RELAY: A Futuristic Interface for Remote Driving

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Abstract

The remote control of vehicles, typically useful in hazardous situations, is a difficult and skilled task. Users experience great difficulty in performing relatively simple operations, such as avoiding obstacles and maintaining control of the device. This contrasts strongly with high user performance when controlling a local vehicle. We suggest that one reason for this is the absence of haptic feedback conveying the physical experiences of the vehicle, the forces that act upon it as it moves. To investigate this issue we have augmented a radio-controlled car with sensors, and constructed a novel control handset that uses ungrounded haptic feedback to display the forces and torques experienced by the car as it is driven.

1. Introduction

Teleoperation is the remote control of robotic or vehicular devices. It has long been accepted that haptic feedback has a useful role to play in interfaces to teleoperated systems [9]. Indeed, it seems obvious that the presentation of information regarding the physical experiences of a remote device would be more effectively presented to the sense of touch than it would be to the sense of vision. For instance, in the situation where a user is remotely controlling a grasping manipulator, such as a pincer, the haptic display of contact (and the subsequent forces involved in gripping the object) seems more appropriate than visually presenting this information [5].

At the very best, visual presentation will require an explicit mental mapping from the actions performed on the local manipulator to the observed action of the gripper, while at worst visual presentation may result in simple tasks becoming extremely difficult to perform. An example of this situation would be when the views provided of the environment fail to capture the salient details required to complete the task; when, due to the absence of an appropriate view, it is impossible to determine if the pincers involved in a gripping action have come into contact with the target object or not.

Remote vehicular control systems are a subset of teleoperated systems and have numerous applications, typically in environments that are in some way hazardous. They have been used to control undersea exploration vehicles [2], suggested for space exploration, and are currently deployed for remotely operated land and air vehicles used by the military [4, 11]. Users of these systems often suffer from problems such as poor depth judgment, inadequate perception of the remote environment and failure to detect obstacles. This low level of performance is in stark contrast to user abilities when in control of a local vehicle. We suggest that this discrepancy may in part result from an absence of haptic cues relaying the vehicle's experiences in the environment.

Drivers rely on haptic cues to maintain control of their vehicles – the feel of the car altering its course as they adjust its controls, and the impact that external disturbances have on it. Often the first indication of losing control of a car is the unexpected change in the tangible qualities of its motion. These kinds of forces are critical to driver skill, and are not represented in current vehicle teleoperation systems.

Haptic feedback has been added to teleoperated systems by several authors in the past, but not under this premise [e.g. 3, 11]. These previous haptic augmentations can be typified by Fong et al. [3], who describe a system in which force feedback is added to a teleoperation interface in order to prevent collisions with objects in the environment. In their system IR sensors mounted all around the remotely controlled vehicle sense the distance to its nearest surroundings. This information is then haptically presented to users, so that as an obstacle is approached, the user feels a force both warning them of an imminent collision, and attempting to adjust the vehicles course away from it. This use of haptic cues to represent surrounding objects, while no doubt practical, bears little resemblance to the role that haptic cues play in real driving situations.

2. Previous Relevant Technologies

2.1. Motion Displays

For many years, the simulated display of vehicular motion has been incorporated into a wide range of applications from flight simulator installations to theme park rides. Such displays typically use hydraulic actuators to rock a stationary pod to support the visual simulation of moving at speed through a terrain. Smaller, chair-based motion displays have also been constructed [12]. However, to our knowledge, there have been no attempts to construct a haptic display to convey a sense of motion of a remotely operated vehicle. Nor has a vehicle simulator been directly used to display live data captured from a real vehicle.

2.2. Consumer Driving Simulators

Force-feedback does play a significant role in both driving and flying games and simulation. The devices used to add a sense of touch to these systems range from vibro-tactile gamepads to force-feedback steering wheels and joysticks. The goal of such systems is essentially similar to that of teleoperation systems – to increase the realism of the cues experienced by a user in order to improve presence or task performance. However, the forces generated by these systems are typically drawn from a simple model, and often only include the display of gross forces, such as impacts. In teleoperation scenarios, there is no easily accessible model of device state from which to generate forces, and, to be useful, we suggest that the force information displayed would have to be substantially more subtle and sophisticated, reflecting the vehicle's continual experiences and not simply large-scale critical events.

3. The Relay Project

In order to explore the feasibility and usefulness of a rich motion display for vehicle teleoperation, we are experimenting with the haptic display of the forces experienced by a radio-controlled car as it accelerates, decelerates, turns or simply bounces across terrain. These forces are gathered by three orthogonally-mounted accelerometers attached to the chassis of the vehicle which track motion in the X, Y and Z planes. This allows us to capture acceleration forces that occur when speeding up or braking, when turning left or right and when going over bumps or dips in terrain.

3.1. Sensing and Transmission System

Current discrete electronic accelerometers allow the conversion of such forces into analog electrical signals at low cost while achieving high linearity and large dynamic range. The main design consideration is to maximize the resolution of the sensors, which in turn will minimize the noise in the system. To achieve this, the maximum forces experienced by the vehicle in question must be measured and the sensors chosen to accommodate this range. The sensor bandwidth should be large enough to capture the required information, but should be minimized to exclude unwanted signals and to reduce transmission bandwidth. For this application the information we require is the acceleration forces that would be perceived by the haptic system of a passenger in the test vehicle. For our initial system we chose a bandwidth of 500Hz that was identified by Minsky *et al.* [7] as suitable for the presentation of the majority of haptic stimuli.

With the sensors designed the next problem was how to transmit the analog electrical signals back to a remote haptic display. Wires could not be used as they would severely limit the mobility of the vehicle and simple optical methods of transmission would also limit the mobility of the vehicle, as they require a 'Line Of Sight' between the transmitter and receiver. Radio waves, which can also be used to transmit electrical signals, provide a very robust solution as they can penetrate most materials and do not require a 'Line Of Sight' between transmitter and receiver. The electrical signals can be transmitted over such a link either in analog form or they may be digitized using an analog to digital converter and then transmitted. The former method is prone to interference from other radio frequency sources and has an inherently larger noise component than the digital method. It is also difficult to transmit multiple signals over a single analog RF channel and the use of multiple RF channels or some form of time division multiplexing would be required. The digital method of transmission has much greater noise immunity than the analog method and allows multiple signals to be transmitted over the same channel utilizing an agreed protocol. For these reasons we chose to use a digital RF transmission system.

To develop a reliable custom RF transmission system it was necessary to develop a test system for the RF link. For versatility, we designed this test-bed link to connect the car to a PC. This meant that the data being sent over the link could be monitored and displayed graphically or haptically using general-purpose force-feedback controllers and allowed us to begin to prototype the force display at a very early stage. The test system was most easily accomplished by designing an RF receiver that included an interface to a host PC, such as RS232 or USB. Early predictions showed that the application would be reasonably data intensive, and so we chose to use a USB interface, which can provide significantly more bandwidth than older technologies such as RS232.

We chose to implement the design using a microcontroller based system, as current microcontroller technologies are capable of incorporating many of the specified design components on a single integrated circuit. This reduced hardware complexity and allowed us to modify system characteristic such as sample rates and resolution by simply upgrading the microcontroller firmware.

The complete system has several parts, but may be split into two main functional units consisting of a remote data acquisition unit and a host receiver unit. The remote unit contains sensors that measure acceleration forces in all 3 axes, the signals produced by the sensors are then digitized by the data acquisition system and the digital data converted to a serial stream, which is then fed to the RF transmitter. The host receiver receives the serial stream from the RF receiver, temporarily stores the data in a parallel form before transmitting the data to a host PC via a USB port. A block diagram of this system is shown in Figure 1.

Initial results showed a large noise component on all of the acquired acceleration signals. This was eventually traced to high frequency vibrations that were being generated by the vehicle motor and coupling into the accelerometers. To remove this noise additional digital signal processing in the form of a low pass filter was implemented on the host PC.

The reliability of the radio transmission system also caused some problems due to synchronization issues with the USB port and interference from other radio sources using the same frequencies. These are mainly due to the internal design of the microcontrollers used and may be overcome with a more complicated hardware design and the introduction of error detection in the transmission protocol.

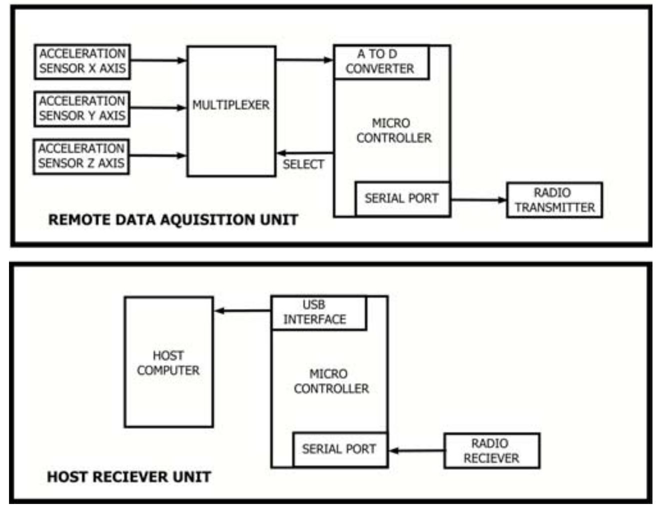

Figure 1. Structure of Prototype System.

4. Handset Design

However, using a PC and general-purpose force feedback controller presents significant limitations when remotely controlling a car. These force feedback devices are typically controlled by a host PC and designed to produce ground based forces, meaning that they are relatively heavy and are intended to operate when placed on a fixed and steady surface. They produce forces that push against a user under the pretext that the equal and opposite forces that are generated by this process will be conveniently absorbed by the weight of the device and its connection to the ground. The scenario contrasts strongly with the normal operation of a radio-controlled car in which the user is freestanding and the controller is handheld. Crucially this enables a user to move around freely to ensure they have the best possible vantage point to observe their vehicle.

The control mechanism used to operate radio-controlled cars is also both relatively unique and effective. Users adjust the position of two one-dimensional analogue joysticks bi-manually. Typically the left hand controls a joystick with a forwards-backwards alignment that adjusts the speed and actuation direction of the motors in the car, while the right hand controls a left-right joystick that alters the steering. Partly as a consequence of the bi-manual manipulation, this system is both sensitive and simple to use. Most force feedback devices do not support this kind of interaction.

Consequently, we chose to design our own handset that supports these controls and this user scenario. We wanted to maintain the familiar control system, and the mobility inherent in the controller design, but couple this with force feedback display. Current handheld force feedback devices, commonly used in computer gaming, are essentially limited to producing vibro-tactile feedback using excentric motors. A sensation of vibration, or "rumble", is produced by the changes in momentum that a motor spinning an unevenly distributed mass can create. This feedback, while simple and effective, does not have the directional qualities that we require for the display of the data gathered from the radio-controlled vehicle.

To resolve this problem, we are in the process of creating a novel design of force feedback controller. In order to meet our primary requirement, namely that the controller should allow a user to move freely while operating the car, we identified two necessary conditions:

- that the handset should be mechanically ungrounded
- that the handset should be wireless.

Achieving our first goal required us to design an ungrounded haptic display, capable of conveying some sense of the motion of the remote vehicle to the user. Despite the growing amount of research in the area of haptic feedback for teleoperated and virtual environments, there has been relatively little work on the use of ungrounded or user-grounded haptic displays. Such displays apply their reaction forces on a part of the body that is separate from the area where haptic display is to occur.

Several glove-based exoskeleton devices exist such as the Rutgers Master [1] and the CyberGrasp [6]. These devices display forces internal to the hand by applying grounding forces against the palm or wrist. However, they are unable to display any forces external to the hand such as those experienced while wielding a hand-held tool. In terms of perceiving ungrounded haptic effects, there is a small literature pertaining to the consequences of displaying the geometric or dynamic characteristics of environments using ungrounded haptic devices. In comparing performance of distance estimation and boundary detection tasks in grounded and ungrounded conditions, Richard & Cutkosky [8] found that ungrounded haptic feedback can provide force cues comparable with grounded displays in boundary detection tasks though, not surprisingly, grounded feedback was better than ungrounded feedback at displaying forces that stem from grounded sources such as simulated walls. In a related study, Turner *et al.* [10] showed that people could discriminate through touch alone the size and stiffness of objects held by a remote gripper based on forces reflected to a CyberGrasp [6]. Moreover, size discrimination with the ungrounded device was comparable to that with a grounded display, though not as accurate as direct manipulation with the hand.

The current scenario for ungrounded haptic feedback differs from these in that we do not seek to display forces related to the properties of objects or their manipulation, but rather to display the forces experienced by the object we are controlling in the remote environment. As such, we are more concerned with conveying the dynamics of the moving object and its interaction with its environment.

The first iteration of this controller used a rack-and-pinion mechanism to move suspended weights along left-right and forward-back axes in response to accelerometer data from the car. However, this handset was heavy and the travel of the weights was limited in both distance and speed of response. A more significant problem was that although the operator experienced the desired forces generated by alterations in the position of the weights, they were also exposed to the forces produced by the mechanical work required to move the weights. Both of these essentially opposite forces were grounded to the same area of a user's hand, and this led to difficulties in perceiving the forces presented.

We designed a second handset to address this issue. We devised a mechanism whereby a movable plate is mounted on the underside of a handset. Forces are generated within the handset and displayed using rotations of the plate. A user grips the handset with both their hands, and their fingers come in contact with the plate. Consequently, the forces generated are grounded by the heels of the hands, and felt by the fingers. The plate is actuated by two servomotors that are physically linked to each other and positioned to move forward\backward and left\right. This is illustrated in Figure 2. Using this simple linkage we have a mechanism which can display linear forces in x and y simultaneously. For instance, when the car accelerates the rear of the plate squeezes in and the front pushes out. Similarly as the car turns left the left side squeezes in and the right part pushes out. When the car is both accelerating and turning these forces are displayed simultaneously. We also included a vibration device in the handset that was mapped to the up/down accelerometer data. Combined these mechanisms have the potential to create a compelling illusion of the forces that the car is experiencing.

Achieving our second goal of building a wireless handset meant implementing all the processing and electronics solely in the handset and the model car, and therefore removing the USB interface and PC from the system. To achieve this we decided to use the same digital radio module as before, in half-duplex mode, so that only one of such modules would be required at either end of the system. This allowed us to send the controlling data from the handset to the car and return the accelerometer data from the car to the handset whilst using only one radio channel. The servos that were used in the car to steer and drive are based on the Futuba standard, and have an update rate of approximately 65Hz.

The design of the electronics was for the most part symmetrical between the handset and the car. Each end consists of a low-cost microcontroller with analog input and USART capability, and a half-duplex digital radio module operating in FSK mode at a frequency of

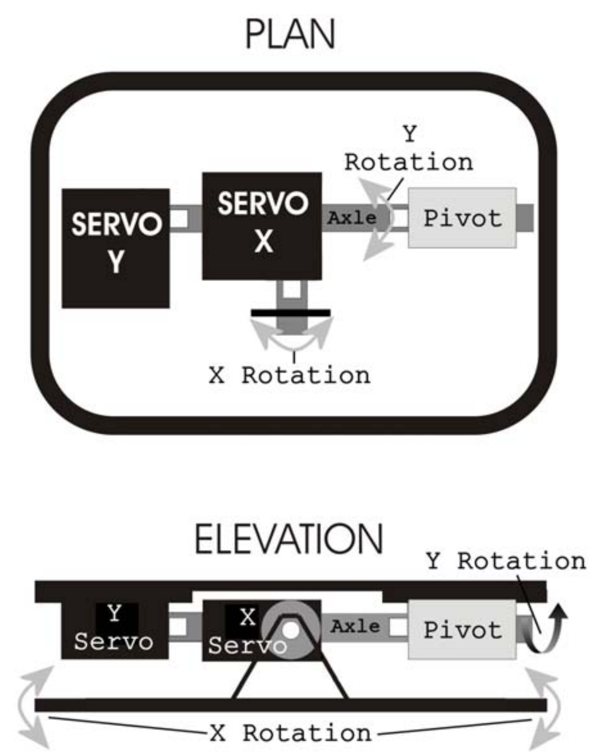

Figure 2. Design of second handset.

450Mhz. The communication between both ends was chosen to be symmetrical, 3 channels of 8-bit data at a sample rate of 65Hz. The handset controller was chosen to be the master, and as such maintains the sample rate at both ends, since the car (slave) side synchronises itself to it.

The handset contains two joystick potentiometers (forward/rev and left/right). The signals from these were low pass filtered, sampled and sent as two 8-bit channels. As such, the third channel in this direction was unused, and dummy data was sent to keep the radio channel symmetrical. On the car end, once received, this data was used to directly control the steering and drive servos.

As before, the car had three accelerometers, the signals from which were buffered, low pass filtered, sampled and sent as three 8-bit channels. On the handset, once received, this data was mapped to the servos that tilt the moveable plate in two planes, and the vibration device mounted within the body of the handset. The vibration device was implemented in a binary (on/off) mode, which would be activated if the up/down accelerometer data exceeded a certain threshold. This mapping provided 'bump' perception to an effective degree.

5. Future Work

The devices are currently prototypes, and several avenues exist for further development. One interesting avenue that we are exploring is the use of gyroscopes to create ungrounded haptic displays. Also, our current wireless connection is maintained through a custom-built radio link that presents us with problems of bandwidth and also with interference from other radio signals in the environment. We are now designing a wide-bandwidth wireless link based on Bluetooth that will overcome these limitations. Finally, we hope to assess this work by conducting an evaluation of the influence that the haptic feedback exerts on user performance and subjective satisfaction.

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