The Development of a Telerobotic Rock Breaker

Elliot Duff, Con Caris, Adrian Bonchis, Ken Taylor, Chris Gunn, and Matt Adcock

Abstract. This paper describes the development of a tele-robotic rock breaker deployed at a mine over 1000kms from the remote operations centre. This distance introduces a number of technical and cognitive challenges to the design of the system, which have been addressed with the development of shared autonomy in the control system and a mixed reality user interface. A number of trials were conducted, culminating in a production field trial, which demonstrated that the system is safe, productive (sometimes faster) and integrates seamlessly with mine operations.

1 Introduction

A rockbreaker consists of a large serial link manipulator arm having 4 DOF that is fitted with a hydraulic hammer and used throughout the mining industry to break oversized rocks. CSIRO has been contracted by Rio Tinto Iron Ore to install a telerobotic control system to the primary rockbreaker at the West Angelas mine, situated over 1000km north-east of Perth in Western Australia. Figure 1a shows the rockbreaker installation at the ROM (Run of Mine) bin. The bin is fitted with horizontal bars at the bottom that prevent oversized rocks from entering the crusher below (see Figure 1b). This arrangement is commonly referred to as a grizzly. Haul trucks carrying ore from a nearby quarry dump their load into the ROM bin. Any oversize rocks in the bin are crushed using the rockbreaker arm. Until now, an operator has had to step out of a control room adjacent to the bin and use a line-of-sight remote control to operate the arm. The rock breaking strategy in this context is determined from a quick visual examination of the rock (i.e. centre hit to shatter the rock, nibble the sides of the rock, or nudge the rock to let it fall through). The available time is

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Fig. 1 Rock breaker (a) at rest over ROM bin (b) breaking a rock on grizzly.

limited by the level of ore in the hoper below the grizzly and the number of trucks queueing at the bin (typically less than a minute). If the rock cannot be broken in time, it must be pushed to the side and the arm returned to its rest position.

The objective of this project was to demonstrate the feasibility of effective and safe telerobotic control over long distances, as part of RioTinto's long term plan to tele-operate their mining operations. This distance introduces a number of technical (communications bandwidth and latency) and cognitive (lack of spatial and situational awareness) challenges that can be addressed by developing technologies at both the local and remote ends of the system. Improving the intelligence of the control system at the remote end (i.e. Cartesian motion, collision avoidance) can mitigate the effects of latency, whilst the development of mixed reality user interfaces (with a combination of live video and 3D computer visualization) can improve the situational awareness for the operator.

Mixed reality arises as a hybrid solution that attempts to overcome the weaknesses of the two extremes: **direct visualisation** of the environment by cameras and **synthetic visualisation** of a software model of the environment by computer graphics. Cameras provide a direct representation of the real world which includes all visible features, but typically only from a limited range of viewpoints. Virtual representations are very flexible with respect to viewing parameters and manipulation, but can only include information that is represented in the software model of the environment, and only to the limit of accuracy to which the dynamics of the real environment can be sensed. Thus, an interface that mixes the two paradigms for visualisation can take advantage of the best features of each, while overcoming some of the disadvantages. In practice, both paradigms provide situational awareness mediated by technology, and so are subject to failures of various sorts. Providing multiple streams of awareness incorporates a level of redundancy that protects against some failure modes.

This paper is divided as follows: Section 2 provides a brief background to tele-operation over the Internet and its applications to the mining domain; Section 3 describes the implementation of the tele-robotics system to a mining rock breaker in a production environmnet; Section 4 describes the results of the field trials; and Section 5, concludes with a discussion and proposal for future work.

2 Background

Tele-operation has been an active field of research and commercial activity for a number of years as it offers a means of isolating an operator from hazardous or uninhabitable environments while retaining the reasoning powers of the human operator. It has a long history, dating back over sixty years to a “master-slave” system[5]. Many systems have subsequently been developed for underwater, radioactive, volcanic, and outer space environments.

During the late 1990s there was a great deal of interest in tele-robotics applications over the Internet [7]. One of the first Web-based tele-operation projects[6] involved a mock-up of an archaeological site situated in a radioactive area. Users could join a queue to take control of a 2.5DOF manipulator, searching for ‘relics’. This work later evolved into a “tele-garden’” system in which users could remotely tend to a garden. To avoid latency induced instability both systems used supervisory control to specify a position in space[14]. Around the same time, researchers developed a Web-controllable, 6-axis robot that allowed operators to stack toy blocks by controlling the gripper and Cartesian position of the arm (again using supervisory control) [16]. This system was subsequently converted to a ‘tele-laboratory’ allowing students to perform parts of their coursework.

With respect to mining, Ballantyne et al. [1, 8] investigated the use of *virtual reality* displays for excavator tele-operation. The display enabled the operator to pre-set no-go areas for the excavator and to also mark areas of the excavation site in which the terrain was perhaps too dangerous for the excavator to navigate. Several Japanese groups have also been investigating tele-operation of mining and construction equipment [15, 10, 9]. Although research was conducted to develop a virtual reality system for the mining industry [2] this technology was never commercially realized. The reasons for this failure is unknown, but at this time, the technology was immature and probably did not provide the appropriate level of immersion and interaction necessary for control (i.e. due to latency and bandwidth issues).

Advances in our ability to develop autonomous systems have extended the possibilities for very high-level task specification, moving tele-operators from manual control to a role which is much more tactical or supervisory[12]. These layers of autonomy introduce different requirements for the human machine interface [4]. One of the main criticisms of tele-robotics is that it does not provide sufficient situational awareness [13] to the human operator to sustain the previous manual levels of production. This is being addressed by a number of research labs across the world (eg. NASA’s Robonaut) and has become a significant research activity within CSIRO.

3 Implementation

The rockbreaker system architecture (see Figure 2) is based around two main components : the Remote Control System (RCS) located at the West Angelas mine and the Telerobotic User Interface (TUI) more than 1000kms from the Remote Operations Centre (ROC) in Perth, Western Australia. The RCS includes:

- CANBus tilt sensors fitted to the boom, jib and hammer and absolute encoder fitted to the slew axis (see Figure 3b);
- two analogue PTZ cameras and a fixed wide angle camera mounted diagonally across ROM bin, connected to three high speed video compression units;
- two pairs of Firewire megapixel stereo cameras, mounted 80cm apart and several metres above the ROM bin (see Figure 3a);
- industrial Ethernet I/O to generate voltages to drive solenoids and measure state of hydraulic control pack;
- a safety PLC that monitors the access in the rockbreaker workspace, and actuates safety relays that provide power to the control unit;
- a Linux PC to run control software and an XP machine to run stereo acquistion software. Both machine were connected to the mine site Intranet.

The control software is based upon our DDX (Dynamic Data eXchange) middleware [3]. It is split into a number of specialized modules. At the top is a communications layer that provides a simple web interface to the controller, and UDP communications for outgoing state information and incoming demands. The advantage of UDP is that it provides the lowest communications latency (which is an important consideration in this application) at the expense of reliability. At the next layer is the **trajectory planner**, which accepts the incoming demands and plans the arms trajectory (i.e. it is able to convert Cartesian demands into a sequence of joint space velocity demands). Below this is the **boom controller** which has PID loops on four joints and is able to detect and alert the operator to the joint limits. At the bottom is the **boom server** which sends the control signal to the Ethernet IO, which in turn generates the control voltages for the proportional directional control valves

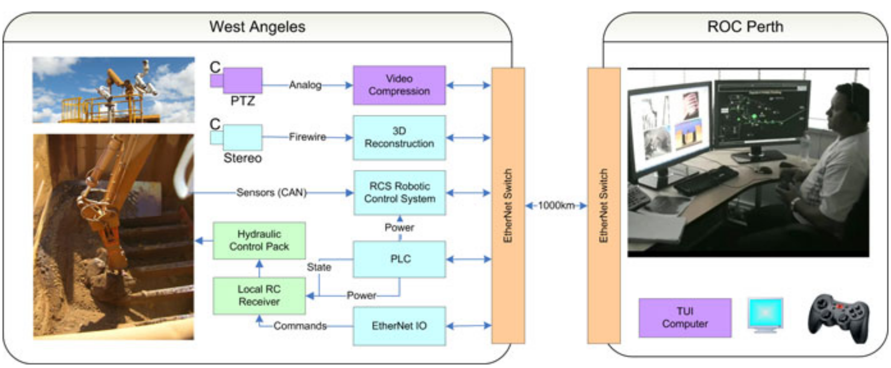

Fig. 2 System architecture showing components at the (a) remote and (b) local locations.

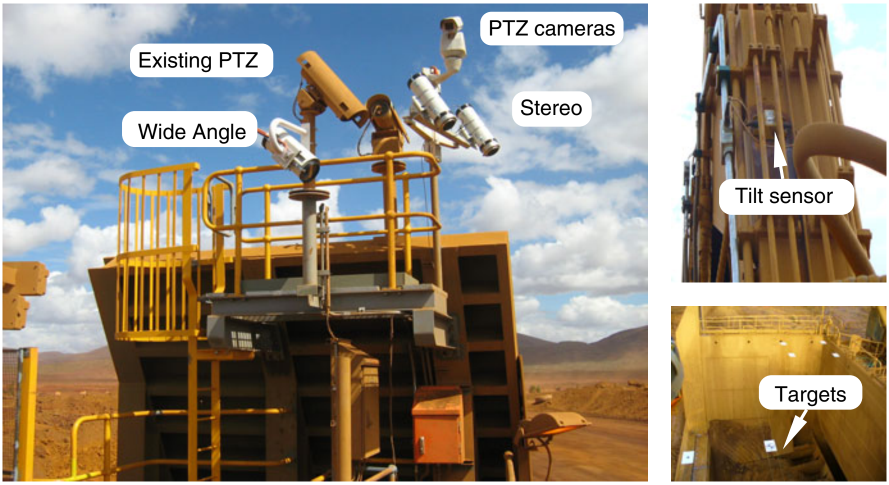

Fig. 3 Installed hardware: (a) cameras (b) tilt sensors and (c) calibration targets in ROM bin.

(solenoids) at the base of the rock breaker. These solenoids cannot be actuated by the computer without explicit control from the Safety PLC. Such control will not be given unless a number of fail-safe steps are taken, including; latching the access gates, a heartbeat from the control computer, and selecting "Computer Enable" in the control room. The Safety PLC also provides access into the site Citect system (which controls the crusher).

Particular care was taken to select hardware that could survive in the harsh mining environment. In summer, the ambient temperature can exceed 50 deg C, and drop below zero at night. The iron ore dust is particularly abrasive and can easily damage electronics. Since the arm dimensions were known, it was possible to use the estimated position of the hammer tip itself to measure the dimensions of the ROM bin (which were different from the mine plan). These dimensions were then used to place visual markers (see Figure 3c) in the ROM bin that were then used to calibrate the seven cameras. This meant that the arm, cameras and ROM bin were all measured in the same frame of reference. This frame of reference was used by the **collision detection** module (using openGL) to detect collisions between the model of the ROM bin and the arm.

Nodding lasers were initially proposed to acquire the 3D surface of the rocks in the ROM bin, but after discussions with the operators, we found that they rely heavily on the texture and colour of the rocks when deciding upon a breaking strategy. A second computer was used subsequently to acquire and process high resolution stereo images. A 3D surface was generated from advanced photogrammetry techniques (commercial product developed by CSIRO called Sirovison). To reduce the effects of stereo shadow a second pair of cameras was mounted diagonally across the ROM bin. To cope with the extreme lighting conditions (dark shadows across the bin in the morning and evening) contrast enhancement was achieved with exposures bracketing. In practice, the system is able to generate 3D surfaces with cm

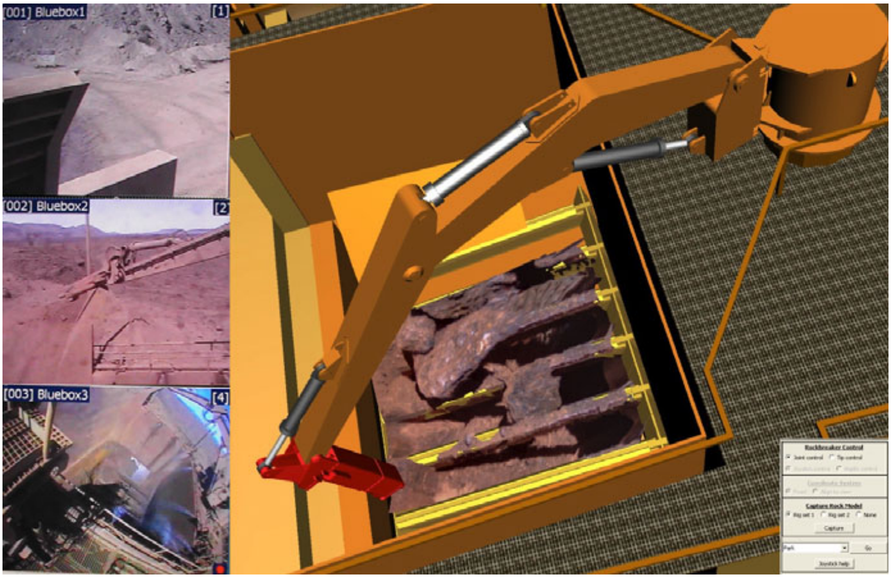

Fig. 4 Three video screens and augmented virtuality of rock breaker overlaid with 3D rock surface.

resolution. Once the 3D surface has been acquired it is converted to X3D and sent to the TUI for rendering onto the 3D virtual screen (see Figure 4). One future advantage of using this photogrammetry software is that it also has the ability to recognize joint sets and fracture surfaces - a valuable feature for future automation.

One of the shortcomings of the previous work has been the ad-hoc nature in which the user interfaces have been developed. Whilst components based robotics (such as Player/Stage, ORCA and Microsoft Robotic Studio) and Web-based toolboxes for LabView and Matlab have moved to the mainstream, the user interfaces have not provided the level of immersion necessary to provide sufficient situational awareness to control dangerous and expensive equipment in remote and unstructured environments. Some researchers have proposed a framework based upon gaming technology [11] which we have (i.e. using Second Life to control a simulation of the rock breaker) and will continue to look into (i.e. Unity). The proposed solution for this project has been to use AJAX3D which merges X3D and AJAX techniques. X3D is an ISO standard for real-time computer graphics that can be viewed with the appropriate viewer (eg. Flux from Mediamachines). Multimedia streams can be placed onto surfaces in the environment (e.g. video onto billboards). The X3D viewer can support audio, stereo displays and haptic devices. Being an open standard there are a number of CAD systems that are able to export drawings to X3D. With AJAX calls to the DOM (Document Object Module) or SAI (Scene Authoring Interface) it is possible to partially load parts of the scene (i.e. update the world) or reload features of the scene (i.e. a joint angle on the rock breaker).

A photograph of the TUI in operation at the ROC is shown in Figure 2b. In front of the operator there are two screens: on the right is the Citect system that is used to monitor the movement of the ore from the crusher down to the stacker/reclaimer; on the left is the user interface designed for the rock breaker control. It consists of the four windows (see Figure 4): three video screens and an augmented virtuality (a 3D computer graphics scene that includes some elements captured directly from the real world).[1] The operator is able to control the rock breaker with the mouse and the gaming joystick (Logitec RumblePad). Projected onto a screen above the two monitors are four video streams from various locations around the rock breaker: one to monitor approaching trucks and another to monitor the state of the secondary crusher. Speakers on either side of the screen reproduce the sounds made at the rock-breaker. This is a very important indicator of the state of the machine: the operator is able to hear the sirens that indicate that the machine is powered; and the sound of the hammer can also be used into indicate whether the hammer is making contact with the rocks (i.e. dry firing). Access to the mine communication systems (RF radio) is provided via a microphone/headset. With this the operator is able to inform the fleet management system of the availability of the crusher.

Once the user has established network communications with the RCS, most commands are accepted through the RumblePad. The right hand trigger button is used as a command validation switch (deadman). The movement of the arm being disabled when the switch is off. The left hand button over-rides the collision detection system to allow the operator to move the arm close to the ROM bin. This is typically used for the cleanup operations. When hydraulic pressure is requested, the RCS expects a heartbeat at 10Hz. The RCS will disable hydraulics after a specified number of heartbeats are missed (in this case, 20 heartbeats or 2 seconds).[2] In the TUI, the operator is able to select different modes of control. They can select in either velocity or position mode in joint, Cartesian or backhoe space (a combination of joint and Cartesian). The two joystick controls on either side of RumblePad are used to control the motion of the arm. The arm can also be sent to pre-configured set points (i.e. Home, Park etc.) or requested to move to a selected location on the 3D rock surface. The user interface is designed around the principal that there is only one primary view that determines the behaviour of the controls. For example, when the PTZ video is the primary display, then the arrow buttons (top left of the RumblePad) are able to pan and tilt the camera. However if the primary screen is the virtual screen, the arrow keys move you up and over the ROM bin (eg. jet-pack mode). The selection of primary screen is controlled by the numbered buttons.

[1] The system was designed so that the layout and size of the screens could be modified upon request. In the trial, rather than the original design of a primary screen with three thumbnails, the operator preferred four screens of equal size with minimal decoration.

[2] Measured over several days, the average round trip time was 56 milliseconds with a standard deviation of 3 milliseconds. On average, there were 3 pings per day that lasted more than 300 milliseconds. The video compression (IndigoVision) ranged in bandwidth from 339 Kbps to 1238Kbps at 25fps 4SIF. The state and demand UDP traffic consumed little bandwidth.

4 Field Trials

Field trials were conducted in mid December 2009. The trial consisted of three 12–hour shifts over 3 days during normal production runs. Two of the shifts started at 4am to allow for testing in night conditions. We used two operators, one at each end of the system. The operator based at the ROC in Perth had not been trained or introduced to the TUI prior to commencing the trials. A second operator was present in the control room at the mine site to supervise the rockbreaker operation and intervene in case of emergency.

During the field trials we were able to remotely replicate the work flow of the local human operator. When the operator is alerted to the presence of a large rock, the operator is presented with an overview of the rockbreaker from a wide-angle video stream and augmented virtuality (see Figure 4). The remote operator is able to "walk around the rockbreaker to inspect the rocks from different angles. Once they have established the appropriate breaking strategy, the operator is able to deploy the arm with the joystick. As the arm is commanded to move, the motion of the arm is replicated in the 3D scene. Simultaneously both PTZ cameras follow the tip of the hammer. When the operator is ready to break the rock, they can switch their attention to the live video stream, which they can use to monitor the breaking of the rock. Once complete, the arm can be automatically sent to the rest position.

Within half an hour of introducing him to the TUI, the operator based at the ROC in Perth, was breaking rocks. At first, the operator was unsure/sceptical of the game like controls, however after some experience with the new interface they were happy to accept the device. At the end of the trial the operator expressed the opinion that the deployment of the arm was faster for breaking "simple" rock configurations, but difficult to deal with complex rock configurations (where rocks are packed on top of one another). The operator made several useful suggestions for changes to the user interface that would address this problem (i.e faster 3D update of rock profile, and manual over ride of zoom control). Over the three days the operator was able to deal with all of the rocks without measurable disruption to production. However there were two safety incidents. In one case, there was a communications dropout, and in a second incident the operator moved the arm into the wall as a result of using a forth camera mounted on a hill over 200m away (this camera was not part of the rockbreaker system) and became confused with motion of the arm. At no time was any damage done to the arm or the ROM bin.

5 Discussion and Future Work

Perhaps the most significant comment made by the operator was when we asked what was the difference between local and remote operations. His reply was *"'In local operations, I can concentrate on the task at hand, and my peripheral senses deal with everything else. When I'm remote, I'm forced to redirect my attention to each screen/window that is front of me. This distracts me from what I am doing."* .

The current generation of control room used in the mining industry contains a number of custom built user interfaces: typically one for each mining process that needs to be monitored. To reduce the cognitive load of switching from one interface to another, we believe that the operator should be presented with a single interface. This interface should be highly immersive, interactive and reconfigurable.

The primary goal of our future work is the development and delivery of a **Mixed Reality Framework** that will provide a unified user interface for accessing and interacting with key areas of the mining operation. The intention of this work will not be to replace the existing remote control systems but to provide a portal to access various third-party systems via the Mixed Reality Framework. To use the web-browser metaphor, which is used to move from one web page to another, this system will provide a Mixed Reality Browser that will enable personnel to browse the state of various mining processes in a 3D context in conjunction with existing 2D interfaces.

In the context of teleoperation, "mixed reality" can be used to refer to interfaces that mix the different pathways to visualisation - direct visualisation via video and synthetic visualisation derived from a dynamic software model of the state of the world. Further, for this mixing to be effective, it must be based on information about the relationship between the pathways. In particular, the cameras themselves (and mobile camera platforms) must be modeled in some way, and the camera models may also be dynamically updated from sensor information. We refer to the combination of all these models, and the relationships between them, as the **composite situation model.** Several things need to be modelled in software as part of the process of situation representation. These models may exist on the same computer as the user interface, or they may be accessed from a centralised world model 'in the cloud'.

Situation awareness through visualisation is only one aspect of teleoperation. The actual operation and control of the remote machine must also be supported through the interface. A mixed reality interface creates opportunities for control paradigms based on direct selection and manipulation of objects within the interface. This includes real objects that have been visualised directly or synthetically, or virtual objects that have been added explicitly for the purpose of interaction. In each case, the same selection and manipulation techniques could be used. Just as a mixed reality interface incorporates a mixture of pathways for situation visualisation, it will also incorporate a mixture of operation pathways: direct operation (for example, the position of a joystick controls the degree of opening of a valve), and indirect or synthetic operation (for example, a virtual version of the arm is moved to a position, then commands are sent to move the real arm to that position). Mixed Reality Interaction represents a fertile area for investigation.

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References

1. Ballantyne, J., Wong, E.: A virtual environment display for teleoperated excavation. In: Proceedings of the IEEE International Conference on Intelligent Robots and Systems, Victoria, Canada, pp. 1894–1899 (1998)
2. Boulanger, P., Lapointe, J.F., Wong, W.: Virtualized reality: an application to open-pit mine monitoring. In: Archives of the 19th Congress of the International Society for Photogrammetry and Remote Sensing (ISPRS), Amsterdam, The Netherlands, vol. XXXIII, Part B5/1, pp. 92–98 (2000)
3. Corke, P., Sikka, P., Roberts, J., Duff, E.: DDX: A distributed architecture for robot control. In: Australian Conference on Robotics and Automation, Canberra, Australia (2004)
4. Duff, E., Usher, K., Taylor, K., Caris, C.: Web-based tele-robotics revisited. In: Proceedings of Australian Conference on Robotics and Automation, Brisbane, Australia (2007)
5. Goertz, R., Thompson, R.: Electronically controlled manipulator. Nucleonics 12(11), 46–47 (1954)
6. Goldberg, K., Mascha, M., Gentner, S., Rothenberg, N., Sutter, C., Wiegley, J.: Desktop teleoperation via the World Wide Web. In: Proceedings of the IEEE International Conference on Robotics and Automation, Japan, pp. 654–659 (1995)
7. Goldberg, K., Siegwart, R.: Beyond Webcams An Introduction to Online Robots. MIT Press, Cambridge (2001)
8. Greenspan, M., Ballantyne, J., Lipsett, M.: Sticky and slippery collision avoidance for tele-excavation. In: Proceedings of the IEEE International Conference on Intelligent Robots and Systems, Grenoble, France, pp. 1666–1671 (1997)
9. Kosuge, K., Takeo, K., Ishida, H.: Teleoperation system of (sic) power shovel for subterranean line work. In: Proceedings of the 23rd International Conference on Industrial Electronics, Control and Instrumentation, pp. 1421–1426 (1997)
10. Minamoto, M., Matsunaga, K.: Tele-presence information and remote-controlled task execution. In: Proceedings of the IEEE International Conference on Intelligent Robots and Systems, Victoria, Canada, pp. 1102–1106 (1998)
11. Richer, J., Drury, J.L.: A video game-based framework for analyzing human-robot interaction: characterizing interface design in real-time interactive multimedia applications. In: HRI 2006: Proceeding of the 1st ACM SIGCHI/SIGART conference on Human-robot interaction, pp. 266–273. ACM Press, New York (2006), `http://doi.acm.org/10.1145/1121241.1121287`
12. Roberts, J.M., Duff, E.S., Corke, P.I.: Reactive navigation and opportunistic localization for autonomous underground mining vehicles. International Journal of Information Sciences 145(1-2), 127–146 (2002)
13. Sellner, B.P., Hiatt, L.M., Simmons, R., Singh, S.: Attaining situational awareness for sliding autonomy. In: HRI 2006: Proceeding of the 1st ACM SIGCHI/SIGART conference on Human-robot interaction, pp. 80–87. ACM, New York (2006), `http://doi.acm.org/10.1145/1121241.1121257`
14. Seward, D., Margrave, F., Sommerville, I., Morrey, R.: LUCIE the Robot Excavator - Design for System Safety. In: Proceedings of the IEEE International Conference on Robotics and Automation, Minneapolis, USA, pp. 963–968 (1996)
15. Taketsugu, H., Takashi, Y., Junichi, A., Masaki, I., Hiroaki, Y.: Experimental land model of tele-operated underwater backhoe with AR technology. In: Proceedings of the International Symposium on Underwater Technology, pp. 339–344 (2004)
16. Taylor, K., Trevelyan, J.: Australia's telerobot on the web. In: 26th International Symposium on Industrial Robotics (1995), `http://telerobot.mech.uwa.edu.au/Telerobot/`