Proceeding of the IEEE
International Conference on Robotics and Biomimetics
Dali, China, December 2019

Development of A Robot System Performing Maintenance Tasks on High-Voltage Power Transmission Lines

Yu Zhong, Ziyang Fu, Manjia Su, Yisheng Guan* and Haifei Zhu

Biomimetic and Intelligent Robotics Lab (BIRL)
Guangdong University of Technology
Guangzhou, China, 510006

Liqiang Zhong

Institute of Electric Power
China Southern Power Grid Co., Ltd.
Guangzhou, China, 510006

***Abstract*— Performing maintenance tasks on high-voltage Power Transmission Lines (PTLs) at high altitude is dangerous and tedious, hence demands robots to take place of human being. In this paper, a robot system is developed to fulfill three of typical maintenance tasks. These tasks are adjusting vibration dampers, cleaning the current deflectors and assembling cotter pin. In general, different tasks require different end-effectors, and work at height demands the system simple and light-weighted. To this end, three special end-effectors are designed by modular method so that they can be connected to a manipulator and changed for the corresponding tasks, similar to a CNC machining center. The whole robotic system consists of three end-effector modules, a tool exchange device, a light-weight 5-DoF modular manipulator, and a desk-top level modular master robot for remote control of the manipulator. The architecture and integration of the system are presented in detail, while experiments are carried out to verify the feasibility and effectiveness of the proposed setup. It is shown that such a system will bring new robotic applications in the working at height of power industry.**

***Index Terms*— Robot System, Design of System, Maintenance Tasks on PTLs**

I. INTRODUCTION

Electric power supply is indispensable for our daily life and production in the modern society. Power transmission networks need to be maintained in a safe way to ensure reliable power supply. The Power Transmission Lines (PTLs) and their accessories are exposed in the outdoors for a long time and operate constantly under mechanical tension, shaking and air defilement, caused by natural factors such as wind, rain and sunshine. These hard operating conditions easily cause problems to the transmission grids, such as vibration dampers being loose and slipping, current deflectors becoming dirty and overheated, or even screw connections becoming unreliable, leading to hidden failures of the electric power supply safety. Therefore, regular inspection and maintenance play an indispensable part in obtaining running conditions, finding potential damages and repairing the faults in time.

There are lots of tasks on PTLs, among which the typical ones include damage inspection along the lines, removing hung objects, adjusting vibration dampers, cleaning current deflectors, fastening screw connections, cleaning insulators, repairing the broken wires, eliminating frozen ice pieces on the lines [1], [2], fine manipulation tasks, such as assembling cotter pin into screw bolt and so on. These tasks currently require especially trained workers with professional skills to perform. Outdoors and at height, these operations are tedious, boring and dangerous, thus are perfect candidate cases, where robots should replace the human workers. As robotic technology advances, a lot of robotic systems are being developed, to replace or assist workers, to accomplish inspection and maintenance tasks on PTLs, and they reduced the intensity of workers and improved the manipulate efficiency greatly.

The robotic systems, for maintenance tasks on PTLs, must possess two fundamental functions: locomotion along the lines and manipulation for maintenance tasks. In terms of locomotion: some robots embrace the cables to implement locomotion [3], [4]; many robotic systems are mounted on crane-type vehicles [5], [6], significantly limiting their flexibility; some robots are fixed on mobile platforms which hanging on the cables with several arms, and most of them can achieve continuous and translational movement, through wheels rolling on the cables and can cross obstacles on the cables [7], [8], [9]. In general, notable progress and achievements have been made in terms of locomotion [10], thus, we will focus on manipulation for maintenance tasks in this paper.

In reality, the manipulation involved in maintenance tasks on PTLs is a hard mission with big challenge. Most of the maintenance tasks on PTLs (excluding de-icing) demand complex motions and/or force/torque of the executing devices, while the motions may be carried out by arms or manipulators. A common approach is to employ one or two arms with special tools in the end of them for the maintenance work [11], [12]. These arms and tools are, in general, designed for only one special and unique task,

*Corresponding author: ysguan@gdut.edu.cn. This work is in part supported by the Key Research and Development Program of Guangdong Province (Grant No. 2017B050506008, 2019B090915001).

largely limiting the applicable prospect and value of such a robot system in the PTLs application field. Furthermore, working at a height and in special environments, conducting each maintenance task using a different robot system would be very demanding in terms of cost, time, labor and finance, from the aspect of system setup and running. Therefore, an ideal solution is to employ a robot system which is highly integrated and adaptive to different tasks as many as possible, the components as few and simple as possible, and keeping a low cost. These requirements raise a hard challenge, regarding robot system design and development, specifically targeted to such subtle missions.

In this paper, three typical maintenance tasks raised from practical demand in the power industry are analysed. Then, the mechanical solution framework is set up based on the target tasks, and three end-effector modules are designed according to maintenance processes. Finally, the design mechanism of the robot system is analyzed and proposed solution methods, experiments are carried out to verify the reliability of the suggested robot system at the same time.

II. Maintenance Tasks and Proposed Solution

A. Problem Definition: Three Tasks

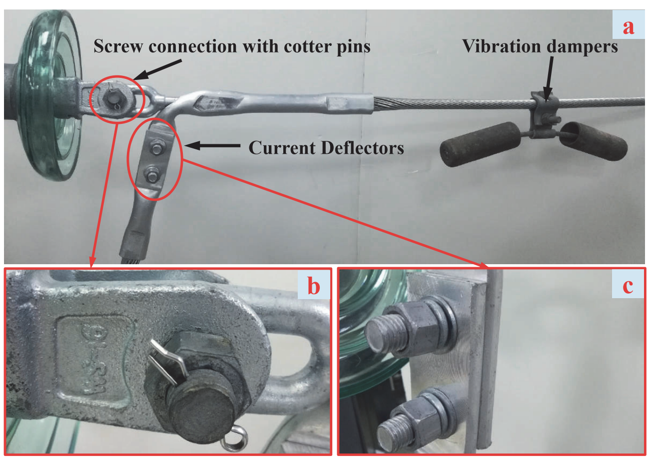


Fig. 1. Accessories used on PTLs.

From all maintenance tasks on PTLs, three typical ones are considered in this section: adjusting vibration dampers, cleaning the currency deflectors and assembling cotter pin.

- *Adjusting the Vibration Dampers*: Vibration dampers are used to reduce the oscillation of high-voltage PTLs by adding weight. The fastening screws of the vibration dampers might loosen sometimes, resulting in slipping of the dampers, as show on the right of Fig. 1(a). The screw connection of dampers need to be fastened or loosened by screwing or unscrewing the nut, to avoid accident or to relocation.
- *Cleaning the Current Deflectors*: The current deflectors are adopted to connect the PTLs. The contacting surfaces of two deflectors could be dirty and oxidized after long-term working, leading to overheated of contacting surfaces and endangers the safe operation of the electric power system, so they need to be cleaned. In order to cleaning their contacting surfaces of current deflectors, the nuts should be loosen firstly so that the two deflectors could be separated for. After the cleaning, the two deflectors should be fastened together by screwing the nuts tightly for better conductivity, referring to Fig. 1(c).
- *Assembling the Cotter Pin*: To avoid the nut dropping out, a cotter pin might be used to cross the bolt. It might happen that the cotter pin is missing in some cases. Thus, a new cotter pin needs to be inserted into the screw bolt to secure the connection, as shown in Fig. 1(b).

Plainly, the three tasks to be conducted on PTLs with a robot system include three maintenance processes: screwing or unscrewing nuts of vibration dampers or current deflectors, cleaning the surfaces of current deflectors and assembling the cotter pin into the screw bolt. These processes are quite different, with varying requirements to be met. Loosening and fastening screw nut demands sufficiently high torque; cleaning surfaces may involve translational or rotational motion, while assembling a cotter pin into a screw bolt requires grasp force and translational motion. It is very difficult or even impossible, using one end-effector, to fulfill all of them, so various end-effectors should be developed to competent to the tasks reasonably.

B. Solution Framework

A robot system is developed to execute these tasks based on a mechanical modularity method. The system is composed of several sub-systems, including a light-weight 5-DoF modular manipulator, a desk-top level modular master robot, three end-effectors and a tool exchange device, as shown in Fig. 2. Each sub-system may be regarded as a module on a system level. Consisting of a few joint modules, the manipulator is also a modular system, and it can be controlled by the modular master robot. The number of degrees of freedom and configurations about the manipulator and master robot can be changed also, depending on the specific task requirements. Furthermore, the three end-effectors and the tool exchange device are also designed as modules with standard interfaces, so that they can easily and uniformly be connected to the manipulator, as well as exchanged for different tasks.

Because each end-effector is designed as a module, with integrated mechanical and electrical interfaces, these can be connected and disconnected to the end of the manipulator automatically. In this way, one manipulator can perform all these different tasks as required. The idea is similar to that of CNC machining center, where different tools are optional for different mechanical processes. In this way, the system may be largely simplified, while the cost will be much lower.

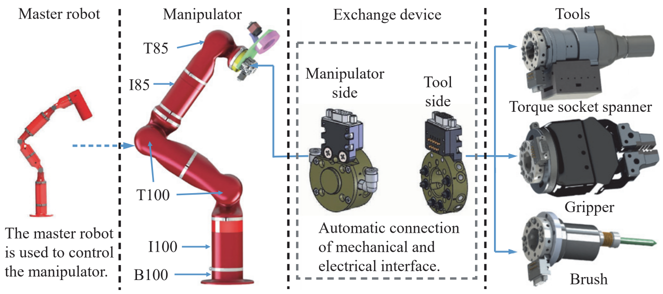


Fig. 2. The framework of mechanical solution for the maintenance tasks on PTLs.

III. Design of Modular End-effectors

As aforementioned, the three maintenance tasks are quite different, and thus require different manipulation to be performed. Since it is not necessary to conduct these simultaneously, there is no need for multiple arms or manipulators. In the robot system, the main and basic motion is performed by one manipulator, whereas the fine manipulation should be executed by different end-effectors, according to the different maintenance processes.

A. Torque Socket Spanner

Regarding screwing or unscrewing nuts of vibration dampers or current deflectors, the major task is to screw the nut, either to loosen or to fasten it. According to common practice, one usually uses a wrench to screw a nut, which requires a large enough space for it to sway. However, it is vast difficulty for a manipulator to achieve such large-scale motion, as well as to align the wrench with the nut (Fig. 3(b)). For these reasons, if a socket spanner installed at the end of the manipulator, the manipulator merely needs to adjustment of posture in a small range so that the spanner align with the nut. And the nut will be loosen or fasten as the rotating motion is performed by socket spanner (Fig. 3(a)).

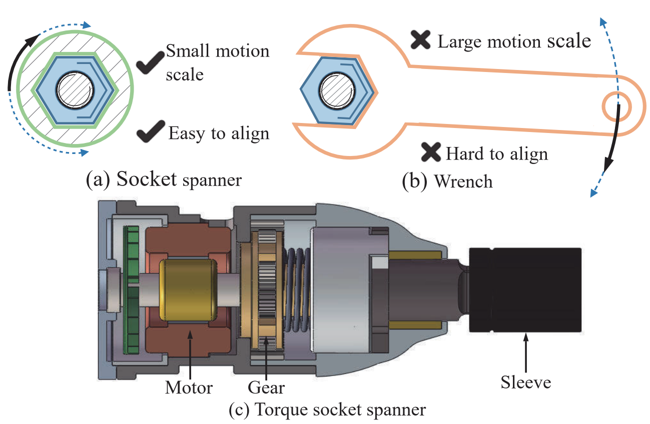


Fig. 3. Nut screwing schematic diagram.

Based on former consideration, a special end-effector module for screwing nut is designed, as shown in Fig. 3(c). The end-effector of the torque socket spanner has a weight of 1.35Kg, producing output torque that can be regulated by the control system. Especially, the sleeve is designed to match the nut size, mounted at the end of the device.

B. Electric Brush

In order to separate two contact deflectors, one sharp tip is usually used, as shown in Fig. 4(a). Once the sharp tip is aligned with the gap, between the two deflectors, the brush can be inserted into the gap by force (Fig. 4(b)). The contacting surfaces of two deflectors can be cleared by the compound motion of brush, it consists of rotational motion around itself and linear motion along the deflectors (Fig. 4(c)).

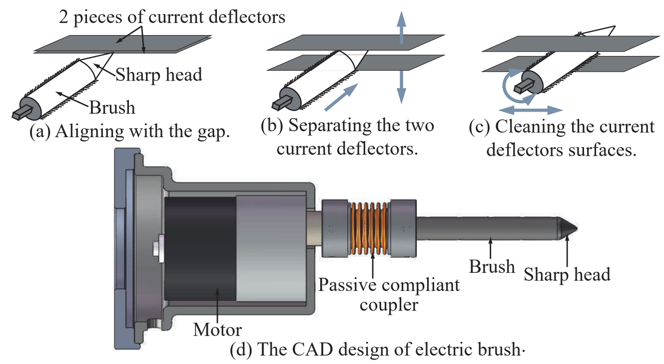


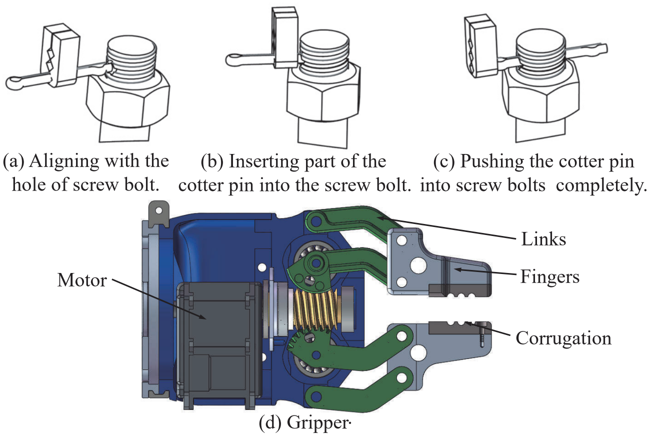
Fig. 4. Current deflectors cleaning schematic diagram.

For cleaning the current deflectors, an electric brush has been designed, it mainly includes a motor with reducer, a passive compliant couple and a brush with a sharp head in the end, as show in Fig. 4(d). The brush has a sharp head tip, so that it can easily insert between the two current deflectors. In addition, the brush body has a passive compliance coupler, so that it can adapt to any unexpected motion undulation. Motion undulation caused by the manipulator is inevitable during the brushing process. As the electric brush is rotating and translating, the current deflector surfaces will be cleared.

C. Gripper

In term of assembling the cotter pin into the screw bolt, it can not be inserted into a corresponding hole of screw bolt directly while it is in a state of freedom. So an important process is to grasp the cotter pin make sure two pins of the cotter pin have contact with each other. For the above reason, two fingers with grooves structure are designed, and the cotter pin can be grasp in the groove regardless of position, as shown in Fig. 5(a). Next, part of the cotter pin can be inserted into the hole when it is aligned with the hole on the bolt (Fig. 5(b)). Following, a strong push will be applied on the head of the pin until it is completely inserted, as shown in Fig. 5(c).

Based on the above analysis, the gripper is presented with two well-designed fingers, which can be opened or closed



(a) Aligning with the hole of screw bolt. (b) Inserting part of the cotter pin into the screw bolt. (c) Pushing the cotter pin into screw bolts completely.

(d) Gripper

Fig. 5. A schematic diagram for assembling cotter pin into screw bolt.

TABLE I
SPECIFICATIONS OF THREE END-EFFECTORS.

Types of end-effector	Torque socket spanner	Electric brush	Gripper
Weight (Kg)	1.35	0.5	1.15
Control signal (1 0)	Tighten	Forward	Open
Control signal (0 1)	Unscrew	Reversal	Close
Control signal (1 1)	Stop	Stop	Stop

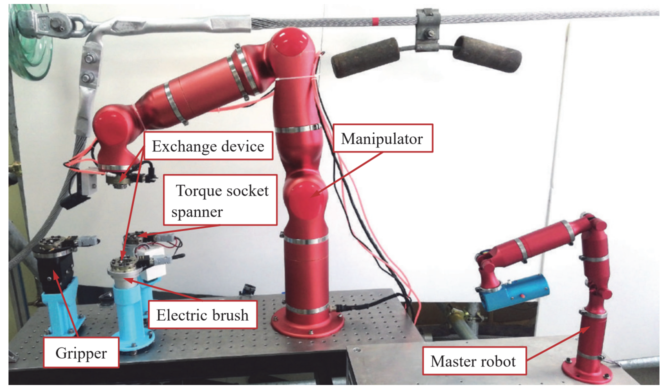


Fig. 6. The mock-up environment and the robot system for multiple-maintenance tasks on PTLs.

TABLE II
SPECIFICATIONS OF FOUR JOINT MODULES.

Types of joint	T100	T85	I100	I85
Workspace (°)	± 120	± 120	± 360	± 360
Output torque (Nm)	65	25	65	25
Weight (Kg)	2.6	1.8	2.5	1.4
Height(mm)	240	214	164	150

in parallel due to adopting a parallel four-bar mechanism. In addition, the gripper has the ability of self-locking, because of its worm gear and worm deceleration mechanism. The special tool is shown in Fig. 5(d).

The three aforementioned maintenance processes can be accomplished, using the above specialized end-effectors. In addition, each specialized end-effector is an electromechanical module, with the same power (24VDC) and control signal interface, whose detailed parameters (Control signals 0 and 1 represent low and high level, respectively) are listed in Table I. It is easy for the manipulator to control the three end-effectors, according to the specified protocols.

IV. DEVELOPMENT OF THE ROBOT SYSTEM

In high-rise maintenance tasks, a heavy system is difficult to be lifted up to PTLs and it will also add additional burden to the PTLs. Therefore, a light-weight manipulator is must employed in the system, and the configuration and degree of freedom of the manipulator are adjustable through using modularity method [13]. The manipulator can be controlled by the master robot and it can connect three specialized end-effectors respectively by the tool exchange device, as shown in Fig. 6, and a detailed description of the system will be presented next.

A. Modular Manipulator

According to the modularity method, the manipulator consists of two types of joint modules, which are T-type module and I-type module. The rotation joint axis and link axes of I-type joints are collinear, while those of T-type joints are perpendicular. Each type of joint module has two models of different sizes. Hence, we have four types of joint modules, which are T100, T85, I100 and I85. The numbers 100 and 85 refer to the diameters of the modules. More parameters can be found in Table II. Each module is an independent and complete mechatronic system, with unified embedded mechanical and electrical interfaces for connection.

According to the requirements of maintenance tasks, a 5-DoF manipulator is assembled using five joint modules. The modules are all connected one by one in serial mode with circular clamps, according to the following structure configuration: B100-I100$\perp$T100$\|$T100$\perp$I85$\perp$T85, where $\perp$ and $\|$ represent the perpendicularity and parallelism relationship between the two adjacent joint axes, respectively, while - means direct connection. Where, B100 is the base of the manipulator.

B. Master Robot

In order to control the manipulator to complete the maintenance task efficiently, we designed a miniature desk-top modular master robot, as shown in the right of Fig. 6. Similar to the manipulator, the master robot is assembled by Tmas and Imas joint modules, and auxiliary modules. With above manipulator and master robot, an isomorphic master-slave system can be built now. therefore, it is convenient, fast and efficient for workers to operate the master robot so that they can teleoperate the light-weight manipulator (slave robot) to fulfill maintenance tasks, and in this field we have some research [14].

C. Exchange Device

The manipulator needs to be able to connect three special end-effectors respectively for different maintenance tasks. A tool exchange device of OX-10B by ENIS is employed, as shown in Fig. 7. The device has a robot side and a tool side, it is controlled by air, realizing the engagement and disengagement of the two parts.

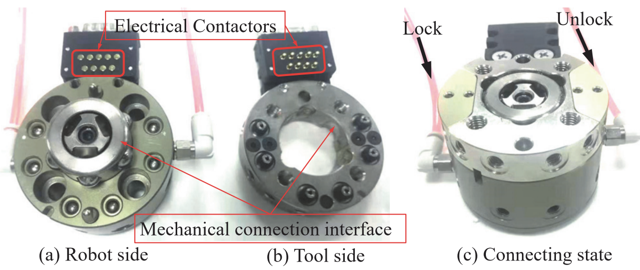


Fig. 7. Tool exchange device.

It is noted that, the permissible error of the axial deviation of the exchange device is 2 mm, the one of the radial deviation is 1 mm and the one of the angular deviation is 3 degrees. After robot side and tool side alignment, the connection is concluded, when 0.3Mpa air is inflated into the locking air port. At the same time, the connectors of power and control signals are coming into contact, as well as the mechanical parts become interlocked. Similarly, these will be separated rapidly, when air is inflated into the unlocking air port.

D. End-effectors

According to the design described in former section, three end-effectors are developed, as shown in Fig. 8. They are the torque socket spanner, the electric brush and the gripper, all containing an exchange device of tool side. In the torque socket spanner, the output screwing torque can be regulated by the controller. In the electric brush, the rotational velocity and torque need not be controlled online, it just needs to adjust to an appropriate value before working according to maintenance task. The transient control signal of the gripper is adequate for grasping cotter pin, since a mechanical interlocking is designed.

V. Experiments

To verify the reliability and performance of the robot system, several experiments were carried out. During the experiments, the manipulator connects or disconnects to end-effector by programming, but the manipulator with end-effector fulfills maintenance tasks by teleoperation.

- Adjusting vibration dampers

Fig. 9 illustrates the whole procedure of adjusting vibration dampers. In Fig. 9(a), the manipulator is going to connect

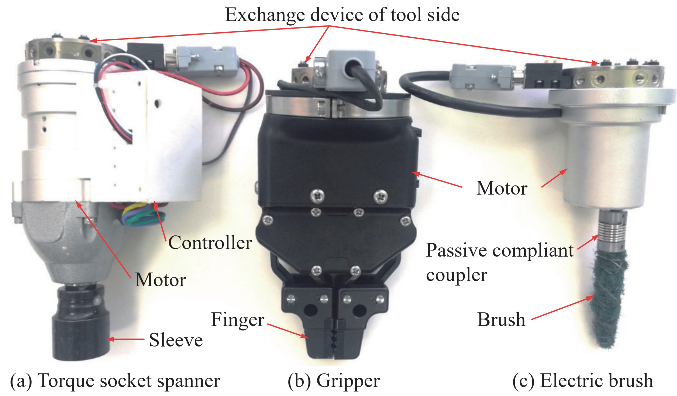


Fig. 8. End-effectors.

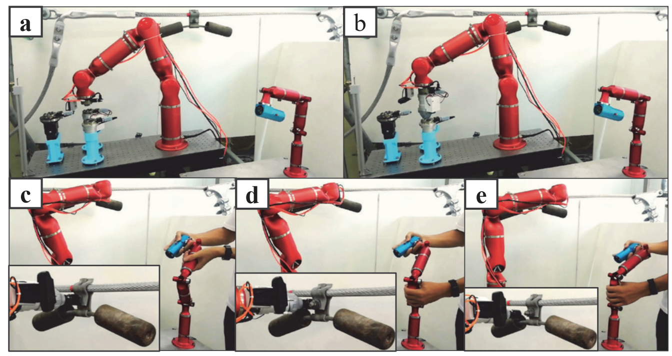


Fig. 9. Adjusting vibration dampers.

the torque socket spanner, while the successful engagement of such end-effector is shown in Fig. 9(b). Then the torque socket spanner loosens the nut, keeping the nuts at the end of the bolt, as needed (Fig. 9(c)-(d)), while the torque socket spanner pushes the vibration dampers to the target position. The last step effectively lock the nut and complete this maintenance task, as shown in Fig. 9(e).

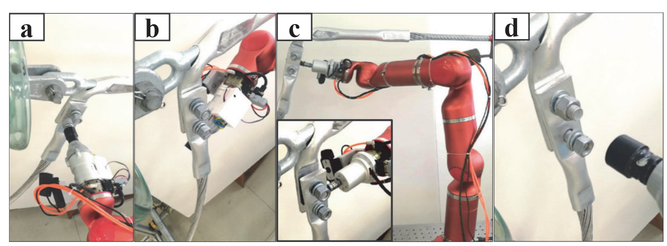


Fig. 10. Cleaning current deflector surfaces.

- Cleaning current deflector surfaces

In this task, the cleaning process is executed: in Fig. 10(a), the manipulator, with the torque socket spanner as end-effector, is loosening the two nuts of the current deflectors. And the torque socket spanner is controlled by the moving manipulator to separates two current deflectors so that there is a small gap between them (Fig. 10(b)). Next, changing to the electric brush, and it is inserted into the gap with the help of the sharp header head, as shown in Fig. 10(c). At the same time, the maintenance task of cleaning the current deflector surfaces is performed by the rotating and translating motions of the brush. After the cleaning is complete, the final step is fastening the nuts by using torque socket spanner, as shown in Fig. 10(d).

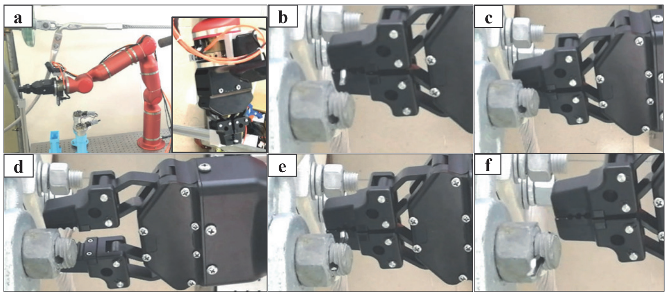


Fig. 11. Assembling cotter pin into screw bolts.

- Assembling cotter pin into screw bolt

Regarding the last maintenance task, the cotter pin was first mounted on a support near by the manipulator so that it is convenient for the gripper to grasp it. In Fig. 11(a), the gripper is grasp cotter pin automatically. Next, the closed cotter pin was moved towards the hole of screw bolt and inserted into the hole (Fig. 11 (b)-(c)). In Fig. 11(d), the fingers of the gripper opened and moved to the bottom of the pin, as the cotter pin still remained in the bolt hole due to its own elastic tension. Then, the fingers closed and pushed the cotter pin into the bolt hole entirely, as show in Fig. 11(e) and Fig. 11(f).

According to the above three experiments, the design of three end-effectors proved to be reliable, while the whole robot system showed high efficiency.

VI. Conclusion

To perform maintenance tasks on power transmission lines (PTLs), we have presented a solution with a robotic system replacing human being in this paper. Designed by modularity method, the robot system is composed of a light-weight 5-DoF manipulator and three end-effector modules for fulfilling the maintenance tasks, a tool exchange device, and a miniature desk-top modular master robot for teleoperation of the slave executing robot (the manipulator and the end-effectors) on site. The end-effectors are designed as modules with unified mechanical and electrical interfaces according to three maintenance processes, and they are able to controllably connect to the manipulator automatically by tool exchange device based on the target maintenance processes, like in a CNC machining center. The slave manipulator and the master robot themselves are also modular so that they can realize potential configurations for even more tasks. The system developed in this approach is flexible and adaptable to multiple tasks with relatively simple components and at a low cost. And three practical experiments were carried out, proving that the robot system is a reliable solution for high-rise maintenance tasks on power transmission lines.

In order to improve the automation and efficiency of this robot system, we will introduce vision and force/torque sensor to develop a semi-autonomous control system in the future. In such a system, the rough motion and positioning of the manipulator is controlled by the operator with the master robot under the video surveillance, and the fine positioning and manipulation will be fulfilled autonomously based on visual and force/torque sensing on-site.

References

[1] S. Montambault, J. Cote, and M. S. Louis, "Preliminary results on the development of a teleoperated compact trolley for live-line working," in *IEEE Esmo- IEEE International Conference on Transmission & Distribution Construction*, 2000.

[2] G. Wu, X. Hua, X. Xiao, Z. Huang, and Y. Li, "Transmission line inspection robot and deicing robot: Key technologies, prototypes and applications," in *International Conference on Applied Robotics for the Power Industry*, 2010.

[3] H. Nakamura, T. Shimada, and H. Kobayashi, "An inspection robot for feeder cables-snake like motion control," in *International Conference on Industrial Electronics*, 1992.

[4] S. Peungsungwal, B. Pungsiri, K. Chamnongthai, and M. Okuda, "Autonomous robot for a power transmission line inspection," in *IEEE International Symposium on Circuits & Systems*, 2001.

[5] M. Nakashima, K. Yano, Y. Maruyama, and H. Yakabe, "The hot line work robot system "phase ii" and its human-robot interface "mos"," in *Proceedings 1995 IEEE/RSJ International Conference on Intelligent Robots and Systems. Human Robot Interaction and Cooperative Robots*, vol. 2, 1995, pp. 116–123 vol.2.

[6] A. Santamaria, R. Aracil, A. Tuduri, P. Martinez, F. Val, L. F. Penin, M. Ferre, E. Pinto, and A. Barrientos, "Teleoperated robots for live power lines maintenance (robtet)," in *14th International Conference and Exhibition on Electricity Distribution. Part 1. Contributions (IEE Conf. Publ. No. 438)*, vol. 3, 1997, pp. 31/1–31/5 vol.3.

[7] N. Pouliot and S. Montambault, "Linescout technology: From inspection to robotic maintenance on live transmission power lines," in *2009 IEEE International Conference on Robotics and Automation*, 2009, pp. 1034–1040.

[8] N. Pouliot, P. L. Richard, and S. Montambault, "Linescout technology opens the way to robotic inspection and maintenance of high-voltage power lines," *IEEE Power & Energy Technology Systems Journal*, vol. 2, no. 1, pp. 1–11, 2015.

[9] W. Song, C. Wang, Q. Zhou, and B. Deng, "Design and validation of a novel robot for power lines inspection," in *IEEE International Conference on Information & Automation*, 2015.

[10] D. Elizondo, T. Gentile, H. Candia, and G. Bell, "Overview of robotic applications for energized transmission line work technologies, field projects and future developments," in *International Conference on Applied Robotics for the Power Industry*, 2010.

[11] W. Jiang, W. U. Gong-Ping, F. Fan, and J. Zhang, "Working manipulator motion optimization of live maintenance robot for high voltage transmission line," *Chinese Journal of Engineering*, 2016.

[12] S. Xiao, H. Wang, and L. Ling, "Research on a novel maintenance robot for power transmission lines," in *International Conference on Applied Robotics for the Power Industry*, 2016.

[13] Y. Guan, L. Jiang, X. Zhangy, H. Zhang, and X. Zhou, "Development of novel robots with modular methodology," in *2009 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2009, pp. 2385–2390.

[14] M. Su, Y. Guan, J. Hu, P. Wu, H. Zhu, X. Zhou, and H. Zhang, "Development and analysis of a bilateral control system for modular master-slave robots with p-p tracking capability," in *2013 IEEE International Conference on Mechatronics and Automation*, 2013, pp. 336–341.