Virtour: Telepresence System for Remotely Operated Building Tours

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Abstract

In this paper we describe Virtour, a public facing system for teleoperated building tours. It aims to facilitate lab and departmental tours by creating a system wherein prospective students can remotely operate a wheeled robot around the Building-Wide Intelligence lab and the rest of the computer science building. Virtour's server architecture builds on the existing Building-Wide Intelligence autonomous robot platform, which is capable of autonomous localization, planning, and navigation. The web client interface is built using modern web technologies to allow users to control our robots from any internet device (e.g., cellphone, tablet, computer). Virtour provides an interface where users can view what the robot sees, as well as control the robot's rotation and camera angle in real time. Navigation is provided using a map where users can select their desired destination and have the robot autonomously navigate there. This approach eliminates the risk of human navigation error by abstracting away movement commands. As a result we can provide users an immersive telepresence system, which is safe to use, and provides a service to our lab and department by allowing anyone to visit to experience the areas first-hand.

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1 Introduction

The University of Texas at Austin has a constant stream of visitors and tours of the campus. Of special interest to us are the large number of tours given at our computer science building. The tour guests range in ages and backgrounds, and tend to be prospective students to both undergraduate and graduate programs, or visiting faculty. Unfortunately, there is a large population of prospective students that are unable to physically come to our campus and are thus unable to partake in the conventional tours.

We designed Virtour to address this problem. Virtour is a public facing system for teleoperated building tours. Virtour builds on the existing Building-Wide Intelligence (BWI) autonomous robot platform. It utilizes the lab's autonomous wheeled robots which can localize, navigate, and perform tasks without human intervention for long periods of time. Through the use of modern web and robot technologies, Virtour allows untrained public users to remotely control our robots in what we call a virtual tour. Our system is created under the principle of shared autonomy, which aims to balance external control abilities while maintaining our rigorous standard of safety and security for the robots and people involved. As such, it provides the user control over what the robot is doing, while simultaneously using the existing the autonomous navigation capabilities and obstacle avoidance to ensure safety and correct operation.

The two major contributions of this work are as follows. First, we present the server framework as described in Section 5. This is system can be extended and used to expose arbitrary robot capabilities to the internet, and can be used for much more than just campus tours. Furthermore, this system was built with security in mind, as described in Section 6, which makes it secure for public web deployment. Our second contribution is the novel approach to the user interface client, which is designed to be accessible by all modern internet-capable devices and adheres to modern web 2.0 standards, as described in Section 4.

2 Related Work

Web-based tours have been an active area of research in the past. The earliest virtual tour system was built to serve as a museum tour guide in 1998 by Burgard et al. (1998). Their robot, Rhino, operated mainly as a physically interactive tour guide that museum visitors could approach and request tours from, but also supported occasional web-based tours where online visitors could vote on defined tours to spectate. Their web-based interface provided images from the on-board camera as well as static cameras placed throughout the museum, and allowed the user to download a Java applet to see real-time information. Web control was limited to voting on a desired tour (from a pre-programmed list) and viewing the robot's image stream.

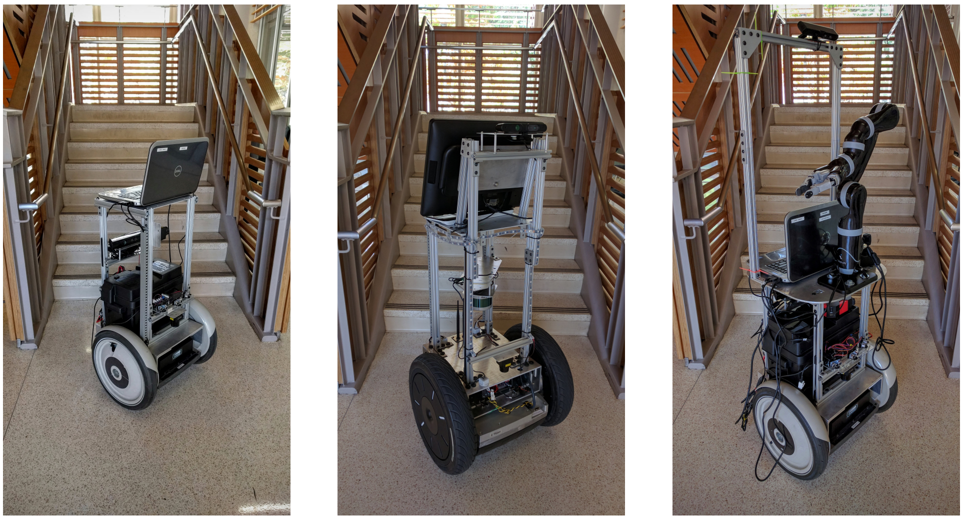
Later work introduced a second-generation museum tour-guide robot by Thrun et al. (1999) named Minerva, which improved on the work done by Burgard. Most of their improvements were in the areas of localization, mapping, simultaneous localization and mapping (SLAM), and human robot interaction (HRI). They improved the virtual tour interface by allowing arbitrary selection of navigation goals, rather than a pre-selected list. However, web control was still limited and their real-time information display required the download of a Java web-applet.

Kim et al. (2004) developed Jinny in 2004, which was yet another autonomous tour-guide robot. Their relevant contribution was the upgraded web-based interface which allowed the user to interact with a natural language parsing system to ask questions, as well as request actions. Their system is built using Java and ActiveX, both of which require special installation for the users.

Virtour differs from these related works in a number of ways. The first is that Virtour's main purpose is to be a telepresence tour system, and thus gives web visitors priority in controlling the robot (unlike Rhino or Minerva, which only occasionally allow web control). Our web client is unique in that it uses only modern web standards and does not require the end-user to download any extra software (e.g., Java, ActiveX). Thus, Virtour is truly portable and can accessed from any web-connected modern device. Virtour is also unique in that it provides the end-user with real-time video feedback and information about the robot. For example, the robot's position is updated on the website in real-time without requiring any additional simulation software. Furthermore, the user's actions are performed in real-time and the results are shown almost immediately; therefore, if a user request for the robot to rotate, he or she will be able to see the robot's camera feed update instantly. As part of Virtour's goal of ease of use, it uses bandwidth scaling of video streaming to reduce the quality of the video according to the end-user's internet connection. Finally, Virtour is novel because it provides the end user with a wide variety of ways of interacting with the robot. Rather than just providing navigation and video streaming, it allows the user to deliver spoken messages and perform tasks.

3 Building Wide Intelligence

Virtour is a part of the Building Wide Intelligence (BWI) project, which aims to develop fully-autonomous mobile robots that exists as permanent inhabitants of UT's Computer Science departmental building. The BWI project lies in the intersection of Artificial Intelligence and Robotics, and works to create robots that are useful as research platforms, as well as helpful



(a) Segbot v2 (b) Segbot v3 (c) Segbot arm

Figure 1: The three active robot platforms in the BWI Lab

to the humans in the building.

Virtour runs on the BWI segbot robot platform — our in-house robot platform which has been in development for over four years. Currently, our lab has four active robots. Three of the robots are based on the older generation hardware and software (Version 2 as depicted in Figure 1a) one of which is also equipped with a Kinova Mico Arm[1] (shown in Figure 1c). We have one Version 3 robot (depicted in Figure 1b), which has been our pilot test as we transition all our robots to new hardware and software. Virtour supports both platform versions, and will adapt its features accordingly (based on which robot you connect to). However, since Virtour is mostly used on the Version 3 robot, we will only describe the latest hardware platform.

3.1 Hardware Platform

All of our robots are powered by the Segway Robotics Mobility Platform (RMP). Our latest generation robot uses the newer RMP 210 version, which comes with two integrated lithium-ion batteries and can navigate at speeds up to 8 m/s and carry up to 45 kg of payload. The frame was designed in-house and supports a large number of sensors. For navigation, localization, and obstacle avoidance, we use a Velodyne VLP-16 Puck LIDAR. Point clouds (3D voxel map) and video data are provided by an Xtion Pro, a device very similar to the Microsoft Kinect. Our latest generation robots also have an additional Hokuyo URG-04LX laser range finder to compensate for the

[1]This version of the Kinova arm has 6 degrees of freedom, a reach of 700 mm, and a mid-range payload capacity of 2.1 kg

LIDAR's blind spots. The robot is equipped with a custom-built computer[2] which runs Ubuntu 14.04. The computer is powered by the RMPs battery, thus removing the need for an external car battery (which was present in our Version 2 robots). The battery life on a running robot is approximately 6 hours when actively using the base for navigation, and 10 when stationary.

3.2 Software Stack

Our robots's software architecture is based on the Robot Operating System (ROS) built by Quigley et al. (2009), which provides us with both the infrastructure to run our robots as a distributed node system as well as the messaging framework to connect all the different components together. ROS also provides us with access to many community packages, such as device drivers, navigation implementations, and planning systems.

Our robots use a hierarchical task-planning architecture for navigation planning (Zhang et al., 2014). A navigation request begins with the logical planner, which uses Answer Set Programming (ASP) to describe the environment (Lifschitz, 2008) – such as which corridors connect with which hallways, and which doors are open – and then uses the ASP solver CLINGO to generate possible plans (Gebser et al., 2014). It then moves to the logical navigator which uses current and previous laser readings (in the form of occupancy maps) and what it knows about the environment to create the navigation plan. Finally, the local planner uses the immediate sensor readings to send commands to the segway base and avoid any obstacles.

Almost all of the software that runs on our robots is open source. Furthermore, all of the code that we write is also open source and available in the public domain[3]. Our software is also released as ROS packages back to the community and is available to install as binaries.[4]

3.3 BWI Related Work

The BWI lab has done extensive work on the planning and learning of action cost. This enables our robots to plan high-level tasks such as navigating to floors using hierarchical planning (Yang et al., 2014; Khandelwal et al., 2014). Using the robot's point-cloud sensors Gori et al. (2015) developed a system to perform human activity recognition. Khandelwal et al. (2015); Khandelwal & Stone (2014) have also developed systems for multi-robot guidance that enable our robots to guide humans to their desired locations. The segbot arm robot has also allowed the lab to develop systems for grounded language learning by playing a game of I Spy (Thomason et

[2] 3.9Ghz i7 processor, 16GB ddr3 RAM, Gigabyte GA-Q87TN motherboard, HDPLEX H1.S heatsink case, and a Acer FT200 monitor

[3] `https://github.com/utexas-bwi`

[4] `http://wiki.ros.org/bwi` and `http://wiki.ros.org/segbot`

al., 2016) as well through human-robot dialog (Thomason et al., 2015). Similarly, the robot arm was used to perform object exploration and ordering using haptic exploratory behaviors (Sinapov et al., 2016).

4 The Web Client

Virtour consists of two platforms: the user facing client, and associated software that runs on the robots. The user client is accessible from a web browser and is built using modern web frameworks to adhere to current web development standards and simultaneously support as many platforms as possible. We decided to use a web-based client because of the increasing prominence of web browsers in people's lives. Furthermore, a web based approach means that our end-users do not have to install any additional software to connect with or use the robots, thus reducing the friction for using our system.

4.1 Client Architecture

The web client was developed using HTML5 and CSS3 to create the visual interface and JavaScript to provide the functionality and connectivity. The web client consists of multiple handlers and ROS clients which are used to communicate with individual robot components such as the tour manager and navigation managers. All ROS requests are routed through roslibjs[5] which serializes them and uses a SOCKET connection to send them to the robot. The image and video streaming are done without roslibjs for optimization reasons and are two separate connections to the robot. In total, the web client communicates to the robot using three different connections. The hierarchy of components and connections can be seen in Figure 2.

4.2 Modern Approach

The web client is designed to be simple and functional while still being aesthetically pleasing to end users. It uses a grid system powered by the popular front-end library Bootstrap 2.0[6] to create a fully responsive web layout. This allows us to support any web-powered platform (e.g., mobile devices, tablets, and computers) by making the website scale and re-organize based on the specifications of the device such as the screen resolution and screen size. An example of responsive scaling can be seen in Figure 3.

When on the website, the user is greeted by a list of our currently active and available robots (as seen in Figure 3). Each robot is represented by a name and associated picture. From here, a user can select a robot to connect to by clicking on the robot's name or image. When the user clicks on the

[5] `http://wiki.ros.org/roslibjs`
[6] `https://getbootstrap.com/`

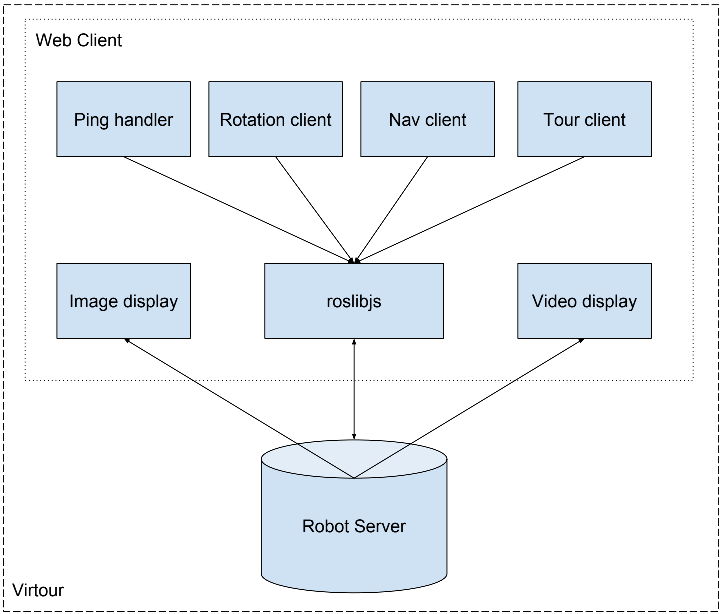


Figure 2: Overview of the Virtour client structure and hierarchy of communication between the different components

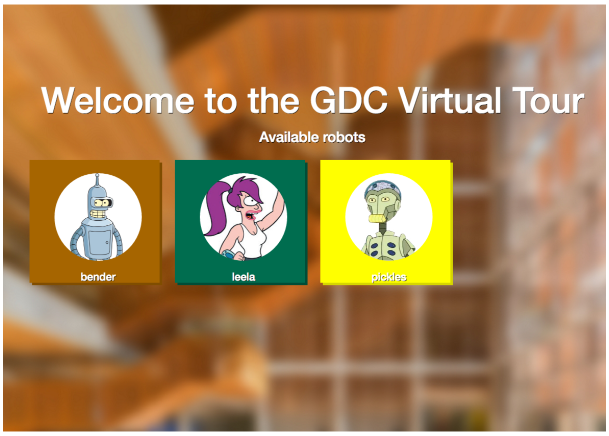
robot, the web client will initiate a tour request to the specified robot. If the connection is successful the client will switch into a tour session.

Tour sessions can be either led or spectated. When spectating, the user has no control over the robot but can see the video stream, robot status, and the location of the robot on the map in real time. When leading a tour the user can actively instruct the robot to perform operations. Each tour can have at most one leader, but no limit to the number of spectators. We built Virtour this way to ensure there is a consistent leader experience (to avoid tour contention by multiple users), and for security reasons, since we can control whether a leader is allowed or not. If the tour has no existing leader and tours are allowed then a visiting user can choose to become tour leader by pressing the "Become Leader" button. Upon success, it will present the user with the leader user interface (UI).

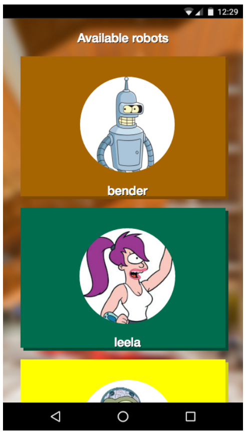
4.3 Leader User Interface

The leader UI adds a number of components to that allow the user to control the operations of the robot. The list of available remote-control capabilities is as follows:

- Rotate the robot



(a) Desktop view



(b) Mobile view

Figure 3: Landing page whenever someone visits the website, from here users can select which robot to connect to

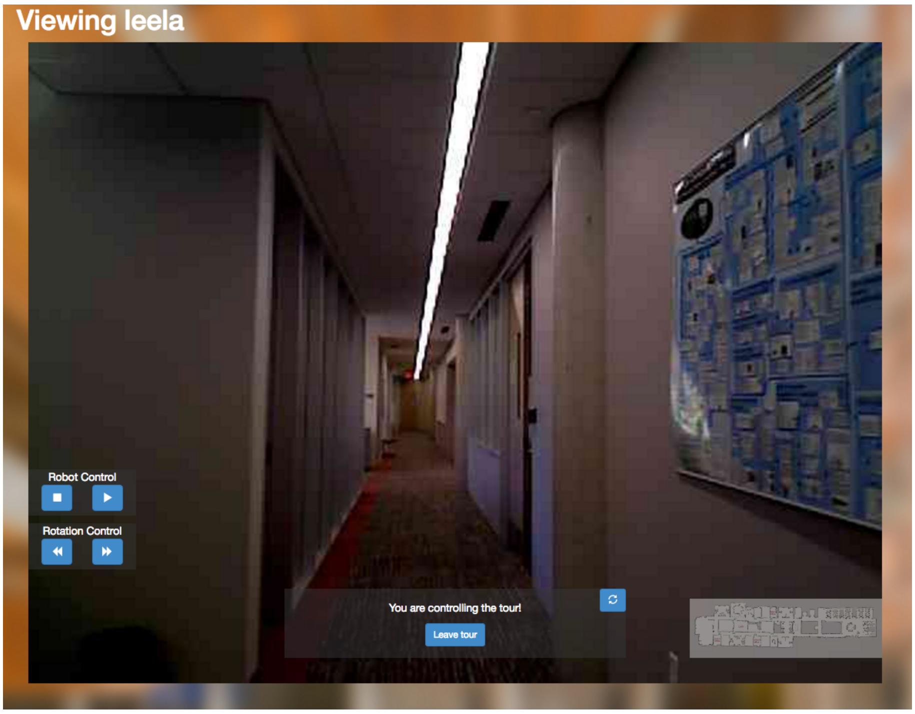


Figure 4: The controls available to the leader whenever they are leading a tour

Figure 5: Navigation interface for leaders which is displayed whenever the mini map is pressed, from here they can select a room or door to navigate to

- Navigate to a room
- Navigate to a door
- Speak a message (using text-to-speech)
- Deliver a spoken message (using text-to-speech) to a location
- Pause and resume a scavenger hunt task
- Move the robot's pan/tilt camera unit

The user can interact with the interface to request any of the tasks. For example, whenever the user is the leader, a pair of directional arrow buttons is shown which will immediately rotate the robot when pressed. Navigation commands are accessed within the navigation pane which can be accessed by clicking on the mini map.

Whenever a user first connects to a robot, the web client will query the robot for the capabilities that it has (e.g., which generation robot, which cameras it has access to, if the camera has servos, etc) and then adapt the user interface accordingly to support whichever robot the user is connected to.

To maintain leader consistency, the leader UI will ping the server at a known interval to ensure the leader is still connected. This allows the server to become aware of a dropped connection. Thus, if the user closes

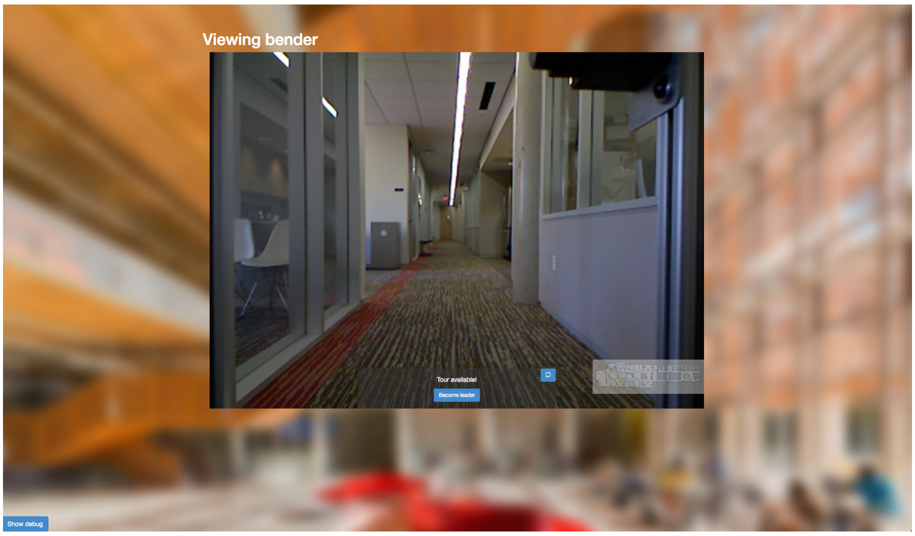


Figure 6: What a user might see whenever they connected to a robot but are not the tour leader

the window or the ping fails, the leader will relinquish the leader status so other users can control the robot.

4.4 Guest User Interface

The guest UI is the default interface presented to the user whenever he or she connects to a robot. The predominant view is the live stream from the robot's camera, which is shown in the center. The robot's camera is placed strategically so as to provide the user with the robot's point of view. This makes the user experience more realistic and makes the tour more engaging.

The interface also displays a mini map of the floor the robot is on, with a marker to indicate the robot's current position. If the robot navigates to another floor (via the elevator), Virtour will recognize the floor change and show the most up-to-date map of the current floor.

Finally, the guest UI has a status box which displays whether or not a tour is ongoing, allowed, or disabled. From here the user can request to become tour leader (if available), or wait for a tour to be available. All our robots have the guest UI enabled at all times, so that users can remotely connect to the robots and experience what they are doing. For privacy reasons, the robot will have turn on indicator lights (using the mounted individually-addressable LED strips) whenever there is someone streaming video (at the moment only supported in our latest generation robot).

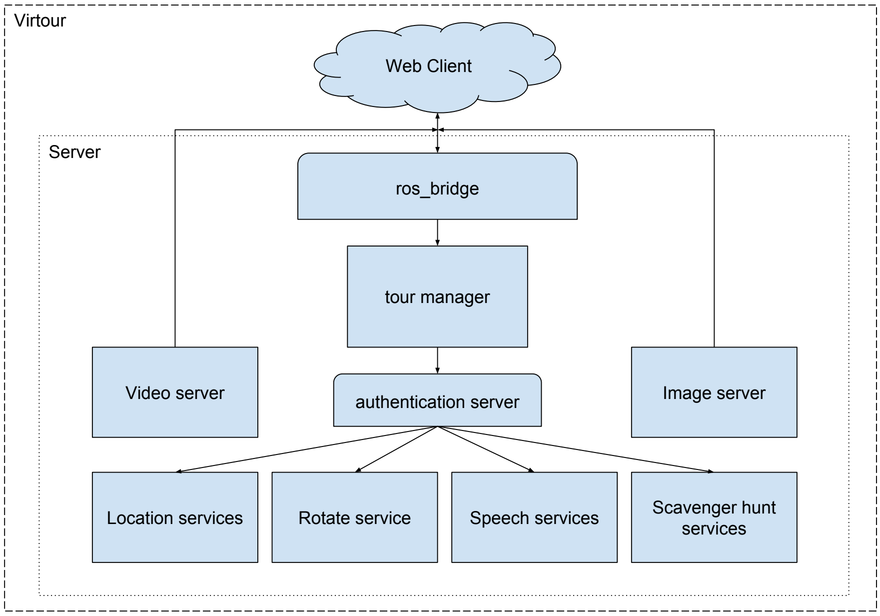


Figure 7: Overview of the Virtour server structure and hierarchy of communication within the server nodes and the web client

5 The Server

The server consists of a number of components which run on the physical robot to enable the web client to perform the required operations. Most communications from the web client go through the ROS bridge node, which is responsible for translating the serialized socket commands to normal ROS commands. This is the case for all action requests and commands. From there, requests are sent to the tour manager, which will authenticate the requests (to ensure they are validly formed and come from an accepted source) and then delegate them to their respective service providers. The robots also have two other open connections for streaming images and video to web clients. The hierarchy of communications can be seen in Figure 7.

5.1 Tour Manager

The tour manager serves the role of maintaining tour integrity and managing active connections with all the clients that are connected to the robot. It maintains of an internal state machine to keep track of whether tours are enabled and, if so, whether one is active. It will also maintain connection with the tour leader through pings to ensure the leader remains alive. If the leader disconnects (by closing the page) or is disconnected (missing a ping), the tour manager will demote them and make tour leadership available again. The tour manager is also responsible for granting tour leader status to clients that properly request it whenever tours are enabled.

5.1.1 Robot Control

The server-side code powering the remote robot control consists of various service providers which use the tour manager to authenticate requests, and then translate them to the appropriate robot commands. For example, the rotate control will take the rotate command (if properly authenticated) and then translate it to raw segway base navigation commands. Message delivery and speaking requests will be routed to their appropriate service providers. Similarly all door or room navigation requests will go to the logical planner in the form of ASP goals. For example, a request to navigate to a specific office will be turned into an ASP goal such that it is impossible for the robot to not be in that location. The navigation and planning stack then take over and will perform the planning and navigation required to accomplish the goal.

5.2 IP management

In order to manage the IP addresses of all the robots, we created smallDNS[7] (small multi-agent locally listable DNS). SmallDNS keeps track of the IP addresses of each of the robots (which are dynamically assigned and thus change from time to time). Furthermore, it also keeps track of which robots are available and running via series of pings. This means that the end user does not need to worry about the changing IPs of the robots or which ones are alive. So when the user visits the home page (Figure 3), they will see the list of currently active robots and will be able to connect to each without having to know the IP address.

SmallDNS consists of a simple DNS server running on our master server, which is accessible from all our robots. The server was written in Python and can handle HTTP requests. It can respond to update requests whenever a robot has a new IP address, as well as conventional GET requests to display the list of robots over text or JSON[8]. It stores everything in-memory for performance reasons, but will write it to disk periodically so that we do not lose information in case the server is stopped.

Each of the robots has a bash script which checks the robot's IP address against the last update IP address to see if there is a change. If the IP has changed, the robot will perform an update request on the server to inform it of the new address. This script is configured using a cronjob which runs every three minutes.

[7]Source code is available at `https://github.com/pato/smallDNS`

[8]JavaScript Object Notation - a human-readable data-interchange format

6 Security and Safety

Security was a top concern in designing Virtour since the system allows external parties to remotely operate our robots. Our two main security objectives were to prevent unapproved or harmful interactions with the robots and to prevent unauthorized access to Virtour. Furthermore, since the robots are physically navigating potentially crowded spaces, we wanted to make sure that safety was a top priority.

6.1 Client Side

The client works to prevent unapproved interactions by only presenting the user with ability to interact with the robot in the approved behaviors. On the JavaScript client-side, we also only create service and action clients (the communication methods that are used to request actions on the robot) that perform specific tasks, rather than general-purpose clients. This reduces the likelihood of an end-user issuing unapproved commands. To identify users, each client is assigned a universally unique identifier (UUID) which is used to authenticate all communication with the robot.

6.2 Server Side

For security reasons, we only allow outside parties to become leaders (and thus have control of the robot's operations) if we explicitly enable virtual tours on the robot. Unlike the guest UI which is enabled any time the robot running, the server implementation of leader control is disabled by default to prevent unexpected access. Furthermore, all operations which affect the state of the robot (ie: rotating and navigating) require proper authentication. The server keeps track of the UUID of the currently active leader, and will only grant that specific client the ability to control the robot. This prevents unauthorized users from executing actions on the robot. To prevent denial of service by any one leader (by not relinquishing their leadership or dropping the connection), the server uses the ping system to ensure that the leader is alive and connected. Furthermore, there is a 15 minute time limit per leader, to avoid a single leader taking perpetual control of the system. Finally, we always have the option to disable tours (via the tour manager) which will immediately evict any active leaders and revoke all remote control of the robot.

Safety for users and the robot is ensured through the use of shared autonomy. Whenever users request navigation to locations via the client UI, the robot will perform the navigation using the full navigation stack which includes the global planner and local obstacle avoidance. Furthermore, the server has a whitelist of pre-approved locations the users can request on the client which it uses to verify all navigation requests, to prevent navigation

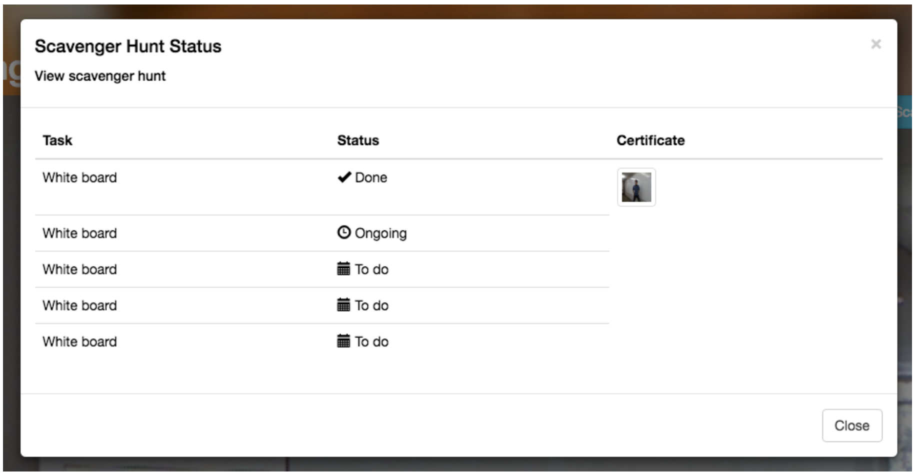


Figure 8: The scavenger hunt task list displays all the active tasks along with their status, and if complete will allow the user to view the certificate

to incorrect or invalid locations. Finally, because of the way rotation is implemented, the robot stays entirely within its footprint when it rotates. When combined with the safety of our navigation stack, this means that in-place rotation is always safe.

7 Scavenger Hunt Integration

In addition to the remote control capabilities available through our website, Virtour was also fully integrated with the Robot Scavenger Hunt by Zhang et al. (2016). The Robot Scavenger Hunt is a framework of tasks that AI capable robots can complete autonomously. These are used to evaluate and compare the performance of autonomous robots that reside in larger spaces and operate autonomously for long durations of times. We supported all four tasks in the task library, which require the robot to find a human wearing a specific colored shirt, to follow a human for more than 10 meters, to deliver a given object, and to find a specific object. All four of these task variations require a certificate of work which are images of the task being accomplished (e.g., a picture of a human wearing a blue shirt). Whenever a robot participates in the scavenger hunt, it is assigned a random set of daily tasks that it must then work to finish that day.

Whenever a user uses Virtour to connect with a robot running the scavenger hunt, Virtour will detect the scavenger hunt and allow the users to interact with the scavenger hunt. For example, the user can see the list of the currently running tasks by clicking on the scavenger hunt button. The server-side portion of Virtour comes integrated with an HTTP image web server which is used to provide the user interface with images of the complete tasks, so if available, Virtour will display the certificates on the website as thumbnails on the scavenger hunt task list (illustrated in Figure 8) but they can expanded to see the full-size image by clicking on them. Finally, if the user is the leader, they can also control the operation of the scavenger hunt by stopping and resuming the current task. This allows a user to stop the current scavenger hunt task, then navigate the robot elsewhere or perform any other supported operation, and resume the scavenger hunt later.

8 Conclusions and Future Work

In this paper, we introduced a novel telepresence system which gives users shared autonomy over the control of our robots. This system allows users to use their common internet-powered devices to access the Virtour website. The Virtour website allows users to securely join an existing tour as spectators, or, if available, to optionally lead a tour. This would give them the ability to make the robot navigate to desired locations and doors, as well as deliver messages, or perform scavenger hunt tasks. Users can experience the tour through the on-board camera which is streamed dynamically to the website as well as to track the robot's movement using the real-time map.

Further work could extend the navigation system to allow the users point-and-click navigation to arbitrary points, while still maintaining shared autonomy. There is also work in adding more ways for remote users to interact with the robot's environment, such as using actuators or interacting via a mounted arm on the robot. There are multiple other ways of improving the client user interface such as adding the display of other information such as distance traveled or battery level information.

Finally, although our focus has been on remotely operated building tours, Virtour has laid the groundwork for a more complete telepresence robot system which could target other commercial uses such as hospitals (for family visits, or nurse checkups), as well other research-oriented projects such as HRI studies or robot monitoring systems. Most of our work is directly applicable and can be tailored to many different uses, since the communication, authentication, and interaction protocols that Virtour uses can be used independently.

9 Acknowledgments

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References

Burgard, W., Cremers, A. B., Fox, D., Hähnel, D., Lakemeyer, G., Schulz, D., … Thrun, S. (1998). The interactive museum tour-guide robot. *AAAI/IAAI*, 11–18.

Gebser, M., Kaminski, R., Kaufmann, B., & Schaub, T. (2014). Clingo = ASP+ control: Preliminary report. *arXiv preprint arXiv:1406.3694*.

Gori, I., Sinapov, J., Khante, P., Stone, P., & Aggarwal, J. (2015). Robot-centric activity recognition 'in the wild'. In *International Conference on Social Robotics* (pp. 224–234).

Khandelwal, P., Barrett, S., & Stone, P. (2015). Leading the Way: An Efficient Multi-robot Guidance System. In *Proceedings of the 2015 International Conference on Autonomous Agents and Multiagent Systems* (pp. 1625–1633).

Khandelwal, P., & Stone, P. (2014). Multi-robot human guidance using topological graphs. In *AAAI Spring 2014 Symposium on Qualitative Representations for Robots.*

Khandelwal, P., Yang, F., Leonetti, M., Lifschitz, V., & Stone, P. (2014). Planning in action language BC while learning action costs for mobile robots. In *Proceedings of the 24th International Conference on Automated Planning and Scheduling* (pp. 472–480).

Kim, G., Chung, W., Kim, K.-R., Kim, M., Han, S., & Shinn, R. H. (2004). The autonomous tour-guide robot Jinny. In *Intelligent Robots and Systems, 2004.(IROS 2004). Proceedings. 2004 IEEE/RSJ International Conference on* (Vol. 4, pp. 3450–3455).

Lifschitz, V. (2008). What Is Answer Set Programming?. In *AAAI* (Vol. 8, pp. 1594–1597).

Quigley, M., Conley, K., Gerkey, B., Faust, J., Foote, T., Leibs, J., … Ng, A. Y. (2009). ROS: an open-source Robot Operating System. In *ICRA Workshop on Open Source Software* (Vol. 3, p. 5).

Sinapov, J., Khante, P., Svetlik, M., & Stone, P. (2016). Learning to Order Objects Using Haptic and Proprioceptive Exploratory Behaviors. In *Proceedings of the 25th International Joint Conference on Artificial Intelligence (IJCAI).*

Thomason, J., Sinapov, J., Svetlik, M., Stone, P., & Mooney, R. J. (2016). Learning Multi-Modal Grounded Linguistic Semantics by Playing" I Spy. In *Proceedings of the Twenty-Fifth International Joint Conference on Artificial Intelligence (IJCAI).*

Thomason, J., Zhang, S., Mooney, R., & Stone, P. (2015). Learning to interpret natural language commands through human-robot dialog. In *Proceedings of the Twenty-Fourth International Joint Conference on Artificial Intelligence (IJCAI).*

Thrun, S., Bennewitz, M., Burgard, W., Cremers, A. B., Dellaert, F., Fox, D., ... others (1999). MINERVA: A second-generation museum tour-guide robot. In *Robotics and Automation, 1999. Proceedings. 1999 IEEE International Conference on* (Vol. 3).

Yang, F., Khandelwal, P., Leonetti, M., & Stone, P. (2014). Planning in answer set programming while learning action costs for mobile robots. In *AAAI Spring 2014 Symposium on Knowledge Representation and Reasoning in Robotics (AAAI-SSS).*

Zhang, S., Lu, D., Chen, X., & Stone, P. (2016). Robot Scavenger Hunt: A Standardized Framework for Evaluating Intelligent Mobile Robots. In *Proceedings of the Twenty-Fifth International Joint Conference on Artificial Intelligence.*

Zhang, S., Sridharan, M., Gelfond, M., & Wyatt, J. (2014). Towards an architecture for knowledge representation and reasoning in robotics. In *International Conference on Social Robotics* (pp. 400–410).