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HIGH-FIDELITY TELEOPERATED SCALED VEHICLES FOR RESEARCH AND DEVELOPMENT OF INTELLIGENT TRANSPORTATION TECHNOLOGIES

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ABSTRACT

This paper presents a systematic design of high-fidelity teleoperated scaled vehicles to be used as a research and development platform for intelligent transportation technologies. Compared to computer simulation and full-scale physical tests, the use of high-fidelity scaled setups provides advantages on testing time and financial effectiveness. The physical design of the vehicles features a 1:14 scale with realistic appearance licensed by car manufacturers. Customized steering system and propulsion control provide high-fidelity maneuver characteristics. Remote control is deployed using a target-host structure over WiFi and can provide seamless switching between human driving and autonomous/assisted driving on the host side. Several possible solutions for real-time panoramic vision feedback are explored, with a tri-camera design based on parallel acquisition interfaces adopted. An adaptive color compression technique is developed to shorten the video streaming latency. A customized miniature LIDAR system is introduced to provide an ultra-small package for on-board installation. As a solution balancing between test fidelity and costs, the proposed scaled vehicles are especially suitable for validation tests during the early stage of research and development. With a long-term goal of developing a multi-vehicle traffic network test platform, ongoing and future work on the construction of scaled buildings and road systems is also discussed.

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INTRODUCTION

Intelligent transportation technologies such as autonomous and assisted driving, connected vehicles, and intelligent traffic control require substantial validation before they can be applied in the real world. This is especially true for system-level technologies (e.g., control of traffic networks) and ones that involve humans factors (e.g., passengers and pedestrians), which are usually conceived based on strong hypothesis/assumptions and have strong system uncertainties. The validation that provides the best fidelity is surely full-scale physical tests if not considering costs. As large research investment has been made possible to related areas, full-scale physical test platforms that consist of whole traffic networks have become available. One of the newest full-scale platforms of such is the 32-acre Mcity by University of Michigan [1], which has a full-scale system of roads and vehicles. It can host tests ranging from safety of autonomous driving [2] to economic viability of transportation systems [3]. The disadvantage of running full-scale tests is the excessive preparation, maintenance, and repair costs, both time-wise and financially. In addition, the serious safety considerations involved are a major burden. That said, full-scale tests are more suitable for the final validation, while alternative measures of low cost and short turnaround time are preferred during the early stage of research and development.

In terms of cost effectiveness, simulation has conventionally been considered as a good alternative to physical tests. Well-known simulation platforms include MiniSim and RTI SimCreator for driving and VISSIM for traffic flows. However, as the pursuit of simulation fidelity advances, the time and financial costs of developing a high-fidelity realistic simulation have increased to no less than constructing a real physical test [4]. The concern is also echoed in the film industry, where physical practical effects are reviving over digital effects in the pursuit of providing a more realistic visual experience [5].

As a solution balancing between test fidelity and costs, scaled physical prototypes have long been used in many areas, such as aerospace and aeronautical engineering, naval engineering, and architectural engineering. Although less adopted yet, a similar concept can be applied to tests on intelligent transportation technologies. By using scaled road systems and remotely controlled (i.e., teleoperated) robotic vehicles, new technologies can be tested with a highly affordable tolerance of failures, which is especially desirable during the early stage of research and development. Some pioneering work has been reported by University of Delaware [6] and MIT [7]. Limits remain in fidelity, especially in terms of providing a realistic representation of real vehicles and driving experience, which can be of particular concern when human factors are involved in the tests. This paper presents a systematic design of high-fidelity teleoperated scaled vehicles that can be used on a variety of tests for intelligent transportation technologies. The design features realistic physical characteristics in terms of both appearance and maneuvering, remote control interfaces that can seamlessly switch between human drivers and autonomous agents, real-time panoramic vision streaming, and a unique miniature LIDAR unit.

PHYSICAL CHARACTERISTICS

Physical fidelity includes both appearance and maneuver characteristics. The former is of particular interest when human experience is involved in the tests. In terms of fabrication, giving the vehicles a realistic appearance is more demanding even at the age of 3D printing. This is because of the limited availability of appearance design models due to the intellectual property constrains from the car manufacturers. A low-cost solution is to build the scaled vehicles based on realistic hobby/collection models made by vendors licensed by car manufactures. A market investigation reveals that most such models are made with a dimension scale of 1:14, which is then used as the standard scale in this project. Figure 1 shows examples of licensed realistic models of a sedan by Rastar and a semi-trailer truck by Tamiya. Both vendors are well-known for their world-leading expertise in precision injection molding. Targeted at hobbyists and collectors, such models are of affordable costs and good commercial availability.

Despite the realistic appearance, the maneuver fidelity of hobby/collection models can be quite poor. In particular, the original steering mechanisms of some models can barely turn enough to realize parallel parking or a sharp turn at a road corner. Thus, construction of the proposed test vehicles begins at rebuilding the steering systems of the original models. Figure 2 shows a rebuilt steering system for a sedan using 3D printing. In addition to a proper mechanical range, the on-board controller can mimic realistic steering dynamics (e.g., oversteer and understeer) via controlling the steering servo.

FIGURE 1. EXAMPLES OF LICENSED REALISTIC MODELS

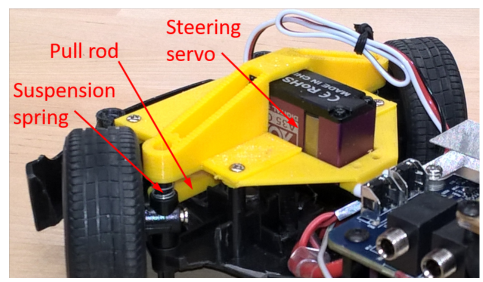


FIGURE 2. REBUILT STEERING SYSTEM USING 3D PRINTING

While all models come with functional suspensions and differentials, some of the more professional models such as the semi-trailer truck by Tamiya also feature servo-controlled gear-shifting transmissions (Fig. 3). Realistic acceleration dynamics, in terms of the response from gas pedal to propulsion torque, is realized by a nonlinear mapping (Fig. 4 top) implemented in the control firmware. The scale of 1:14 does not really allow any space for a clutch and mechanical brakes. Nevertheless, because of the relatively high internal resistance of the propulsion motor and its drive, a zero applied voltage by grounding all poles stops the motor almost instantaneously. The idling, taxing, and braking dynamics can then be emulated using a time-variant low-pass filter applied only to the falling edges of the acceleration/braking signal. Variable braking strength can be realized by adjusting the time constant (decaying rate) of the filter according to the control signal from the brake pedal (Fig. 4 middle and bottom). The weight of the vehicles, along with the acceleration and braking strength, are scaled from the real vehicles using a similitude analysis method as discussed in [8].

The onboard cameras are positioned at a location that provides a realistic point-of-view as that of a human driver sitting

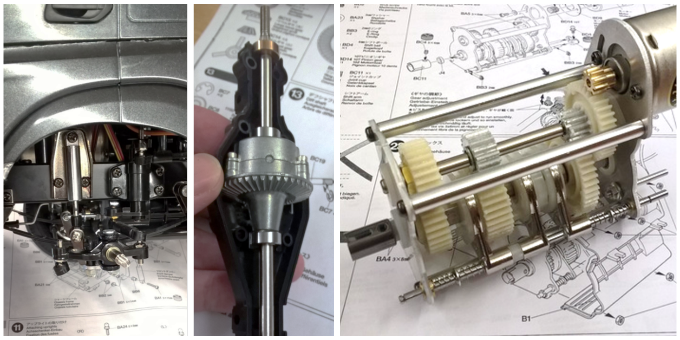


FIGURE 3. SUSPENSION, DIFFERENTIAL & TRANSMISSION

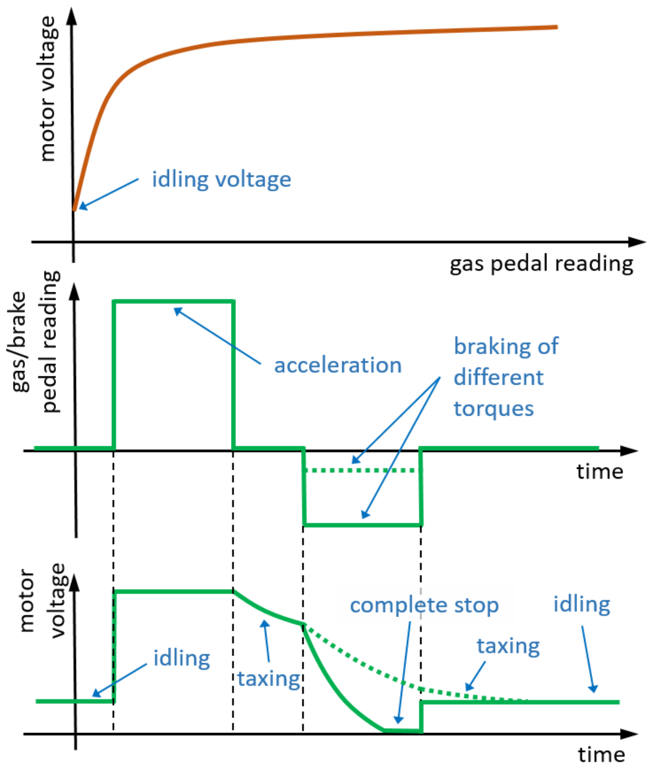


FIGURE 4. ACCELERATION AND BRAKING CONTROL

inside a real vehicle. All vehicles are modified to have LED-based full lighting systems, including illumination, turn, braking, and backup signals. Laser cut acrylic mirrors with adjustable mounts are installed to replace the mock-up side mirrors on the original models. An optional LIDAR unit (discussed later) can be mounted on top of the vehicle to provide obstacle detection for autonomous/assisted driving.

TARGET AND HOST CONTROL SYSTEMS

A 7.4*V* Lithium-ion battery pack is used to power the DC bus of the onboard electronics. The vehicles are controlled via WiFi connections by remote control consoles. The control console can either be operated by a human driver or autonomous driving software. In case of a human driver is operating, a driving cell (Fig. 5) is used to provide a realistic experience. The cell also provides a realistic hands-off riding experience if autonomous driving is enabled.

FIGURE 5. REMOTE CONTROL CONSOLE AND DRIVING CELL

The target (vehicle) and host (remote console) control system is deployed as shown in Fig. 6. The target controller receives maneuver commands from the host while streams back real-time video and other sensor readings. The decision making for driving is made on the host side either by a human driver or by autonomous software. With such a structure, human or autonomous driving does not make any difference on the target side.

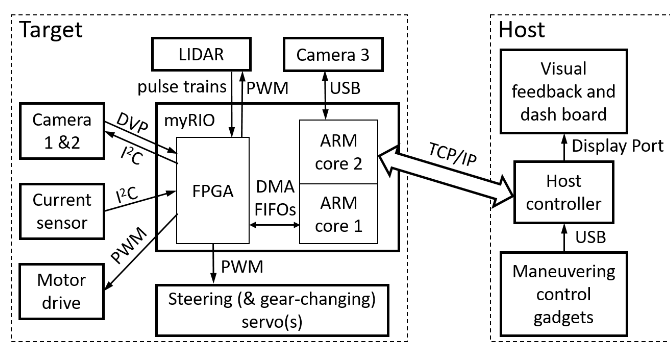


FIGURE 6. TARGET-HOST CONTROL SYSTEM

The myRIO controller by National Instruments (NI) is used as the target controller (Fig. 7). It employs the Reconfigurable

I/O (RIO) system of NI based on FPGA, as well as a dual-core ARM processor and embedded WiFi module. The FPGA-based RIO system is particularly beneficial to deploy high-speed video acquisition from multiple cameras. Steering and gear changing (truck only) of the vehicle are actuated using RC servos which have embedded motor drives and only require single PWM signals as position commands. The propulsion motor is controlled using a DRV8701 MOSFET gate drive by Texas Instruments. Acceleration, braking, idling, and taxing dynamics of real vehicles are mimicked using control algorithms implemented in the ARM processor. Due to the space limit of the 1:14 scale, the sedans cannot afford the installation of speed sensors. Instead, a state observer based on current and voltage sensing of the motor is used to estimate the speed. The internal data streaming in the target controller is based on Direct Memory Access (DMA) FIFOs. Wireless streaming of control and feedback signals between the target and the host is realized using TCP/IP connections. Computation on the host side runs on a desktop PC of high-end configuration. In addition to powerful CPU and GPU, the host controller is equipped with a Neural Compute Stick 2 by Intel [9] to boost optional deep learning functions for autonomous driving.

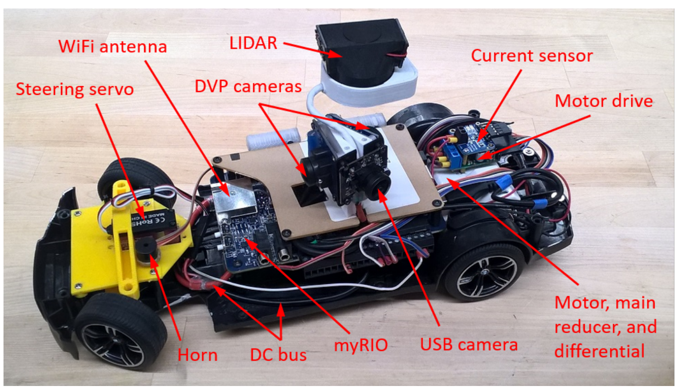


FIGURE 7. ON-BOARD ELECTRONICS

VISION SYSTEM

In order to obtain a real-time panoramic view, several possible solutions have been explored (Fig. 8). A first attractive off-the-shelf solution is to use a commercial 360-degree camera such as Samsung Gear 360, Ricoh Theta, and Insta360. These cameras use a back-to-back dual-sensor setup and internal image preprocessing to give a seamless spherical panoramic view. However, the acquisition and transmission latency of these cameras is too long ($\times 1s$ level) to be used for real-time vision feedback (even under the lowest resolution available), which is not really the application they are designed for. The latency comes from the limited speed of the USB interface as well as the excessive image scale that covers the entire spherical view. The full spherical view is actually not necessary for the application on the proposed vehicles, which requires only a circular (for sedans) or even just a half-circular (for trucks) band-shaped panoramic view. Considering these factors, a second design is built using a single up-facing camera and a conic mirror to provide only a circular panoramic view. A so-called First Person View (FPV) camera is used. FPV cameras are specially designed cameras for radio controlled drones. Their analog wireless transmission can provide a latency shorter than $5ms$, which is ideal for remote driving. However, despite available high resolutions, the image sharpness is too low to accommodate a clear panoramic view. The analog wireless transmission also severely interferes with the WiFi connection for vehicle control. Moreover, fabrication of a customized high-quality conic mirror that can give a proper optical sharpness can be costly.

FIGURE 8. AN OFF-THE-SHELF DUAL-SENSOR 360-DEGREE CAMERA AND AN FPV-CAMERA + CONIC MIRROR SETUP

Inspired by the recent trend of multi-camera configurations for smartphones, a tri-camera setup came into consideration. As shown in Fig. 7, three cameras are installed with a triangular alignment. Instead of inter-device communication protocols such as Camera Link and USB, Digital Video Port (DVP), an inter-component protocol is used. As a parallel protocol, DVP provides much faster real-time video acquisition. Its implementation, in terms of programming is also much simpler than its more recent successor MIPI and costs less computing resource of the FPGA. The popular OV7670 cameras by Omnivision with DVP interfaces are used due to their detailed and public accessible firmware documentation, which allows end-users to customize many useful internal functions. In particular, the function of setting an internal sampling window allows the camera to output only the pixels in a specific region-of-interest and thus avoids unnecessary acquisition latency. With 15 lines for each DVP connection, the I/O's of myRIO can support up to two OV7670 cameras. Due to the limited sensor size, lenses with ultra-wide angles (e.g., $> 200°$) cannot be applied to the OV7670 cameras, making the two cameras incapable of covering the whole 360-degree view. A third USB camera is thus added to cover the narrow blind spot between the two DVP cameras and provide a full 360-degree view. Considering the longer latency of the USB connection, the USB camera is pointed to the rear-left direction of the vehicle, which is rarely looked at directly by a human driver while driving a car. The camera set are located to mimic the point-of-view of a human driver when sitting in a real vehicle.

The DVP protocol is implemented in the FPGA module of the target controller. Despite a $40MHz$ clocking rate of the FPGA, due to the need of synchronization intervals and other auxiliary signals, the actual sampling rate of the two DVP connections is 2×24 MBytes per second. After grabbed by the FPGA, images are sent to the ARM processor of the target controller (via DMA FIFOs), where they are preprocessed, compressed, and then streamed to the host controller via a point-to-point TCP/IP connection. In addition to the widely used jpeg compression, a unique adaptive color compression is developed to shorten the streaming latency. Unlike conventional color-space reduction that uses a predefined color palette or fixed number of bits for the red/green/blue (RGB) values of each pixel, the proposed method uses an adaptive bit allocation strategy that dynamically adjusts bits of the RGB values based on a periodical color evaluation of the raw images. The goal is to minimize the total number of bits used by each pixel while preserving the image quality to an acceptable level. Compared to conventional color compression, the proposed adaptive method gives a better quality while realizing a smaller data size (Fig. 9). With the above techniques, a total of $200k$ pixels (from all three cameras) per frame are streamed to the host at 24 frames per second with an end-to-end latency of $170 \sim 200ms$, which is at about the maximum level of visual latency acceptable to human drivers [10, 11]. For autonomous/assisted driving, additional latency may be introduced by heavy image processing. The negative impact can be reduced to some extent by applying a predictive learning algorithm [12] to the image processing results. The algorithm gives a "prediction" of the present state using the delayed historic data.

FIGURE 9. ADAPTIVE COLOR COMPRESSION

LIDAR UNIT

A 360-degree scanning range finder (i.e., a LIDAR) is needed for many autonomous/assisted driving technologies. A popular off-the-shelf product is the A2 series by RPLIDAR. Despite the claim of having the smallest package among its peers, its weight ($325g$) and size ($\phi 76 \times 41mm$) are still too much to be accommodated on the 1:14 scaled vehicles. A customized design is then developed (Fig. 10). A miniature motor for automatic zooming of camera lenses is repurposed to rotate a scan head via a worm drive. The scan head has a ring of miniature permanent magnets embedded around its bottom part. The magnets are sensed by two Hall-effect sensors to provide pulse-train signals as incremental angle readings as well as an absolute zero mark. A good option of the ranging sensor (mounted on the scan head) is the VL53L0X Time-of-Flight (ToF) laser-ranging IC by STMicroelectronics, which provides the smallest package ($4.4 \times 2.4 \times 1.0mm$) on the market [13]. The sensor provides a range of $2m$ (corresponds to $28m$ at a 1:14 scale) with an accuracy up to ±3%. Two back-to-back range sensing modules are installed on the rotating scan head to scan two half-circles simultaneously. A total of 30 samples are grabbed per revolution at a speed of $20ms$ per sample. A miniature slip ring connector by SENRING is used to support the rotating electrical connection between the base and the scan head.

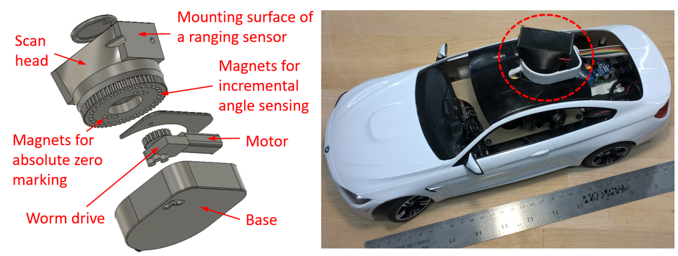
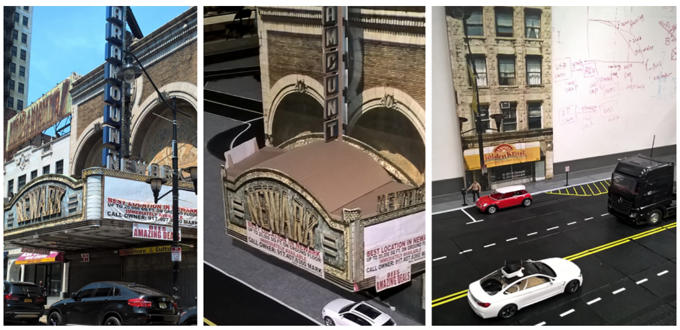


FIGURE 10. CUSTOMIZED DESIGN OF A MINIATURE LIDAR

CONCLUSIONS AND FUTURE WORK

This paper presents a systematic design of high-fidelity teleoperated scaled vehicles to be used as a test platform for intelligent transportation technologies. Compared to full-scale tests and computer simulation, the proposed design provides advantages on testing time and financial effectiveness. The physical design of the vehicles features a 1:14 scale with licensed realistic appearance as well as high-fidelity steering and propulsion characteristics. Remote control is deployed using a target-host structure and provides seamless switching between human driving and autonomous/assisted driving on the host side. Different solutions for real-time vision feedback are discussed. A customized design of miniature LIDAR is presented.

The vehicle is especially suitable for validation tests during the early-stage development of intelligent transportation technologies. The long-term goal of the project is to develop a high-fidelity scaled traffic network based on the presented vehicles. The whole system is expected to be able to emulate multi-vehicle traffic scenarios, and provide a test platform for a variety of related research. Ongoing and future work includes construction of scaled buildings and road systems using information obtained from Google Earth. (Fig. 11, 12). Sample tests are being prepared, including tests on human driving behaviors and autonomous/assisted driving techniques such as automatic lane keeping/changing, freight platoon forming, and emergency handling. Head tracking goggle display is also being tested to provide the remote drivers/passengers a more realistic vision experience.



A real building in the city of Newark, NJ — A scaled replicate for the platform — High-fidelity scaled road system

FIGURE 11. SCALED BUILDINGS AND ROADS

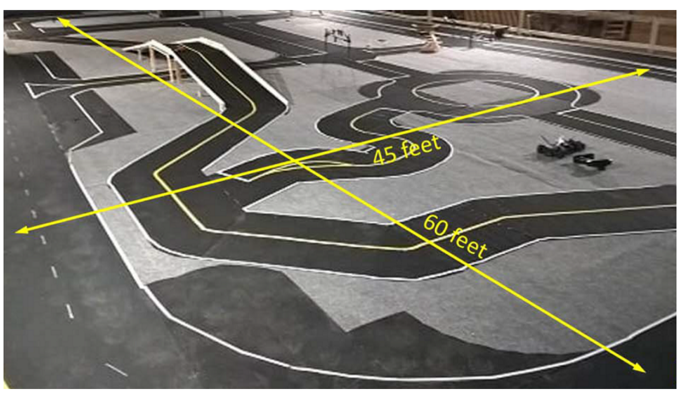


FIGURE 12. ONGOING CONSTRUCTION OF A 1:14 SCALED ROAD NETWORK

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