Sensor Augmented Virtual Reality Based Teleoperation Using Mixed Autonomy

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A multimodal teleoperation interface is introduced, featuring an integrated virtual reality (VR) based simulation augmented by sensors and image processing capabilities onboard the remotely operated vehicle. The proposed virtual reality interface fuses an existing VR model with live video feed and prediction states, thereby creating a multimodal control interface. VR addresses the typical limitations of video based teleoperation caused by signal lag and limited field of view, allowing the operator to navigate in a continuous fashion. The vehicle incorporates an onboard computer and a stereo vision system to facilitate obstacle detection. A vehicle adaptation system with a priori risk maps and a real-state tracking system enable temporary autonomous operation of the vehicle for local navigation around obstacles and automatic re-establishment of the vehicle's teleoperated state. The system provides real time update of the virtual environment based on anomalies encountered by the vehicle. The VR based multimodal teleoperation interface is expected to be more adaptable and intuitive when compared with other interfaces.
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1 Introduction

Teleoperation can be broadly defined as controlling a system from a distance. One of the primary motivations behind teleoperation research is the need to perform tasks in places that are unsuitable for human presence. Unmanned aerial vehicles (UAVs) for reconnaissance in hostile regions [1], researching the ocean floor without risking a diver's life [2], and exploring a damaged nuclear reactor using a teleoperated ground vehicle are a few examples in which teleoperation can play a vital role. These scenarios require spontaneous and critical decision making, which cannot be carried out by autonomous agents, so human participation is important [3]. Moreover, humans possess excellent problem solving skills [4] and capabilities for making rational decisions with partial/incomplete and/or incorrect information [5].

Teleoperation of a vehicle typically involves direct visual feedback (such as the hobbyists' radio controlled (RC) airplane) or indirect visual feedback from onboard video cameras or laser scanners [6]. Such systems are subject to time lag in the transfer of the video feed as well as the control commands, resulting in increased task completion time [7] and system instability [8]. If the operator input and vehicle reaction are not intuitively linked in time, an increased potential for loss of situational awareness for the teleoperator can occur. Moreover, the video feed obtained from the camera provides a limited or "soda straw" [9] view of the environment due to the camera's limited field of view (FOV). A camera lens with a shorter focal length can increase the field of view. But a shorter focal length leads to higher peripheral distortion of the camera images and lower image resolution, which in turn affects the operator's telepresence [10]. These challenges motivate researchers to develop teleoperation interfaces that can accommodate lag, reduce cognitive work load, provide intuitive interaction, and are easy to train and adapt to. Teleoperation interfaces may be classified into various types, including multimodal/multisensor, augmented reality (AR), virtual reality (VR), and novel/unique interfaces [6]. This application review presents a review of these interface types followed by the proposed architecture for a virtual reality based multimodal interface, its implementation, and preliminary results

2 Teleoperation Interfaces: A Review

2.1 Multisensor/Multimodal Interfaces. Lack of peripheral vision due to the limited FOV can be compensated by adding more cameras and sensors. This approach requires the operator to pay attention to several different video feeds simultaneously to create a consistent mental image of the world [11]. This increases the operator's stress and distracts her/his focus away from the task at hand. Researchers have been working on providing integrated environment data by augmenting multiple sensors [12] including camera and 2D and 3D laser range finders [13]. Sugimoto et al. [14] presented an interface that merges the past images of an exocentric camera (camera located behind the vehicle) with the current images of an egocentric camera (camera located on top of the vehicle) to provide better peripheral vision. Hughes and Lewis [15] proposed the idea of having multiple vehicle mounted cameras that can be controlled by the operator independent of the orientation of the vehicle. The interfaces have multiple data streams from multiple sensors and cameras, which may be subject to different and variable lags. So synchronizing them before they are presented to the user can be challenging.

2.2 Augmented Reality Interfaces. Teleoperation interfaces use AR predominantly in the form of graphical overlays and simulated imagery. The AR through graphical overlays and stereo video presented by Milgram et al. [16] gathers quantitative spatial information from the task environment and develops a partial model of the remote 3D work site. The most common AR technique, sometimes referred to as synthetic imagery, involves overlaying and registering text and images (e.g., generated from sensor information [17]) onto a live video feed or computer generated scene [18]. AR interfaces are also used in assembly and maintenance processes [19], where the instructions and reference lines can be superimposed over video or graphics representation of models. AR in the form of synthetic imagery is effectively used in military applications for overlaying landmarks, threat zones, target locations, etc., over live video feeds or over a priori terrain information [20]. Although AR helps in providing more information to the operator, it cannot compensate for the loss of situational awareness due to the time lag and the lack of peripheral vision.

2.3 Novel/Unique Interfaces. Interfaces that are unique and that cannot be categorized into existing types are classified as novel. Fong et al. [21] employed a lightweight, portable, touch sensitive personal digital assistant (PDA) for teleoperating a ground robot. The PDA navigation tool displays a fusion of collected sensor data overlaid on a map in order to improve operator situational awareness. Control interfaces with haptic force feedback devices were developed to provide a realistic feel for the operator when driving the vehicle [22]. The interface transforms

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the range sensor information into spatial forces using linear models. The forces are then experienced using the haptic device. Although such interfaces can add comfort to the operator and improve performance, they cannot compensate for the inherent limitations of the system such as lag or limited peripheral vision.

2.4 Virtual Reality Interfaces. The teleoperation interfaces discussed above in one way or another do not satisfy most of the basic requirements. The idea of using VR to compensate for these limitations was suggested by Milgram and Ballantyne [23] in his review on Virtual Environments for Remote Operations, a VR interface for controlling and manipulating telerobotic systems. The taxonomy proposed in his model suggests that a VR based interface in the form of supervisory control with considerable autonomy for the remote system is viable and far more flexible than AR interfaces.

VR is widely used in various teleoperation applications ranging from underwater/subsea exploration [24,25] to surveillance using air vehicles [26]. In general, these efforts toward VR interfaces indicate that a 3D representation of the task environment provides users with a higher degree of comprehension compared with 2D viewing. In addition, it allows the operator to select arbitrary views. In contrast to restricted camera views of video based teleoperation, operator views in VR interfaces are not limited to placement and orientation of the camera mounted on the remote vehicle. In some applications views can be controlled by the operator "on-the-fly." Immersive projection VR display devices such as CAVE automatic virtual environment (CAVEs) can provide users with an extremely wide field of view and a high degree of telepresence [27]. Also, stereoscopic visualization assists operators in better estimation of distances between vehicle and objects in the task environment [28]. Moreover, CAVE-like projection displays are shown to improve operator performance in look-out tasks such as teleoperation, in which the user requires peripheral vision of the task environment [29].

However, most of the current VR based teleoperation interfaces do not exploit VR technology to its fullest. VR is essentially used as a visualization tool to display the sensor feedback, and there is generally no separation between the real state and the VR simulation state. Hence limitations due to lag persists. In our previous work, Walter et al. [30] presented a VR based teleoperation system for ground vehicles that uses a large-scale immersive virtual environment as the primary visual context for the operator. The VR environment is augmented with sensor-generated meta-data. This provides a broad FOV that fosters situational awareness. The system accommodates lag by essentially enabling the operator to control a simulated vehicle in the future of the actual vehicle: providing it a time series of goal states. The interface separates the real and simulated states and thereby ameliorates the interface challenges caused by signal lag time. The interface provides a wider field of view and reduces the cognitive work load on the operator. The system enables far better navigation performance than video based teleoperation. Of course, state separation assumes the primacy of the virtual world created a priori and that the operator believes what is perceived through the simulation. Research in terrain simulation and modeling has evolved sufficiently to provide three dimensional graphics models from satellite data, just short of real time [31]. Hence, the virtual terrain can be very accurate.

However, the possibility of an operating environment being different from its virtual representation is high in dynamic environments, and change might occur in both time and space. The challenge lies in identifying ways to detect environmental change relative to the virtual model of the environment, to use this information to enable the vehicle to adapt to the change, and to provide the operator with the dynamically updated environment. The research presented in this paper builds on Walter's VR teleoperation approach by integrating onboard vehicle sensors to enable it to adapt to dynamic environments. In addition, the world model is subsequently modified to provide the operator with a dynamically updated virtual environment. The system retains all the components of Walter's VR teleoperation system, thus maintaining the advantages of accommodating lag and limited FOV. However, the real vehicle in this system is augmented with sensors and significant onboard computational power to support an obstacle detection system and decision making. The resulting system is essentially a fusion of VR teleoperation with autonomous obstacle avoidance and path planning.

Sensor augmentation is the prerequisite for any vehicle to perceive the surrounding environment in real time. Considerable research has been reported on sensor fusion interfaces, where multiple sensor data from the real vehicle are integrated and presented to the operator. NASA Ames Research Center [32] has conducted an extensive study on developing interfaces using real time sensor data. The images from the surface stereo imager fitted on the vehicle are processed to provide photorealistic terrain models of the interior. Research by Jarvis [12] and Ricks et al. [13] suggests sensors, varying from charge-coupled device cameras to laser range finders, for acquiring information real time. However, it is noteworthy to understand that these proposed systems are modeled for teleoperating vehicles in completely unknown environments, where the teleoperator relies entirely on the lagged data and images. In the proposed approach, an overview of which is presented in Kadavasal and Oliver [33], a sensor augmented vehicle is teleoperated based on an a priori model in a virtual environment. The immediacy of the sensory data coupled with a certain degree of vehicle autonomy will not only help the vehicle adapt to dynamic environments but will also retain the edge over other teleoperation systems in overcoming time lag and limited FOV.

There are a wide range of sensors with varying characteristics that are available for depth measurement, and it is necessary to understand their advantages and limitations for this application. Meier et al. [34] and Fong et al. [21] presented comparative reviews on a range of depth measurement techniques including stereo vision, laser range finders, and sonar. The papers suggest that stereo vision provides good angular resolution with low cost and high speed. The disparity map technique using coordinated stereo images is effective for detecting small objects. However, it is unfit for detecting objects that are too close or far away from the cameras. Moreover, lack of textures in the scene and low lighting may result in extremely noisy depth resolution. Sonar, on the other hand, can detect objects that are far away and is not affected by environmental lighting. However, sonar has poor angular resolution and is prone to error caused by nonperpendicular and off axis targets. Further, specular reflections may result in range errors and poor depth resolution. Laser scanners are predominantly used in various teleoperation systems for obstacle avoidance. They have good depth resolution and are not affected by the environmental limitations. But they do have low update rates when compared with other vision systems and cannot detect smaller obstacles. Our current prototype system is developed for a lighted indoor environment with small static and moving obstacles. Stereo vision based sensor systems are suitable for such situations.

3 VR Teleoperation With Mixed Autonomy

3.1 Architecture. Figure 1 shows the detailed architecture for VR based multimodal teleoperation. The system has three major components, namely, the stereo vision based obstacle detection system, the vehicle adaptation system, and the VR based control station. The operator's commands are sent to the VR simulation that predicts the dynamic state of the virtual vehicle, including its position, velocity, acceleration, and heading. The vehicle dynamics simulation produces the simulated state, which is used to position the virtual vehicle and to provide a desired location for the teleoperated vehicle. The idea of driving the simulated vehicle and making the teleoperated vehicle follow is based on the wagon tongue path planning algorithm [35]. The teleoperated vehicle uses the simulated states as a series of goal states. A simulation

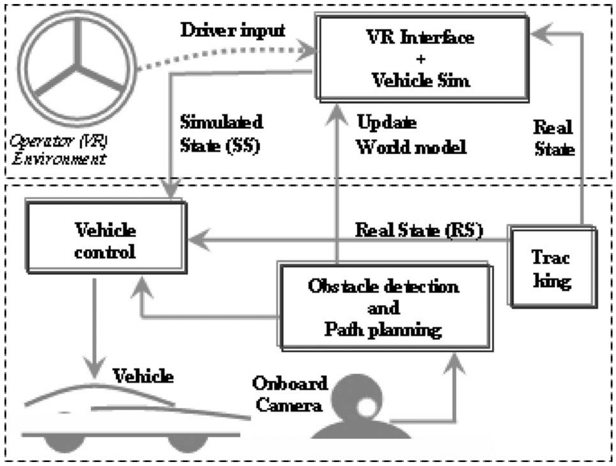

Fig. 1 Architecture

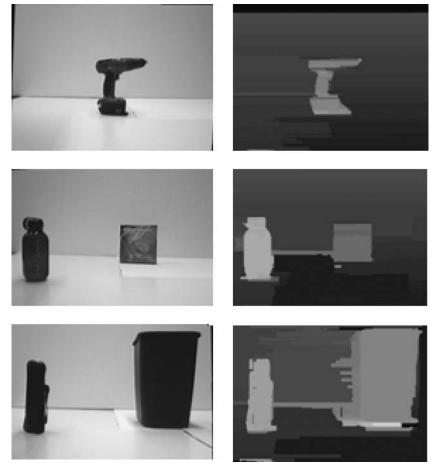

Fig. 2 Disparity map results for static camera

run onboard the vehicle determines the inputs required to get the vehicle to approach the simulated state from its current state. To calculate these inputs, the current state of the real vehicle (real state) is required, which is calculated, in this application, using an InterSense precision motion tracker [36]. To assist the operator in assessing the deviation between virtual and physical manifestations of the vehicle, an "informed state" is computed as the difference in vehicle positions between the simulated state and the real state. The informed state is used to generate a wireframe box surrounding the simulated vehicle that expands or contracts depending on the magnitude of this discrepancy. This virtual envelope allows operators to adjust their control to obtain higher fidelity with the remote vehicle, closing the loop between the human and the computer controlling the remote vehicle.

The vehicle is augmented with two onboard synchronized cameras and onboard computation for image processing. These components act as the vehicle's senses. Synchronized stereo vision allows the vehicle to identify any object within a stipulated distance. If the obstacle distance is within the preset threshold value, the vehicle creates a warning. The warning informs the operator about the new (i.e., not modeled a priori) object in the travel path along with the distance to the object and its dimensions and coordinate positions in state space. It also provides an estimated time to collision. The new object is computed as the difference between the real and premodeled environment and is placed in context in the virtual environment. This update is intended to provide the operator with visual reference for the next time the vehicle is operated in the vicinity of the new object.

With the new object detected and a warning issued, the vehicle becomes autonomous. Using the latest real state from the tracking system and the risk map, the autonomous vehicle identifies the nearest goal position that is along the actual path but sufficiently clear of the new object. The vehicle continues driving toward the identified goal without halting. The autonomous vehicle upon reaching the intermediate goal position reattaches itself to the wagon tongue; i.e., the vehicle again follows the simulated vehicle's path and is no longer autonomous.

The operator is informed about the new path, and the wireframe box around the simulated vehicle is updated to denote the degree of the vehicle's deviation from its simulation. However, if a path cannot be generated by the vehicle adaptation system, the vehicle stops. The operator is informed about the scenario and provided with real time video inputs. The video frames are placed in context with the vehicle position in the VR model for a better understanding of the situation. The vehicle is now teleoperated to a safer position using the video inputs. The system facilitates VR based teleoperation with or without video, thereby earning the name multimodal.

3.1.1 Obstacle Avoidance System: Stereo Vision. The stereo vision system is comprised of two cameras that are connected in series and synchronized. The images from the two cameras produce different perspectives of the same scene, which helps in calculating the difference in relative displacement of the objects in the scene. This relative displacement is referred to as disparity. Simple projective geometry shows that the amount of disparity is inversely proportional to the depth of a point in the scene [37].

A fast stereo matching algorithm is necessary to calculate the disparities between the images in real time. Zitnick and Kanade [38] presented a cooperative algorithm to compute disparity using correspondence. This iterative algorithm identifies the match within the predefined 3D space and accounts for occlusion. However, the algorithm in practice takes about 8 s per iteration for a 256×256 image size. The maximum flow formulation N-Stereo algorithm by Roy and Cox [39] is another stereo correspondence algorithm that computes precise depth maps albeit with relatively large computational time. The stereo correspondence method adopted in our vision system is based on Birchfield and Tomasi's [40] pixel by pixel stereo matching algorithm. The algorithm estimates the disparity values by matching the pixel intensities of the images. The algorithm introduces methods to identify nontextured regions and achieves a balance between computational time and depth map precision.

The intrinsic and extrinsic camera calibration parameters are computed, and the images are rectified. The stereo correspondence algorithm computes the disparity map from the rectified images, the results of which are shown in Fig. 2. The figure shows the camera image along with the computed disparity map. The process rate for the disparity map is approximately 2 Hz. The algorithm proves to be effective enough to provide precise object surfaces with distinguished separate regions. The disparity map is then converted into a depth map using projective geometry. An optimum threshold is computed to identify the nearest objects. The objects are segmented using a region growing method, and its dimensions are calculated. Since the stereo vision system is affected by the environmental lighting and the camera setup, the resulting depth maps may be noisy.

3.1.2 Vehicle Adaptation. The system incorporates an optimized path finding method that identifies feasible alternative paths after correlating and synchronizing the previously available terrain knowledge and risks with the new environment data. In the proposed system, the a priori model state space is classified into various zones depending on the level of risks, as shown in Fig. 3. It is assumed that the terrain data and risks are continuously updated within the operator's environment from various information resources (e.g., newly found enemy assets). The vehicle operation

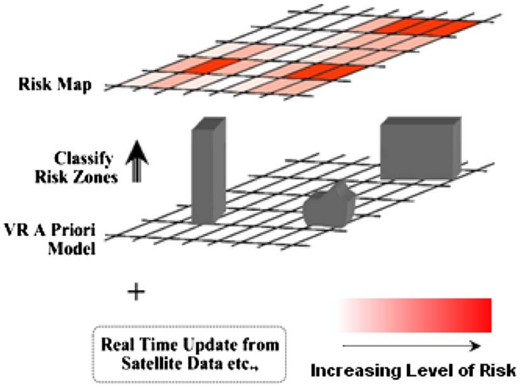

Fig. 3 Risk map classification

can be classified beforehand by the operator with respect to the level of caution that is necessary. The caution level indicates the degree to which the vehicle can take chances in precarious situations. The virtual world provides the real vehicle with a risk map of neighboring regions corresponding to each goal state. The method will account for the real-state error. The autonomous vehicle will have the risk map for the current position and will relate the new object position to the risk map. The path planning method will then identify the new path for the vehicle based on the actual goal state (simulated state), the risk levels of the neighboring zones, and the preset caution level. Depending on the preset caution level, the vehicle will consider either a high, moderate, or low risk neighboring zone as the alternate path. The autonomous vehicle then reaches the intermediate goal position and reattaches itself to the wagon tongue; i.e., the vehicle follows the simulated vehicle's path and is no longer autonomous. In the proposed system, we anticipate that the operator will be able to predict the autonomous vehicle's strategy, thereby reducing the reaction time of both the operator and the vehicle considerably.

3.2 Implementation. The initial prototype vehicle is built on a toy radio controlled car platform and is controlled by motor servo control phidgets and a Microsoft sidewinder force feedback wheel. Two Unibrain synchronized Fire-wire cameras are connected to the onboard mini-itx mother board. The stereo vision obstacle detection system is tested for depth reliability and object tracking. Table 1 presents the depth reliability results for the stereo vision camera. The data is collected in static camera conditions for two different light settings with a process rate of 2 Hz. The results show that the stereo vision system is reliable for identifying small obstacles in indoor conditions. The interface is implemented with VRJUGGLER [41], an open source portable C++ library for developing the VR platform. The interface uses Open Scene Graph [42], an open source high performance 3D graphics toolkit written in STANDARD C++ and OPENGL graphics programming language for rendering. The 3D VR model of the vehicle environment and the vehicle is built using MAYA, a 3D modeling tool. The prototype of this system is operational and currently in testing.

Table 1 Stereo vision depth results

Stereo vision–static camera			
Lighting	Object type	Measured depth (m)	Actual depth (m)
Bright	Small	0.52	0.5
Dull	Small	0.54	0.5
Bright	Large	0.57	0.5
Dull	Large	0.57	0.5
Bright	Small	1.05	1.0
Dull	Small	1.1	1.0
Bright	Large	1.06	1.0
Dull	Large	1.13	1.0
Bright	Small	1.6	1.5
Dull	Small	1.68	1.5
Bright	Large	1.6	1.5
Dull	Large	1.68	1.5

4 Discussion and Conclusion

The system essentially performs a switch operation from teleoperator control to autonomous control in situations where the operator cannot intervene. The vehicle then re-establishes its teleoperated state and follows the operator's commands. By allowing the vehicle to temporarily detach from the simulated state during the warning period, the operator continues driving in the simulated state with additional knowledge about the real state in the form of the wireframe box. Thus sensor augmentation enables the teleoperated vehicle to adapt to situations in which the operator inadvertently directs the vehicle toward a previously unmodeled object. In addition, VR aids the teleoperation process by improving the field of view and, thus, situational awareness. The research results lay the foundation for developing a VR based multimodal teleoperation system that operates with mixed autonomy. We are currently working toward integrating the VR interface with the obstacle detection and the vehicle adaptation system. The VR based multimodal teleoperation interface is expected to be more adaptable and intuitive when compared with other interfaces.

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