PARAROVER

A Remote Controlled Vehicle with Omnidirectional Sensors

Simon Lok, Shree K. Nayar

February, 1999

CUCS-003-99

Department of Computer Science
Columbia University
New York, NY 10027, U.S.A.

lok@cs.columbia.edu
nayar@cs.columbia.edu

This work was supported in part by the VSAM effort of DARPA's Image Understanding Program and a MURI grant under ONR contract No. N00014-97-10553.

Contents

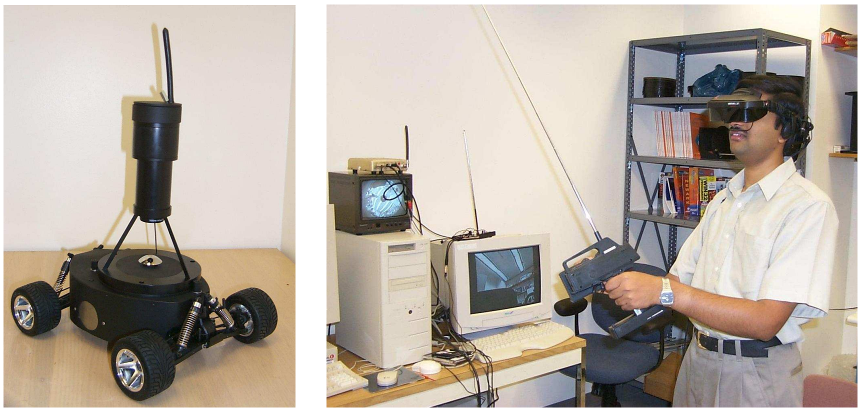
Abstract

The process of teleoperation can be described as allowing a remote user to control a vehicle by interpretting sensor information captured by the vehicle. One method that is frequently used to implement teleoperation is to provide the user with a real-time video display of a perspective camera mounted on the vehicle. This method limits the remote user to seeing the environment in which is vehicle is present through the fixed viewpoint with which the camera is mounted. Having a fixed viewpoint is extremely limiting and significantly impedes the ability of the remote user to properly navigate. One way to address this problem is to mount the perspective camera on a pan-tilt device. This is rarely done because it is expensive and introduces a significant increase in implementation complexity from both the mechanical and electrical point of view. With the advent of omnidirectional camera technology, there is now a second more attractive alternative. This paper describes the *PARAROVER* , a remote controlled vehicle constructed in the summer of 1998 to demonstrate the use of omnidirectional camera technology and a virtual reality display for vehicular teleoperation, audio-video surveillance and forward reconnaissance.

1 Motivation

The concept of using unmanned vehicles for surveillance and forward reconnaissance by proxy in potentially hazardous environments has been with us for many years.[3]. Recently, the deployment of systems to accomplish this task has become a theme of interest in law enforcement, military and space exploration programs.

Unlike traditional reconnaissance vehicles, the *PARAROVER* is designed to immerse the user in the target area. This is accomplished using two key pieces of technology, an omnidirectional video camera [2] and the associated *Remote Reality* [1] display system.



(a) (b)

Figure 1: (a) The *PARAROVER*. (b) A user operating the *PARAROVER*. He is wearing the *Remote Reality* HMD on his head and holding the remote control unit in his hands. The unwarped perspective image that he sees is displayed on the computer monitor near the middle of the picture.

While wearing the *Remote Reality* HMD (head mounted display), the operator is completely immersed in the environment near the location of the *PARAROVER* . The user has complete freedom of viewing direction, as the omnidirectional video camera mounted on the *PARAROVER* captures a 180^o by 360^o hemispherical field of view. The *PARAROVER* is also equipped with an on-board microphone that permits the user to hear any sounds within the immediate vicinity of the *PARAROVER* . The converse functionality is provided by a small lapel microphone attached to the front of the Remote Reality HMD and speakers on-board the *PARAROVER* .

In addition to applying omnidirectional camera technology, the *PARAROVER* is designed to be compact, low cost and capable of quickly maneuvering through hostile environments. The vehicle itself is not in any way autonomous, as it relies completely on a human to drive it. The speed at which the *PARAROVER* operates is comparable to that of a human jogging or walking briskly.

2 System Overview

2.1 Chassis

The chassis of the *PARAROVER* is a product made by *HPI Racing* known as the *RS4 MT Monster Truck*, part number 501. This vehicle chassis was chosen because it is made of ABS plastic, features four-wheel drive and has a very wide chassis. The fact that it is made out of ABS plastic is important because ABS plastic is easy to perform the modifications that were necessary to mount the custom platform on which the omnidirectional camera is attached.

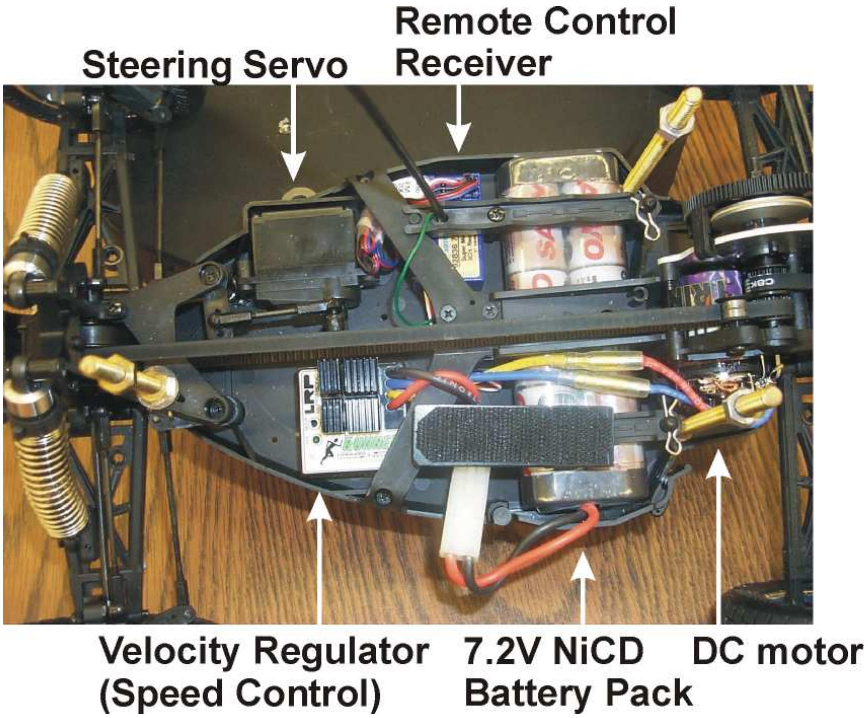
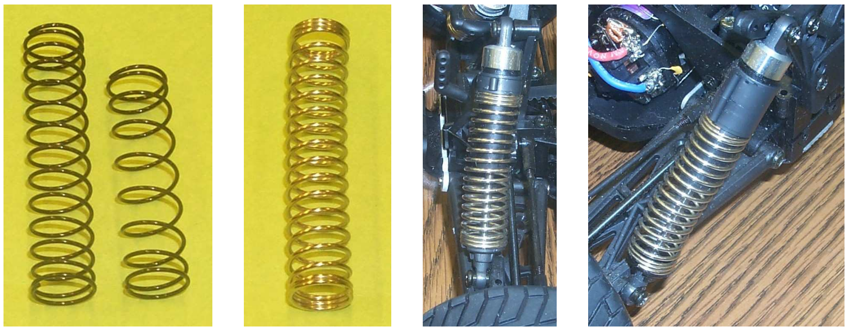


Figure 2: The *PARAROVER* chassis.

Four wheel drive was chosen in order to give the *PARAROVER* a robust drive-train capable of traversing different kinds of terrain. The wide chassis is critical to system stability because of the use of the omnidirectional camera. The camera tower is approximately 1.25 feet tall, and hence, the center of gravity of the *PARAROVER* is significantly altered by it's presence. Without the wide profile, the vehicle would encounter difficulties performing turns at anything but extremely low velocities.

2.2 Suspension

The primary modification to the after-market vehicle chassis was in the suspension system. The stock chassis was equipped with oil-filled shocks that were designed to support the weight of the vehicle itself and nothing more. The additional payload of the custom metal body, omnicam, wireless video transmitter, FM audio receiver and speakers, and additional DC power subsystem added approximately 15 pounds of weight to the vehicle. This caused the stock vehicle chassis to sag to the point that it almost touched the ground. The use of stiffer springs and more viscous shock oil as well as spring spacers brought the vehicle back to the proper height.

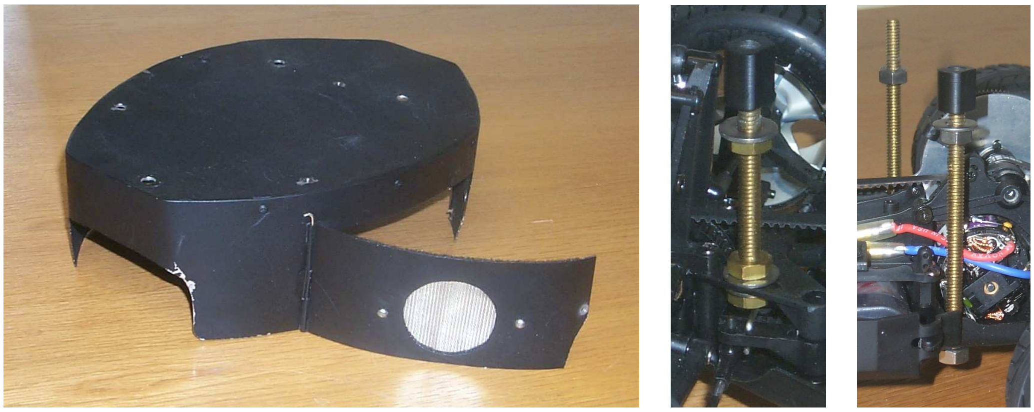


(a) (b) (c) (d)

Figure 3: (a) The original springs that came with the HPI chassis. (b) The spring used to stiffen the suspension. (c) Detail of front shock absorbers and (d) rear shock absorbers.

2.3 Body

The body for the vehicle was custom built by the mechanical engineering shop at Columbia University's Fu Foundation School of Engineering and Applied Science. Sheet metal was chosen as the material type because of it's malleability and tensile strength. The body is fastened to the chassis via three brass bolts nuts that rise up through holes drilled into the ABS plastic chassis. The bolts are designed to be adjustable and allow the body to be mounted at a slight, user defined angle. This was done because preliminary tests demonstrated that placing the omnicam at a slight angle forward made the process of teleoperation easier.



(a) (b) (c)

Figure 4: (a) The custom platform on which the omnidirectional camera is attached to. (b) & (c) The bolts on the chassis which hold the custom platform in place.

The custom body plays two roles in the *PARAROVER* system . It provides a mounting bracket for the speakers and pocket-radio for the full-duplex audio system in place and also serves as a platform on which the omnidirectional camera is attached. Since the omnidirectional camera that was selected for this implementation of the *PARAROVER* had facilities to be mounted on a ceiling for use as a security camera, it was very easy to use those same screw holes to bolt the camera onto the custom body. Three field strip screws were used to ease disassembly and maintenance procedures.

2.4 Radio Control System

The radio control system provides the user with the interface to the drive (throttle) and steering electro-mechanics on the *PARAROVER* . A commercial system known as the *Airtronics CX2P* was chosen because of its low cost and use of FM signal encoding and transmission in the 75 MHz band. The FM signal encoding provides a higher SNR compared to the AM encoding that is more common in the radio controlled vehicle market. In addition, the use of the 75MHz band as opposed to the 25 MHz band was chosen for its of higher signal penetration and better skin depth characteristics.

2.5 Omnidirectional Camera

A single omnidirectional video camera is the primary sensor that enables the *PARAROVER* to be maneuvered and through which the user can be immersed into world around the omnicam. A

Figure 5: The hand-held radio controller that allows the user to cause the *PARAROVER* to accelerated, decelerate and turn.

commercial version of the omnidirectional video camera[2] called the *Paracamera*, manufactured and sold by *Cyclovision Technologies, Inc.*, was used in the implementation of the *PARAROVER* . The omnicam captures a complete hemispherical 360 x 180 degree picture at video rate (30 Hz). This key piece of technology separates the *PARAROVER* from the traditional reconnaissance / surveillance vehicle, as it permits the user to be immersed in the environment of the *PARAROVER* without any moving parts.

2.6 Wireless Video System

The wireless video system allows the NTSC video signal produced by the omnicam onboard the *PARAROVER* to be transmitted back to a remote location where the user teleoperates the rover. Since this is the primary method by which the user is able to maneuver the rover and ultimately perform the action of reconnaissance, this part of the system must be particularly robust. Furthermore, the rover may not be within a line-of-sight of the user. In fact, there may be any number of obstacles of various materials between the user and the *PARAROVER* unit, even if the actual distance between the *PARAROVER* and user is small, such as inside a building.

A commercial system manufactured and sold by "HDS, Inc." was chosen for use in the *PARAROVER* because of previous experience. The transmitter (marketed by HDS under the name "Series 0 Wire-

Figure 6: The omnidirectional camera that is mounted on top of the *PARAROVER* chassis.

less Video Miniature Transmitter") is extremely small (1.60″ x 1.60″ x 0.74″) and draws only a few hundred milliamperes of current. The transmitter is housed in a custom housing at the top of the omnicam tower. This location was chosen in order to prevent the 2.4 GHz omnidirectional antenna from blocking the field of view of the user. The corresponding receiver unit is an HDS "Series 7 Wireless Video Receiver." The system uses FM encoding of the NTSC video signal created by the omnicam. The wireless link can be maintained over a distance of 2 miles in open space.

2.7 Full-Duplex Audio System

The *PARAROVER* is equipped with a full duplex audio system to make the notion of immersion more realistic. While wearing the Remote Reality HMD, the user can hear sounds as if they were actually present at the physical location of the *PARAROVER* . In addition, any sounds that originate from the vicinity of the user are transmitted and played back on the speakers attached to the side of the *PARAROVER* .

A microphone that is attached to the top of the camera tower facilitates the capture of audio

(a) (b)

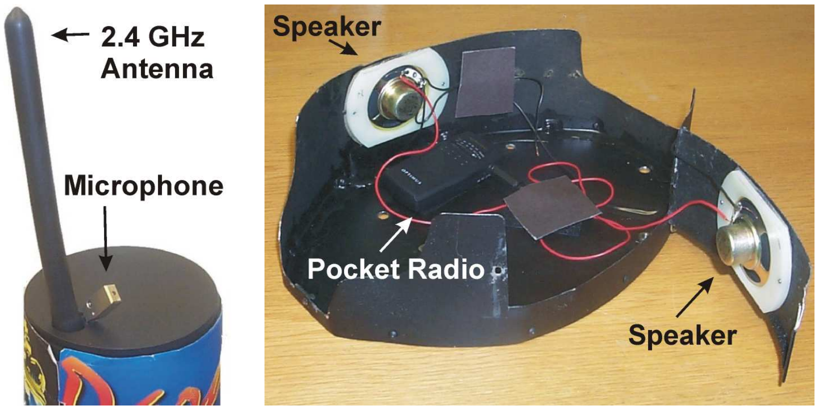
Figure 7: (a) HDS Series 7 Wireless Video Receiver. (b) HDS Series 0 Wireless Video Miniature Transmitter mounted on top of the omnidirectional camera.

from the *PARAROVER* to the user. Any sound within the immediate vicinity of the *PARAROVER* is transmitted as a 5 MHz FM sub-carrier on the 2.4 GHz video signal. This functionality was built into the after-market HDS wireless video system that transmits the omnicamera image back to the user.

The reverse process of transmitting sound from the user to the *PARAROVER* is facilitated by a small lapel microphone that is attached to the HMD of the Remote Reality system. This microphone is connected to a small pre-amplifier that is attached to the left side of headband that holds the HMD in place. The amplified signal is then passed to an FM transmitter that sends the signal using a commercial FM band to small pocket radio mounted on the underside of the *PARAROVER* body. The pocket radio is connected to two speakers that have been mounted on either side of the *PARAROVER* body.

2.8 DC Power System

The *PARAROVER* is powered by two sets of batteries. The first set is a bundle of six 1.2 volt 1200 mAH C-size nickel cadnium batteries that powers the drive-train, steering servo and remote control electronics. This particular configuration was chosen because it is commonly used in remote control vehicles, and hence, battery packs, chargers and conditioners are easily available. The 7.2 volt battery pack is held in place by a cradle built into the HPI chassis that is specifically designed for this purpose. In order to recharge the batteries, the operator must remove the pack from the vehicle and attach it to a commonly available 7.2 volt NiCD charger.



(a) (b)

Figure 8: (a) The microphone that is mounted on top of the omnidirectional camera. (b) A view of the *PARAROVER* body upside-down. The small pocket radio can be seen in the center of the body.

Figure 9: The battery holders embedded into the base of the omnidirectional camera. The omnicam was held "upside-down" while taking this picture.

The second set of batteries powers the omnidirectional camera and wireless video transmitter. A separate power system was chosen primarily because it isolated the sensitive eletronics in the wireless unit from the electrical noise generated by the DC motor. In order to satisfy the voltage and current requirements of both the video camera and the wireless transmitter, ten 1.2 volt 800 mAH nickel-metal-hydride batteries were embedded into the base of the omnidirectional camera. Due to physical size constraints, battery sockets were used instead rather than assembling all ten of cells into a battery "pack" such as the one used to power the rest of the *PARAROVER* . In order to recharge the cells, they need to be removed and placed into an aftermarket charger/conditioner for NiMH batteries.

2.9 Remote Reality Display System

The omnidirectional video camera captures an image from a parabolic mirror which is difficult to interpret unless processed. For many applications, a processed image displayed on the screen of a computer is sufficient. For the *PARAROVER* , a virtual reality system is used instead.

(a) (b)

Figure 10: (a) A image captured from an omnidirectional video camera in its raw form. (b) A perspective image generated from the omnidirectional image data in (a). This is similar to what the operator of the *PARAROVER* would see.

The *Remote Reality* [1] system was developed by Terrance Boult of Lehigh University. It provides a perspective unwarping of the circular image transmitted by the *PARAROVER* omnicam with a viewing direction that is based on the user's head orientation. In addition, the HMD has built-in earphones that replicate any sound that is picked up by the microphone on the *PARAROVER* .

Figure 11: The *Remote Reality* HMD. The small lapel microphone attached to it for the audio subsystem can be seen in sitting in the middle of the front visor panel.

The use of the Remote Reality makes the teleoperation of *PARAROVER* a very natural process. It creates the illusion that the user is actually sitting in the driver seat of the *PARAROVER* . The user can look around at the surroundings around the *PARAROVER* by simply moving his or her head.

3 Performance

3.1 Mechanical

Cruising Speed	12 MPH (7.5 $\frac{m}{s}$)
Top Speed	20 MPH (12.5 $\frac{m}{s}$)
Acceleration	4 $\frac{MPH}{s}$ (2.5 $\frac{m}{s^2}$
Turning Radius	5 $feet$ (1.5 m) minimum
Turning Radius	10 $feet$ (3 m) at cruise speed

3.2 Electrical

Battery Running Time	1 $hour$ continuous use
Battery Running Time	3 $hours$ typical use
Video Signal Transmission Distance	2 $miles$ (3.2 km) free space
Video Signal Transmission Distance	350 $feet$ (1200 m) indoors
Control Signal Transmission Distance	1 $mile$ free space
Control Signal Transmission Distance	250 $feet$ indoors

4 Evaluation

4.1 Successes

Overall, the *PARAROVER* was well-received at the various DARPA meetings that it was demonstrated at. In addition, the initial design goals of demonstrating omnicam technology for teleoperation and environment immersion, minimizing the system cost and attaining better than average mechanical performance, were all met.

The *PARAROVER* successfully demonstrated the use of omnidirectional video camera technology for vehicular teleoperation and target site immersion. It is this feature that sets the *PARAROVER* apart from traditional unmanned forward reconnaissance / surveillance devices.

The cost of the current *PARAROVER* implementation and Remote Reality system is relatively low (approx. $6000) compared to other systems of this type. The majority of the cost went into the HDS wireless video system (approximately $3500). This could have been alleviated by using a less costly wireless video system in the implementation, but the HDS system was chosen because of good experiences with HDS in the past in other projects.

Finally, the *PARAROVER* is remarkable in that it is capable of attaining relatively high speeds compared to similar more expensive devices being developed at this time. However, due to an offset center of gravity, the *PARAROVER* is limited in speed while turning. This was discussed in Section 4.2.

4.2 Limitations

The operation of the *PARAROVER* is restricted by a number of factors of which the most notable are the wireless communication systems. Since the *PARAROVER* is teleoperated by a remote user, the signals from the remote control system and the wireless video system must be properly received by the appropriate party. Since the wireless systems operate on different electromagnetic frequency bands, the material penetration, skin depth and propagation properties of the signals are very different. This often leads to a situation where one system operates correctly when another does not, resulting in the user "driving blind" or being able to see but not control the *PARAROVER* . This is particularly problematic indoors, where multipath propagation can cause serious problems for almost any kind of wireless device.

A second limitation in *PARAROVER* operation is due to the omnicam tower. The *Cyclovision Paracamera* is more than 1 foot high, with almost all of it's weight in the upper 1/3 of the tower. This causes a significant offset of the *PARAROVER* 's center-of-gravity in the upward direction, thereby compromising mechanical stability. An attempt to counter the offset was made by placing the DC power cells for the camera and wireless video transmitter at the base of the camera tower. In addition, the remote controlled vehicle chassis was specifically selected because of it's wide wheel base. Although both these factors helped to mechanically stabilize the *PARAROVER* , the vehicle must still be decelerated to less than half of it's normal operating speed before making sharp turns.

Finally, the actual process of teleoperating the *PARAROVER* is somewhat deceiving in that it would seem to be straightforward because it resembles driving an automobile. However, after working with the *PARAROVER* for some time, it becomes apparent that significant training is required before a user can safely and effectively operate the *PARAROVER* . The main reason for this is because the *PARAROVER* operator sees the world through the perspective of a fictitious person that would be sitting on the "roof" of the vehicle and not inside. Driving from this perspective is difficult, but more importantly, it is not the same as driving an automobile. In particular, collision avoidance and traversing terrains with multiple obstacles becomes much harder and takes practice.

The latter two issues are being addressed as a new, enhanced version of the *PARAROVER* will be assembled in March 1999. The second generation *PARAROVER* will use a recently developed folded omnicam. This new omnicam is significantly smaller and lighter than the model mounted on the current *PARAROVER* . In addition, most of the weight in the new folded omnicam is at the base of the camera, thus alleviating the center of gravity problem with the current *PARAROVER* . The lower profile of the new omnicam should also permit mounting in such a way that the viewpoint is lower. This should allow the user to see the *PARAROVER* 's tires and hopefully be able to avoid obstacles and collisions better.

Relevant WWW URLs

Columbia Automoted Vision Environment	http://www.cs.columbia.edu/CAVE
Columbia University	http://www.columbia.edu
Cyclovision Technologies	http://www.cyclovision.com
Defense Advanced Research Projects Agency	http://www.darpa.mil
DARPA Video Surveillance and Monitoring	http://www.darpa.mil/iso/iu/vsam2.htm
HDS	http://www.hdscorp.com
HPI	http://www.hpiracing.com

References

[1] T. Boult. Remote reality. In *Proc. of ACM SIGGRAPH 1998*, Orlando, 1998. Technical Sketch.

[2] S. Nayar. Catadioptric omnidirectional camera. In *Proc. of CVPR 1997*, pages 482–488, Puerto Rico, June, 1997.

[3] Thomas Sheridan. *Telerobotics, automation and human supervisory control*. MIT Press, 1992.