A System Design for Teleoperated Road Vehicles

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Abstract: The possibility to provision road vehicles unmanned and on demand will have an important influence on the development of new mobility concepts. We therefore present the teleoperated driving of road vehicles. This paper outlines the basic concepts, including a static multi-camera design, an operator interface with a sensor fusion based display, and a cellular network based video transmission and communication architecture. We also show how we manage to fulfill the system's technical requirements with our hard- and software design and point out the occurring problems due to communication limitations and lack of situation awareness. Finally, we propose solutions to guarantee driving safety.

1 INTRODUCTION

We are living in a world with a rapidly growing population. The number of megacities with more than ten million people will probably double in the next decades (United Nations, 2012, pp. 5 f.). This will have an immense effect on daily mobility. Climate change and finiteness of fossil fuels enforce this trend. But there is definitely no sign of a post-automobile society (Canzler and Knie, 2009, pp. 11 f.). The future of inner-city mobility will be integrated mobility concepts, in which the automobile is one means of transport among others and used in a collaborative way in form of car-sharing (Canzler and Knie, 2009, pp. 16 ff.). This leads to an essential issue: How will the cars be provided and distributed?

The automation of car-sharing distribution would be the most efficient and comfortable way. The optimal use-oriented vehicle would be driven autonomously to the customer. After usage, the autonomous car would park itself or drive to the next customer. Despite the progress achieved in the research of autonomous vehicles in the last thirty years, the machine perception has not reached the human perception skills, by far. Competitions, such as the DARPA challenges, demonstrate the achievements of modern robotic research (see (Thrun et al., 2006), (Fletcher et al., 2008), (Kammel et al., 2008)). These challenges suggest that autonomous driving in urban environments is nonetheless possible. However, the results of these challenges are more applicable in military purpose. A fail-safe driving in public mixed traffic is not yet feasible (Stiller, 2005, p. 5).

In contrast, teleoperation is a suitable solution to achieve the automated distribution of automobiles. Since the human performs quite well in the driving-relevant skills, due to the large amount of experiences and the ability to anticipate (see (Abendroth and Bruder, 2009, pp. 13 f.), (Stiller, 2005, p. 9), (Dickmanns, 2005, p. 204)) it is reasonable to keep him in the loop.

2 TELEOPERATION

Teleoperated robots are commonly used for exploration or surveillance tasks on ground, in the air, and underwater. Current applications are underwater maintenance of oil platforms or reconnaissance in conflict areas by drones, for example (see (Fong and Thorpe, 2001)). Despite the different applications of telerobotics, there are three characteristic elements that are part of every teleoperated system (Winfield, 2000, pp. 148 f.):

Robot: The teleoperator is very application-specific. Generally, it consists of at least the communication hardware to receive the control signals. Furthermore, a camera is often essential. The additional actuator and sensor equipment depends on the application and the needed on-board autonomy (see

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(Winfield, 2000, p. 149)).

Communication Link: The transmission of sensor and control signals is done via a communication link. Ground and air vehicles usually need a wireless connection. In contrast, underwater vehicles are often tethered because of the low communication bandwidth of acoustic links. Besides bandwidth, latency is the most important criterion for the choice of the communication architecture (see (Sheridan and Verplank, 1978, pp. 69 f.), (Farr et al., 2010), (Winfield, 1999)).

Operator Interface: The operator controls the robot from an operator workstation. The interface is usually multi modal, consisting of at least a display visualizing live sensor data from the robot. The main element is commonly a video image from the robot's perspective. Steering wheel and pedals but also joysticks or touch devices are commonly used as control inputs (see (Scribner and Gombash, 1998, pp. 4 f.), (Fong and Thorpe, 2001), (Fong et al., 2001), (Kay and Thorpe, 1995)).

3 DRIVING TASK

Designing a teleoperation system for remotely driving road vehicles requires the analysis of influencing variables of human driving. A human driver uses mainly four senses. Most important are the visual sense and the aural sense, but the haptic and vestibular system are also partially involved during driving (Jürgensohn and Timpe, 2001). The visual sense and the aural sense are the two far senses that allow a time- and position-related prediction. This makes these two senses the most important for the high dynamic of the traffic environment (Negele, 2007, p. 7).

The visual sense is not only used to perceive the own position and environment, but also to predict and anticipate the behavior of other traffic participants (see (Abendroth and Bruder, 2009, p. 6), (Negele, 2007, p. 10)).

Furthermore, visual stimuli have the greatest influence on velocity perception and choice of adequate speed (see (Lank, 2010, pp. 54 ff.)). Correct velocity estimation is essential for vehicle driving. Driving with inadequate speed is the main cause of accidents in Germany (Statistisches Bundesamt, 2011, pp. 25 f.).

Visual information can nowadays be well perceived by camera systems and can be realistically rendered in modern imaging systems (Negele, 2007, p. 10).The transformation of this sensory information to the operator interface is necessary to achieve the same driving performance of an on-board driver. This process equals the design of a driving simulator.

4 SYSTEM DESIGN

The overall concept is illustrated in Fig. 1. The operator who remotely controls the car needs to have an understanding of the car's surroundings. As explained, the most important sense for driving a car is the visual one. Therefore, we need to capture the surroundings with cameras. According to EU directives, a horizontal view angle of at least 180 degrees is required in the front to steer a vehicle. The side mirror views should at least provide about 12 degrees each. There should also be a rear view with about 20 degrees (The European Parliament And The Council, 2004), (The European Parliament And The Council, 1977).

To obtain a smooth video playback, the frame rate is set to 25 frames per second (fps), like in the European PAL video standard. Transmitting the raw images in color over a cellular connection would be impossible due to the huge amount of data. A single camera with 640x480 pixels, 3 bytes per pixel and 25 fps would require a bandwidth of about 184 megabits per second (Mbps). To reduce the data rate, the video is video-encoded.

On the operator side, the images are decoded and displayed on a wide angle screen with a field of view similar to the vehicle's. The reactions of the operator are captured using a suitable input device and transmitted to the vehicle. The controllers in the vehicle then compensate the errors between demanded and current values.

The following sections give a detailed overview of the concept structured by the classification introduced in Chapter 2.

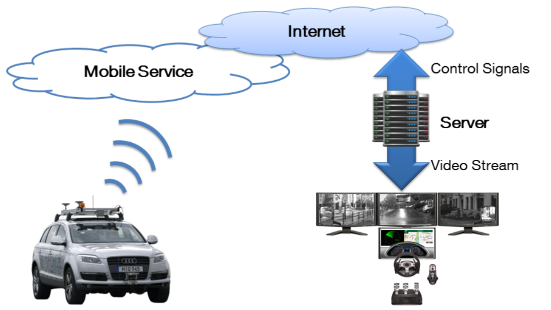

Figure 1: Data transmission scheme for teleoperated road vehicles.

4.1 Vehicle Architecture

The experimental vehicle, an Audi Q7 equipped with sensors and actuators, can be seen in Fig. 2. The system design differentiates between the hardware and software architecture of the experimental vehicle. The hardware architecture describes the used sensors and actuators that are necessary to fulfill the primary and secondary driving task. The primary driving task consists of steering, accelerating, braking and shifting. The secondary driving task includes mostly the manipulation of the lighting system and the windscreen wiper.

To fulfill the requirements on the field of view, the camera system in the vehicle consists of eight cameras. Each camera provides a resolution of 640x480 pixels. Fig. 3 shows the five industrial GigE cameras mounted on the front of the vehicle, which cover a field of view of approximately 240 degrees. Three further USB cameras cover the side mirrors and the rear view (see (Diermeyer et al., 2011)). In a single camera setup with restricted field of view panning would be necessary to help the operator to negotiate tight corners and avoid obstacles (McGovern, 1987, p. 4). But camera panning must be fast enough (Kay, 1997, p. 131). Hence, we decided to use a static multi-camera setup which permanently covers the complete surrounding. A software pan then displays the relevant detail of our complete surrounding. This has the advantage that it is much faster and more reliable than any mechanical panning system. Since color displays have a huge effect on the perception of objects, compared to gray scale displays (Kay, 1997), all cameras provide color images.

A long range radar scanner and three single layer laser scanners are used to measure the surroundings. The radar scanner has a horizontal opening angle of 16 degrees. Each of the laser scanners has a 180 degrees field of view. This hybrid sensor network is combined by a competitive and complementary sensor fusion approach (see (Durrant-Whyte, 1988)). The competitive aspects are increasing the reliability and accuracy in front of the vehicle. The complementary fusion results in 360 degrees surround view.

In order to process the data from the different sensors, two central processors are used. The video streams coming from the cameras are processed and encoded by an automotive-suitable CarPC running a data processing framework on a windows operating system. It also handles the complete communication between the vehicle and working station. Alongside the CarPC, a rapid prototyping unit capable of real-time processing undertakes the tasks of reading the data from sensors, processing its information, and sending appropriate control signals to the actuators according to measured data and the driver's inputs coming from the working station. This rapid prototyping unit is basically responsible for the primary driving task.

To achieve the steering functionality, a hollow shaft motor has been built in the steering column directly behind the steering wheel. This motor can be overridden anytime if a safety driver is sitting in the vehicle.

The acceleration and braking functionality is achieved through an electronic interface to the motor control unit to communicate the desired motor torque and deceleration. According to Isermann, "For automobiles, (usually) a safe state is stand still (or low speed) at a nonhazardous place." (Isermann, 2006). In order to guarantee a safe state, it is necessary to ensure the ability to brake at any moment. Therefore, an additional pneumatic system is incorporated to the vehicle, which makes use of a loaded air tank to directly press on the braking pedal. A further redundancy is implemented on a separate microcontroller. In case of a malfunction of the rapid prototyping unit, it will trigger a full braking emergency stop using the pneumatic valves.

To change the direction of driving, a shift-by-wire system was implemented in the experimental vehicle, which replaces the original Audi shifting mechanism.

The secondary driving tasks are also manipulated by the rapid prototyping unit. These functions are already electronically controllable in a today's vehicle

Figure 2: Experimental vehicle equipped with sensors and actuators.

Figure 3: Front camera system covering a field of view of 240 degrees with five cameras.

Figure 4: Comparison of video compression with high (640x480, 25.0 crf) and low (320x240, 30.0 crf) quality.

via CAN bus communication.

The software architecture consists of three layers. The network layer establishes the IP-based data communication to the operator interface. It contains a connection-oriented TCP connection for managing and initializing the communication link and a connectionless UDP connection for data transmission. The connectionless data transmission leads to less overhead and latency. In the data layer the sensor and control data processing is performed. The validity of the data flow and access management is verified. The lowest level is the hardware communication layer. Here, the different sensors and actuators are accessed by CAN and Ethernet protocols.

4.2 Communications

The vehicle is wirelessly controlled. With respect to the possible travelled distance of the teleoperated vehicle, the communication infrastructure needs to cover a wide area. To avoid a proprietary solution, mobile Internet is a sufficient way of using an already established infrastructure. Fortunately, the network coverage for cellular connections is constantly growing and the available transmission speeds are increasing. The current release 8 for 3G mobile networks specifies a nominal peak downlink rate of 42 Mbps and an uplink rate of 11 Mbps for HSPA+ (3GPP - 3rd Generation Partnership Project, 2013). In newer releases, the data rates will be even higher. For 4G networks, the currently specified data rates are 300 Mbps for down- and 75 Mbps for uplink. The next evolutionary step, LTE Advanced, is expected to provide peak data rates of even 3 gigabits per second for down- and 1.5 gigabits per second for uplink. However, as shown in (Tenorio et al., 2010), actual bandwidth highly depends on signal strength and the number of users in a network cell and can be much lower than the nominal value. The fastest currently supported 3G network standard in Germany is DC-HSPA with a nominal downlink data rate of 42 Mbps and 10 Mbps uplink, which is provided by Telekom Deutschland GmbH. With 4G, the company even offers 100 Mbps down- and 10 Mbps uplink. Since the video transmission requires much more bandwidth than the control input transmission, the upload bandwidth is the limiting factor for our system. Therefore, we currently use an Internet connection over 3G and, where available, a 4G network as communication channel. Since 10 Mbps is the highest nominal peak uplink data rate, one can assume that the actual data rate will usually have about 1 to 3 Mbps. This is not sufficient to transmit all video images with best quality settings but good enough to get an overview of the whole scene and transmit specific parts of the image with higher quality. The three rear cameras for instance are only necessary for lane changes or reverse driving. Due to the restricted bandwidth, the video images are encoded using the state-of-the-art H264 video codec. The compression parameters - e.g. constant rate factor (crf) - and image size are continuously adapted to the available bandwidth to ensure a smooth transmission. If necessary, some cameras can even be omitted totally. To select the best parameters, a heuristic logic is used, which depends on the driving situation and the camera. The rule-based approach starts reducing the quality at the outer cameras. The driving relevant front camera gets the best quality setting. Fig. 4 shows a comparison of an encoded 24 fps video with 640x480 pixels and a constant rate factor of 25 and the encoded video with 320x240 pixels and a constant rate factor of 30. Compared to the uncompressed video with about 177 Mbps, the bit rate could greatly be reduced to 1678 Kbps for the high respectively 222 Kbps for the low resolution video.

According to (Krenik, 2008), the transmission time with a mobile 3G HSPA connection is about 50 milliseconds in each direction. For 4G networks, the

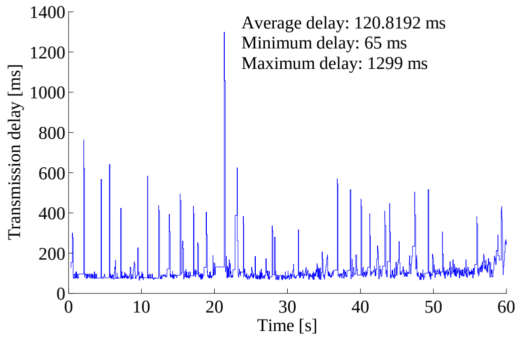

Figure 5: Measured transmission delays during test drives using a 3G network.

time delays could be reduced to 5 milliseconds in each direction for small packets (Krenik, 2008). Fig. 5 shows an example of the round trip time (RTT) for video and control data in a 3G cellular network that we measured. The RTT states the time that it takes to transmit a video image to the operator and transmit a control packet back to the vehicle. This does not include processing times on the CarPC or the operator PC. While the minimum time delay resulting from the round trip time is about 65 milliseconds, it sometimes takes longer to transmit the packets. Even peaks of over 1 second are possible. In this case, the average time delay for the transmission was about 121 milliseconds. The measurement complies with the measurements in (Prokkola et al., 2009), where the average RTT in a 3G HSPA+ connection was about 72 milliseconds. To keep the time delay of the video transmission as low as possible we use the connectionless UDP-based RTP protocol.

4.3 Operator Interface

The working station with which the operator drives the vehicle is shown in Fig. 6. It can be compared to a static driving simulator.

To realize a high feeling of presence, the workstation is assembled as a vehicle cockpit. The workstation is equipped with conventional driver inputs as a consumer force-feedback wheel, pedals and gear shift. The operator sits on a usual driver seat. To achieve an adequate field of view, three 24” monitors are arranged next to each other. The place is sufficient to show all five front cameras in parallel. The side and rear mirror cameras are overlaid in the corners when necessary.

The operator interface again consists of three layers. The network layer is the counterpart to the network layer of the vehicle. Here, the operator sends the request to take over control via the TCP-based communication. The data layer mainly consists of decoding and displaying the images and requesting the control inputs. As described above, the quality and the number of the displayed cameras are adapted to the actual communication bandwidth. Furthermore, the operator can choose different camera setups. Additionally, the operator interface shows extra information regarding the driving task as vehicle speed or turning signals. In order to enhance the information available to the operator, we use a sensor fusion display (see (Fong et al., 2001)). Especially, depth perception which is important for orientation and velocity perception (see (Goldstein et al., 2008, pp. 185 ff.)) is difficult in a tele-environment. To improve the distance estimation of the operator, we use the environmental sensor perception of the vehicle. The data of the lidar scanners are combined in a grid based approach. The occupancy grid gives a top view perspective of the obstacles in the surrounding to the operator. This map is especially relevant during slow parking maneuvers and can be displayed on an additional monitor. During driving, the fusioned lidar and radar scanner data is perspectively overlaid in the video image to highlight obstacles. According to literature, operators of teleoperated vehicles often lose their orientation (see (Kay, 1997, pp. 10 f.)). Thus, we use a navigation map that can be shown on the separate monitor. The hardware layer is the lowest level of the software architecture and provides access to the control devices.

Figure 6: Operator workstation with three monitors, control inputs, and driver seat.

5 RESULTS

We did several teleoperated test runs on our test track. The test track is 650 meters long and consists of a single lane road with 4.5 meters width. There are no explicit road markings. The shape of the track is an s-curve with minimal radius of 200 meters (Fig. 7).

Figure 7: Birds view on section of the test track. White lines are the tracked road boarders by the top lidar scanner, the red line is the driven path (satellite image by Google Earth).

During experiments the operator saw the videos with an artificial constant time delay of 500 ms. The total round trip time was about 550-600 ms. The average speed during the experiments was about 30 km/h. The speed was controlled by cruise control and the operator kept the settings constant for most of the time. Under these conditions the operator was able to safely keep the vehicle on the track and he was even able to react on dynamic objects as pedestrians. The standard deviation of the lateral offset was about 0.4 meter. This shows that the operator was able to follow the lane with only little error in lane keeping. The lateral offset was measured by the top laser scanner that tracks the road borders. Under the described conditions, the operator tends to steer the vehicle with periodic inputs of 0.25 Hz. This still leads to a stable behavior, but could become critical, if the speed was increased and thus the phase margin reduced.

6 DISCUSSION

A variable time delay greatly influences the driving performance. It was determined that a smooth image sequence is rather helpful for the operator. The artificial time delay of 500 ms showed to be unproblematic for a driving speed of 30 km/h. However, test drives have shown a reasonable speed compared to other teleoperated road vehicles, such as (Appelqvist et al., 2010). Due to time delays, highly dynamical maneuvers are not possible. Speeds up to 50 km/h should be possible with our experimental platform under stable time delay conditions, 35 km/h had been reached in the preceding tests.

Using current cellular networks, a maximum of three cameras could be simultaneously transmitted because of bandwidth limitations. This is not a limitation, since experience showed that not more than an horizontal field of view of approximately 135 degrees is needed for normal straight drive. This corresponds to three cameras transmitted simultaneously. Using gray-scale images instead of color images would slightly reduce the required data rate but would make it difficult to drive e.g. through shadows.

7 OUTLOOK

During our test drives, we identified several problems that need to be solved for safe remotely controlled driving. In (Lutz et al., 2012), we give an overview of the legal requirements that must be met and show possible solutions. We also experienced that even with 25 images per second it is difficult to estimate the vehicle's speed just by relying on the video stream. To guarantee a safe drive, two important aspects are being investigated. First of all, the lack of situation awareness produces an effect of nonrealistic driving feeling, which causes the operator to perform differently compared to sitting directly inside the vehicle. To solve this problem, methods are being studied and implemented, where visual, aural and haptic channels are used.

Moreover, emergency strategies during connection loss need to be developed. The implemented approach is the so-called *free corridor* (Diermeyer et al., 2011), in which the trajectory of a full braking is shown to the operator and he is responsible for keeping it free from obstacles all the time.

One of the biggest challenges for the teleoperation are time delays caused by the sensors and signal processing as well as the transmission. While it is possible to slightly decrease sensing and processing times, there will still be a certain time delay in the data transmission which depends on the wireless transmission technology and the constitution of the Internet connection. Since this is beyond our reach, we elaborated two strategies to reduce the delay effects on the vehicle control which will further be elaborated in the future. By predicting the vehicle's position and the positions of outside traffic participants, we can modify the captured video images and give the operator a preview of the traffic scene (Chucholowski et al., 2013). A different approach is to replace the direct control of the vehicle by an indirect control strategy. Instead of directly passing steering wheel, acceleration and brake pedal inputs, we use a shared control approach and generate high-level goals which are automatically achieved by the vehicle as described in (Gnatzig et al., 2012b) and (Gnatzig et al., 2012a).

8 CONCLUSIONS

In this paper we presented the requirements to achieve unmanned vehicles through teleoperation, showed our solutions to meet those and outlined the problems that we faced so far. With the presented system we could successfully realize a teleoperated road vehicle scenario. In the near future, teleoperation could be a solution for upcoming demands resulting from new mobility concepts.

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