

Real-Time Monitoring and Remote Guidance of Mobile Robots Using Multimodal Digital Twins

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Abstract—Although digital twins have been playing a pivotal role in the management of the lifecycle of physical robotic systems of systems, they have hardly been employed to guide mobile robots in real-time. In fact, the guidance of such systems requires functionalities, including the perception of targeted locations and avoidance of collisions, that build upon spatial information beyond internal robot states usually acquired using proprioceptive sensors. In this case, exteroceptive sensors help meet this demand. Nevertheless, such sensors have received little attention thus far in the development of digital twins. On the other hand, the completion of various spatial objectives, such as reverse motions, might require the awareness of the historical internal state of the distant robot. For instance, the current energy budget is likely to constrain the reachability of the initial state after a while, even when spatially and kinematically feasible. We therefore embrace these challenges with a multimodal approach to provide and employ digital twin of mobile robots. We collect data about the internal state and camera-captured neighborhood of the robot in real-time. The robot operator is thereby provided with a multi-dimensional state and perception view that characterizes the robot, elevates situational awareness, and facilitates decision support. We then develop a versatile graphical interface that helps monitor and steer mobile robots. Since the bidirectional approach is intuitive and user friendly, even novices can remotely guide a mobile robot with multi-modal situational awareness. We show the versatility and effectiveness of our approach in use case scenarios in practice.

Index Terms—Robotics, Multimodal Data, Digital Twins, Industry 4.0, Industry 5.0, Society 5.0, Human-Mobile Robot-Interaction, Systems of Systems

I. INTRODUCTION

The Robot Operating System (ROS) stands as a ubiquitous middleware framework in the realm of robotics serving as a foundational platform for constructing robot systems and developing robot applications. However, for individuals possessing limited or no prior exposure to robot software, navigating the intricacies of ROS can prove challenging. This challenge is particularly pronounced for users who rely on robotic assistance and require an intuitive means of interacting with these machines. In response to this need, a platform-independent web application was meticulously crafted. Designed with accessibility in mind, this application facilitates seamless monitoring and control of locally networked robots. Users gain access to critical information, including battery status and motor temperatures, all presented through an intuitive web interface. Notably, this application is compatible



Fig. 1. Picture of the Husky UGV by Clearpath

with any device supporting web browsers, ensuring widespread accessibility and usability. The robotic platform employed in our research is the Husky Unmanned Ground Vehicle (UGV) manufactured by Clearpath Robotics. This medium-sized mobile robot depicted in Fig. 1 operates on the ROS2 distribution Humble Hawksbill. The Husky UGV boasts a substantial maximum payload capacity of 75 kg rendering it suitable for transporting and accommodating various auxiliary components. Researchers can mount additional robots, peripherals and specialized tools on this versatile platform. Its robust

design and adaptability make it an ideal choice for a wide range of robotic applications [2].

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III. IMPLEMENTATION AND DESIGN

The system architecture of the web application can be dichotomized into distinct backend and frontend components. These components synergistically leverage an array of tools and frameworks to facilitate seamless operation.

A. Backend

The web application is a Flask application. Flask is a micro web framework that is characterized by providing the core features to create a python web based application. Flask is also very flexible and highly expandable [4]. The following tools are used in the backend:

- SQLAlchemy is a Python SQL toolkit and can be integrated into Flask as an extension. SQLAlchemy allows users to link Python objects to SQL databases using Object-Relational Mapping (ORM). This allows, for example, database queries to be made using Python code instead of SQL commands. The extension is also database-agnostic. Python code can be used unchanged for various SQL-based databases such as SQLite, PostgreSQL or MySQL. SQLite3 is used as a database to store ROS and user data. SQLite3 is a serverless database. This characteristic renders it operable in a self-contained manner, devoid of any supplementary software dependencies or intricate configuration settings. Consequently, it exhibits resource efficiency by minimizing the utilization of extraneous computational resources.
- The Roslibjs JavaScript library and the Rosbridge v2.0 protocol are used to establish bidirectional communication with the robots and the web application. The Rosbridge server it contains, provides a WebSocket connection so that web browsers can communicate with Rosbridge. Roslibjs is employed as a JavaScript library to interact with ROS topics, enabling the subscription to and publication of these topics. A quintessential example of this interaction is the publication of a geometry_msgs/Twist message on the /cmd_vel topic of the Husky robot which initiates its movement. The geometry_msgs/Twist message is composed of linear and angular vectors, which represent the velocity in free space. Specifically, these vectors are expressed in terms of m/s and rad/s, respectively, in a right-handed coordinate system. In the context of the Husky robot, a linear velocity of 1 m/s in the positive x-direction corresponds

to forward movement at a speed of 1 m/s. To induce rotational movement, an angular velocity is specified in the z-direction. Positive and negative values correspond to counterclockwise and clockwise rotations respectively.

- The Web Video Server is a ROS package that allows HTTP streaming of ROS image topics. This integrates the live image from a Zed 2i camera from StereoLabs into the web interface.
- Flask-Login and Werkzeug.security extensions are used to handle login, logout, and session functions as well as to enhance user password security through password hashing. Additionally, it is possible to register new user accounts and assign permissions/priorities via...

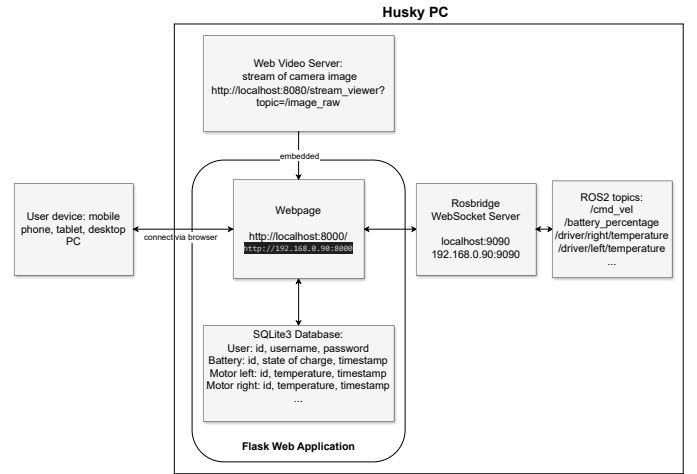


Fig. 2. Backend architecture of the web app

Fig. 2 illustrates the backend architecture and the method by which users can interface with the Husky robot via the web application. This system is designed to operate on any device equipped with a web browser, utilizing the IP address of the Husky's onboard computer for connectivity. The user interface provides real-time access to a stream of visual data from a Zed 2i camera as well as control options for the robot. Additionally, it displays current ROS data, including metrics such as the battery State of Charge (SoC) and motor temperatures. A key feature of this system is its ability to track and store historical data in the SQLite3 database. This allows for longitudinal analysis of the robot's operational data, which can be instrumental in performance optimization and troubleshooting. This system provides a flexible and accessible platform for robot control and data monitoring. It underscores the potential of web-based interfaces in enhancing the usability and functionality of robotic systems. The use of an IP-based connection protocol further emphasizes the system's adaptability and broad accessibility. The incorporation of a database for data tracking and storage demonstrates a commitment to data-driven decision making and performance optimization.

B. Frontend

The primary objective of the front-end design is to enhance user-friendliness through visually intuitive elements. Additionally, the application aims for robust platform independence, ensuring that users are not constrained by specific devices when accessing the web user interface. To achieve this, the web application is meticulously crafted to be compatible with a wide range of devices including desktop PCs and mobile platforms. The tools discussed here are then shown in IV in the graphical user interface.

- Leveraging the free and open-source CSS framework Bootstrap version 4.6, we optimize responsiveness and seamlessly integrate with prevailing web standards such as HTML5, CSS3, and JavaScript. In the context of Bootstrap, the layout structure is organized using the grid system for arranging elements within a web page. Additionally, a navigation bar is crafted to reinforce user navigation. Furthermore, the implementation of a battery display is achieved through the utilization of the Bootstrap class `.progress-bar`. This class enables precise control over visual representations of battery levels or other progress indicators.
- Plotly.js, an open-source graphing library serves as a powerful tool for constructing interactive and touch-enabled visualizations. It facilitates the creation of dynamic plots that allow users to zoom in and out as well as capture screenshots of relevant data.
- The Husky is supplied with a physical controller as standard. Teleoperation is achieved through the utilization of an analog joystick and the left and right shoulder buttons to set a specific maximum velocity. To extend this functionality to the web interface, Nipple.js is employed. This library empowers the configuration and display of a virtual joystick. Additionally, a horizontally scrollable velocity slider is created using the Bootstrap class `.form-control-range` to set a desired maximum speed.
- The app exhibits versatility in its control mechanisms. Users have the option to teleoperate the robot via a physical keyboard, provided they have one readily available. For users lacking a physical keyboard connection, an alternative method involves utilizing the “WASD” touch keys displayed within the application interface. These touch keys can also be used for the robot movement. The Husky can be driven more precisely using the keyboard buttons. This can be useful when parking, for instance.
- Three.js is a powerful and lightweight 3D graphics library that can be served as a versatile tool for rendering digital representations of robots within web browsers. In combination with Ros3djs, a digital twin can be created in the browser that mirrors the physical movements of the real robot. Animations can also be added. For example, a blinking or lighting up of the visualized husky in the browser when the battery SoC is low. As an ongoing project, we have successfully integrated a 3D model of the Husky into our application as a proof of concept.

C. Interaction between backend and frontend

The battery state of charge is used as an example to explain the data flow between the backend and frontend.

1) *Direct display of the battery SoC:* The current value of the battery which is published by the ROS topic `/battery_percentage`, is visualized directly in the user interface with Bootstrap each time the message is received. For this purpose, a ROSLIB.topic object is created beforehand in JavaScript that subscribes to the corresponding ROS topic, allowing real-time updates. It is also possible to send messages to this topic, as is the case with the Husky controller. In this case, the virtual joystick position sends a twist message to the `/cmd_vel` topic to move it. The connection between the app and the Husky is established via the WebSocket.

2) *Capturing the values:* In the backend, a route is defined in the Flask web application that listens for HTTP POST requests at the `/save_data` endpoint. If a POST request is received, the incoming JSON data is queried. In this scenario, a battery object is then created with the percentage value and adds it with an id and a timestamp to the database session (Fig. 2). In the event of a database failure, the current battery SoC can still be displayed. The same applies to the engine temperatures.

3) *Visualizing the data from the database:* The SoC for the battery is visualized using Plotly.js as a line chart. This process involves several steps. Initially, data is fetched from the backend database. After processing to ensure compatibility with Plotly.js, it is prepared for visualization. The resulting line diagram represents the battery SoC over a certain time span. Flask facilitates the transfer of Python variables to the frontend. These variables are utilized within HTML templates or JavaScript via Jinja2, a template engine. Users can interact with the system by selecting specific days from a drop-down list. The recorded data corresponding to the chosen day is displayed.

4) *Connecting to an Open Platform Communications Unified Architecture:* A pre-existing DataConnector (DC) has been specifically developed for the Husky as part of a prior project. This DC leverages the Open Platform Communication Unified Architecture (OPC-UA) standard. Through this connector, the ROS data from the Husky can be efficiently retrieved. The retrieval process is facilitated by a client program integrated into the web application and the acquired data is persistently stored in the database. In the event of an OPC-UA server failure, the system is designed continue displaying the real-time ROS data of the Husky (Fig. 3).

IV. VALIDATION AND SHOWCASE

To test the responsiveness of the front end of the web application, the app was accessed from different devices. The Flask application can run on the Husky’s onboard PC or on another PC in the same local network as the Husky with access to the ROS topics. The application was mainly tested on the mobile onboard PC (i5-1135G7 CPU and 16 GB RAM) to serve the locally stored files to the client. The representation of the data page is shown in Fig. 3. In this controlled experiment

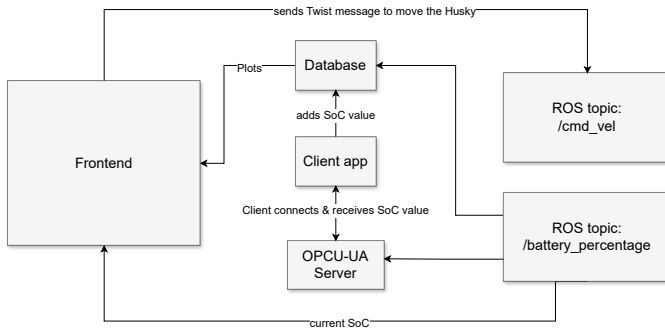


Fig. 3. Interaction between frontend and backend

we investigate the visual representation of the web application interface across two distinct devices: a Samsung Galaxy S10 cell phone and on a desktop PC with a full HD monitor. The purpose is to discern how design elements and user experience differ between these platforms. On the left hand side the /data page was accessed using a Samsung Galaxy S10 cell phone while on the right hand side the site was displayed on a full HD monitor. Embedded within the navigation bar is a real-time indicator of the battery SoC. This value is updated dynamically as the Husky operates. Additionally, a status display reflects the active WebSocket connection, providing essential feedback to the user. These elements were crafted using the Bootstrap framework. The current motor temperatures are visualized using angular gauge charts. These succinct representations allow rapid assessment of temperature levels. Below that, the motor temperature data are plotted as line charts. Both visualizations were generated using Plotlyjs. Positioned at the bottom left corner, a similar display exists for the battery Soc. Due to space constraints only a truncated version is visible in Fig.3. In order to view the battery SoC plot on the desktop view it is required to scroll down. On the Galaxy S10, the navigation bar undergoes compression, resulting in a more compact layout. A convenient drop-down menu arrangement allows users to access elements sequentially by scrolling vertically. The control interface features a live image display of a Zed 2i camera, which serves as the primary view. Positioned centrally, this display provides real-time visual feedback. Beneath the image, the speed controller resides. The speed slider is adjustable from 0.1 m/s to a maximum of 1 m/s and is accompanied by a numerical readout. The interface includes touch-enabled controls: a virtual joystick positioned at the bottom left and virtual keyboard keys at the bottom right. These intuitive input mechanisms facilitate precise guidance control of the Husky robot. Their placement at the screen's edge aligns with the ergonomic orientation of handheld devices such as cell phones or tablets, enhancing user comfort and efficiency. Fig. Y. shows screenshots of the Galaxy S10 and the Microsoft Surface Pro (5th Generation) side by side. The 3D model route shows the visualized Husky as depicted in Fig.X. It is possible to view the model from different angles. The elements listed here have been tested with the most common browsers such as Chrome, Firefox or

Edge in different versions and on different devices. Browsers and versions that are supported by Bootstrap can be viewed on the Bootstrap page [6].

V. CONCLUSION

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