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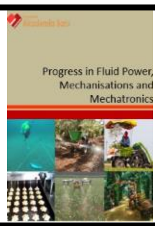

Advanced Field Robotics: Teleoperated Excavator System (TES)

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ABSTRACT

The progress of teleoperated excavators, related issues and the current development of the system is presented in this paper. Teleoperation of an excavator system has been associated with issues on control strategy, feedback displays, perception, latency and sustainability. Case studies on the teleoperated excavator system in Japan for post disaster recovery operation and various research developments in unmanned and teleoperated construction vehicles are also presented. The recent development in various disasters around the globe should enlighten the public and the government on the future direction in the advanced technology for post disaster management and risk analysis and reduction. High risk and dangerous post disaster recovery operation requires the use of heavy vehicle teleoperation. This paper also presents the current development of teleoperated excavator system for field robotic study in Universiti Teknikal Malaysia Melaka. The study deals with teleoperated electro-hydraulic actuator system or T-EHA for the teleoperation of a mini excavator system. The design, simulation and control aspects of the system is also presented.

Keywords:
Teleoperated Excavator System, Remote Control, Field Robotics.

1. Introduction

The use of unmanned or teleoperated heavy machineries for post disaster recovery operation are being discussed for the purpose of making an example of the research, development and the possibility practical application of such technology in Malaysia. Heavy machinery teleoperation technology is well established, with excellent examples, such as the use of teleoperation system for the building of a volcanic lava diversion dam and the removal of radioactive-contaminated debris in Japan by using a fleet of teleoperated construction machines [1]. Issues regarding the use of teleoperation are discussed, with regards to human-machine interaction. Practical application in Japan, and research and development of such technology around the globe is explained, with highlights on the teleoperated excavator research and development being conducted at Universiti Teknikal Malaysia Melaka.

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2. Control, Feedback and Perception Issues

The teleoperation of excavator system has been associated with issues on control strategy, feedback displays, perception, latency and sustainability. A very good teleoperation system is needed to make sure that human can work effectively in the extreme condition. The first issue regarding teleoperation in excavators is the various type of control approach. The oldest control methods are known as direct control or manual control, indicating that the operator is controlling the motion of the robot directly and without automation. The system also provides force feedback, auditory feedback, tactile feedback and even virtual and augmented reality for the operator. The manual control requires a lot of training, before the operator becomes familiar with the standard operating procedures of the system. This includes how the excavator responds to the given command and how the operator must respond to the feedbacks. Issues arise from operation with meticulous task can be tedious if carried out for long periods of time using manual control. On the contrary, control method known as the supervisory control [2], refers to the extent to which the teleoperated excavators can function independently of the human operator. It can be achieved if the remote computer, located at the inaccessible site acquires some part of the control function. The operator can thus provide task planning to the remote computer, which can execute the command to the manipulator.

The second issue regarding teleoperation is the feedback displays and human sensory perception. In general, humans are good at feedback perception and task planning, while machines are better at performing and handling complex and repeating tasks, which involve fast control response. During teleoperated excavation for dangerous post disaster application, the machine is designed to be a faithful slave to deal with a high-risk task while the human operator uses control interfaces to direct the excavator from a safe location. The interface, as shown in **Figure 1**, usually provides a means for sending position commands to the robot and providing various feedbacks, either in the form of visual, auditory and force feedback to the operator.

Fig. 1. Interface for nuclear disaster teleoperation. Note the use of gas mask on the teleoperator

The design goal of the interface is to provide the feeling of presence for the operator, so that the operator could simultaneously control and handle various operations. Therefore, the interface must be designed such that the operator can effectively receive the feedback while controlling the robot. Failure in perceiving the feedback may result in unwanted accident. A post disaster recovery operation in the aftermath of Fukushima nuclear power plant incident demonstrate an example of lack of tele-presence during an operation, whreby a small explosion had occurred due over grasped oxygen tank by a teleoperated excavator involved in the recovery operation [3]. The third obstacle in teleoperated excavator has been latency, which is the time delay between the operator commands to the excavator arms responding to those commands. Latency can be caused by network setup and the internet speed. It can also be classified as audio latency, computer operating system latency and even mechanical latency. A real-time teleoperation is the best possible way to counter the latency effect. Unfortunately, the latter approach is not easily achieved for long distance bilateral teleoperation. Supervisory control, with fully autonomous capability sometimes offers a way to counter the problem of time delay in teleoperation. For instance, the operator can select debris, such as bricks and specify the required tasks, such as grasping and removing the bricks. The information needed to operate on the specific debris is stored in a database or provided by the operator. The task is later conducted, with the system providing supervised control for the excavator [4]. Teleoperated excavator concept can be classified into master-slave system and master-subordinate-slave system. In general, master-slave system basically is a direct control over the machine, as shown **in Figure 2.** A master system is often a joystick that is driven by the operator. Slave system is the machine that is remotely controlled by the commands sent by the master. As the operator or the master command a movement, the slave or modified excavator will follow the commands. The system usually involves the use of modified, remotely controlled proportional directional control valve [5].

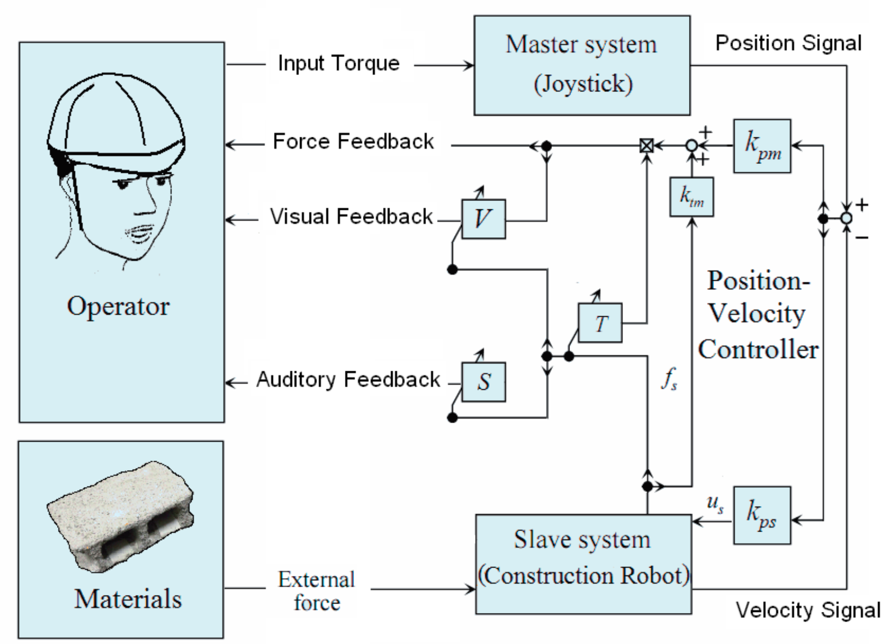

Fig. 2. Master-slave system with position-velocity controller

A master-subordinate-slave system works indirectly with respect to the previous concept. The system involves commands from the operator or master, which is received by a subordinated, in a form of a humanoid robot, or subordinate system. The subordinate system later commands the excavator, or the slave, on the operator's seat, by following the command given by the human operator. Both systems will affect issues on time delay, feedback and sensory perception. It will indeed influence the overall efficiency of the system. The final issue is on how to sustain teleoperation for a longer period. Sustainability is the ability to be used without being completely used up or destroyed, involving methods that do not completely use up or destroy natural resources and the ability to last or continue for a long time [6]. Teleoperation in the excavators and other heavy construction vehicles consume a lot of diesels. Unless hybrid or electric construction vehicle becomes familiar, the available option is only on the fossil fuels. Solar energy is another option to obtain sustainability in teleoperation, especially in the recharging process of the batteries. The use of water hydraulics as the sustainable power transmission medium can also be implemented, although still in limited applications [7-9].

3. A Case Study from Japan

Teleoperated constructions by excavators and backhoes have been carried out throughout Japan. The implementation of such technique due to the disaster caused by volcanic eruption gives birth to a new era of the teleoperated excavator system in Japan, as shown in Figure 3.

Fig. 3. Unmanned excavators in Sabo works

The rapid progress in teleoperated excavator technology and their use in disaster areas throughout Japan have been observed in the restoration works due to volcanic eruptions at the Mount Unzen in 1994 and the eruption of the Mount Usu in 2000, which marked the first large-scale teleoperated excavators for post disaster recovery works. In 1991, the Mount Unzen-Fugen volcanic eruption caused a lot of damages to the surrounding areas. The eruption causes large number of houses and amenities, such as a railway and roads to be seriously damaged by pyroclastic and debris flows. The material flowed down from the volcano, typically along the river channel and was frequently spotted during the rainy season of 1993, due to heavier rain. In 1994, the Government of Japan decided to implement a construction technique known as Sabo, which can dig and carry away safely the deposited sediment from the hazard area at risk of a pyroclastic flow. Sabo works is a Japanese construction technique that ensures safety from sediment-related disasters occurring in various forms in various places [10]. The Sabo works at the Mount Fugen was conducted using the teleoperated excavator system. It was remote-controlled by human operators. The operators received real-time video images, such as three-dimensional pictures, video images taken by the monitor cameras and other control pictures using a wireless system. The commands from the operators were transmitted through wireless links, with mobile communication relay system used to transmit the signals to each remote-controlled machine at a specific lower frequency. It was possible to control the construction equipment from hundreds of kilometres away by using a multiplex communication system [11]. Between March and April of 2000, the eruption of Mount Usu forced an evacuation of about 16000 residents. About 400 houses destroyed or damaged after the eruption. The teleoperated excavators were introduced to prevent the mud from flowing into the city and to minimize the damage from the eruptions [12]. In Mount Fugen case, the operation was conducted farther away from the previous experience, with challenging condition such as radio frequency interferences and bad visibility conditions, contributed by buildings, trees and harsh conditions. Unmanned operation had to be conducted from the city outskirts and many radio relay stations had to be used in between the operation room and the construction site. The radio interference in the area was overcome by the installation of multiple antenna towers. The latest use of teleoperated excavators in high scale disaster area were in 2011, when Tokyo Electric Power Company (TEPCO) began using remote-controlled, unmanned heavy equipment to remove debris from the Fukushima nuclear power plant, following the big Tohoku earthquake and tsunami. The teleoperated excavators were deployed into the site of the stricken power plant to help clear roads and passages of radioactive debris, as shown in Figure 4.

Fig. 4. Unmanned excavators at nuclear disaster area

The site was covered in radioactive rubble and debris, due to the earthquake, tsunami and two hydrogen explosions in reactor buildings, complicating the recovery process [13]. The deployed unmanned vehicles consisted of various construction machineries and each remotely controlled from various companies [14]. The entire operation was managed from a mobile control room, where operators could watch video from the cameras and manipulate the machineries. The clearance operation began when both units rolled into place near a debris-strewn area. The excavator, which had been fitted with a giant grapple, picked up debris and dropped it on the back of the dump truck.

Once full, the excavator knocked closed the lid of the container and the dump truck moved to a temporary dump site. The unloading operation took about an hour to complete and then the cycle began again [15]. Table 1 shows the technological transition of teleoperated excavators and unmanned construction vehicles in Japan.

Table 1
Technological transition of teleoperated excavators and unmanned construction vehicles in Japan [16]

	1991～1995	1996～2000	2001～2005	2006～2010	2011～2014
Kind of Work Contents of Work	Removal of Soils and Rocks (Earth Work)				
	Concrete Structures				
			Steel Slit Structures		Debris Removal /Decontamination
					Precast Concrete Structures
Wireless Technology	Specified Low Power Radio				
	Simplicity Radio				
			Wireless LAN		
					Optical Fiber Cable (Ultra Long Distance)
Autonomous, Robotic and Other Technologies		3.1. Remotely Controlled Robot (Robo Q)			3.4. Ultra Long Distances (Optical Fiber Cable,etc.)
			3.2. Rubber Artificial Muscle Robot	3.3. Autonomous Construction Machinery	
					3.5. Unmanned machinery for use in radioactive environments
					3.6. Monitoring (Bird's EyeView Images)
Major Disasters	･Large Scale Pyroclastic Flows from Mt.Unzen (Fugen) (1991) ･Great Hansin-Awaji Earthquake Disaster (1995)	･Volcanic Eruption of Mt.Usu in Hokkaido (2000) ･Volcanic Eruption of Miyake Island (2000)	･Niigata Chuetsu Earthquake (2004)	･Sichuan Inland Earthquake in China (2008) ･Iwate-Miyagi Nairiku Earthquake (2008)	･Great East Japan Earthquake (2011)

4. Research Development around the World

Teleoperated excavator, backhoe and dozers are gaining popularity around the world [17]. This section clarifies some of the practical contributions to the system. At the same time, some earlier theoretical and modelling studies are left out due to the limited resources, time frame conflict and language barriers. The development of a teleoperated excavator for military applications was presented in 1992, as shown in Figure 5. The research aimed at using the Tele-robotic Small Emplacement Excavator or TSSE excavator, to retrieve unexploded ordnance or radioactive waste. The system achieved the required tasks remotely with negligible productivity losses due to remote operation [18].

Fig. 5. Teleoperated excavator for unexploded explosives retrieval

Fig. 6. Haptic small backhoe

The concept of master-subordinate-slave tele-earthwork system, which replaced the human operator by using a teleoperation system known as RoboQ is introduced in 1994. RoboQ is basically a pneumatic powered master-subordinate-slave system, which has been successfully used in disaster struck area in Japan [19]. In another development, the use of an autonomous loading excavator system that is capable of loading trucks with soft material at the speed of expert human operators has been introduced in 1999. A supervisory control system identified the truck, measures the soil on the site and helped the excavator to modify both its digging and dumping plans based on settlement of soil [20]. In 2002, researchers from Georgia Institute of Technology had developed a haptic backhoe, as shown in Figure 6. The arm was attached with valves that was mounted with position sensors and controlled by the haptic interface. The haptic backhoe was able to detect underground obstacles and avoid unwanted damage afterwards. Although not equipped with remote-controlled ability, the system was able to reduce training time and enhance perception in digging accuracy [21]. In Japan, a joint venture of Kawasaki Heavy Industry, Advanced Industrial Science and Technology Institute and Tokyu Construction Advanced Institute had resulted in the development of master-slave system which used a humanoid robot to operate and control an excavator in 2003. A field test had demonstrated the humanoid robot's ability to replace the human operator in excavation duties on a backhoe. The humanoid robots were reported as capable of moving in the same manner as humans [22], [23]. The same master-subordinate-slave concept had been proposed by researchers from Tokyo Institute of Technology in between 2004 to 2008. They had developed a remote-controlled pneumatic rubber muscles robotic system that replace the human operator in controlling the excavator as shown in **Figure 7** [24],[25]. The teleoperation had increased working efficiency of more than 50% compared to the direct operation of the excavator.

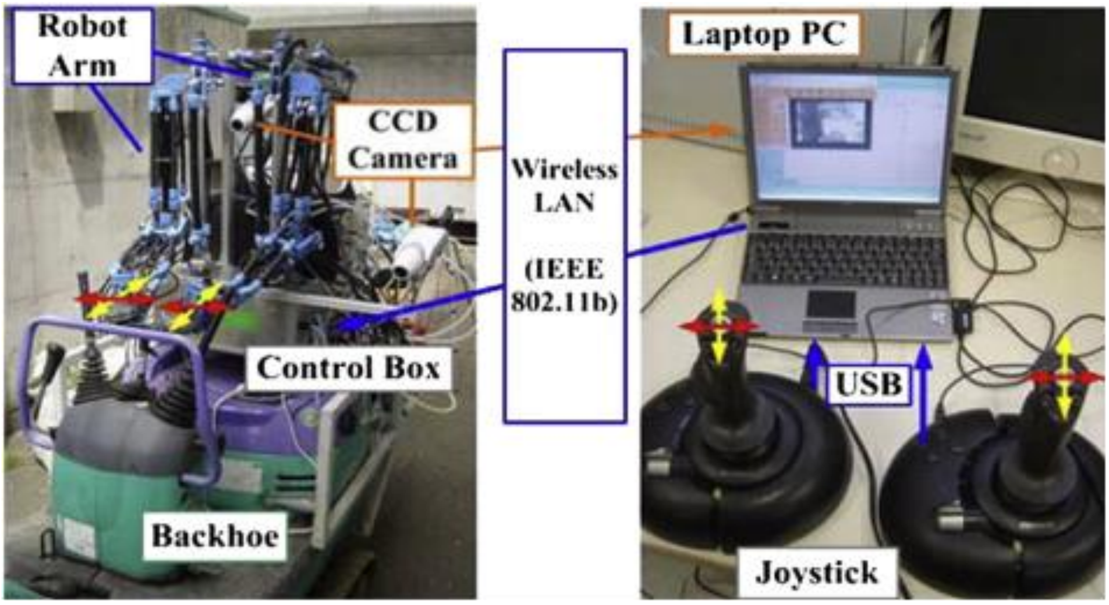

Fig. 7. Teleoperation using specialized robot arm on an excavator

Meanwhile, researchers from University of Tsukuba had focused on developing a test rig of an excavator for underwater applications in 2006 [26]. They had studied ways in visualizing 3-D images for underwater leveling works. A land-based test rig of underwater teleoperation excavator had been developed, as shown in Figure 8. The results of the research had been verified with the accuracy of leveling is sufficient for practical leveling work.

Fig. 8. Underwater teleoperated excavator

In South Korea, researchers from Universiti of Ulsan had developed a teleoperated excavator by using master-slave system, which is presented in 2008. The electro-proportional pressure valve was used as the slave, as well as advanced programming for controls [27]. In the same year, a concept of dual-arm double front construction machinery system had been introduced [28]. The system had two manipulators with a grasping mechanism, with 6 degrees of freedom, each including 5 single-rod hydraulic cylinders and one hydraulic motor. The research also involved the design of a simulator to provide the necessary learning technique to control the dual-arm excavator system, as shown in Figure 9.

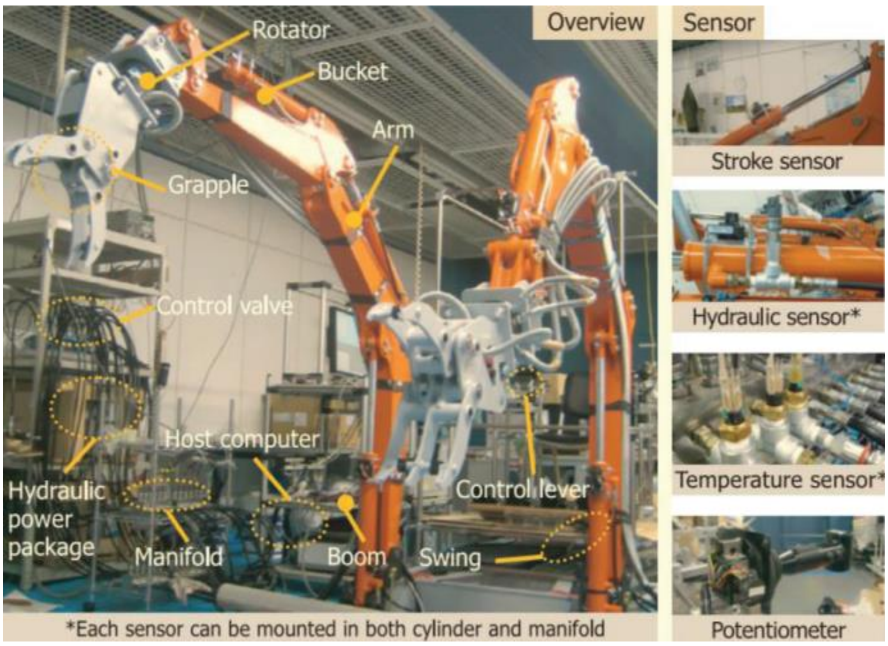

Fig. 9. Dual-arm excavator system

In the same year, researchers from Seoul National University had proposed an interesting proposal of using the movement of human arm that controlled the movement and manipulation operation of the excavator, as shown in Figure 10 [29].

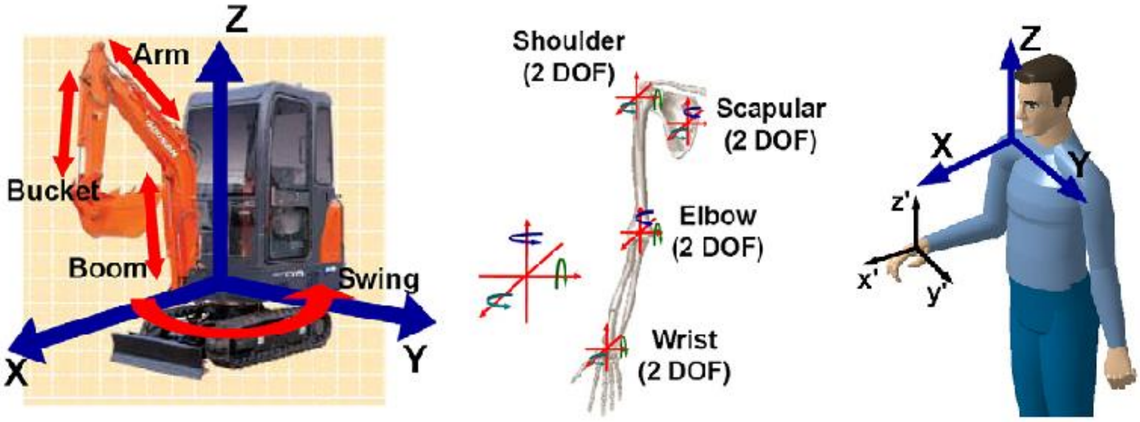

Fig. 10. Human arm-controlled excavator

In 2009, researchers from Doosan Institute of Technology had published a design of an intelligent excavating system by converting the traditional hydraulic system to an electro-hydraulic system [30]. The same concept was applied by Korea University's researchers, who had designed an intuitive haptic device for controlling an excavator, as shown in Figure 11 [31]. Meanwhile, various research on tele-grasping sensory perception of a grapple-attached excavator had been conducted in Gifu University whereby a force feedback joystick is used to operate the grapple, which significantly improved sensory perception of a slowly grasped soft object [32,33].

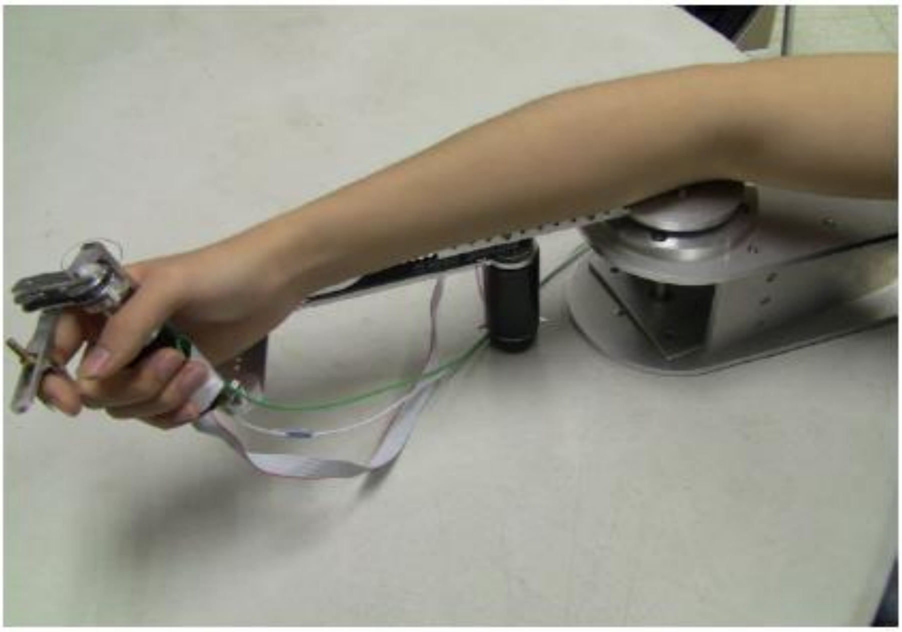

Fig. 11. Newly design haptic device for excavator

The research also includes sensory perception to various modalities, as shown in Figure 12, where the perception of the human operator was evaluated by using 2D, 3D and virtual visual feedback. Precision grasping was also being tested by using auditory feedback, along with force feedback [34-36]. In 2012, researchers from King Mongkut's University of Technology had evaluated the performance of a master-slave tele-controller unit using an excavator. Lab and field test had been conducted with satisfactory results, as shown in Figure 13 [37].

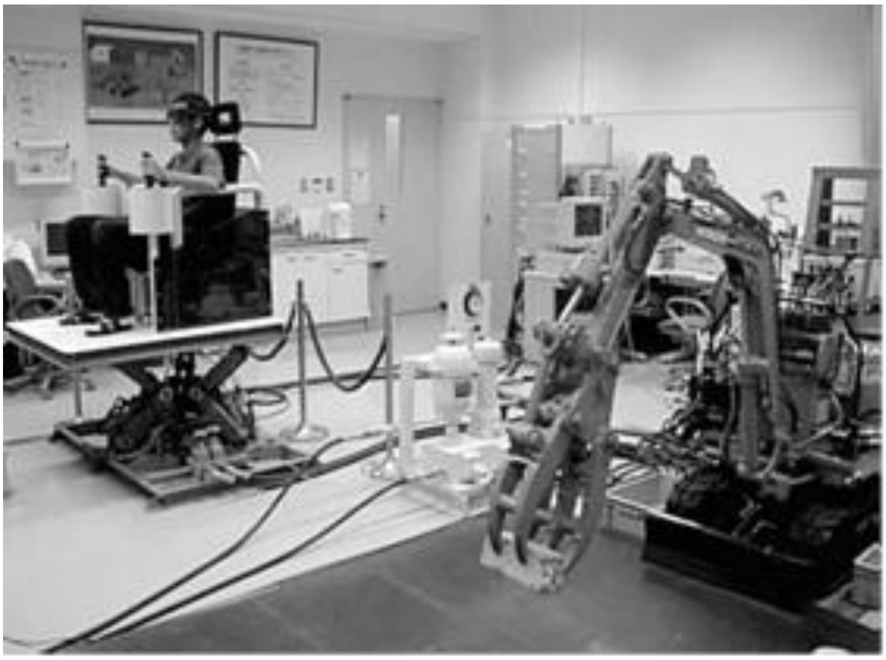

Fig. 12. Teleoperated excavator with tele-grasping performance at Gifu University

Fig. 13. Teleoperated excavator from King Mongkut's University of Technology

5. Research and Development in Malaysia

Researchers from Universiti Teknikal Malaysia Melaka had developed a specialized teleoperated electro-hydraulic actuator for teleoperation of a mini excavator system. The tele-robotic platform was developed by using a tie-rod cylinder and coupled with a 24 VDC electro-hydraulic valve, with a 2.4 GHz radio-controlled Arduino based transmitter and a receiver unit. The T-EHA system is designed so that it can be remotely controlled on any construction vehicles. The overall dimension for T-EHA is 464 mm x 88.5 mm x 200mm (base x width x height), as shown in Figure 14.

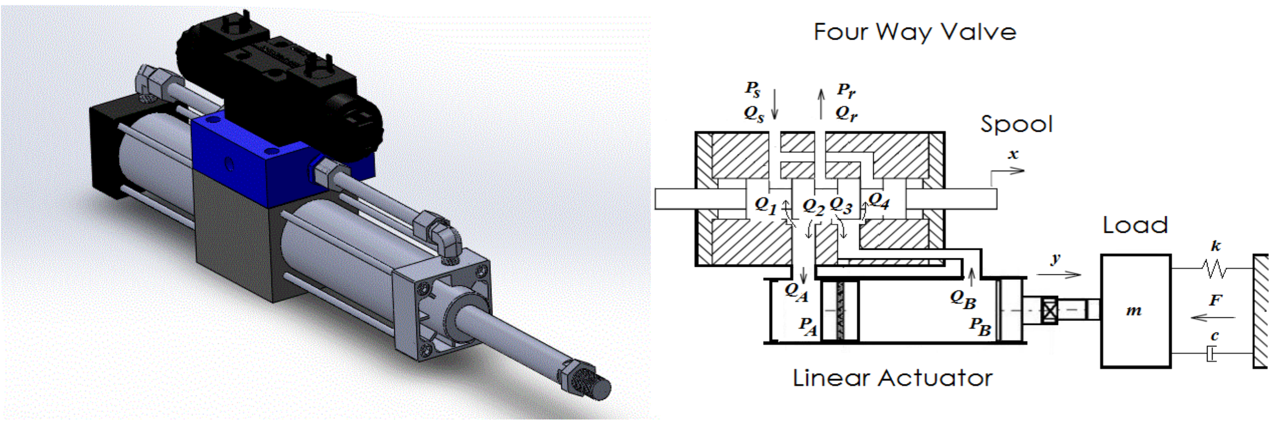

Fig. 14. Teleoperated Electro-hydraulic Actuator (T-EHA)

T-EHA is based on the single rod actuator, whereby the load is represented by the excavator lever, and is shown as a single mass-spring damper system, represented by mass, spring rate and viscous coefficient as *m*, *c* and *k* respectively. Figure 3 shows that P_A and P_B are the fluid pressures on the A and B sides of the actuator, respectively, and actuator force efficiency is represented by η_{af}. In this paper, the published simulation results of T-EHA is limited to the movement of mini excavator's boom, and the system is using position control system. The motion of T-EHA can be represented by [38].

$$m\ddot{y} + c\dot{y} + ky = \eta_{af}\left(A_A P_A - A_B P_B\right) - F - F_o \tag{1}$$

The equation shows the overall dynamics of the T-EHA, which is influenced by the design of the linear actuator and the spool valve. By neglecting the inertia and viscous damping, the final equation can be represented as follows:

$$ky = \eta_{af}\left(A_A + A_B\right)K_p x - F \tag{2}$$

The control law for the displacement of the valve can be written as,

$$x[v] = \begin{cases} 1 \quad (move), & if \quad v = 24 volt \\ 0 \quad (stop), & if \quad v < 24 volt \end{cases} \tag{3}$$

where v represents the input voltage on the T-EHA. The movement of the lever is influenced by the extension and retraction of T-EHA stroke, y. T-EHA stroke will manipulate the lever movement, and hence the spool, through a measured gain. By neglecting typical spring system, the equation can be represented as,

$$m\ddot{Y} + \left(c + \frac{A_A^{\ 2} + A_B^{\ 2}}{2K_c}\right)\dot{Y} = \eta_{af}\left(A_A + A_B\right)K_p X - F \tag{4}$$

The whole equation can be represented by the block diagram as shown in Figure 15 [39].

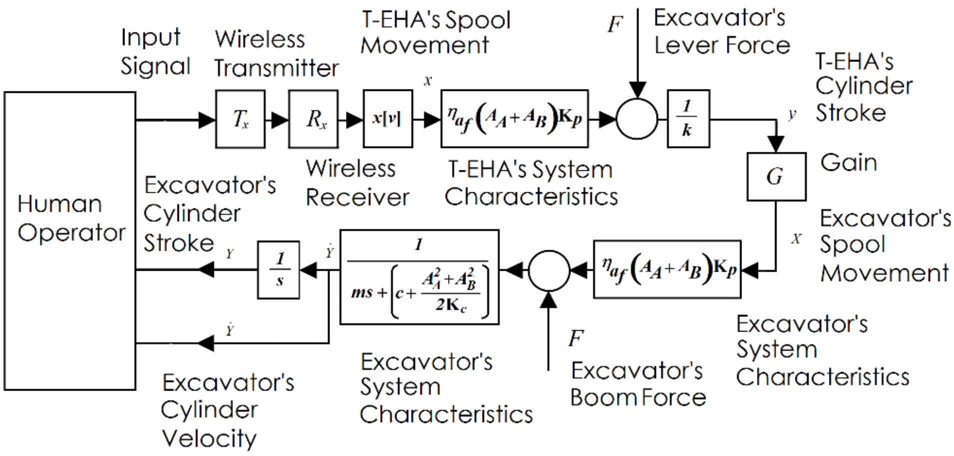

Fig. 15. Block Diagram of the System

According to the block diagram, the human operator will adjust the input signal accordingly, to control the boom's movement. Figure 16 and Figure 17 illustrates the mini excavator and the set-up of T-EHA arrangements for mini excavator teleoperation in laboratory test. T-EHA teleoperation has been tested by using an Arduino wireless transmitter and receiver system. The transmitter acts as the master system, which remotely control the T-EHA from a distance.

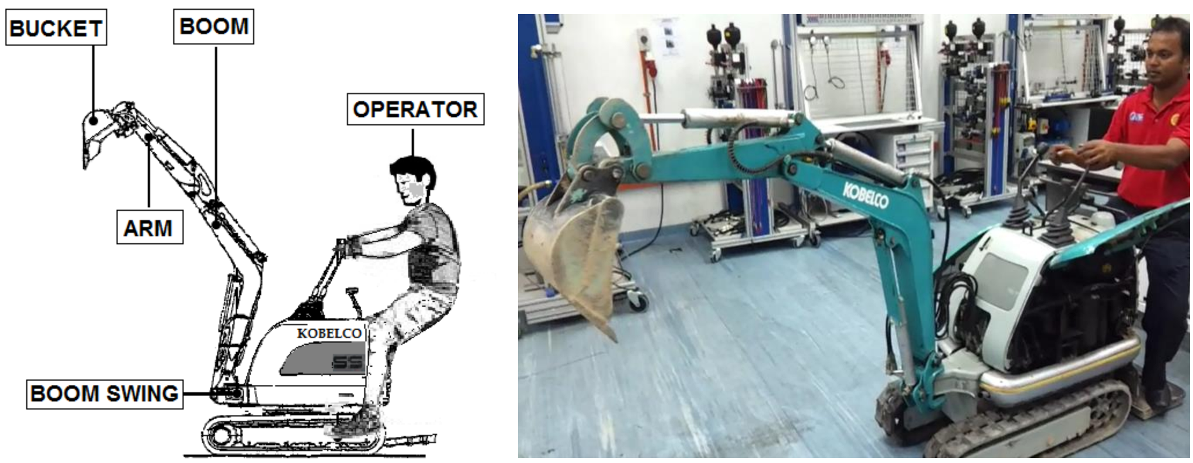

Fig. 16. Manually Operated Mini Excavator

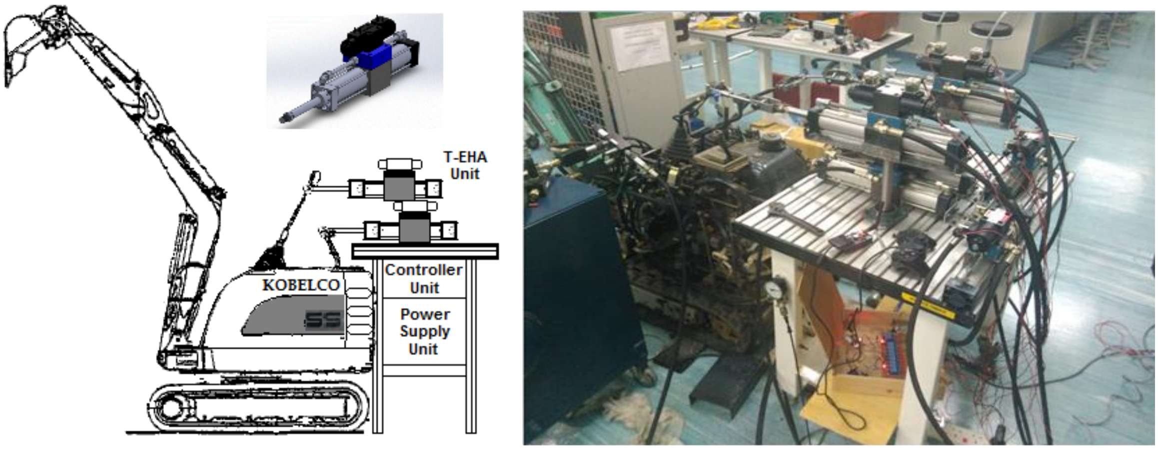

Fig. 17. Teleoperated Mini Excavator for Laboratory Test

Laboratory teleoperation of T-EHA on a mini excavator has been successfully conducted, as shown in Figure 18 and Figure 19. For the laboratory test, the signal is transmitted by using wireless PS2 Controller Starter Kit, or SKPSW transmitter where its command library is included in the Arduino Integrated Development Environment (IDE) programing software. The signal influences the actuation of T-EHA, and hence the movement of the excavator's boom. Simulation using MATLAB has also been conducted for the movement of the boom's cylinder based on the block diagram. The input signal is simulated, and tested by referring to the diagram. Figure 20 to Figure 24 show simulation results of the entire T-EHA and excavator's boom movement. In the simulation, the human operator provides the simulated input signal, which is created for the purpose of analyzing the simulated movement of the boom [39,40]. The pattern of the graph for T-EHA's cylinder stroke and excavator's spool movement is the same. Since the T-EHA's cylinder stroke influences the excavator control lever movements, the spool of the excavator's valve begins to slide when pushed by T-EHA's cylinder, and causes the excavator's boom cylinder to extend. The moment T-EHA's cylinder reaches maximum stroke, the flow rate of the T-EHA becomes zero, and the T-EHA cylinder maintain its maximum stroke for a certain duration. The same situation occurs for the motion of the excavator's boom cylinder. The influence of gravity is also noted when the boom is lifted, as shown in Figure 24.

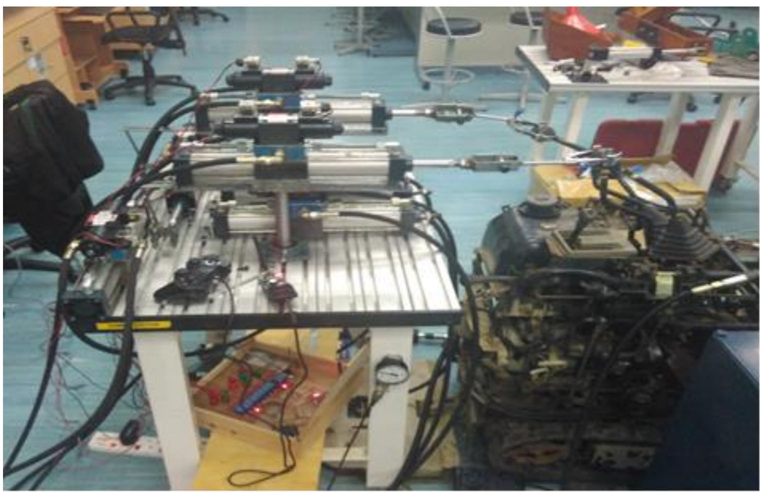

Fig. 18. Laboratory test on T-EHA

Fig. 19. Mini Excavator's Boom Movement Test

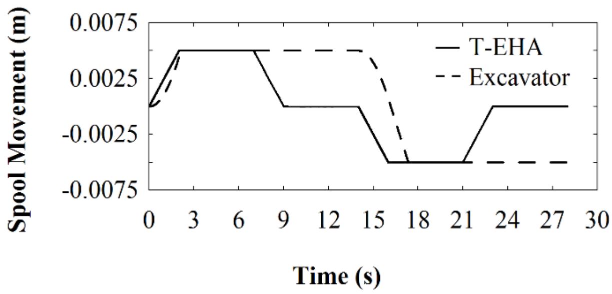

Fig. 20. Spool Movement on T-EHA and Excavator's Boom

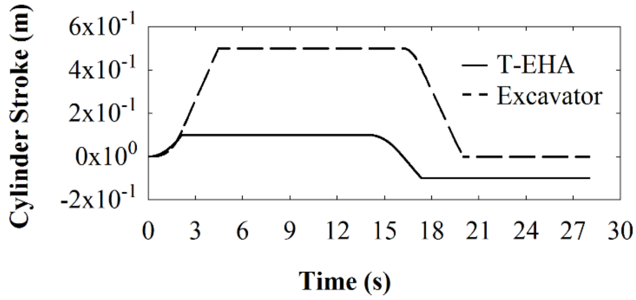

Fig. 21. Cylinder Stroke on T-EHA and Excavator's Boom

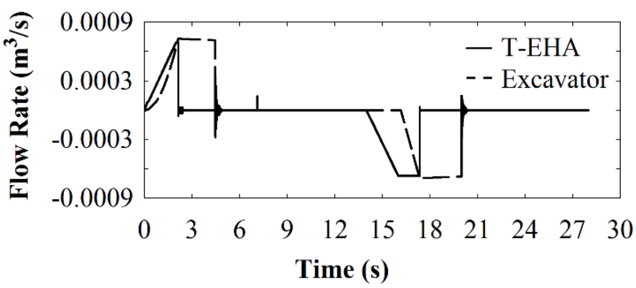

Fig. 22. Flow Rate on T-EHA and Excavator's Boom

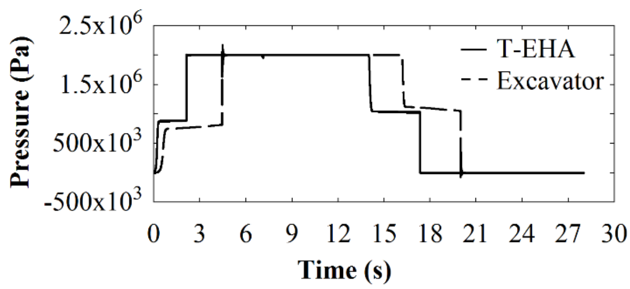

Fig. 23. Pressure on T-EHA and Excavator's Boom

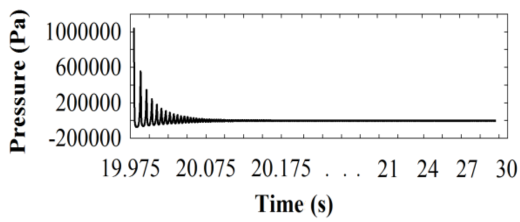

Fig. 24. Pressure fluctuation on excavator Boom's cylinder

7. Latest Trend in Teleoperated Excavator – Drone Support

This segment introduces the latest trend in teleoperated excavator technology, whereby the use drone is finally being integrated to support teleoperation purposes, as shown in Figure 25 and 26. In teleoperated excavator system, human operators always in direct control of the excavator.

Fig. 25. Teleoperated excavator with drone support

Fig. 26. Field test of the excavator with drone support

The use of drone-assisted operation by continuous visual feedback at any angle and condition will definitely bring satisfaction for an effective teleoperation. In Japan, researchers from the Impulsing Paradigm Challenge through Disruptive Technologies Program (ImPACT)'s Tough Robotics Challenge Program, which include Osaka, Tohoku, Kobe and University of Tokyo, with support from the Artificial Intelligence Research Center, National Institute of Advanced Industrial Science and Technology had developed and tested a construction robot for disaster relief in 2017 [41]. The visual display from the system has included the use of various imaging technology, which also include the use of a tethered drone which is linked to the teleoperated excavator. At the same time, research development from Gifu University had come out with the same idea of using a drone to help the human operator control a teleoperated excavator [42]. A lab test has been conducted in order to see the performance of the system that uses a viewpoint movement system that uses a drone to present a video from a proper viewpoint in relation to the work, as shown in Figure 27.

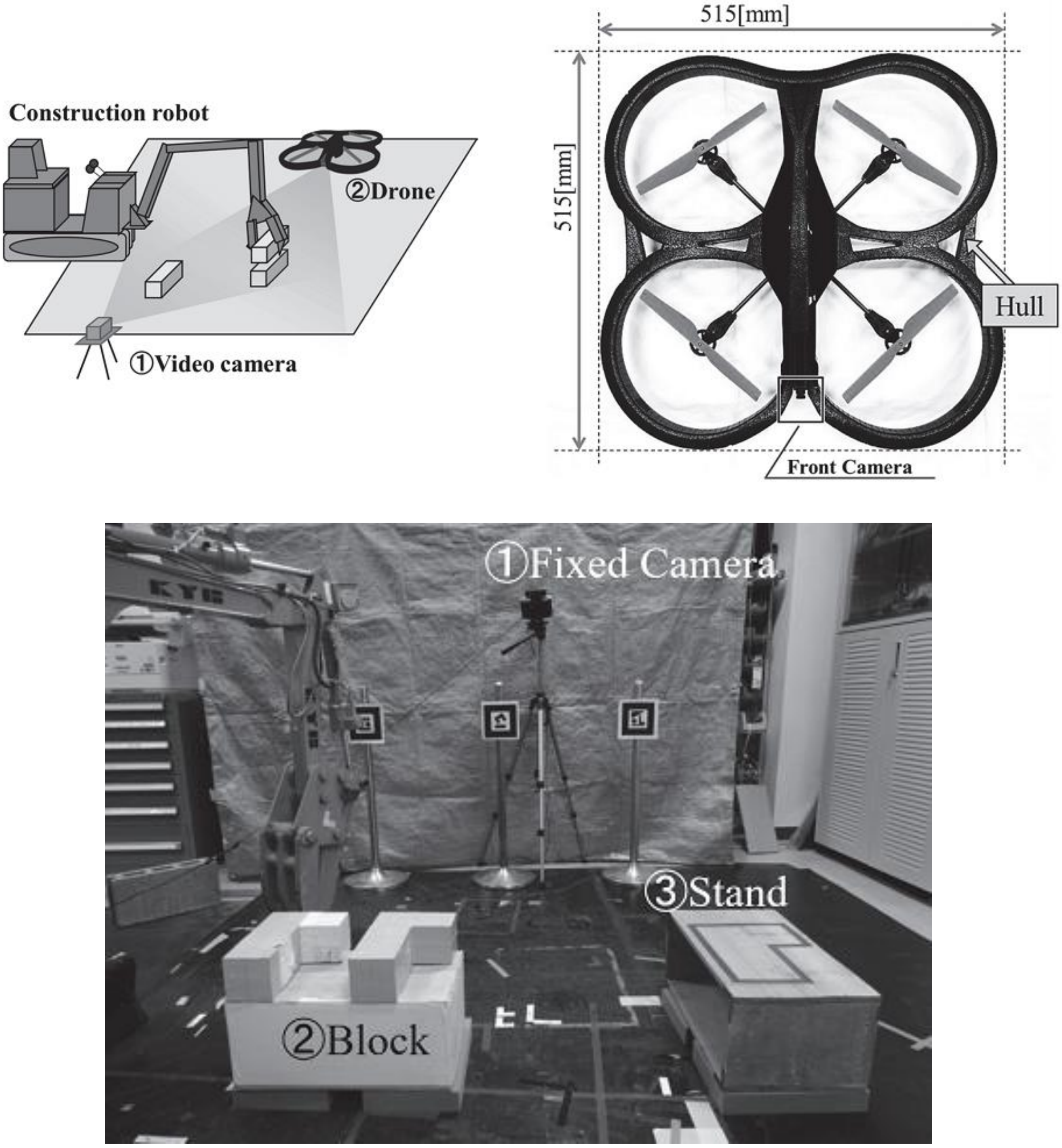

Fig. 27. Lab test of teleoperated excavator with drone support

8. Conclusions

High risk and dangerous post disaster recovery operation requires the use of heavy vehicle teleoperation. The progress of teleoperated excavators and related issues on control strategy, feedback displays, perception, latency and sustainability of the system has been presented in this paper. Teleoperation of excavator system has been associated with the post disaster recovery operation in Japan and various research developments in the unmanned and teleoperated construction vehicles worldwide. The recent development in various disasters around the globe should enlighten the public and the government on the future direction in the advanced technology for disaster risk reduction and post disaster management. The current development of teleoperated excavator system for field robotic study in Universiti Teknikal Malaysia Melaka has also being presented, which deals with the design, simulation and control aspects of the system. In the last section, the latest teleoperated excavator technology with drone support is also presented.

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