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Automated Vehicles Controlled by Smart Infrastructure – the Architecture of Managed Automated Driving (MAD)

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Abstract

The German national project MAD Urban is investigating the possibilities of smart infrastructure, which is not only providing additional information for "Cooperative Automated Vehicles" (CAV) on the road, but is also taking over parts of the vehicle automation function. This paper provides an overview of the system architecture developed in the project for this approach, which includes coordinated cooperative behaviour planning for several so called "Managed Automated Vehicles" (MAV) within the area monitored by road side sensors. Furthermore, a functional description of the major system components is provided, which are currently implemented and will be demonstrated in 2024. Besides, this paper already summarizes some challenges discovered so far.

Keywords:

System architecture; vehicle automation; connected automated driving; edge processing; V2X; V2I

Introduction

Automated vehicles are under development and in research for many years, however, market breakthrough is not visible. The reasons are multilayered: e.g. automation function complexity, lack of use, acceptance, high cost, unclear regulations, safety and security obstacles, unconvincing business models. A key problem overall is the complexity of the traffic system and the variety of situations which may occur. It is necessary to understand and cope with a gigantic number of traffic situations and environmental conditions. This is especially true if an automated vehicle should operate in a wider area, and is not only bound to a very restrictive Operational Design Domain (ODD) [1], e.g. on a highway with clear lane markings and under clear weather conditions. When targeting at urban or even door-to-door mobility, the number of possible situations grows exponentially. As result, the complexity of the vehicle automation function also grows similarly, while also the number of required sensors or used sensor types increase, since some situations work better using LIDAR while others need camera or RADAR input, and as redundancy is also a key requirement for driving functions on higher levels. Consequently, the price per automated vehicle will be very high. This is even true if only fleet vehicles on specific routes are considered. Even then, the vehicle itself needs to bring all sensors and computation power to solve all possible situations en-route.

But there is a different approach, where sensor inputs are provided by other road users or by local infrastructure, making use of Collective Perception. The biggest advantage of such systems is that vehicles can have a much larger field-of-view, or even different perspectives on the same scene. Specifically, sensors mounted to local infrastructure have a perspective from higher altitude, being able to provide a better overview with less line-of-sight obstruction. Furthermore, local infrastructure-based sensors can be tailored to match the exact road topology and the climate conditions and a reduced set of possible scenarios at the given spot, making them the optimal solution for the given area, possibly outperforming vehicle capabilities. If the current research questions in the field of Collective Perception, regarding e.g. trust issues, latency and bandwidth limitations etc. are solved, then the number of sensors, specifically for fleet vehicles operating on pre-defined routes, can be reduced. This is esp. true when the route is equipped with infrastructure-based sensors, completely or at neuralgic points.

Besides, there are also projects currently running or already completed which go even beyond the exchange of sensor data. The interaction goes from simple information provision (e.g. Cooperative Awareness Messages, CAM [2]), to advisories (e.g. speed advice in Signal Phase and Timing Extended Messages, SPaTEM [3]), and currently also starts to go into an agreement seeking. A full spectrum is described in SAE J 3216 [4]. When touching the extremes, i.e. when fully controlling vehicles remotely by components not being part of the vehicles themselves, e.g. by local infrastructure, backend/cloud services, or remote operators, this spectrum nevertheless is very limited. Therefore, the authors also proposed a different approach in [5], the Cooperation Levels. When remote entities are mandated to control automated road vehicles, the performance of the traffic system can be drastically improved [6]. In case of a route fully covered by an infrastructure-based system, neither costly sensors nor large computation equipment is required in the fleet vehicles, further reducing the per vehicle costs.

The German national project Managed Automated Driving (MAD) Urban [8] is trying to identify the boundaries of infrastructure-based vehicle control, investigating several aspects of the spectrum, including Collective Perception, but also maneuver, trajectory or even steering control calculated and provided for automated vehicles within the covered area by local infrastructure. While [5] described the general approach, this paper describes the developed system architecture, as it is currently being deployed on different test sites in Germany. It therefore provides a system overview first and then briefly describes the different components. After the component overview, a functional overview of the system is given. Then, a set of challenges is provided which have been already identified, before the paper is concluded.

General MAD system overview

The MAD system needs to consist of several components, as shown in Figure 1. From bottom to top these are first of all the vehicles. As indicated before, some fleet vehicles operating only within areas covered by local MAD hardware may have drastically reduced sensor and computation power. Such vehicles are called "Managed Automated Vehicles" (MAV). Nevertheless, the available road-based infrastructure is also used in a backward-compatible way by sending and receiving standard or quasi-standard ITS-G5 messages, such as Collective Perception Messages (CPM) [8]. Those messages may also be received by all other vehicles equipped with ITS-G5 connectivity, e.g. Cooperative Automated Vehicles (CAVs), and can therefore also positively impact the behaviour of those.

On the road side, sensor systems, so called "Road Capturing Units" (RCUs) are needed. An RCU therefore broadly can be seen as a single hardware unit, possibly consisting of several sensors, like e.g. a pole with mounted cameras pointing at multiple directions. The data of several RCUs is integrated in an "Edge Processing Unit" (EPU). Each EPU is therefore fusing the incoming data of the connected RCUs into a local digital shadow. This digital shadow is then used for the prediction of vehicle movements as well as for the planning of the behaviour of the connected MAVs in range of the EPU. It therefore also has direct access to the required communication devices in the field for the local area, the Road Side Units (RSUs). By using the available data, the EPU also takes care of the cooperation and coordination of the different behaviours of MAVs and other vehicles in range on the road, depending on their level of cooperation. If e.g. a CAV is providing its own goals by sharing Maneuver Coordination Messages (MCM) or similar, the EPU can take this data into account for planning the behaviour of the MAVs in the area.

The EPUs therefore act as individual instances. The placement close to the road ensures low latency communication to the vehicles and also scalability of the overall system. For management, logging and higher-level services, the different EPUs nevertheless are connected with each other by backend systems. Finally, also the technical supervision of the complete system (including the MAVs), the so-called "MAD Operation Center" (MOC), is attached to the backend. In case of issues on the road or by any of the subsystems, a remote coordinator can take the required steps, from tactical remote assistance up to full remote driving of the MAVs. The remote coordinator can therefore also take advantage of using the available data, e.g. infrastructure video streams, object data included in the digital shadow, etc.

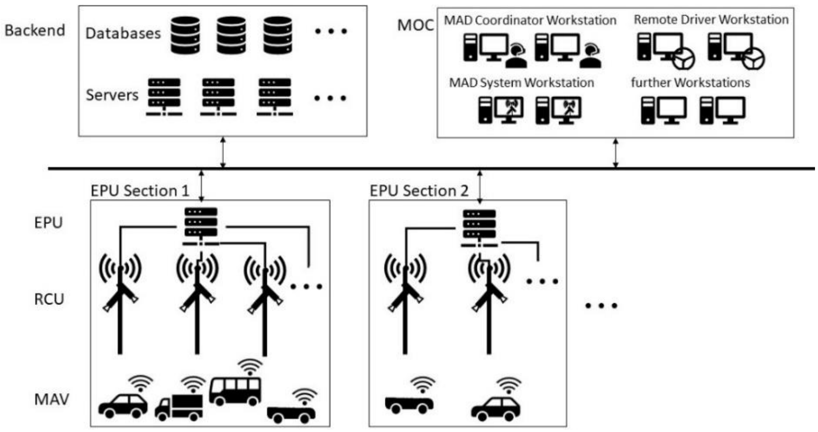

Figure 1. The MAD system architecture overview

While the different components are described in more detail in the next section, it is also very important to clearly define the different areas of responsibility. Here, one crucial aspect is that an EPU can only calculate valid behaviours for an area it is able to closely monitor and which is within communication range of the EPU. It is therefore highly depending on the ranges of the attached RCUs, which in turn are depending on the used sensors and their respective ranges. The MAD section is representing the union of all connected EPU sections and therefore represents the area of responsibility, control and accountability of an MAD Operation Center.

Figure 2 provides an overview on the different ranges, the respective naming and how they are hierarchically related. It is important to note that the depicted sensor ranges are not necessarily similar to the technical ranges they may have on their respective datasheets. Instead, those ranges are highly dynamic, and related to the currently available data quality. This quality in turn is depending on several attributes, such as weather conditions, object detection capabilities (e.g. number of required data points on an obstacle to detect it), required accuracy etc. Since the RCU section is depending on the included sensor ranges, its geometric dimension also will be dynamic. Same is true for the EPU and MAD sections. More details are described in the section "Challenges" further down.

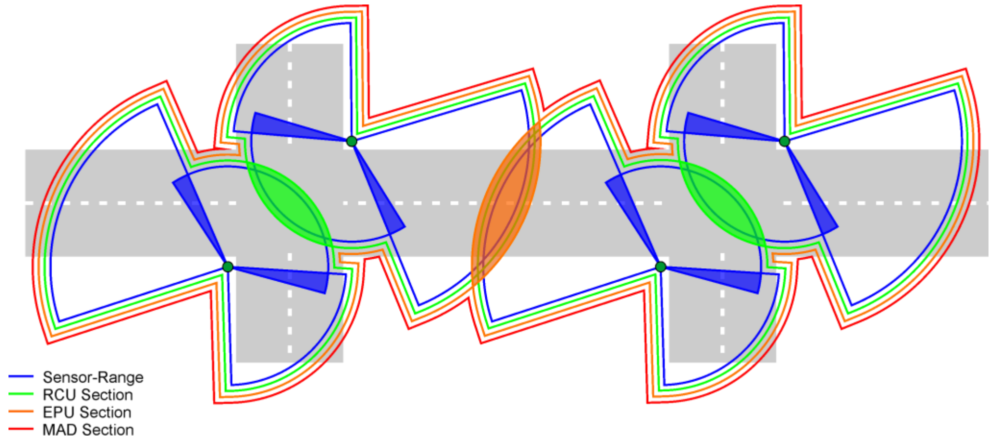

Figure 2. The ranges and geometric dimensions of operating areas of the different MAD components. Overlapping areas of instances on the same level are highlighted in the respective color

System components

In the following, the components of the MAD system are described in more detail.

Vehicle classification

The first set of vehicles considered are the MAVs. Since here perception and decision-making tasks are located in the infrastructure, it is possible to reduce the sensor set and intelligence in the vehicle, compared to regular CAVs. Some safety functions to reach a secure state if other options fail (e.g. connection loss to the infrastructure) have to be implemented in the vehicle. For that, a sufficient sensor set and sufficient computation capabilities have to be still available in the vehicle.

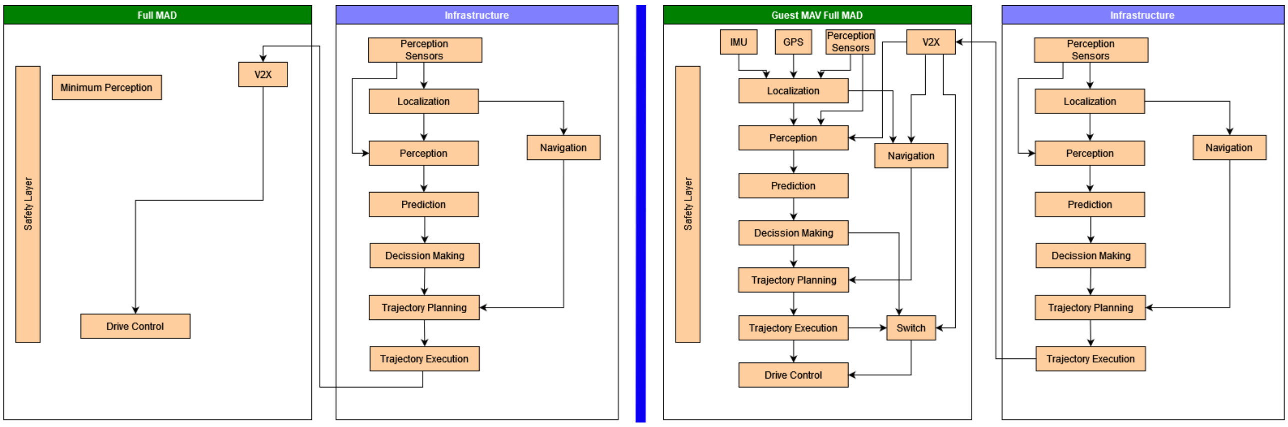

Figure 3: Comparing vehicle architectures. Full MAD (left) vs. a fully equipped CAV participating in full MAD as "Guest MAV" (right).

MAVs can be split into two categories: Vehicles specifically designed for operation in an MAD environment and vehicles using MAD as a service for driving in the area covered by the MAD system (Guest MAVs). The first can take full advantage with the reduction in vehicle side automation capability, but can only be operated in the MAD system area. This category mainly aims at fleet vehicles like the U-Shift vehicle [9] used in the

MAD project. Guest MAVs are vehicles with a regular vehicle-based automation system. They can use the MAD system to extend their Operational Design Domain (ODD) by the complex urban environment covered by the MAD system or use the MAD system to improve the operation. In addition, also CAVs can benefit from the MAD local infrastructure, since standard message containers for CPM and Maneuver Coordination (MCM) are sent out on the standard ITS-G5 channels.

Road Capturing Unit

For the MAD concept a series of Road Capturing Units (RCU) is a crucial component on the road side which guarantees the extensive perception of the surroundings and enables the direct communication with the oncoming MAVs. Therefore, an RCU consists of multiple sensor modalities and a communication unit called Road Side Unit (RSU). Generally, the types of sensors to be installed vary from visual sensors such as monocular or stereo camera to detection-and-ranging systems like LIDAR and RADAR. Each sensor type has different advantages and disadvantages regarding their sensor coverage, sensor resolution, operational conditions and measurement principles. The numbers and combination of different sensors depend on the requirements for the specific map topology. For more specific use-cases and complicated road topologies, more exotic sensors such as infrared cameras or micro-Doppler radars might also be considered on an RCU.

The advices and decisions derived from the perception with the sensor units need to be transmitted immediately to the MAVs so these can take actions accordingly. The RSU mounted on the RCU is responsible for establishing the vehicle-to-infrastructure communication which is needed for enabling information exchange between EPU and MAVs. The data can also be assembled and forwarded to the Backend which allows e.g. remote operators to gain the situational awareness required to make informed decisions.

Edge Processing Unit

Automation of vehicles in the infrastructure brings the challenge of having high demands regarding low latency as well as high computation power. To meet these requirements, units with high computation power located at the road side are used. These EPUs aggregate multiple MAVs and RCUs. They offer high-speed connection to the other components of the MAD architecture, by on the one hand bundling the available RSUs with their wireless communication to the vehicles and on the other hand by having e.g. fiber optical connections to the backend. EPUs are used for tasks like object detection, trajectory and behavior planning, decision making, and local traffic management.

An EPU is a computation unit located at a road segment of interest, e.g. an intersection. The required computation power is linked to the corresponding size of the EPU section and the related wireless communication range to the vehicles. The computation power is required to offer real-time object recognition to support the automated driving function, sensor fusion to accumulate the information from all local sensors into a consolidated local environment model/digital shadow, object management in an EPU section and service level data management like making local information available to a global backend infrastructure, e.g. traffic flow information, health/status information, video streams for remote driving. Furthermore, an EPU also has to link to other local hardware components, e.g. traffic light control. This link can either be direct or indirect, i.e. by receiving related SPaTEM and topological (e.g. MAPEM [3]) data. Finally, one important aspect for the EPU is that it is including a precise high definition map of the EPU section. This is required in order to do a correct matching of detected objects to the road network as well as for planning the behaviour.

MAD Operation Center

This is the general operations' center for a complete MAD section. It could be integrated in a traffic management or fleet operation center. The MOC includes different workstations for the different tasks that have to be done. Multiple MOCs at different locations are possible. The role of the MOC in the MAD ecosystem spans from system monitoring, dispatching, incident and event management, to new activities in relation to the handling of automated systems, like technical supervision of automated vehicles and their operating area, tactical remote assistance or even remote driving. Therefore, several different work stations need to be available. The number of workstations is related to the number of vehicles which are controlled by the MOC (although not necessarily in a 1:1 relation), the size of the related MAD section and its complexity.

Backend

The most important tasks of the backend are (i) the management and supervision of all connected entities, (ii) data logging, and (iii) connection to additional (cloud) services. In terms of management, several activities are performed. Among others these include the monitoring of all system components, the generation of warning messages in case of any system limit or system failure, and the establishing of data connections, e.g. directly from a remote driver to the driven vehicle and from specific road side or vehicle cameras to the remote driver/coordinator. Such connections should not be centralized, since bottlenecks need to be avoided. In addition, data needs to be harmonized and pre-processed for providing it to the MOC. Data logging is also very important since EPUs and MOCs directly influence the behaviour of vehicles on the road. Similar to the regulations for automated driving, all events, control commands and related input data must be recorded to be used e.g. for forensics. Finally, the MAD system can be attached to further data services. Among others, these could be any management services, like e.g. fleet management or any demand-oriented Mobility-as-a-Service (MaaS) applications. Furthermore, additional services for checking the current Operating Domain (OD) attributes of the area to fulfil the vehicles' ODDs may be required, such as weather, event, rescue mission or road works/road closure related data. These kinds of interfaces will not be part of the project MAD Urban, but require additional attention in future projects.

System functions

Infrastructure-based perception, object detection and tracking

The tasks for infrastructure-based perceiving, detecting and tracking objects and surroundings differ greatly from those of vehicles thanks to its optimized sensors setups. The infrastructure sensors are to be mounted as stationary units and hence can be tailored beforehand regarding their altitude, position and angle to perceive and track objects with a higher accuracy than those of a moving car. Depending on the road topology and conditions, the number and type of sensors to be deployed can be selected to meet the requirements for the specific area for easy adaption. For instance, one could consider an infrared camera to be better suited for a considerably cold and snowy region than a conventional imaging sensor which might struggle to differentiate moving objects from stationary due to heavy blinding effects. This a priori optimization step provides a broader field of view and more robustness in detection through well-thought-out redundancy.

For MAD concept, RCU is the data collecting infrastructure unit which is typically equipped with imaging sensors such as mono and stereo cameras, but also other sensor types are possible. The RCU collects raw sensor data and primarily filters out the relevant information such as position, velocity and orientation of MAVs and other dynamic objects. By using the RSU component of the RCU, also digitally received objects, e.g. by CAM or CPM are included. The first detection results of all sensors and data receivers are directly forwarded to the EPU for further processing. An EPU will perform a sensor data fusion and ensure the validity of the results by cross-checking. Subsequently, an object list is created of the fused data which lays the basis for the EPU to plan the trajectories of incoming MAVs.

Infrastructure-based automated driving

As highlighted earlier, leveraging infrastructure provides a broader field of view, offering advantages for all types of vehicles. The availability of vehicle data, obtained through infrastructure-based sensor detection and communication technologies like CPM or MCM, in conjunction with a high-precision digital map, facilitates infrastructure-based automation. Within the MAD section, infrastructure encompasses a spectrum of automation functionality, ranging from providing advice and suggestions to exercising direct control. To achieve this, the infrastructure must predict the future behavior of vehicles, also referred to as agents, within its range. Prediction plays a pivotal role in the decision-making process, enabling informed decisions once the future behavior of each agent is anticipated. In this context, employing intention prediction models is imperative for forecasting how the traffic scenario will evolve, considering the physical state of vehicles, potential maneuvers, and interactions between traffic participants in the upcoming seconds. The prediction approach combines an interaction-aware motion model with a physics-based and maneuver-based model. Bayes' theorem is applied: the prior estimate considers the rational evolution of the traffic scenario, while the likelihood adjusts the prior estimate by incorporating data detected or received from the vehicles. This allows for consideration of the possibility of irrational decisions by the participating vehicles that may have been discarded in the prior estimate. The output of the approach is a probability distribution over a set of representative trajectories for each vehicle.

Upon predicting the future intentions of the agents, decisions can be made using a game-theoretic framework. As the decision-making process considers the future possible trajectory of the traffic, it can be abstracted into a simple form of maneuver or even converted into control values. Consequently, the output of the decision made at the infrastructure can be categorized as maneuver, trajectory, and direct control. In this context, a maneuver represents a safe action considering the future state of traffic, such as staying in the lane, changing lanes, or coming to a stop. A trajectory is a sequence of positions and velocities for the vehicle to follow, while direct control is directly affecting acceleration/deceleration and the steering angle.

The nature of the decision, depending on the vehicle type in the MAD section, can be viewed as advice or control. For full MAVs with limited sensors and automation capability, the decision always involves control. For instance, the decided trajectory for MAVs, considering the future traffic state, is converted into control values like acceleration/deceleration and steering angle. These values are transmitted frequently via I2V communication to the MAVs individually, and their state is relayed back to the infrastructure through V2I communication. A robust controller unit at the infrastructure adjusts control values of the individual MAVs.

Guest MAVs, equipped with sensors and automation functionality, can benefit from the infrastructure's decision due to its larger field of view. In this case, vehicle automation can evaluate the advised maneuver/trajectory and compare it to its own, deciding which one to execute. These types of suggestions are beneficial in areas where the vehicle sensors are at their limit or obstructed, for example, in turn scenarios.

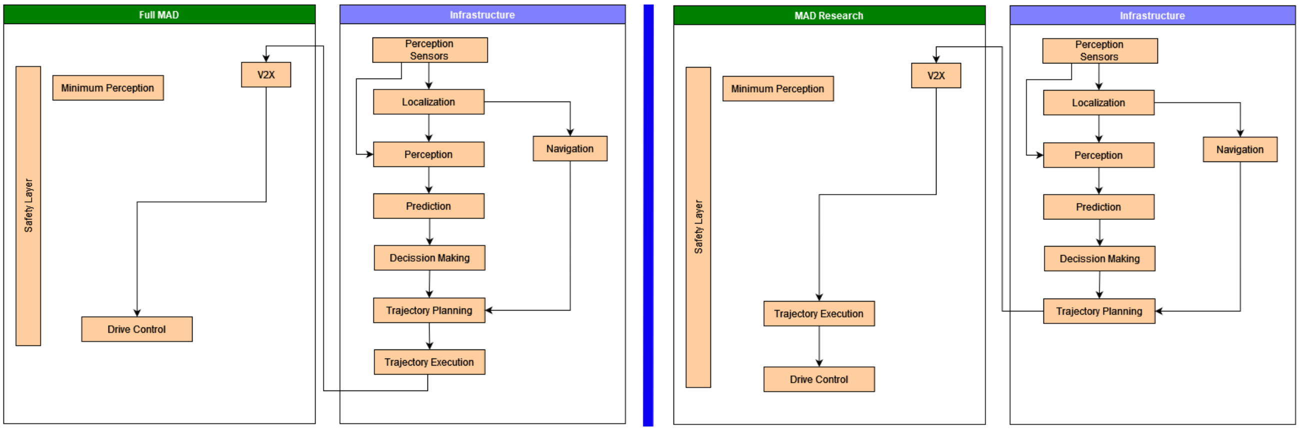

Figure 4: Comparison of direct control of MAVs (left) and trajectory control (right).

When infrastructure is taking over the planning and control of automated vehicles in range, this can also be used to harmonize the behaviours of all road users in the section. When also linked to traffic signalling systems the optimal behaviour of all traffic participants can be calculated and directly applied. The coordinated movement of multiple road users can drastically improve traffic safety and throughput.

Technical supervision and remote operation

Technical supervision of automated vehicles is mandatory in several countries, including Germany [10]. Although supervision on its own is already beneficial in terms of e.g. safety, the link to any kind of remote operation is beneficial, since supervisors can directly influence the behaviour of the vehicle on the road instead of just monitoring it. While remote driving as one option of remote operation is discussed controversially, as it requires a 1:1 connection of a remote driver to a vehicle unit with the additional requirements for ultra-low latencies and a high bandwidth, remote assistance may be more in focus in future systems, as it allows remote operators to e.g. acknowledge maneuvers planned by the vehicles themselves, in general removing time criticality. Nevertheless, remote coordinators often need to fully understand the current state and situation of the automated vehicle when remote operation is required. In some cases, different perspectives are helpful here. In MAD, these kinds of perspectives are available due to the attached RCUs. Online data of the RCUs can be requested by remote coordinators to get an overview of the situation.

On the other hand, remote operation of MAVs is also more complex for remote operators, since it not only involves the supervision of the vehicle, but also of the infrastructure-based system including RCUs and EPUs, as well as the respective sub-systems and functions. The project MAD Urban therefore is only briefly touching all the related research topics, as it simply creates the framework for further testing, and brings remote operation as such to an extreme in terms of available inputs and data sources. Therefore, also the different possible kinds of remote operation, being it remote driving or different shapes of remote assistance, are not finally decided yet.

Challenges

Up to now, two major challenges have been identified. Both are described in the following and need to be investigated more closely.

ITS-G5 communication limitations

The initial idea of MAD Urban was to provide messages to the vehicles in different frequencies, as maneuvers do not change as often as trajectories, which again do not change as often as direct control inputs. Initially, it was planned to use very small messages with a frequency of 50 to 100 Hz for the direct control. It has to be taken into account that direct control also requires a related answer with a similar frequency to make it a closed loop control. In order to achieve backward compatibility with current approaches, it also has been decided to use WLAN-p/ITS-G5/DSRC technology for the message exchange. Nevertheless, this brings several limitations, such as a small bandwidth, limited message sizes, the respecting of duty-cycles and time intervals between consecutive messages [11]. In a nutshell, the demanded high frequencies are not possible due to the given limitations. Basic calculations resulted in the maximum frequency of approx. 40 Hz in case of a free channel and a mean message size of about 100 bytes. Since also other messages will be present on the channel in MAD, such as CAM, SPaTEM, MAPEM, DENM [12] and CPM, and since several vehicles will be present in an MAD section, it has been decided that the maximum frequency used in MAD will be 10 Hz on this channel. Consequently, the direct control of the vehicles will be limited to this frequency. Since 10 Hz is also a common frequency for exchanging trajectory data, and since data on the maneuver level does not require a lot of additional data, it has been decided to include all three inputs to the MAVs in one single message at 10 Hz. Tests being performed in 2024 will show if this approach is practically working on the road.

Of course, new communication standards may allow higher bandwidths and may change the approach. Therefore, MAD Urban is also setting up an additional parallel data channel using WLAN6 and its MESH capabilities. Results of this approach will be available by the end of 2024.

Dynamic EPU section range, obstructions and EPU hopping

As mentioned, the EPU section range is depending on the number and field-of-views of the used sensors and RCUs, as well as of existing buildings and other constant obstructions, such as signs and traffic lights. Besides this static component, the sensor ranges are also dynamically changing depending on e.g. actual weather conditions and vegetation. It is important for the planning activities in the EPU to always know the dimension of the EPU section, since the planned trajectories can only be calculated within its boundaries. At least two research questions arise from this: (i) how are the dimensions clearly defined, and (ii) what happens at the boundary of an EPU section, since an MAD section comprises of several EPU sections.

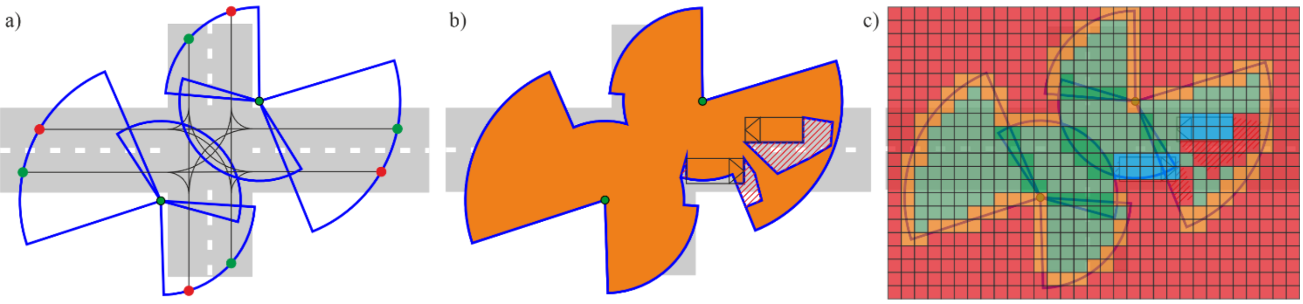

Figure 5: Different possibilities for EPU section range formats: as in MAPEM (a), as polygons with dynamic obstruction areas (b) or as grid, also including color values representing confidence values (c)

The preliminary approach for the second is that EPU sections must overlap, and that the dimensions are always also communicated to the vehicles, so that the vehicle itself can decide on which input is used for driving. In order to avoid discontinuities or jumps at the boundary of an EPU section, it is also required that the next EPU section also receives the trajectory and direct control information of the previous. As the section dimensions are communicated to the vehicles, its format needs to be compact. Possible ways are using a similar format than those of the MAPEM message, simple polygons or even grids, although those are requiring significantly more data, see Figure 5.

One additional question related to the dynamic EPU section range is whether also dynamic objects and the obstruction they are causing should be included in the calculation. This question becomes extremely relevant when the infrastructure sensors are blocked very often, e.g. in case they are mounted in a height of 3 meters while trucks are passing by closely. In such situations, the sensors are often detecting the trucks, but the whole area behind the trucks is obstructed and cannot be used for behaviour planning. A similar situation occurs when an MAV is radially moving away from a sensor. In such cases, the MAV itself obstructs the sensor, so that the sensor can never detect obstacles just in front of the vehicle.

Using multiple sensors along the road which are placed intelligently reduces this effect, but nevertheless obstructions of the path of the controlled vehicles will still occur frequently. The MAD system needs to be aware of these obstructed areas while planning the movement of the vehicles. It is still an open research question how much these obstructed areas are influencing the planning action at the road side, but as a first approach, confidence values for free spaces and/or obstacles will be used. The confidence values will be affected also by the amount of passed time since the obstructed area could be scanned. While confidence values can easily be communicated in grid-based notations, it is more difficult to also include them in e.g. polynomial formats.

Conclusions

This paper presented the current preliminary system architecture for Managed Automated Driving as it has been derived in the German national project MAD Urban so far. Besides the description of the general setup and its functional implementation also first challenges of the approach have been identified. The whole system is currently implemented and will be tested on test sites in Germany in autumn 2024.

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