360 VR Based Robot Teleoperation Interface for Virtual Tour

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ABSTRACT

We propose a novel mobile robot teleoperation interface that demonstrates the applicability of robot-aided remote telepresence system with a virtual reality (VR) device in a virtual tour scenario. To improve the realism and provide an intuitive replica of the remote environment at the user interface, we implemented a system that automatically moves a mobile robot (viewpoint) while displaying a 360-degree live video streamed from the robot on a virtual reality gear (Oculus Rift). Once the user chooses a destination location among a given set of options, the robot generates a route to the destination based on a shortest path graph, and travels along the route using a wireless signal tracking method that depends on measuring the Direction of Arrival (DOA) of radio signal. In this paper, we present an overview of the system and the architecture, highlight the current progress in the system development, and discuss the implementation aspects of the above system.

1 INTRODUCTION

In addition to the entertainment industry, Virtual Reality (VR) has a myriad of potential application areas such as tourism [22], industrial design [6], architecture, real estate, medical care [7, 8], and education [20]. Among these applications, we are interested in the use of VR in a virtual tour scenario, where users can be provided with vivid touring experiences of real-world environments. For instance, in the 2017 Google I/O conference, Google introduced the motif of educational VR content using smartphones, with the main feature being that students can watch 360-degree field trip videos to realistically learn what they see in a book. Through the pilot studies, students could engage in more immersive, interactive, and social activities to obtain enhanced learning experiences.

Currently, such virtual tour applications have limitations mainly in terms of displaying a prerecorded media (video or panorama images) [9, 13, 21]. In [9, 21], the studies constructed a 3D map for a virtual tour of world cultural heritage, but they do not reflect real-time situation. In [13], the authors proposed a web-based telepresence system with 360-degree panorama image. This mobile robot platform adopts a landmark-based path planning entered by the users. The monitoring window provides an omnidirectional image but does not present it using a VR device. In addition, existing research and applications can only adjust the viewpoint only at a fixed position or move using manual control.

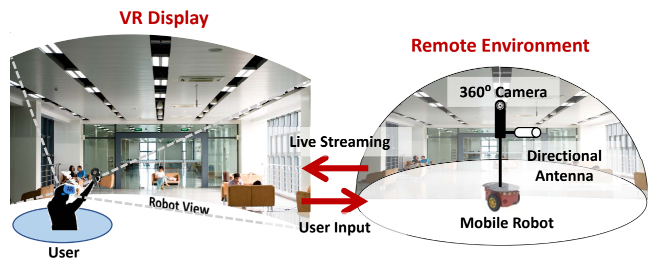


Figure 1: Illustrative example of the proposed VR interface.

Therefore, to mitigate such limitations and to realize a true immersive remote tour experience, this study proposes a system exploiting a VR display that produces a (near real-time) stream of the live 360-degree camera from a moving agent, specifically a mobile robot. Figure 1 illustrates an example scenario of the proposed system. The VR display shows the general interface so that the user who is equipped with a VR device can visualize the robot's 3D view and also control the robot to navigate through the remote environment (and change the viewpoint).

Recent years have witnessed active research in robot control using VR [4]. Particularly, immersive teleoperation systems using Head Mounted Displays (HMD) have been developed [10, 12]. Telepresence via the VR interface has shown to be easier and more intuitive than interfaces using liquid crystal displays and joysticks [3, 11]. For instance, in [1], a panoramic image is generated by joining the images taken by the omnidirectional camera on a Remotely Operated underwater Vehicle (ROV), and the VR display renders the combined image to improve the spatial perception in the underwater environment. In another study [14], a VR-based teleoperation interface is developed to allow users to perform specific tasks (assembling work) with a robot manipulator by mimicking the user's movements operated with the VR controller, which is more accurate than the conventional auto assembly used in automated processes.

These previous studies show that the VR interface can be more effective than the general display (such as a screen and a joystick controller) and can be used in real life through an integration of various systems. Taking inspirations from these works, in this paper, we propose a VR interface that incorporates a 360-degree camera from a mobile robot to better utilize the immersive experience of

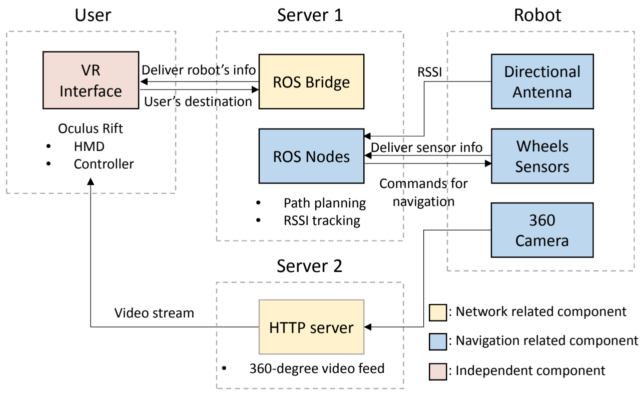


Figure 2: An overview of the proposed 360 VR based virtual (remote) tour system.

the VR display. Additionally, we design an autonomous navigation system for the robot through a wireless signal tracking method [15, 16]. This way, the users are expected to feel less fatigue (and not worry about fine tuned movement control) during the virtual tour experience through the VR display and have a more relaxed experience by minimizing the mental workload of navigating the environment.

Moreover, we expect that this platform can be generalized to realize an intuitive telepresence robot with a 360-degree camera video streaming interface in VR environments. Therefore, the usability of the VR based robot interface can be improved not only for the case of virtual tour but also broadly for the general telepresence case.

2 METHODOLOGY AND SYSTEM DESIGN

This section provides the overall architecture and discusses the user interface (UI) components for building the entire system.

2.1 System Architecture

To fully support the concepts of the envisioned virtual tour, we determine the following essential components: a VR video streaming and rendering, robot's signal tracking for the indoor autonomous navigation, and integration with VR interface. Figure 2 shows an overview of the overall system architecture. This categorizes the system into three entities: VR user interface at the client (User), a mobile robot which is the moving agent (Robot), and path planning and tracking function to generate the robot path (Server).

The robot's path planning features are integrated with Robot Operating System (ROS) [19], which is a powerful tool to simplify the development processes in robotic programming. The VR device and the robot are interconnected with an HTTP server for video streaming and Rosbridge[1]-based socket communications for robot control.

The 360-degree camera shoots a wide angle of view with distorted images through two fisheye lenses. Each fisheye lens captures the image with a viewing angle over 180 degrees. We used a camera (RICOH THETA S) which uses the proposed concept of combining two fisheye lenses to create a total of 360-degree image. Thus, by stitching the image frames like orange guidelines in Figure 3(a), a live video stream is rendered on a spherical object shown in Figure 3(b). Each fisheye image is presented on each hemisphere to produce a panoramic image in one perfect sphere. The 3D display the user can see is shown in Figure 3(c) (but stretched to 2D in the picture). Since each lens takes more than 180 degrees of photographs, when cutting and joining each sphere, a part of the original photograph is cut and merged. At this time, a slight boundary is created in the panoramic photograph. To improve the quality of streaming in terms of latency, we have to change the streaming settings such as reducing the bitrate of the video frame or streaming buffer size, because the camera needs to send two photos together, which is a feature of dual fisheye lenses. Due to this limitations, the changes of settings may degrade the quality of video. Therefore, there is a trade-off every time we do this post processing.

2.2 Telepresence Robot Server

Once the users select their destinations using the UI, the robot starts to plan the path based on the registered Wi-Fi Access Points (APs) and tracks the generated path using the directional antenna based wireless signal tracking method proposed in [15]. Wi-Fi signal tracking can take several advantages in terms of cost effective and supporting a consistent live streaming and path planning. By using indoor APs, the server can consistently keep streaming the live video in a farther space. Also, even though the selected destination is not in the line of sight, the path can be generated by passing through the waypoint AP where the robot is accessible at the current location.

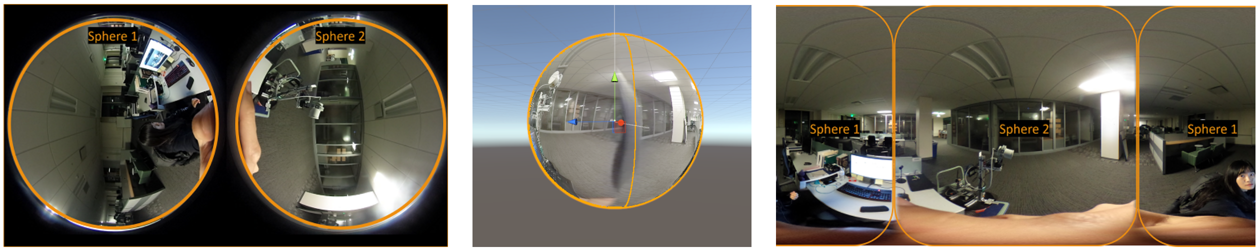
2.2.1 Hardware. Multiple APs are pre-installed throughout the environment, and they can serve as a way point or the destination for the robot's tracking as illustrated in Figure 4. This approach is cost-effective, compared to other infrastructures using beacons or RFID. It is also very effective as typical Wi-Fi APs can be utilized.

A 360-degree camera and a rotating Wi-Fi directional antenna are connected to the onboard computer on a mobile robot that provides ROS-compatible driver. The directional antenna measures the Wi-Fi Received Signal Strength Indicator (RSSI) within a specific angular range rotated by a servo pan system. This angular scan of the RSSI is then used to calculate the Direction of Arrival (DOA) of the Wi-Fi AP. The built-in ultrasonic sensors on the mobile robot are used to determine the DOA of the obstacles, which is then used to avoid obstacles on the trajectory.

2.2.2 Software. The software module includes a path planning algorithm, which finds the shortest path from a graph consisting of the location and name of indoor APs[2] and a signal tracking algorithm that allows the robot to closely follow this path, i.e., to enable the robot to track the assigned destination AP. The proposed system utilizes the Floyd-Warshall algorithm to find the global shortest path that contains whole information on the shortest routes between all vertices. Notably, the predefined graph has many more edges than vertices. In terms of cache memory efficiency, it is therefore more

[1]Rosbridge is a JSON API that provides a connection to non-ROS platforms.

[2] The graph is designed such that the vertex indicates a node including the location and name of the AP.



(a) Guideline of image stitch (b) Rendered sphere (c) Generated panoramic image at the HMD

Figure 3: Rendering process of the 360 video stream.

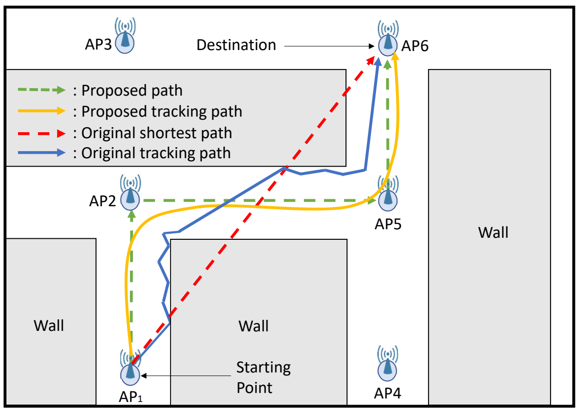


Figure 4: An example scenario in which the link between AP1 and AP6 are blocked (in the graph representation). Therefore, the path is generated as AP1-AP2-AP5-AP6.

beneficial to use a Floyd-Warshall algorithm over DijkstraâĂŹs algorithm, which is another famous shortest path algorithm

Figure 4 provides an illustration of path planning algorithm. The original shortest path from AP1 to AP6 (shown in red dotted lines) cannot be used because the path is actually blocked by the walls, thus the robot would move in blue line path by tracking AP6 and avoiding the walls. Obviously, these blue path are undesired for the virtual tour scenario. Moreover, if AP6 is too far away from the starting point, the robot cannot detect AP6 and reach the destination.

Therefore, if the distance from the user to the destination is too far to reach it or there are many obstacles on the way, a sub-optimum path is created to the destination via the other APs (shown in green dotted lines in Figure 4). We achieve this by having the edges in the graph adopt a radio signal propagation model [2] and enabling generation of more feasible paths that are less prone to obstacles and physical blockage. Thus, The cost of an edge increases when the path loss value gets higher.

The wireless signal tracking method measures the signal strength transmitted from the AP at different rotation angles (of the directional antenna), and then the robot heads in the direction of the wireless signal DOA. This approach is cost-effective, but if the AP is not in the line of sight, the characteristic of the radio signal is

Table 1: Integration with ROS (used ROS topics)

	Topic	Msg
Publisher	RosAria/cmd_vel	geometry_msgs/Twist
	DOA	std_msgs/Int32
Subscriber	RosAria/sonar	sensor_msgs/PointCloud
	RosAria/pose	nav_msgs/Odometry
	Pathwaypoints	std_msgs/String
	isMoving	std_msgs/Bool
	RosAria/motors_state	std_msgs/Bool

reflected or absorbed by the obstacles such as walls (shadowing and multi-path fading). Thus, DOA estimation is noisy in nature. The proposed system solves these issues through the combination of the following methods: moving window average, probabilistic filtering, and ultrasonic sensor fusion.

First, a moving window average and probabilistic filtering compensates for the fluctuating RSSI values. Assuming the robot only moves forward, the directional antenna gets signal strength measurements ($RSSI^f(\theta_i)$) from -90 to +90 degree range (of the directional antenna rotation). Due to the multi-path effects, the RSSI values are not consistent in every measurement even if the robot is stationary. Thus, the proposed method finds DOA using the smallest sum of average and variance of $RSSI^f(\theta_i)$ as follows:

$$\tilde{\Theta}_i = \underset{-90<\theta\leq 90}{\arg\min}\ \alpha \mathrm{VAR}(RSSI(\theta_i)) + \beta|\mathrm{AVG}(RSS(\theta_i))| \quad (1)$$

where $\tilde{\Theta}_i$ is the estimated DOA, $RSSI(\Theta_i)$ is the RSSI measurement at the ith angle, VAR($\cdot$) is the variance of $RSSI(\theta_i)$, AVG($\cdot$) is the moving window average of $RSSI(\theta_i)$ over n measurements, and α and β are positive gains.

The robot estimates the DOA after every angular scan by the directional antenna (we obtain one scan for approx. every second) with a 2.4 GHz frequency band. In addition, the robot uses the sonar sensor values to avoid obstacles. While the Wi-Fi DOA provides a general indication of where the robot is moving, the ultrasonic sensors provide local information to prevent collisions dynamically.

3 IMPLEMENTATION ASPECTS

This section discusses the implemented system with demonstrations and screen captures of the interface. Oculus Rift [18] and OpenVR

SDK are used for constructing the user interface. Pioneer 3-AT (P3AT, which uses a four-wheel differential-drive mechanism) is used as a moving agent that navigates the generated path. The developed system is shown in Figure 5(a).

As shown in Figure 5(b), the user can select and change the destination through the VR controllers interacting with UI components watching the 360-degree view of the robot displayed on the HMD of the UI. Additionally, the UI has a fixed canvas that shows only the accessible destinations from the current position and sends the selected destination information to the robot for path planning and tracking of AP nodes.

The signal tracking approach effectively finds a reasonable path, tracks the destination, and avoids obstacles while maintaining the best DOA. In other words, the robot scans RSSI and tracks the angle of the strongest signal strength while moving. Table 1 indicates the published and subscribed ROS topics from the robot. The client side subscribes to the 'DOA' topics to know the DOA value for each RSSI scan. Another published topic, 'cmd_vel' broadcasts a linear and angular velocity to the P3AT robot. The subscribed topics, such as 'RosAria/sonar', 'RosAria/motors_state' and 'RosAria/pose', return the current value of sonar sensor measurements, motor status, and odometer values, respectively. Also, 'Pathwaypoints' and 'isMoving' are custom topics to synchronize the movement of a robot with the client side. For instance, 'Pathwaypoints' topic delivers the name of the destination AP.

4 CONCLUSION AND FUTURE WORK

We proposed an intuitive robot telepresence system with VR based interface for a remote tour scenario. Specifically, this paper focuses on the development of a system that integrates a 360-degree video stream, VR based user interface, and a mobile robot for navigating the remote environment. The presented architecture can be used to enhance and realize an immersive telepresence system with more relaxed control experience compared to tiresome existing methods that use the manual control rather than autonomous navigation [3, 5, 11, 17].

Due to the characteristics of the 360 camera video, it is necessary to transmit a frame of a large size, so that in a normal network environment, a significant latency occurs. While testing, we observed several frame drops during playback of the video. This issue is affected by the performance and the state of the stream server, and it is found that it disappears in the local network with a wired connection. Currently, we are working to improve the wireless network experience mainly in terms of achieving a reasonable latency while maintaining a high-resolution 360-degree video for VR.

In the future, we plan to conduct a user study to qualitatively compare the difference between the VR interface using a 360-degree camera and the control environment with existing telerobot interfaces. Based on the outcomes of the user study, we will incorporate the user feedback and build up other essential functionalities to be added.

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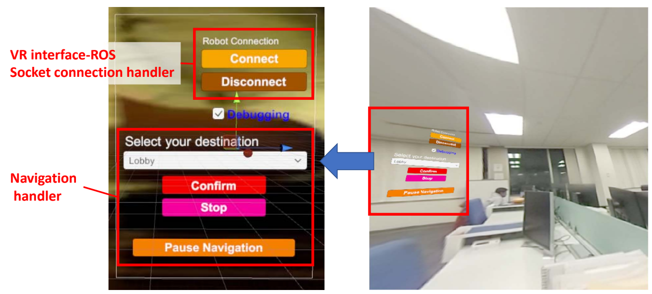
(a) The user with the VR interface (left), the mobile robot with a 360 camera (right)



(b) Control panel in the UI (left), Video stream on the HMD (right)

Figure 5: The proposed 360 VR based robot teleoperation interface for virtual tour.

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