TESTING AND VERIFICATION OF ACTIVE SAFETY SYSTEMS WITH COORDINATED AUTOMATED DRIVING

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ABSTRACT

Although more and more virtual development methods are used for testing and verification of active safety systems, there is still a need for extensive testing of the overall system in a *real* environment. The quantitative validation requires a wide range of different parameters to be controlled – most systems require adjustments of the speed of a „vehicle under test“ and a „target vehicle“ as well as their relative positioning in distance and angle. Using human drivers these parameters are only adjustable by performing a multitude of tests with statistically distributed results. Automatically driven manoeuvres offer the chance for a directed adjustment of all relevant parameters, requiring fewer tests, thereby creating a much more efficient testing operation. The technological challenge and control task is that two vehicles pass each other precisely at a predefined time and speed. Being able to control this, even tests which could not be performed up to now due to safety risks for the drivers, will be possible.
The presentation reports on a common project of Daimler with Anthony Best Dynamics (ABD) and TU Graz, which resulted in a system using coordinated automatically driven vehicles. The need for precisely driven manoeuvres , resulting specifications for the testing methodology of coordinated path-controlled vehicles, and the challenges of its realisation will be explained. The resulting testing environment, hardware solutions and the methods for planning of safe testing trajectories will be illustrated. Results of the achieved accuracy are presented. A view on the role of this type of testing among other testing methods for precrash systems completes the paper.

MOTIVATION AND GOALS

The introduction of active safety systems has a significant impact on testing methods for vehicles: the testing procedures do not only require to bring the vehicle itself into a predefined driving state, but they also need to place the vehicle into a specific location on the road, or even other traffic members into a given relation to the vehicle under test. For example, testing of lane departure warning and avoiding systems requires the control of the vehicle's position with respect to the lane markings; testing of adaptive cruise control or of crash avoidance systems needs two or more vehicles with a predefined relative speed and precisely controlled timing.

A huge amount of the work for ensuring the functional performance of the systems is done in the virtual domain, in which a lot of experiments with parameter variations can be designed to test the algorithms. But still there is a need to verify the sensor and system performance finally in the real world, especially under critical borderline conditions. Using human drivers, the testing of such conditions is time consuming (because the conditions cannot easily be reached by a single test), or it could even be dangerous for the drivers to test crash-prone situations. With this goal several systems have been proposed to bring the vehicle under test exactly and safely into those conditions, for example [1], [2] and [3].

The coming generation of active safety systems with automatic collision avoidance will call for even more testing because of higher and quantitatively measurable reliability requirements, partially derived from the coming ISO 26262 standards. This was the reason for Daimler to develop a flexible and efficient testing methodology for precisely performing testing manoeuvres, which should be applicable to all kinds of traffic situations as the testing environment.

CLASSIFICATION OF TESTS AND SPECIFICATIONS

A detailed analysis of the testing manoeuvre catalogs of current and future active safety systems was performed to analyse the exact requirements for such a system. It revealed several categories with different reasons for more precision (see fig. 1):

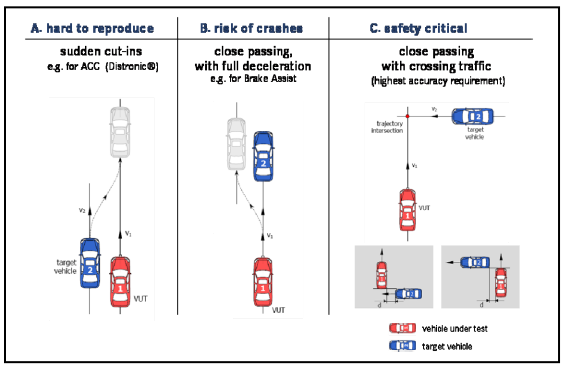

Figure 1. Manoeuvers with precision requirements.

A) manoeuvres which are hard to reproduce
B) manoeuvres which often lead to minor accidents
C) manoeuvres which are too dangerous for human drivers

It turned out that a large share of those categories could be improved significantly by a system which would drive a vehicle automatically along a predefined path under strict timing conditions; several vehicles need to be coordinated with exactly the same time base. Especially the typical "no fire" situations of crash avoidance systems ("close passings") could be tested this way very efficiently.

The accuracy requirements for the vehicle guidance system were specified as follows: Passing of any moving or stationary target should be possible with a distance of 20cm; this leads to requirements of a path following error of less than ±10cm in lateral direction. The longitudinal precision needed depends upon speed; a precision of ±40cm at a speed of 20m/s (72km/h) is equivalent to reaching any track point within a time tolerance of ±20ms (see figure 2). This time tolerance restriction is a requirement which can be generalized to other speeds.

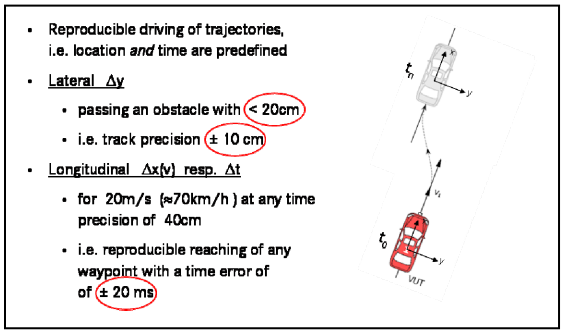

Figure 2. Requirements for driving accuracy.

There were further requirements for the design of the system: The automatic guidance must be capable of handling at least driving speeds in urban environments (70km/h), with the potential to reach higher speeds as well. It should be possible to install the system into any vehicle, in order to test vehicles in any phase of the development program. Traffic situations of up to 4 coordinated vehicles will be needed, and all the situations should be simulated before the real testing. Safety of personnel and equipment has highest priority; dangerous manoeuvres should be performed without a diver in all vehicles in the test. Finally, the system should be applicable on any test track.

TECHNICAL CHALLENGES AND SOLUTIONS

A large portion of the specifications could already be met by a "path following" control system, based on steering and pedal robots, developed by ABD. The system can automatically follow a predefined path, the actual position being measured by an Inertial Measuring Unit (IMU) backed up by a Differential Global Positioning System (DGPS) to ensure long term accuracy in the cm range. The system could be used to perform path following in a mode with a driver in the car, but also in a driverless mode with a safety controller and emergency brake actuators as necessary additional components. Figure 3 shows the implementation of the driving robots in a Mercedes test vehicle.

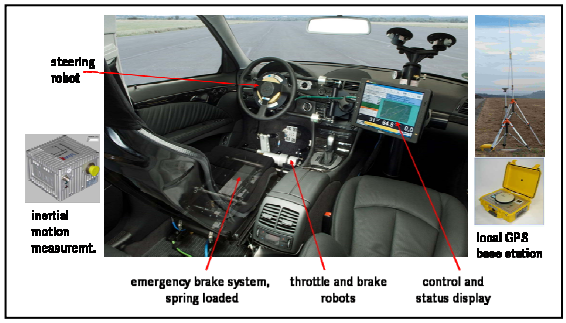

Figure 3. Driving robot integrated in test vehicle.

The challenge for the coordinated driving concept is to control a single vehicle not only laterally, but also longitudinally with high accuracy. Besides this, two or more vehicles should be able to perform precisely synchronized manoeuvres. This could be accomplished using ABD's system by implementing a trajectory control (i.e. ensuring lateral and longitudinal positioning *and* timing) based on GPS-time for each single vehicle, which is accurately available on all vehicles as an output of the DGPS system [4].

Planning of the trajectories needed much more care than for path following of a single vehicle: traffic situations are planned in detail with predefined trajectories for every vehicle. Each vehicle should know in advance what to do at any time instant,

with some freedom to react in different variants depending on the actual situation. In order to avoid accidents, the test manoeuvres can be simulated in advance, considering even deviations from the planned path in case of loss of control due to unforeseeable factors.

All vehicles are controlled from a common base station; from here the operator starts the test manoeuvres via a WLAN network, the actual position and speed error is supervised, and the test can be interrupted at any time - if necessary. A thorough safety concept was designed to ensure safe operation and shut-down procedures. Figure 4 shows the base station with two test vehicles.

Figure 4. Base station and two test vehicles.

REACHED PRECISION AND REPRODUCIBILITY

In order to reach a precise trajectory control, the parameters of the system have to be adjusted carefully. However, the system is quick to configure and only requires basic information to be entered for the vehicle, such as maximum brake pedal force, and geometric information for the location of the IMU with respect to the wheelbase. A predictor model for the vehicle dynamics is not used and instead the necessary precision is achieved entirely using PID control with feedback from the IMU. The control parameters are easily derived from a set of simple open-loop driving tests. Once the parameters are set for a vehicle class, the controlled operation of the vehicle leads to very reproducible performance of the trajectory control.

Figure 5 shows a measuring set up for verification of lateral and longitudinal control accuracy. It consists of several strip-switches which close a contact when pressed down by the vehicle tire; the staggered position of the strip-switches allows for lateral resolution of 1 cm, while the timing of closing the different contacts is used for longitudinal verification.

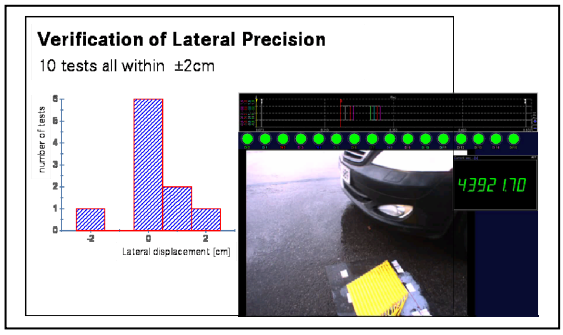

Figure 5. Lateral precision.

The absolute accuracy of the trajectory control in straight line driving has proven to be quite high. Typically, the lateral path following error was measured to be in the range of ±2cm, the longitudinal time error in the range of ±10ms (equivalent to a distance error of ±20cm at a speed of 20m/s). Indeed, if there is sufficient time to stabilize in the steady state condition, the longitudinal error is normally significantly less than this. In dynamic manoeuvres a lateral error of ±10cm and a distance error in the range of ±1m were found; however, the reproducibility of the same manoeuver was similar to the steady-state accuracy . Thus, the dynamic deviation can be considered and compensated in critical sections of the trajectories.

One important feature is the reproducibility of stopping to a point with rather high deceleration. Figure 6 shows the results of the verification measurement; all endpoints of this test were within a circle of 10cm. In summary, the system allows for very precise trajectory control of the vehicles, as long as the manoeuvers stay away from the physical limits of vehicle dynamics.

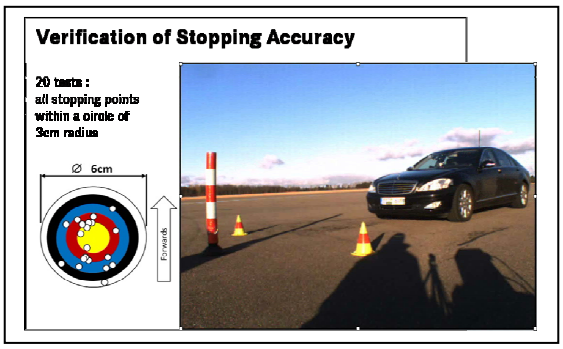

Figure 6. Precision of stopping point

PLANNING AND SIMULATION OF TESTS

For planning of the trajectories of several vehicles, a manoeuvres planning tool is implemented There are several methods to plan a trajectory of a vehicle: the simplest method is to record the track which a human driver has driven; this trajectory

can be used as a template for repeated automatic driving of the same trajectory. A second method is to construct a trajectory from basic elements (see figure 7). The tool allows combining straight tracks, curves, lane changes, sinusoidal segments, slaloms, or spirals; and speed profiles for every section can be planned to provide exact timing. In "critical sections", defining maximal tolerances for lateral and longitudinal error sets the thresholds for controlled interruption of the test. It is also possible to define sections, in which the path following system allows for certain freedom of the vehicle control, i.e. acc speed control, emergency braking or lane keeping support.

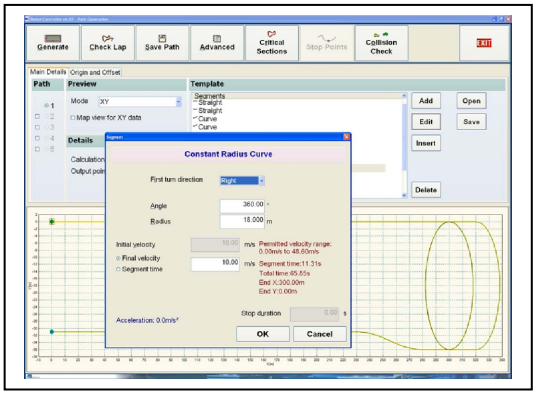

Figure 7. Planning tool.

Planned trajectories can be saved, retrieved and modified. This way, a set of manoeuvers for covering a parameter variation test can be built. Finally, this results in a database of easily repeatable verification procedures for an assistance or active safety function.

Once the trajectory is planned, the simultaneous manoeuver of several vehicles can be simulated in order to verify that the relative vehicle motion will be as intended. The resulting tracks are visualized as overlay to calibrated aerial photographs or maps of test areas; this way it can also be verified that the paths stay on the available surfaces. The simulation checks for physical limits and for expected dynamic deviations from the planned trajectory.

Figure 8. Simulation of a test.

SAFE OPERATION

Safe operation was one of the main challenges of the system design; it was laid out with highly reliable respectively redundant components. Nevertheless the position information might degrade at any time, and other failures could happen unexpectedly.

When a driver is in the car, he needs to keep a contact switch closed for automatic control; he can always interrupt the manoeuvre by releasing the contact, and he regains full control of the vehicle as in conventional test driving situations. This mode of operation can be used to perform traffic scenarios where the main focus is on improving repeatability or accuracy.

For safety critical scenarios, the vehicle is operated in the driverless mode. Figure 9 shows the safety components and their interaction with the other vehicle components for this mode. The safety controller verifies continuously the integrity of the system by monitoring of watchdog signals, the communication channels and other safety relevant states. If one vehicle should operate outside of predefined limits (but is still controllable), the safety controller initiates a *controlled shut down procedure* for all vehicles. This procedure will also be activated in case of a communication loss, and it can be triggered manually by the operator in the base station.

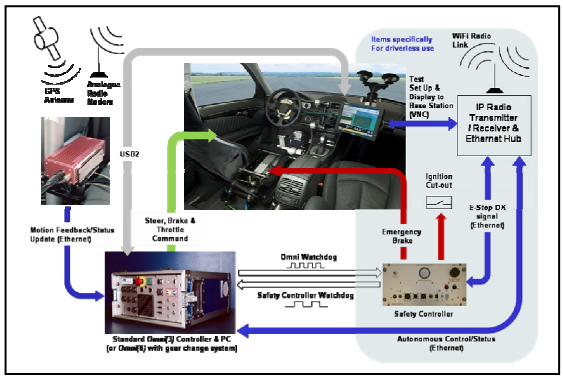

Figure 9. Control and safety components.

In case of a complete loss of control (e.g. steering or brake robot failure), or after pushing the *emergency stop* button by the operator, the safety controller activates a spring loaded safety brake system. The emergency stop will also be activated if the vehicle should leave the predefined limits of the test field.

Controlled shut down procedures are necessary because emergency braking of all vehicles in the test could lead to disastrous results: a planned trajectory with close passing of vehicles could end in a crash. To avoid this, for each point of the

planned trajectory and for each vehicle, settings for steering and pedal robots in two time slots are planned in advance. The result of this shut down procedure is simulated for the whole test manoeuvre in order to verify a safe shut down, whilst also considering the possible tolerances.

The simulation is based on "PC-Crash", a standard program for crash simulation [5]; the concept and implementation was the task of the *Vehicle Safety Institute*, Technical University of Graz. Figure 10 shows an example, how shut down procedures may be defined and verified for a close passing manoeuvres in an intersection scenario; although the traces of the possible shut down procedures seem to intersect, this definition is safe due to the given timing constraints.

By defining the controlled shut down procedures adequately, "safe" places on the test track can be set up for objects (like cameras, traffic signs, etc.), which should not be hit even in the case of deviations from the planned trajectory.

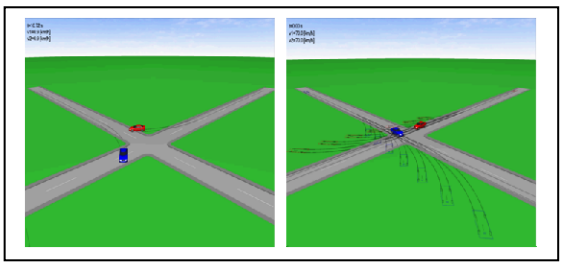

Figure 10. Example for safe vehicle traces for controlled shut down procedures

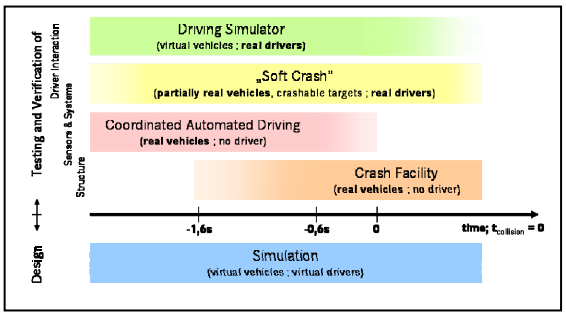

Figure 11. Validation of pre-crash systems with complementary testing methods.

CONCLUSIONS

The presented method using *controlled automated driving* of test vehicles can fulfill the specifications and has proven the potential for efficient and safe verification of assistance and active safety systems. Test procedures can be performed much more precise and repeatable than with human drivers; the risk of crashes is significantly less than with human drivers even in very close passing manoeuvres.

This way, the compliance with specifications of assistance and active safety systems can be verified efficiently; the comparison of different sensor configurations or software versions can be done with less experiments. Manoeuvres at the borderline between "system must react" and "system should not react" can be tested precisely by controlling the relative absolute position and speed of several vehicles in a traffic configuration.

As shown in figure 11, this method has its place in a set of complementary verification methods. While simulation is used for system design in a completely virtual world, the driving simulator focuses on the behaviour of real drivers, and the crash facility focuses on the structural aspects of real vehicles. Crashes with soft targets allow the checking of systems and the driver's interactions around the time of crash, but some questions were still left open. The performance verification of *real* sensors in interaction with control algorithms in *real* traffic situations up to points very close to a crash is the realm of controlled automated driving.

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