Survey on Teleoperation Concepts for Automated Vehicles

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Abstract—In parallel with the advancement of Automated Driving (AD) functions, teleoperation has grown in popularity over recent years. By enabling remote operation of automated vehicles, teleoperation can be established as a reliable fallback solution for operational design domain limits and edge cases of AD functions. Over the years, a variety of different teleoperation concepts as to how a human operator can remotely support or substitute an AD function have been proposed in the literature. This paper presents the results of a literature survey on teleoperation concepts for road vehicles. Furthermore, due to the increasing interest within the industry, insights on patents and overall company activities in the field of teleoperation are presented.

I. INTRODUCTION

Automated Vehicles (AVs) are the key technology of tomorrow’s mobility. Their development has been a focus of academic and industrial research for decades, and market introduction is increasingly imminent. The first truly driverless vehicles, i.e., without a safety driver, are already to be found on public roads in different parts of the world. However, remaining challenges and complex or even currently unknown edge cases pose a real threat to the utilization possibilities of AVs. With increasing popularity, a teleoperation technology is seen as and being developed as a fallback solution for Automated Driving (AD) functions. By enabling remote operation, the AV can be supported by a human operator who is not located in the vehicle. Requesting this remote support whenever an AD function reaches the limits of its Operational Design Domain (ODD), the objective of teleoperation technology is to provide a safe and efficient solution to overcome these limitations. Once the AV is brought back into its nominal ODD, it can again continue its journey fully automated as before. Over the years, a variety of different teleoperation concepts relating to how a human operator can remotely support or substitute an AD function have been proposed in the literature. This paper presents the results of a literature survey on teleoperation concepts for road vehicles and provides insights into relevant company activities and patents in the field of AV teleoperation.

A. Human Interaction with Automated Vehicles

The idea that a human could assist the AV on the fly in situations where the vehicle is uncertain about what to do, can also be found outside the context of remote vehicle control. Guo et al. [1] proposed a hierarchical driver-vehicle cooperation framework that includes interfaces at different functional levels to incorporate actions from an on-board human passenger into the actions of the AV.

Further to this, Walch [2], in his driving simulator studies has demonstrated in different use cases that such human-machine collaboration with different input modalities could be a feasible way of overcoming AV system weaknesses while still enjoying a high level of acceptance among users.

However, while these concepts offer valuable insights into modes of human interaction with automated vehicles, they do not utilize teleoperation technology and as such were not considered in the survey presented in this paper.

B. Taxonomy

Throughout the years, various terms have been used to describe similar or even the same teleoperation techniques. With increasing activity in this field, this became even more apparent. Bogdoll et al. [3] identified this lack of common taxonomy for teleoperation concepts and gave an extensive overview of the terminology used across the automotive domain, while proposing improvements. Building upon that taxonomy survey, the SAE J3016:2021 standard [4] and guidelines on automated vehicles [5], [6], Table I shows the adopted terminology used in this paper. The term teleoperation is used as an umbrella term that encompasses all functionalities needed to remotely support operation of automated vehicles.

C. Contributions

Over the years, different teleoperation concepts for road vehicles have been developed and researched. However, until now, have not been systematically summarized and categorized. In this work, these concepts are collected and grouped in respect of their technical functionalities. Their advantages and disadvantages are highlighted, emphasizing the research motivation and discussing respective industry activities. Finally, this work contributes to establish existing taxonomy in the field while making proposals for the concepts not introduced or covered so far.

| Term                  | Description                                                                 |
|-----------------------|-----------------------------------------------------------------------------|
| REMOTE DRIVING        | System is fully under remote control.                                       |
| REMOTE ASSISTANCE    | System receives event-driven remote assistance from the operator, while still being responsible for the driving task. |
| REMOTE MONITORING    | System is remotely monitored with very limited intervention possibilities.  |
II. SCIENTIFIC LITERATURE ON TELEOPERATION CONCEPTS

In this section, AV teleoperation concepts available in the literature are reviewed and grouped with respect to their functionalities. This review includes remote driving and remote assistance teleoperation concepts, while remote monitoring has been omitted because of its limited possibilities for influencing AV operation\(^1\). Fig. 1, summarizes and graphically presents the reviewed teleoperation concepts. The upper part of the figure illustrates the simplified functionalities of an AD function. This pipeline consists of the modules (1) SENSE, comprising sensors and perception algorithms, (2) PLANNING of behavior, path and subsequent trajectory, and (3) ACT with trajectory following module and the vehicle actuators. The bottom of the figure depicts the reviewed remote control concepts as they relate to the AD pipeline. The position and width of each bar correspond to the design of the teleoperation concepts proposed in the respective literature, meaning the concepts either replace the corresponding AD function blocks or enable interaction with them. Furthermore, in Table II, the approaches are grouped thematically according to similar technical functionalities. For each concept group, a denomination is defined. In the following subsections, these concept groups and their respective references are reviewed in more technical detail.

A. Direct Control

The most fundamental remote control concept is direct control, illustrated in Fig. 2. A mobile network is used to transmit sensor data from the AV to the operator. The data are visualized and the operator provides control signals, such as steering wheel angle, throttle and brake pedal position, gear shifts and various other events (e.g. horn, headlights, wipers), that are transmitted back to the AV. Direct control is subject to different challenges that the remote operator has to cope with, such as transmission latency [32] or reduced situational awareness [33].

\(^1\)E.g. triggering emergency braking or a minimal risk maneuver with no possibility to influence the driving task or assist the vehicle while in nominal operation mode.

| Concept            | Publications | Input Devices |
|--------------------|--------------|---------------|
| Direct Control     | [7]–[17]     | SW&P          |
| Shared Control     | [18]–[23]    | SW&P          |
| Trajectory Guidance| [13], [24]–[26] | SW&P, M&K    |
| Waypoint Guidance  | [14], [27], [28] | M&K          |
| Interactive Path Planning | [29], [30] | M&K          |
| Perception Modification | [31] | M&K          |

SW&P - Steering Wheel & Pedals, M&K - Mouse and Keyboard

In 1997, Bensoussan and Parent [7] introduced a direct control concept that relies on visual information from a camera coupled with data from ultrasound sensors. The operator uses a joystick to interact with the vehicle. Even for this limited system, the advantage of the human operator, being in a safe and remote location while the vehicle operates in a potentially hostile or dangerous environment, was evident. However, it also became apparent that transmission latency and situational awareness pose a real challenge in utilizing this control concept. Appelqvist et al. [8] developed a remote
control setup in which the teleoperation technology is mainly built from Commercial Off-The-Shelf (COTS) components by realizing the direct control interaction between the operator and the vehicle through a steering wheel and pedals. In addition, the authors provided technical details on latency measurements as well as considerations on the overall system performance. In 2013, Gnutzig et al. [9] introduced and experimentally verified a general system design for teleoperated road vehicles. This system relies on video streams coupled with occupancy grid map data obtained by laser sensors. Additionally, Shen et al. [10] used a Head-Mounted Display (HMD) with the objective of improving the driving performance of the operator.

With the growing interest in remote operation systems, Hofbauer et al. [11] developed a system enabling direct control interaction with a vehicle being teleoperated in the CARLA driving simulator. Schimpe et al. [12] tried to fill the gap in publicly available software for remote driving functionalities by publishing an open source software implementation. One objective of the software stack is to enable quick and flexible deployment to different types of automotive vehicles. Based on these research activities, this direct control implementation was successfully used within the projects UNICARagil [13] and 5GCroCo [14].

Over the years, various testbeds were developed to provide information on whether, when, and how direct control can be used. Research activities generally used passenger vehicles for experiments. However, some other vehicle types also served as demonstrators. Ross et al. [15] investigated the minimum system requirements for effective teleoperation of an off-road ground combat vehicle. Bodell and Gulliksson [16] remotely controlled a truck within a simulation environment and evaluated the handover process between autonomous operation and manual control. Finally, Wu [17] applied the teleoperation to recreational vehicles by remotely controlling an electric golf cart.

Due to technological progress in hardware and software, the direct control concept has reached a high degree of maturity and is the subject of numerous publications. However, challenges concerning the direct teleoperation concept still remain. The performance of the human operator as well as the safety of the vehicle is highly dependent on the latency [32] and stability of the mobile network [34]. Consequently, different concepts for further improvement of the direct control experience were investigated and implemented. Taking the transmission latency into account, Chucholowski et al. [35] presented a predictive display for the operator, where the position of the teleoperated vehicle and interacting dynamic objects are predicted. Moreover, Tang et al. [36] introduced the Free Corridor to reach a safe end state in the event of a connection failure. Graf et al. [37] combined the benefits of these two concepts into the Predictive Corridor approach.

Another critical challenge of direct control is the operator’s reduced situational awareness by only perceiving the vehicle environment via various visualizations of sensor data [33]. To improve the situational awareness, Georg et al. [38] developed an adaptable interface for teleoperation and evaluated different visualization concepts [39], including the use of an HMD [40]. HMDs were also investigated by Shen et al. [10] and Bout et al. [41]. Hosseini et al. took a different approach to compensate for the challenges mentioned above by introducing assistance systems for use in the execution of longitudinal [42] and lateral [43] guidance.

B. Shared Control

In recent years, shared control emerged as a teleoperation concept that copes with the insufficiencies of the direct control concept. Its primary objective is to assist the operator in real-time to improve the safety of both the ego vehicle and other road participants. Of the AD functions, only a functional perception module is required, i.e., the proposed approaches work with an object list or a representation of the free space as an input. As for direct control, the interface for the human operator is a steering wheel and throttle/brake pedals for lateral and longitudinal motion control commands respectively. The operator’s control commands are transmitted to the vehicle, where they are accepted by the shared controller as desired control actions. If the shared controller deems them safe, the commands are executed. If not, the shared controller is able to intervene, i.e., override the control actions in order to prevent an imminent collision with an obstacle or road departure, as visualized in Fig. 3.

In the literature on shared control, the control method Model Predictive Control (MPC) is well-established, forming the basis for all approaches reviewed in this survey. Anderson et al. [18] developed an automation component, computing safe steering commands in a free corridor. Based on a risk metric, the risk of the operator’s steering commands is continuously evaluated, so that in situations where a greater risk is anticipated, the automation is granted a higher control authority. This approach was validated in a user study with a real test vehicle and human operators in the loop. Going beyond this, Schimpe and Diermeyer [19] proposed an MPC-based shared steering control approach for the avoidance of obstacles, which are modeled as repulsive potential fields. The corresponding validation was carried out in simulations without an actual human in the loop. Another approach, suggested by Qiao et al. [20], models the human-machine interaction through Nash equilibrium-based, non-cooperative games. Although the hardware of a real teleoperation test vehicle was introduced, the presented results are generated within a simulation environment.

Schitz et al. [21] introduced an MPC-based assistance approach in a cruise control (velocity-only) fashion. The controller maintains the vehicle at a safe velocity and distance to dynamic preceding vehicles and cross-traffic in urban environments. This approach exemplifies the potential of shared control for improving the safety and comfort of autonomous vehicles.

Fig. 3. Shared control concept. The controller can override the human operator in real-time in order to keep the ego vehicle and other road participants safe.
scenarios. While experiments with a test vehicle are reported, details about the operator’s interface and the teleoperation setup are not given.

Finally, two approaches are cited that are capable of overriding and combining both operator’s steering actions as well as velocity control commands. First, Storms et al. [22] presented a shared control system based on MPC, that assists the operator in the task of static obstacle avoidance. The controller was validated in studies by remotely controlling small mobile robots within an unstructured simulation environment with a human in the loop. Second, Saparia et al. [23] developed another MPC-based shared control approach for vehicle teleoperation in urban scenarios. Using a concept of MPC-based predictive display, a strategy for mitigating latency in the teleoperation system was also proposed. Validation of the controller was carried out in simulation.

In general, shared control is subject to similar challenges to those faced in direct control as described in the previous section. However, with the requirement of a functional perception module, the operator is assisted in terms of collision avoidance, effectively improving safety.

C. Trajectory Guidance

In trajectory guidance mode the operator takes over the tasks of perception and the entirety of planning, which enables this concept to overcome problems at various levels of the AD pipeline. The operator’s control commands are given as trajectories consisting of a path and corresponding velocity profile, as visualized in Fig. 4. This trajectory is then tracked by the vehicle which is only responsible for the low-level control. This relieves the operator to some extent, especially with regard to latency-critical control tasks. Since the same interface from the trajectory planning module of the AD function is used, remote trajectory guidance can easily be integrated within the AV software stack.

Gnatzig et al. [24] implemented a trajectory guidance approach in a discrete manner. The operator provides trajectory segments of several meters generated with a joystick or steering wheel and pedals. The vehicle follows this trajectory and stops at the end if the operator has not appended another trajectory segment in the meantime. While this teleoperation concept decouples the operator from the task of vehicle stabilization, it does not allow for dynamic adaptation of the current vehicle behavior.

Hoffmann et al. [25] proposed a concept that converts each control command provided through steering wheel and pedals, into a desired trajectory that ends in a standstill. While this allows for dynamic adaptation of the desired vehicle behavior, the level of decoupling between the human and vehicle stabilization task is reduced because the human operator plans the desired trajectory at higher frequencies.

Jatzkowski et al. [13] also introduced a concept that provides trajectories for the trajectory-following controller of the AD function pipeline. However, further details on how these trajectories are specified were not given. Kay and Thorpe [26] developed a concept that allows the operator to define discrete waypoints that are associated with the desired velocity, effectively turning a waypoint sequence into a trajectory that is strictly followed by the vehicle. This concept is closely related to the next subsection, with the main difference being the missing trajectory (re-)planning on the vehicle side.

D. Waypoint Guidance

Waypoint guidance is a teleoperation concept in which the human operator takes responsibility for decision making and path planning. As shown in Fig. 5, the operator typically specifies discrete waypoints on a camera image or a map through mouse clicks. These waypoints are then fitted into a path that is transmitted to the vehicle, where the trajectory planning module of the AD pipeline aims at tracking it, while taking into account vehicle surroundings perceived by the perception module. As a result, the traveled path can deviate from the specified waypoints to some extent.

Approaches for waypoint guidance have been developed in different flavors. For instance, a basic implementation often referred to as indirect control, was demonstrated in the project 5GCroCo [14]. Björnegard [27] created waypoints by driving a simulated vehicle in a virtual environment. The real vehicle then mimics the behavior of the simulated vehicle by following the recorded waypoints. Finally, the approach of Schitz et al. [28] creates a corridor along mouse-clicked waypoints, in which the vehicle performs trajectory planning in an automated manner.

To conclude, with waypoint guidance the operator is not responsible for low-level control and the AV makes the final decision, so a larger part of the AD pipeline must be functional as shown in Fig. 1. This also means that only a limited dynamic intervention by the operator is possible, which might result in time-inefficient stop-and-go driving behavior. On the other hand, this property makes this control concept more robust in the face of network latency issues.
E. Interactive Path Planning

Interactive path planning allows the operator to intervene at the decision making level of the AD pipeline. This concept was introduced by Hosseini et al. [29] by enabling real-time interaction between human and machine at the path planning level, and was later extended by Schitz et al. [30]. Optimal paths are computed automatically and visualized through augmented reality, where the operator chooses a suggested path, as shown in Fig. 6. In general, interactive path planning can be divided into two phases. In the first phase, a grid map is created and used to find multiple path candidates with a modified Rapidly-Exploring Random Tree (RRT) algorithm. This algorithm is able to find feasible paths in real-time and has been adapted to work without a preset target point. It favors smooth paths that do not cross lane markings. The next step reduces the number of paths by applying a clustering algorithm such as k-means [29] or DBSCAN [30]. The best path (e.g., in terms of smoothness) from each path cluster is chosen and suggested to the operator. This gives the operator one path from each cluster to choose from. In the second phase, the path chosen by the operator is further optimized to avoid obstacles and improve smoothness while maintaining driveability. Optimization can be conducted using the potential field method [29] or CHOMP [30]. Finally, the optimized path is then automatically tracked by the AV.

The level of abstraction reduction of this teleoperation concept comes at the cost of requiring a functional set of AD modules such as perception, trajectory planning and following, which, on the other hand, effectively reduces the operator’s workload, thus providing the main benefit of this concept.

![Fig. 6. Interactive path planning concept. A human operator takes over decision making and selects a path based on multiple suggestions.](image)

F. Perception Modification

With the objective of supporting the perception module of the AD pipeline, Feiler and Diermeyer [31] proposed a teleoperation concept for perception modification. Conceptually visualized in Fig. 7, this approach enables the resolving of situations in which either a false positive or an indeterminate and neglectable object detection hinders the AV operation. In this case, perception data, i.e., an object list and a grid map, are transmitted to a human operator and visualized in a 3D environment. With a video overlay, the human operator assesses the situation and draws a polygon around the object with mouse clicks and keyboard inputs. Once approved, the information is sent to the vehicle and the AD function classifies that area either as a free space or an obstacle. If the approval frees the desired path, the AV can continue its operation.

As described, this approach does not replace but enables interaction with the perception module of the AD pipeline. It resolves perception-related fail cases of the AD function and can be seen as a complement to the aforementioned concepts of shared control, waypoint guidance and interactive path planning, which all assume use of a perception module. Since the operator is not part of any planning or control task, it is assumed that the overall workload is lower that that of other teleoperation concepts.

![Fig. 7. Perception modification concept. A human operator interacts with the perception module of the AD function to resolve indeterminate object detections.](image)

III. INDUSTRY ACTIVITIES RELATING TO VEHICLE TELEOPERATION

In addition to academic research, companies are also active in the area of AV teleoperation. Fig. 8 shows the number of patents published globally over the last 21 years. The data are based on results for the search term ‘Vehicle Teleoperation’, obtained through the Google Patents search engine. This terminology proved to filter out patents that are not directly related to automotive technology. The search was limited to include the filings in English for the time period from the year 2000 to 2021. The exponential growth in the number of published patents is apparent.

For a long time, remote control of AVs was reserved for specific operational scenarios, usually in locations that would be dangerous and hazardous for manual operation by humans. However, finally it became evident that no matter how good full autonomy is, self-driving vehicles will always require...
some kind of remote monitoring, assistance, or driving to overcome challenging traffic scenarios. In consequence, teleoperation is being accepted as a viable fallback solution. This has not only motivated existing companies to increase their research and development activities in this field, but also motivated new startups to emerge thereby helping industry to scale up. In this context, Zoox became one of the most prominent companies at the forefront of research with numerous patents, e.g., [44] and [45] as well as public demonstrations. A good example can be seen in the video [46] in which Zoox demonstrates its vision of waypoint guidance and perception modification on the streets of San Francisco. In contrast, Ottoopia showcased both direct control and interactive path planning concepts as part of their Tel Aviv demonstration [47] and joined forces with Motional to integrate teleoperation support into AVs [48]. Volkswagen published a number of teleoperation-related patents, e.g., [49] and has only recently announced teleoperation field-test activities with the German startup Fernride [50]. Furthermore, DriveU and EasyMile are collaborating to bring teleoperation to different AV types. Also worthy of mention are a number of other companies such as Argo AI, Aurora, Baidu, BMW, Robert Bosch, Cruise, Einride, Mercedes-Benz, Nissan, Phantom Auto, Renault, Vay, and others who are making significant advances in the field of AV teleoperation technology.

IV. CONCLUSION

This paper has presented a systematic review of the literature on different teleoperation concepts and given an insight into their adoption in the AV industry. The concepts were grouped and discussed in terms of their applicability as fallback options with respect to the AD pipeline. In summary, it can be concluded that there is a wide variety of teleoperation concepts that can successfully handle different fail cases or ODD limitations within the AD pipeline. However, not all of them have the same significance, and, given their different functionalities, benefits and disadvantages, they will coexist in the future and continue to offer robust fallback solutions to AVs with new concepts and features yet to come.

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