Open Source Software for Teleoperated Driving

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Abstract—Teleoperation allows a human operator to remotely interact with and control a mobile robot in a dangerous or inaccessible area. Besides well-known applications such as space exploration or search and rescue operations, the application of teleoperation in the area of automated driving, i.e., teleoperated driving (ToD), is becoming more popular. Instead of an in-vehicle human fallback driver, a remote operator can connect to the vehicle using cellular networks and resolve situations that are beyond the automated vehicle (AV)'s operational design domain. Teleoperation of AVs, and unmanned ground vehicles in general, introduces different problems, which are the focus of ongoing research. This paper presents an open source ToD software stack, which was developed for the purpose of carrying out this research. As shown in three demonstrations, the software stack can be deployed with minor overheads to control various vehicle systems remotely.

I. INTRODUCTION

Teleoperated driving (ToD) allows a human operator to remotely control an unmanned ground vehicle (UGV). In the context of automated driving (AD), ToD is a promising solution. To some extent, it can be used to replace in-vehicle fallback drivers because edge cases of the AD function can be remotely resolved.

Whereas ToD has numerous possibilities, it also introduces new challenges, which are the focus of current research activities. These include vehicle control subject to latency conditions [1], connection loss [2], management of limited network bandwidth [3], or reduced operator situation awareness [4]. The primary objective of this paper is the presentation and provision of a ToD software stack to the research community. Its usage is not inherently limited to automated vehicles (AVs), but may be extended to any type of on-road or off-road UGV. Therefore, this paper presents software for carrying out research into various teleoperation concepts and vehicle platforms.

A. Related Work

Over the years, various teleoperation systems for UGVs have been presented. Bensoussan and Parent [5] proposed a teleoperation setup for small, urban carsharing vehicles as long ago as 1997. The paper focuses on the hardware setup of the system. Gnatzig et al. [6] describe a system design for teleoperated road vehicles. In addition to hardware components, the work also presents and discusses the communication setup with the experienced bandwidth and latency of the mobile network. Bodell and Gulliksson [7] describe simulation of the remote control of a truck. Different input devices were implemented to investigate their influence on teleoperation. The operator is provided with a stitched video stream containing additional information such as velocity or a map. Shen et al. [8] describe a software and hardware architecture for teleoperating road vehicles in wireless networks. The video feeds of an actuated stereoscopic camera are visualized to the operator through a head-mounted display (HMD). Georg and Diermeyer [9] propose an immersive interface in a three-dimensional environment that provides the operator with information from various sensors. The interface, presented to the operator through multiple displays or an HMD, can be adapted through scenes with different settings. At the time of publication of this paper, TELECARLA from Hofbauer et al. [10] is the only available, open source software for ToD. Based on the Robot Operating System (ROS), it is an extension of the CARLA Simulator [11], providing the operator with an interface to directly steer and control the velocity of the vehicle.

The software stack, presented in this paper, is also based on ROS and was primarily developed for carrying out ToD research. However, interfaces between components follow established concepts of AD functions, e.g., object lists or trajectories. This enables integration or extension of ROS-based AD software such as the open source stacks Autoware [12] and Apollo [13].

B. Contributions

In this paper, a ROS-based software stack is presented the purpose of which is to support research in the field of ToD. The system design is modular, allowing easy integration with existing AD software. With a conventionally designed vehicle interface, the software can be deployed with minor overheads to remotely control various vehicle systems. This is shown in three demonstrations. The source code is open source and available on GitHub[1].

II. ROBOT OPERATING SYSTEM

ROS is an open source software framework for scalable robot applications [14]. It is well-established in academia, and is also becoming increasingly popular in industry. Use of ROS leverages the publisher-subscriber paradigm. Packages containing nodes can be seamlessly integrated into software that becomes complex, but still remains modular. With ROS providing a structured communication layer above the host operating system, the user/developer can focus more on the functionality of nodes and less on their interaction. Besides this, the ROS ecosystem also offers a wide range of tools, e.g., for data visualization and logging.

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https://github.com/TUMFTM/teleoperated_driving
III. SYSTEM DESIGN

The complete system architecture is shown in Fig. 1. It is separated into vehicle and operator sides which are connected via the Network (blue). On the vehicle side, the Bridge forms the Vehicle Interface (grey), interfacing various hardware components such as sensors and actuators. The Lidar, Video and Projection packages form the Perception (green), responsible for processing the sensor data and transmitting it to the operator. The Operator Interface (yellow) comprises three packages. These are (1) the Manager, connected to all other packages and managing the ToD session, (2) the Visual package, that displays the output from the perception packages and other data from the vehicle, and (3) the Input Devices that form the interfaces to various input device hardware components. From the output of the latter, the Control packages (orange), i.e., Command Creation and Direct Control, generate and transmit the control commands from the operator to the vehicle. Reflecting the structure of the ROS packages in the code repository, the color-coded groups leverage modularity and scalability. For instance, a new control concept would be introduced as another Control package.

A. Bridge

The Bridge contains the packages to create the interface with various vehicle systems. It is assumed that certain data feeds, such as an odometry feed and other vehicle feedback, are available from the teleoperated vehicle. If this is the case, the data are transmitted through the Network to the operator. Also, the Bridge handles launching of the camera and LiDAR sensor drivers, the data of which are processed and transmitted by the Perception packages. Finally, dependent on the control mode, see Sec. III-E, the Bridge is also responsible for forwarding the respective commands from the operator to the actuation system of the vehicle.

B. Perception

The Perception packages are responsible for processing, transmitting, and finally preparing the visualization of the vehicle sensor data for the operator.

1) Video: As the primary source of information in ToD, video streams of the cameras on the vehicle are transmitted to the operator. In the system described, this is done using GStreamer [15], a modular framework for different multimedia streaming applications. Due to its speed advantages, the H.264 codec [16] is used to compress the videos. The video streaming sessions are established and controlled by the GStreamer RTSP Server Library [17]. The complete video streaming framework of the system offers a lot of flexibility. This includes adaptable parameters, such as the encoder bitrate, the video resolution scaling factor and cropping of the videos. The reconfiguration can be done either manually or automatically. The full functionality of the framework is described in [3].

2) Lidar: The Lidar package handles the transmission of the data from an array of LiDAR sensors on the vehicle to the operator. There, the data can be displayed in the Visual package, see Sec. III-D.2, or projected over the video, see Sec. III-B.3. In addition, the Lidar package also processes the data in certain ways for other AD functions. For instance, object lists are generated from laser scans performing naive euclidean clustering. Also, a grid map, containing the occupancy of the vehicle surroundings, is constructed.

3) Projection: Based on vehicle feedback and sensor data, the Projection package generates visual projections, which support the operator during teleoperation. For instance, the operator’s anticipation of the future vehicle motion is improved through a projection of the vehicle lane. Assuming the current steering wheel angle (SWA) value remains constant, the kinematic vehicle model equations are used to predict the locations of the left and right vehicle front edges. The obtained lanes are then superimposed on the video streams as a texture in the Visual package, using the pinhole camera model and the OpenCV library [18]. Fig. 2 shows a snapshot of the video that is displayed to the operator. In addition to the vehicle lane, the image also shows projections of the reflections from a 2D front laser scanner.

C. Network

A central part of the ToD system is communication via the network in order to connect vehicle and operator sides. In the system described, almost all the data is transmitted by the Network package. The package contains templated...
sender-receiver pairs to transmit serialized ROS messages. In general, latency-critical data, such as control commands or LiDAR data, are transferred via UDP. Other data, such as the system status message from the Manager package, see Sec. III-D.1, are transferred over TCP using Message Queuing Telemetry Transport (MQTT) [19].

D. Operator Interface

The Operator Interface consists of the packages that either display data to the operator or offer an interface that the operator can interact with.

1) Manager: The Manager package is used to establish and manage the status of the connection between the operator and the vehicle. A graphical user interface (GUI) with several functionalities is provided to the operator. Firstly, the IP addresses of the operator side and vehicle in question can be entered. Secondly, the actual teleoperation, i.e., transmission of control commands, can be started and stopped. Thirdly, the operator can switch between different input devices, see Sec. III-D.3, vehicle control modes, see Sec. III-E, and video rate control modes, see Sec. III-B.1.

2) Visual: The Visual package provides a function-rich and flexible HMI for the operator to perform the teleoperation. Adopting multiple concepts from [9], it displays received data from the Perception and Bridge packages in various ways. A 3D world, comparable to the rviz package [20], is constructed using the OpenGL API. Inspired by the open source game engine Hazel [21], the Visual package uses the Entity Component System (ECS) design pattern through the entt library [22], based on the composition over inheritance principle. An overview of selected entities, i.e., the objects constructed and visualized in the HMI, is given in Table I. Support for an HMD has also been introduced. This provides an even more immersive experience during teleoperation. Snapshots of the HMI, exhibiting a view of the vehicle model and giving an impression of the projection of video streams on either rectangles or a spherical canvas, are shown in Fig. 3 and Fig. 4.

The aforementioned ECS pattern has been shown to offer great flexibility. It leaves the package with great potential for future improvements and extensions.

3) Input Devices: The Input Devices interface supports various input device hardware. For instance, the package is compatible with multiple USB devices. It also provides a virtual joystick that can be used without additional hardware. The outputs of this package are continuous axis values and discrete button states. In configuration mode, the allocation of axes and buttons to signals, such as the desired SWA or change in gear position, can be adapted for new input devices.

E. Control

Generally speaking, Control packages generate, transmit and process control commands. Based on the output of the Input Devices, the control commands are generated in the Command Creation package and split into

• the primary control commands, which concern the lateral and longitudinal motion of the vehicle,

• and the secondary control commands, e.g., the gear position or indicators.

The control architecture has been developed with the objective of supporting a multitude of control modes. In Direct Control mode, the primary control commands are directly transmitted to the vehicle for execution, i.e., the operator controls the vehicle at stabilization level. Other control modes, such as a shared control approach [23] or a concept to modify the perception of the vehicle [24] are also under development and will be integrated into the software stack.

IV. USABILITY

The presented software stack has been developed and designed with the objective of making it applicable for a multitude of UGVs, and to support ToD research. The ROS framework is used to ease maintainability and modularity of the system. Hard-coding of parameters, such as actuation limits, sensor names or coordinate frame identifiers, is strictly avoided. Instead, these are specified in configuration files.
### TABLE I

**ENTITIES CREATED IN THE VISUAL SCENE AND THEIR PROPERTIES.**

| Entity         | Description                                                                                                                                 |
|----------------|-------------------------------------------------------------------------------------------------------------------------------------------|
| Scene Camera   | Camera capturing the scene of the visualized entities. Follows the position of the vehicle model.                                     |
| Coordinate Frame | Coordinate systems to describe relative positions of data, e.g., laser scans relative to the sensor. Used to transform positions into the coordinate system of the vehicle model to coherently render the complete scene. |
| Vehicle Model  | The 3D model of the vehicle. Its position is continuously updated based on the odometry feed received from the vehicle.                      |
| Speedometer    | An alpha-numeric display that shows the commanded and actual velocities of the vehicle as well as gear positions.                         |
| Video Canvas   | A surface used for spherical or rectangular video data visualization. For a spherical projection, the underlying presumption is that the calibration of the sensor stack, both intrinsic and extrinsic, is provided. |
| Laser Scan     | The reflections from obstacles, captured by a laser scan sensor.                                                                           |
| Vehicle Lane   | Projected motion of the vehicle, calculated based on the current steering wheel angle. Can also be used to display a different path, e.g., the vehicle motion planned by an automated driving function. |
| Top View       | Rectangular display of the visual scene from above, captured by another scene camera.                                                        |

Based on these, the system components construct and provide their functionality. For instance, the robot transform tree, video pipelines of the RTSP server, or sensor-receiver pairs for the transmission of laser scans are instantiated based on lists of transforms and sensors specified in the configuration files. In addition, to finally use the presented software stack to teleoperate an arbitrary UGV, a Bridge package, interfacing the vehicle-specific sensors and actuators as shown in Fig. 1, needs to be provided. This package itself is assumed to provide a ROS interface that follows a certain straightforward topic naming convention.

## V. DEMONSTRATIONS

Flexibility and usability, as discussed in the previous section, are demonstrated through the deployment of the software on a full-size passenger car, a 1:10-scale RC car, and a driving simulator. A video, showcasing the demonstrations, is available.

### A. Passenger Vehicle

In this demonstration, a full-size passenger vehicle, an Audi Q7, is teleoperated. The sensor setup consists of three front-mounted, and one rear-mounted camera. Four fisheye cameras, mounted at the front and rear bumper, and below the left and right side mirrors, enable the operator to monitor the close surroundings of the vehicle. One 2D laser scanner is also mounted on each of the front and rear bumpers. All sensors are connected via USB 3.0 or Ethernet to the vehicle PC, which is equipped with an Intel Xeon Gold 6130 2.10 GHz 16 core processor and 32 GB of RAM. Commands are written to, and feedback read from the vehicle CAN bus through a dSpace Autobox, also connected to the vehicle PC via Ethernet. The end-to-end delay, the so-called glass-to-glass (G2G) latency [25], of a 40 Hz, 520p video feed, transmitted over a wired connection and displayed to the operator on a gaming monitor, operating at 144 Hz, is approximately 104 ms. A thorough assessment and comparisons of the latency for different configurations within the same system are provided in [26].

![Fig. 5. Steering wheel angle (SWA) tracking (top) and velocity tracking (bottom) during teleoperation of the passenger vehicle. Actual values from the vehicle and desired values input by the operator are plotted against time. In addition, engagement of the emergency stop (EStop) and the gear of the vehicle while in park position are shown. Enlargement of SWA plot at 460s exhibits actuation latency of approximately 100ms, as perceived by the operator.](https://youtu.be/bQZLCOpOAQc)

The described vehicle is teleoperated on private roads for approximately 100 s. A safety driver is located in the vehicle, who releases the emergency stop and is ready to take control of the vehicle at all times. The teleoperation is started and stopped at a standstill. The driving course consists of a narrow lane change, defined by foam cubes, two left turns and two stop lines. The performance of the tracking of the SWA and the velocity are shown in Fig. 5. Upon release of the emergency stop, it can be seen that the actual SWA accurately follows the commands from the operator. In the zoomed-in section at around 460s, the experienced actuation latency of around 100ms becomes apparent. As the signals are logged on the operator side, this actuation latency includes (1) the transmission of the operator’s command to the vehicle and therein to the dSpace Autobox, (2) the actual latency of the steering actuator, (3) reading of the actual SWA value from the vehicle CAN bus, and (4) the transmission of this signal back to the operator. The velocity, desired by the operator, is also tracked reliably. After shifting gear from park to
modularity and scalability to facilitate deployment of the software on different vehicles with only minor overheads. In this paper, this was demonstrated with three systems, namely a full-size passenger vehicle, a 1:10-scale RC car and a driving simulator. While further technical aspects, such as innovative control concepts, are to be developed and validated in the future, the software will also be used for research involving human-machine interaction studies.

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Fig. 7. Operator’s view while teleoperating the driving simulator.

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