed teleoperation is conducted.

2. Impedance Control Model

Since a complete live-line maintenance task is composed with a set of basic action essentials, such as grasping the cable, screwing the bolt, putting a peg in hold and so on. Each action should be completed only when both the magnitude and direction requirements of force and motion imposed on the target object through the manipulator end-effector are satisfied simultaneously. Different actions always correspond to different requirements. To satisfy these requirements, an impedance control strategy is designed to realize the motion and force control of the slave manipulator.

The main idea of impedance control is modelling the interaction between two bodies as a compressing of a spring-damper system [10]. The second-order dynamic model of the end-effector of manipulator interacting with the environment in Cartesian coordinates can be described as
\[ K_M \Delta \dot{v}_{dc} + K_D \Delta v_{dc} + h'_{dc} = h' \]  

(1)

where \( K_M \) denotes the inertial matrix, \( K_M \) the coefficient matrix of damping, \( h' \) the variation of force on the end-effector, \( h \) the total force applied on the end-effector, \( \Delta v_{dc} \) the value of the actual velocity of the end-effector varying from the desired, and the superscript \( c \) represent the variable being described in Cartesian coordinates. The modeled interaction between the end-effector of manipulator and the environment is depicted in figure 3.

Figure 3. model of the interaction between the end-effector of manipulator and the environment.

And then, the control law of the impedance control can be described as

\[
\begin{align*}
\dot{v}'_r &= \dot{v}'_d + K_p \left( h'^e - h'_c \right) \\
h'_c &= h - K_s \Delta \dot{v}_{dr} \\
h'_c &= h - K_v \Delta v_{dr}
\end{align*}
\]

(2)

where \( \dot{v}'_r \) and \( \dot{v}'_d \) denotes the reference and the desired velocity of the end-effector, respectively, \( K_p \) is the coefficient matrix of stiffness, \( h'_c \) and \( h'_c \) represents the spring force and external force applied on the end-effector, respectively. The impedance control strategy is described as figure 4.

Figure 4. Framework of impedance control system.

3. Impedance Control-based Teleoperation System

To map the end-effector movements between the master and the slave device and make the both devices always working with a similar frequency providing a good experience of operation, in this paper, two spring-damping models are applied in the teleoperation control strategy.

The 1st spring-damping model is set to connecting the positions of the end-effectors of the master and slave device with each other virtually. This dynamic model is described as

\[
f_{m2s} = K_{m2s} \left( p_m - p_s \right) + D_{m2s} \left( \dot{p}_m - \dot{p}_s \right)
\]

(3)

where \( K_{m2s} \) and \( D_{m2s} \) denotes the coefficients of stiffness and damping respectively, \( p_m \) and \( p_s \) denotes the absolute position of the end-effector of master and slave device in Cartesian coordinates respectively, and \( f_{m2s} \) is the output force. Then, in the impedance control of slave manipulator, \( f_{m2s} \) can be dealt as a virtual external force to drag its end-effector moving. The modeled interaction between the end-effector of master haptic device and the counterpart of slave manipulator is depicted
in figure 5.

![Figure 5.](image)

**Figure 5.** Model of the interaction between the end-effector of master haptic device and the counterpart of slave manipulator.

The 2nd spring-damping model is set to connecting the positions of the end-effector and the base of slave device virtually. This dynamic model is described as

\[
f_{s2m} = -K_{s2m}(p_m - p_s) - D_{s2m}(\dot{p}_m - \dot{p}_s)
\]

where \(K_{s2m}\) and \(D_{s2m}\) denotes the coefficients of stiffness and damping respectively and \(f_{m2s}\) is the output force. Then, \(f_{s2m}\) is a real force acting on the operator hand through the master device end-effector. The modeled interaction between the end-effector and the base of master haptic device is depicted in figure 6.

![Figure 6.](image)

**Figure 6.** Model of the interaction between the end-effector and the base of master haptic device.

In addition, the workspace ranges and the original points of the master and the slave device are always different from each other. To overcome it, a transformation is required to calculate the position of the end-effector of master device in the coordinates fix to the base of slave device real-timely. The transformation is described as

\[
p_m' = F(M_{m,i\rightarrow f}M_s)
\]

where \(M_{m,i\rightarrow f}\) is a 4×4 matrix representing the Euler angles and position of the end-effector of master device relative to its original point, \(M_s\) is also a 4×4 matrix representing the Euler angles and position of the end-effector of slave manipulator in Cartesian coordinates, \(F\) is the mapping relation of a rigid body between the positions and Euler angles and the corresponding rotation matrix.

With (2)-(5), an impedance control-based teleoperation is established, as described in figure 7.
4. Experiments and Results

4.1. Experimental Setup

This paper builds a master-slave teleoperation physical experiment platform. The master haptic device is an Omega.7 produced by Force Dimension, and the slave manipulator is a UR16e made by Universal-Robots. The controller is a rapid prototype controller, Baseline, produced by Speedgoat. And the six-axis force/torque sensors, mounted on the end-effector of slave manipulator, is produced by Sunrise Instruments. Both the working frequencies of the master and slave site are 500Hz, the communication frequency between the both site is 1000Hz. In addition, a special tool for peeling the coating off cables was designed and mount on the end-effector of UR16e. The main parameters of these device are detailed in table 1. The framework of teleoperation system is described as figure 8. The definition of the coordinates of the end-effector of master and slave device is described in figure 9. And the physical experiment platform is shown in figure 10.

| Number | Type            | Exterior         | Parameters                                  |
|--------|-----------------|------------------|---------------------------------------------|
| 1      | omega.7 (Dimension) | workspace        | translation: 160 x 110 mm                    |
|        |                 |                  | rotation: 240 x 140 x 180 deg               |
|        |                 |                  | grasping: 25 mm                             |
|        |                 | forces           | translation: 12.0 N                         |
|        |                 |                  | grasping: ± 8.0 N                           |
|        |                 | resolution       | translation: < 0.01 mm                      |
|        |                 |                  | rotation: 0.09 deg                          |
|        |                 |                  | grasping: 0.006 mm                          |
|        |                 |                  | stiffness closed-loop: 14.5 N/mm            |
| 2      | UR16e (Universal Robotics) | Payload | 16kg                                        |
|        |                 | Reach            | 900mm                                       |
|        |                 | Weight           | 33.1kg                                      |
| 3      | M3712A (Sunrise Instruments) | Capacity | Fx:400N; Fy:400N; Fz:800N                    |
|        |                 |                  | Mx:6Nm; My:6Nm; Mz:6Nm                      |
| 4      | Baseline (Speedgoat) | Configure      | CPU: 2 GHz 4 cores                          |
|        |                 |                  | RAM: 4G DDR3                                |
|        |                 |                  | OS: Simulink Real-Time™                    |
|        |                 |                  | Interfaces: Ethernet, CAN, AIO              |
4.2. Experiments

First, the experiment to demonstrate the tracking performance is conducted as shown in figure 11. The experimental results are shown in figure 12. The ref curve denotes the reference trajectory of end-effector position generated with master haptic device, the cal curve denotes the ideal trajectory of end-effector position of the slave manipulator calculated with the controller, and the act curve denotes the actual trajectory of the end-effector position of slave manipulator. The results show that the movement of the end-effector of the slave manipulator can track the reference generated with the master haptic device with good dynamic response and acceptable precision.
peeling consists of a roller-blade carrier mounted on the end-effector of left manipulator, and a special designed electric wrench for clamping the roller-blade over the cable coating mounted on the end-effector of right manipulator. When the peeling operation started, the left manipulator took the roller-blade carrier moving towards the cable and stopped when the cable being in the middle of roller-blade carrier, as shown in figures 13a and 13b. Then, the right manipulator took the electric wrench moving towards the roller-blade carrier and stopped when lock bolt of roller-blade carrier being inserted into the location hole of wrench, as shown in figures 13c and 13d. Finally, after the roller-blade being clamped in place, the wrench left from it and the blade started rolling to peel the coating of cable off, as shown in figures 13e and 13f. The experiment result shows, under the effect of impedance control-based teleoperation, the both manipulators can co-operate to completing a complex maintenance.

![Graphs and diagrams](image-url)
Figure 12. Tracking performance of platform.

(c) Euler angle on the \( o \)-direction

(d) Euler angle on the \( a \)-direction

(a) Initial state

(b) movement of roller-blade carrier

(c) movement of electric wrench

(d) stop of electric wrench moving
9

5. Conclusion
This paper developed an impedance control-based teleoperation system for the robotic live-line maintenance. Owing to the inherent advantages of impedance control and teleoperation, the manipulator can meet the requirements of highly-precise force and motion control and satisfy a good adaptability of the variety of desired action to complete a complex operation. In the future, we will try to integrate an autonomous trajectory planner with a computer vision positioning system into this system to improve the intelligence of live-line maintenance robot.

Acknowledgments
This research is financially supported by Work Robot System for Electric Power Industry-Topic 2: Research on Robot Technology and Equipment for Live Work on Distribution Network (No. GDKJXM20192275).

Reference
[1] Lu S, Li Y and Wei Q 2009 Robotic live-working for electric power lines maintenance Proc. IEEE Conf. on. Industrial Electronics and Applications pp 1716-1719.
[2] Tsukahara K, Tanaka Y, He Y, et al. 2008 An experimental robot system for power distribution line maintenance robots-System architecture and bolt insertion experiment IEEE/RSJ Int. Conf. on Intelligent Robots & Systems pp 1730-1736.
[3] Maruyama Y, Maki K and Mori H 2002 A hot-line manipulator remotely operated by the operator on the ground Proc. of IEEE 6th Int. Conf. on Transmission and Distribution Construction and Live-Line Maintenance pp 437-444.
[4] Tsunemi K, Maruyama Y, Yano K, et al. 1998 Development of a hot-line work robot, “Phase II” and a training system for robot operators IEEE Int. Conf. on Transmission & Distribution Construction 147-153.
[5] Santamaria A, Aracil R, Tuduri A, et al. 1997 Teleoperated robots for live power lines maintenance (ROBTET) 14th Int. Conf. and Exhi. on Electricity Distribution pp 1-3.
[6] Kim C H, Jung S and Jeong T 2007 Relative position measurement method for a live-line work robot IEEE Int. Conf. on Control pp 998-1001.
[7] Wang J, Zhang G, Hui Z, et al. 2008 Force control technologies for new robotic applications IEEE Int. Conf. on Technologies for Practical Robot Applications pp 143-149.
[8] Banthia, Vikram, Maddahi, et al. 2018 A prototype telerobotic platform for live transmission line maintenance: Review of design and development Transactions of the Institute of Measurement and Control 40 3273-3292.
[9] Guo C, Tarn T J, Xi N, et al. 1995 Fusion of human and machine intelligence for telerobotic systems *Proceedings of 1995 IEEE International Conference on Robotics and Automation* pp 110-3115.

[10] Siciliano B and Khatib O 2008 *Springer Handbook of Robotics* (New York: Springer-Verlag).