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Effectiveness of Spatial Coherent Remote Drive Experience with a Telexistence Backhoe for Construction Sites

Charith Lasantha Fernando† [1], MHD Yamen Saraiji[1], Yoshio Seishu[2], Nobuo Kuriu[2], Kouta Minamizawa[1], and Susumu Tachi[3]

[1]Graduate School of Media Design, Keio University, Japan
[2]Technical Development Section, Machinery Department, Obayashi Corporation, Japan
[3]Institute of Gerontology, The University of Tokyo, Japan

Abstract

In this paper, a spatial coherent remote driving system was designed and implemented to operate a telexistence backhoe over a wireless network. Accordingly, we developed a 6 degrees of Freedom (DOF) slave robot that can mimic the human upper body movement; a cockpit with motion tracking system and a Head Mounted Display (HMD) where the operator was provided with a HD720p ultra low latency video and audio feedback from the remote backhoe, and a controller to manipulate the remote backhoe. Spatial coherent driving could help manipulating heavy machinery without any prior training and perform operations as if they were operating the machinery locally. Moreover, construction work could be performed uninterrupted (24/7) by operators remotely log-in from all over the world. This paper describes the design requirements of developing the telexistence backhoe followed by several field experiments carried out to verify the effectiveness of spatial coherent remote driving experience in construction sites.

Categories and Subject Descriptors (according to ACM CCS): I.2.9 [Artificial Intelligence]: Robotics—Operator Interfaces

1. Introduction

Driving vehicles and heavy machinery remotely may allow human operators to perform actions at a distant location. There has been several [FTB03, FTB01b] teleoperation vehicle driving works for ordinary vehicles. However, in this paper we focus on teleoperation into construction heavy machinery so that the human operator could isolate from the construction site. This may result in the effectiveness where he could perform operations with safety, effectively and much efficiently compared to working on the physical site. Moreover, if the teleoperation task could be performed over Internet, construction work could be carried out uninterrupted (24/7) by operators remotely log-in from all over the world.

During the past three decades, the majority of research in vehicle teleoperation has centered on multi monitor telepresence systems [NFG89, KP00, McG88] where the operator is looking at the remote environment through multiple displays showing the video feed from multiple cameras placed on the remote site and the vehicle. More recent vehicle teleoperation systems have emphasized the use of multi-modal operator interfaces and supervisory control [FT01, FTB01a] where sensor fusion displays combine information from multiple sensors or data sources into a single, integrated view [Foy92]. These systems provide information through notifications at the navigation screen or Heads up display technologies (HUD). These modern navigation techniques may be useful for ordinary vehicles that uses sequential based manipulation approaches. However, it's not practical to use these on a real construction machinery where complex manipulations has to be performed simultaneously with safely and confidentially.

Similarly, there has been several works explaining the effectiveness of a humanoid robot to drive an industrial vehicle instead of a human operator [HNK*03, YNK*03] remotely. Human operator performs control lever manipulations and the tasks are applied into the remote vehicle via the humanoid robot who sits on the remote backhoe. Sim-

† charith@kmd.keio.ac.jp

ilar work has been done with only one pneumatic robotic arm system for controlling the levers of the industrial vehicle with a pneumatic rubber muscles (PARM) [SNK06, SK08]. CCD cameras were provided for remote vision. These systems provide technical capabilities of driving an industrial vehicle remotely, however, the visual flow and spatial coherent relationship between the remote side and local side has not been mapped. Offroad terrian driving requires to continuously look and confirm the surroundings as well as the front, rear and sides for any obstacles. Naturally humans tend to confirm these by looking at side and back mirror. However, cameras placed on the sides, outside the vehicle or in the field as 3rd person view would not give the same visual flow. Therefore, these systems does not allow the human operator to embody himself into the machine nor to feel the vehicle boundaries in a natural manner.

In order to address the above points, a 6 DOF robot system was placed in heavy construction machinery where the robot is synchronized with the operators upper body movements to produce human-like neck movements. The motion parallax 3D view receiving from the remote side is interactive and could be experienced via a fullHD head mounted display (HMD). The visual and kinesthetic correlation between the robot and the operator allows the operator to embody himself on the remote vehicle and experience motion parallax 3D imagery in a natural manner with a latency less than 200ms.

2. Spatial Coherent Remote Driving Experience

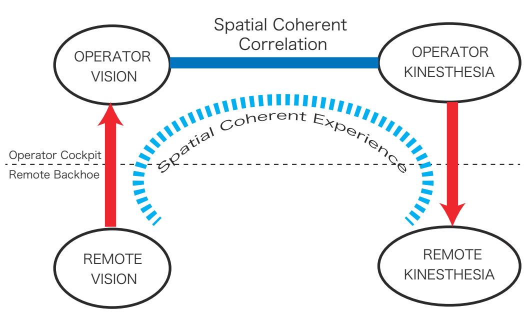

Figure 1: *Extending the Bodily Border towards remote Backhoe*

The “Bodily Border" in teleoperation can be explained as the awareness of body’s position and posture [HH11, VR09] at any given moment. These two functional elements used by humans to understand and perform actions with the awareness of a body’s position at any given moment. Humans also extend their bodily border to tools that they use. For example, after few hours of using a hammer, humans can naturally use it without thinking about targeting the correct position of the nail, how much force needed etc. Similarly in driving a vehicle, the driver usually can understand the vehicle boarders inside his brain. Sometimes, when a driver changes vehicles it takes few time to get used to the new vehicle border.

Telexistence enables a human experience spatial coherent mapping between the remote-local side and allow to have real-time sensation of being at a place other than where he actually exist, and to interact with the remote environment [Tac10, TMFF12]. These systems not only provide visual and auditory sensation, with the development of TELESAR master-slave robot system [TTKK85, TAM89, TAM90, TY94, TA97, TKIZ04] a combination of vision, auditory and kinesthetic sensation was achieved. A less complex and minimal telexistence system “TORSO” [WKK*07] provides human-like neck movements to visually interact and explore 3-dimensional details in a remote object in a more natural and comfortable manner.

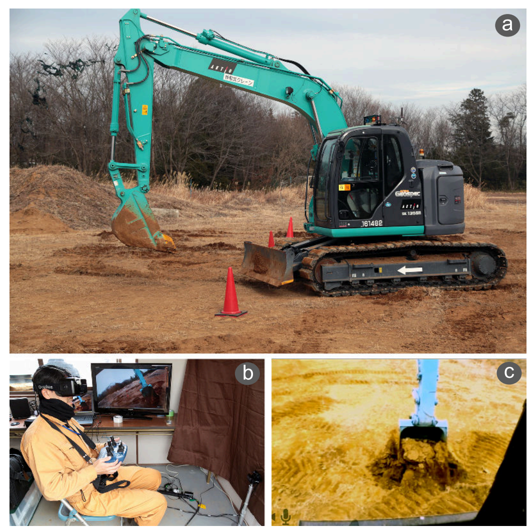

Figure 2: *System Description (a) Remote Backhoe, (b) Operator’s Cockpit, (c) HMD view*

This spatial coherent coordination explained in telexistence could be used to model a system that is capable of providing embodiment into the remote vehicle space. It is useful when doing complex tasks where they could perform multiple limb movements without concentrating and looking everything at once. As shown in Fig. 1, the user is supposed to see his own hands and arms at the same place that he would expect them to be. In case of this example, robot vision is transferred to the user and user kinesthesia is transferred to the robot.

In this system we achieve the spatial coherent correlation by capturing the stereo visuals from the backhoe and reconstruct on the operators cockpit with a head mounted display. When the operator changes the point of view (PoV), the remote side cameras has to capture on the same PoV. As shown in Fig. 2(a) a 6 DoF robot system is used to mount the camera head, where it follows the user movements synchronously.

If the operators hands could be modeled and functional as a robotic hand in the remote robot, he would see his own hands operating the levers inside the backhoe. However, this could be very complex and to maintain a very low latency manipulations, mechanical arms might not be the best option. Thus the operators hands were captured using a depth camera, segmented from the background and provided as an overlay to remote video feed. As shown in the Fig. 2(b) the operator wears a wide angle binocular head mounted display that has motion sensors to capture the position and orientation of the head. These data has been used to model the kinematics for driving the robot torso and head. With the above configuration, when operator moves around to see some specific thing around the vehicle, as shown in Fig. 2(c) the robot moves accordingly and provides spatial coherent visuals together with his own hands superimposed so that he could feel the presence inside the remote backhoe manipulating the levers. Furthermore, with the awareness of the body in vehicle space, the operator could understand the vehicle borders with respect to the surroundings.

3. System Implementation

3.1. Overview and Operator's Cockpit

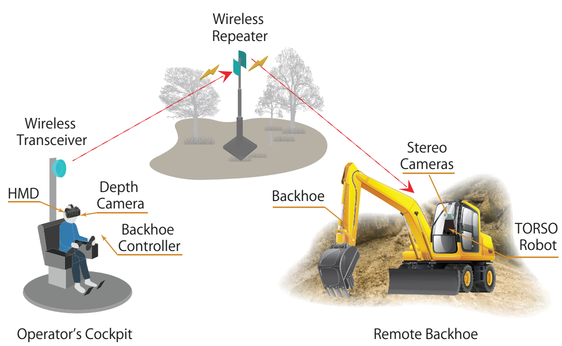

Figure 3: *Telexistence Remote Backhoe, System Overview*

As shown in Fig. 3 the system can be divided into 3 functional elements. A cockpit where the operator manipulates the remote backhoe, wireless data transmission/retransmission equipment and the slave telexistence backhoe. On the operator side, commercially available wide angle HMD (Model No: Oculus Rift DK2) is used to track the users head motion and provide processed video and audio data received from the remote telexistence backhoe. For mobility and manipulating the backhoe arm is controlled with the default backhoe remote controller. A depth camera placed on front side of HMD front captures the real time hands, controller and superimposed onto the remote video. A proprietary wireless transceiver operating at 2.4Ghz band was used to transfer the 3D video data as well as robot commands.

A radio controlled backhoe (Model No: Acera Geospec SK135SR-2) is used as the main carrier. It can remotely controlled for over a 2km distance with the default remote controller. A 6 DoF telexistence robot system is mounted on the backhoe's drivers seat adjusting to match the exact height of a typical operator.

3.2. Slave Robot System

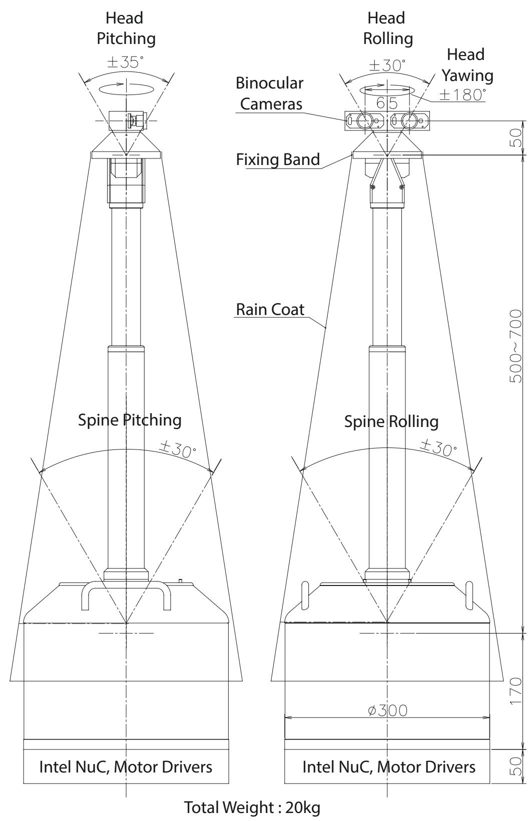

Figure 4: *CAD Drawings of 6 DoF Telexistence Robot*

Fig. 4 shows the 6 DOF telexistence slave robot used as the main component to design and implement the spatial coherent remote drive experience. The robot consists of 3 rotational DOF dexterity which acts as the neck, followed by 2 rotational DOF as hip and 1 translational DOF as the spine. The position and orientation of the operatorÕs head and upper body is captured from the HMD's tracking system and IP streamed to the remote site. On the robot side, received Cartesian space data is converted into the joint space with Inverse Kinematics and send to the PID controller to calculate the necessary parameters to drive the motors.

Two Full HD camera modules (Model No: Logitech C615) were used to create the stereo camera module required by the system. To match the Oculus interpupillary distance (IPD), two cameras were placed at a distance of 64mm each other. To match the field of view (FOV) of the Oculus, camera's stock lenses were replaced by wide conversion lens unit (Model No: MAGICA-WM) to archive a FOV of 100°. The camera lens unit is very light weight (320g) so that the dynamics of the human head could be maintained when installed in the 6 DOF robot.

For video grabbing, inverse kinematics and motor control algorithms, a board PC (Model No: IntelR NUC Board D54250WYB) is used. A PCIe to PCI bus expansion box (Model No: ECH-PCI-CE-H4B) is used to connect the D/A, A/D and Interrupt Counter boards that has been used in the robot. PCI expansion box connects to mini PC via a Mini-Card (mPCIe) to PCIe X1 bus adaptor (Model No: KZ-B26-030) The A/D and interrupt counter boards connects to the encoders and photo interrupters where as motor drivers connects to the D/A board.

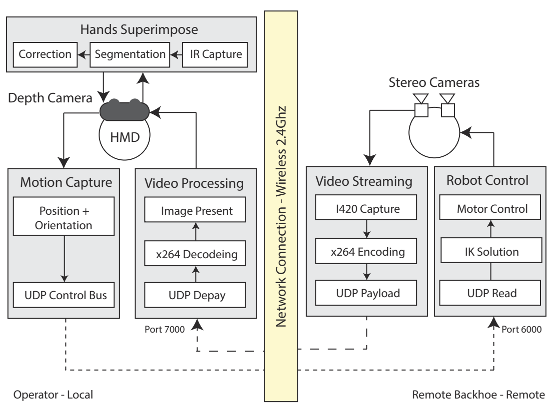

Figure 5: *Data Flow Diagram of Spatial Coherent Drive System*

Fig. 5 shows the data flow diagram of the spatial coherent drive system. Operators head position and orientation is captured from the Oculus DK2 camera, sent to the remote side via the UDP control bus. The received data is converted into joint space that used to drive the 6 DOF robot's motors. The robot moves according to the operator, and the stereo camera data was grabbed at 720p resolution at 60fps with I420 format. The frames were then H264 encoded and streamed with a UDP payload. On the operator's side the payload was demuxed, H264 decoded and images were further processed for lens distortion correction, color space correction, and finally applying oculus lens distortion. A depth camera (Model No: Leap Motion) is mounted on the front surface of the Oculus to capture the operator's hands and other selected devices such as controller. Captured IR data cloud is segmented, corrected and the hands were masked out from the other noise data.

With the above system, operator could experience motion parallax and binocular parallax 3D vision of the remote

Table 1: *Spatial Coherent Drive System Specifications*

	HMD	Cameras
Diagonal FOV [deg]	100°	100°
Aspect Ratio	16:9	16:9
Sensor [inch]	5.7 LCD	1/3 CMOS
Focal Length [mm]	50	$70 \sim \infty$
IPD [mm]	64	64
Body Weight [mg]	440	320
Resolution/eye [px]	960×1080	1280×720
Scan Rate [Hz]	60.00	60.00
Latency [ms]	20 or less	130 or less

backhoe where the 6 DOF robot (TORSO) mimics operator's upper-body motion.

Table. 1 lists the specifications of the entire system. The end-to-end network latency was calculated with a small experiment setup by placing the remote camera in front of the local PC screen. The PC generates a constant blinking Black and White display pattern and it has been captured through the remote camera and feedback to the same local PC. The Black and White pattern is synced on both sides via a cue flag that is being sent over the network. The time taken to travel the pattern is then calculated. Data was captured as 1s intervals, 30 repeats and averaged to get the delay. Same procedure was carried several times under different environmental conditions and it was found that the average latency is 160ms. Since the Oculus DK2 has 20ms latency from input to display on the screen, total delay was calculated as 180ms.

The latency and the picture quality plays a important role in delivering a smooth embodiment experience over telexistence. The minimum requirement for not getting simulator sickness and dizziness in virtual reality and telepresence has been found [NST*12, DGKT15] as latency less than 200ms. With the latency measurements it was found that the latency requirements for producing smooth virtual reality experience is satisfied.

4. Field Experiments

4.1. Experimental Procedure

The spatial coherent remote drive system with a telexistence backhoe was constructed successfully. It has been proved that the end-to-end latency was not an issue to embody the human operator onto the remote backhoe. However, these values are theoretical and far from reality. There are several psychophysical effects related to embodiment as well.

Therefore, to fully understand the capability of operating the backhoe remotely, a real drive test was conducted.

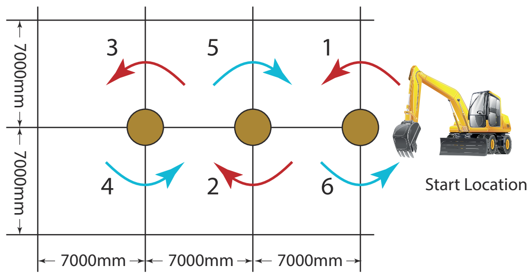

Figure 6: *7m long, 8 Shaped Drive Track Course*

As shown in Fig. 6 , a 8 shaped test drive route was decided to evaluate the telexistence backhoe remote driving experience. 3 red traffic cones were placed on the turning points to indicate the points. The center-to-center distance was kept at 7000mm which was the standard strict turning curve specification of the backhoe. Subjects were chosen from 3 different groups such as backhoe drivers, remote control backhoe drivers, and non-experienced drivers who does has training in backhoe driving, but does not practise in an everyday mannar. Furthermore, all the subjects belongs to one of the Japanese building construction machinery plant (Obayashi Coorporation)

As shown in Fig. 7, we conducted 2 experiments with the same procedure, but under different environmental conditions. Backhoe drivers and non-experienced drivers were given instructions on how to use the remote controller to move front, back, curve and turn manipulations. Remote controller backhoe drivers skipped this step. Arm manipulation was disabled on the remote controller except for the remote controller backhoe drivers. Once the remote control explanation was done, they were given HMD to wear, then the controller on their hand. They were asked to look straight front to initialize the local position and connected to the remote backhoe. Once connected, they could see as if they were inside the backhoe (Fig. 2(c)). Also, before moving to the start point, when they look down, they could see their own hands on the remote backhoe and holding the remote controller. Telexistence backhoe was parked few meters behind the start point. They were asked to move forward, and time taken to follow the entire course from start point, turn 1 - 6 and return to start point was measured.

The subject sits on a separate cockpit room, 10m behind the start point and the data communication was occurred through the dedicated wireless transceiver beamed by two collinear antennas one on the cockpit room and other on telexistence backhoe. The experiment coordinator stays behind the subject where he could see the remote backhoe in his vicinity and was instructed to act immediately and stop the backhoe if some emergency situation occurs.

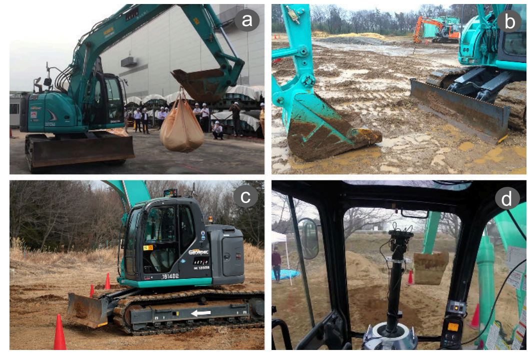

Figure 7: *Experimental Conditions of Telexistence Backhoe Remote Drive System*

4.2. Experiment I: Telexistence Backhoe Drive on a Tarmac

The first experiment was done at a machinery plant (Obayashi Coorporation, Tokyo Machinery Plant, Kawagoe, Japan) surrounded by many heavy industrial machinery and a tarmac. The experiment was carried out with remote backhoe operators (2), t'backhoe operators (3) non-experienced backhoe operators (35).

Before assembling the 6 DOF robot on the drivers seat, remote backhoe operators were given the same experimental conditions and the track course where they sit directly on the backhoe. The same subjects were asked to control the backhoe in the same track course with remote controller while looking at the backoe from outside. At this step the operators moved with the backhoe as they could not see the visuals from first person perspective. Next, they were given HMD and drive under completely remote. The time taken to complete each manipulation type was tabulated as shown in Table. 2. As can be seen, the remote control took almost 1.23 times than direct manipulation. However, the operators did not operate under fully remote manner. Therefore, operating with the spatially coherent remote system, drivers achieved an average time of 330sec.

Table 2: *Completion time of Direct, Remote Controlled, and Telexistence Backhoe Driving*

Manipulation Type	Duration	Performance Ratio
Direct	125sec	1
Remote Controller	154sec	1.23
Telexistence HMD	330sec	2.64

The telexistence backhoe was experienced by backhoe operators as well as non-experienced backhoe operators. With just understanding the remote control commands, almost everyone was able to complete the track course successfully without hitting the traffic cones. However, the time was not recorded because the comparison data could not be taken as they have less experience on driving the real backhoe.

Figure 8: *Picking up a Sand Sack and Placing on a Crosshair marked on tarmac*

Next, as shown in Fig. 8, the remote backhoe operators were further given instructions operate the backhoe arm. A sand sack (800mm diameter) was placed on the first turning point and was asked to pick it up at it's handle. They were able to successfully perform the operation without consuming much time compared to direct manipulation. They further mentioned that the situational awareness (ability to freely move on the remote backhoe cockpit) allow them to look at the surroundings, side mirrors so that they could build confidence. Also ability to determine the depth using the stereovision allowed them to understand the arm position correctly on the space that they were embodied. This let them to perform arm operations much faster than any other remote controlled backhoe manipulation.

4.3. Experiment II: Telexistence Backhoe Drive on a Muddy land

Next experiment was carried out in a muddy land (Public Works Research Institute, Tsukuba, Japan). Experiments were carried out for two days where the first day was sunny and the second day had heavy rains. The experiments were carried out with remote backhoe operators (3), backhoe operators (5) non-experienced backhoe operators (25).

The experiment procedure was exactly the same as the previous and course completion time was recorded. However, it was not compared due to uneven weather conditions through out the subjects. Everyone was able to complete the course successfully without hitting the traffic cones. The time taken was not significantly different compared to the first experiment. Once the experiment was finished, remote backhoe operators were asked to perform arm manipulations. As shown in Fig. 9, they were asked to dig the land and fill a close by place with the rubble. It was confirmed that the full operation of a backhoe was possible completely remote as well as under extreme weather conditions.

Figure 9: *Digging the land and filling*

5. Conclusion

We proposed a system that can operate and manipulate heavy machinery in construction sites remotely using a telexistence backhoe as if the operator is controlling the machine physically. In order satisfy the above condition, we designed and constructed a 6 DOF slave robot that can mimic the human upper body movement, a cockpit with motion tracking system and a head mounted display where the operator was provided with a HD720p ultra low latency audio/video feedback from the remote backhoe. Spatial coherent driving could help manipulating heavy machinery without any prior training and perform operations as if they were operating the machinery locally. In order to confirm the ability of performing remote construction work, several field experiments were carried out with remote backhoe, backhoe, and non-experienced backhoe operators. A track course was decided under 2 terrain conditions and the completion time of track course was compared with the different operator groups. It was confirmed that the telexistence backhoe system can perform the full operation of a backhoe including navigation and arm operations under various environmental conditions as if they were inside the backhoe. Moreover the low latency video transmission over IP network proved that the operator could embody himself onto the remote environment due to not getting simulator sickness or dizziness. Though the currently the backhoe was controlled on a distance of around 100m wireless without any retransmission the infrastructure supports to tele-operate the backhoe over long distance, within two countries or even two continents. This could enable the construction work to be performed uninterrupted (24/7) by operators remotely log-in from anywhere in the world.

Acknowledgement

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