Towards Autonomous Vehicles:
Developing Highly Automated Vehicles for Structured and Unstructured Environments

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In this paper some of the latest HORIBA MIRA developments on systems for the simulation and development of automated vehicles are introduced. For the structured environment case the emphasis is on the longer term research challenge of developing systems for cooperative automated driving allowing the benefits in both safety and efficiency to be realised in the future. This includes developments on traffic simulations and management systems since these will also be key to reaching the longer term vision of cooperative autonomous driving. For the unstructured environment case the emphasis is on the shorter term development challenge of engineering unmanned vehicles that can be safely and reliably deployed in demanding customer specific off-road environments. Finally, some conclusions and a selection of future works are presented.

Introduction

Automobiles have become essential to our life and so will higher levels of automated driving. Automated Driving is, for the European Road Transport Research Advisory Council (ERTRAC), one of the major technological advancements shaping our mobility and quality of life in the future.[1] Amongst the main drivers for higher levels of automated driving are: safety, reducing accidents caused by human errors; efficiency, increasing transport system efficiency, reduced emissions of vehicles; comfort, freeing the user for other activities when automated systems are engaged; social inclusion, ensuring mobility for all; and accessibility, facilitating access to city centres. Furthermore the importance of cooperative automated driving has been recognised by the European Commission who have coordinated the establishment of the C-ITS Platform where industry representatives and public authorities have agreed on a shared vision for the coordinated deployment of Cooperative Intelligent Transport Systems (C-ITS) in Europe.[2] This is an important step towards connected and cooperative cars as C-ITS enable vehicles to communicate with each other and with the infrastructure, an essential step to enable efficient highly automated driving. The impact of the advancement in Connected and Autonomous Vehicles (CAV), will reach many adjacent sectors including insurance, telecommunications, electronics, technology, IT, transportation, logistics, advertising, digital and retail.[3]

The HORIBA MIRA offering[4] on the advancement of future vehicle and systems technology is helping in the development and testing of reliable technology, required to eventually achieve a deep penetration level of vehicles with high-automation features integrated. There is an active programme of research and development in Autonomous Vehicles and their related technologies carried out for both on-road structured environments and off-road unstructured environments.

The research scope for both environments are complementary. For the on-road structured environment, the ever-increasing complexity of vehicle systems and the incorporation of newer Advanced Driver Assistance Systems (ADAS),[5] is making the process of comprehensive validation and implementation of system design increasingly challenging. The high number of different subsystems, use cases, environmental conditions and driver profiles, among many other factors, makes the testing and validation of all the vehicle's automated systems under all possible combination of factors unfeasible. Intelligent, configurable test protocols and specialized simulation and test facilities dealing with this validation process complexity are required. Additionally, as CAVs come to rely on external information for planning of safety related functions, any corruption or misuse of these communication channels could compromise vehicle safety. Added to the challenges for CAVs is the inter-operability and market penetration.

Off-road environments are largely unstructured. Unmanned Ground Vehicles (UGVs) are a class of autonomous vehicles that are typically designed to be used instead of manned vehicles particularly in dull, dirty or dangerous applications. Although these vehicles are unmanned they still normally have a “man in the loop”, i.e. in a supervisory or monitoring capacity. However, navigating complex terrain at speed with minimal human supervision represents a major challenge for UGVs. For example, this requires advanced on-board perception systems featuring innovative algorithms for interpreting challenging environments such as mountains, deserts, woodland and wetland. Key challenges are the sensor suites and sensor fusion needed to provide perception information to the automation control systems to enable the vehicle to operate in off-road terrains and in harsh environmental conditions. This combined with addressing key engineering requirements such as reliability, safety and operational integration with other systems means that advanced algorithms coupled with appropriate test and validation tools are also required.

In this paper some of the latest HORIBA MIRA developments on systems for the simulation and development of automated vehicles are introduced. For the structured environment case the emphasis is on the longer term research challenge of developing systems for cooperative automated driving allowing the benefits in both safety and efficiency to be realised in the future. This includes developments on traffic simulations and management systems since these will also be key to reaching the longer term vision of cooperative autonomous driving. For the unstructured environment case the emphasis is on the shorter term development challenge of engineering unmanned vehicles that can be safely and reliably deployed in demanding customer specific off-road environments. Finally, some conclusions and a selection of future works are presented.

Automated Driving in Structured Environments

Automation in passenger vehicles and public transport systems offers many societal benefits but there are significant challenges for the industry to address before high levels of autonomy[6] can be deployed widely. HORIBA MIRA has expertise in many of these crucial areas such as vehicle engineering, functional safety, test and verification. Furthermore, a number of strategic research themes have been identified which are supported by internally funded and collaborative research and development activities. These themes include autonomy in complex urban environments, cooperative driving algorithms, simulation, safety and cyber security. Current collaborative programmes include UK Autodrive which is trialling different levels of automation for private road vehicles and public transport “pods” in two UK cites, and UK CITE which is exploring hybrid-connectivity approaches to connected vehicles on highways and urban roads.

The need for a scalable approach to component and vehicle testing, and to support the development of CAVs, has led HORIBA MIRA to develop a set of simulation tools. The Cooperative Driving Simulation and Robotics testbed allows for rapid iterations and benchmarking of cooperative and automated driving algorithms. The Cloud based Traffic Management System (CTMS) simulation system[7] allows integrated simulation of vehicles and traffic management systems in a scalable, and hierarchical, distributed cloud-based computing architecture. These tools have all been designed for real-time simulation to support advanced hardware-in-the-loop (HIL) testing.

Cooperative Driving Simulation and Robotics

This testbed (see Figure 1) was created to allow rapid evaluation of new control algorithms in a controlled and repeatable way. Within this simulated environment any number of real vehicle controllers can be run with an accompanying plant model to replicate the real-time effects of control decisions. Central to this is the powerful concept of an “Environment Manager”. The Environment Manager has an awareness of the full road network, and the real time status of all the vehicles, allowing it to feed each vehicle controller with a realistic set of sensor inputs. This starts with parameters such as speed, heading and position but can be extended to include more complex aspects such as wireless communications data or object tracks from ADAS sensors. For example in a cooperative driving scenario the individual vehicle controllers each send out periodic beacon messages, based on the ETSI Cooperative Awareness Message (CAM)[8]. When the Environment Manager receives a new CAM it decides

Figure 1 Cooperative Driving Simulation and Robotics demonstrator. Real moving Robots interact with simulated Tracks and Vehicles.

Figure 2 NGV at the Master Intersection in the City Circuit Proving Ground

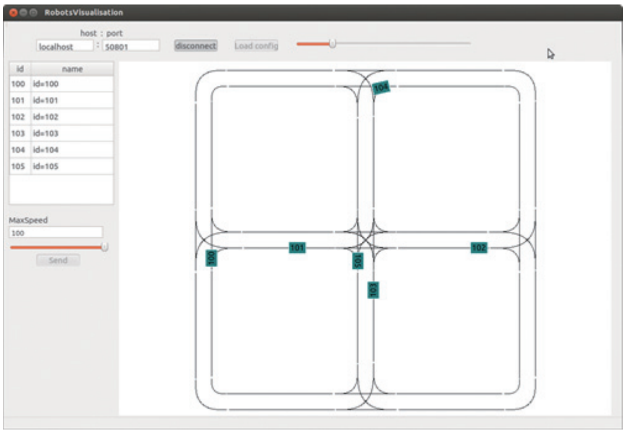

Figure 3 Configuration tool of the Cooperative Driving Simulation and Robotics tested

which vehicles would be in range to receive that message and it rebroadcasts it to those controllers only.

Running the simulation in real-time allows physical vehicles to interact with simulated vehicles and events, known as Vehicle Hardware-In-the-Loop (VeHIL). This demonstrates the validity of the simulation and models and can be used as an initial demonstration of high risk functions such as automated overtaking and merging at junctions. As an interim step HORIBA MIRA have built a fleet of small robot vehicles to allow engineers to quickly check the validity of simulation by introducing physical vehicles in the laboratory.

HORIBA MIRA's Network Guided Vehicle (NGV, see Figure 2)[9] [10] is a research and demonstration vehicle platform which utilises cooperative Vehicle-to-Vehicle (V2V) and V2I/I2V systems for both safety and control of highly automated driving functions. The latest automation software being developed at HORIBA MIRA is written in a modular way which allows algorithms developed in simulation to be directly ported to robots, and then to the full size vehicle. Most recently this approach has been employed to demonstrate multiple vehicles operating independent automated driving controllers in scenarios such as platooning, intersection priority management and merging with traffic at slip roads. The controllers can process complex road maps and derive situation awareness from V2X messages received from surrounding vehicles, which may be real or simulated.

Cloud based Traffic Management System

HORIBA MIRA's Cloud based Traffic Management System is a complex urban traffic management solution aiming to optimise traffic flow by means of coordinated cooperation between the vehicles and traffic signal controllers. The system is realised as a collection of cloud services deployed on the ITS-Cloud platform. Such a design ensures scalability and reliability of the system, and provides an abstraction layer between the traffic control algorithm and the sensing/actuating equipment.
A microscopic traffic simulation tool[11] has been developed to cooperate with the CTMS and is used to evaluate the traffic management strategies implemented. The main goal of the simulator is to provide a universal and extensible platform for simulating complex traffic conditions on a microscopic scale (see Figure 3). It has been designed as a tool to support research on traffic control and its impact on general vehicle flow and individual vehicle behaviour. Each vehicle in the simulation is a semi-independent agent that can have its behaviour customised. Vehicles equipped with wireless communications can communicate with the infrastructure using V2I communications enabling them to receive intersection approach advice and dynamic routing information. Vehicles can also engage in cooperative driving such as platooning.

Using this simulator it has been demonstrated that both traffic throughput, expressed in terms of travel time and energy expenditure, can be optimised using adaptive and cooperative intersection and vehicle management methods such as Cooperative Adaptive Cruise Control (CACC). Current research includes the simulation and modelling of real urban and strategic highways along with their ITS features required for CAVs. In the short term modelling will be used to inform some of the first use cases in the UK enabled by the Vehicle-to-All Communications (V2X) and automation technologies, for example CACC, stable platooning[12] [13] and cooperative intersections.

Test Facilities and Equipment

The HORIBA MIRA City Circuit is a proving ground specifically for automated and connected vehicles, and related ITS technologies. The test facility features a network of urban roads including cross roads, T-junctions, and hill sections, and it features different types of road surface, road markings, and roadside equipment. What makes this facility unique is that this safe, controlled, and realistic physical environment is coupled with an equally controlled and representative wireless environment. Wireless communications including cellular networks, Global Navigation Satellite System (GNSS), Wi-Fi and Dedicated Short Range Communications (DSRC/V2X) all increasingly play a role in how cooperative automated vehicles will perform. The City Circuit can provide, and deny in a controlled way, the availability of each of these networks. This allows the creation of a wide range of test scenarios ranging from ideal conditions, through to intermittent network coverage, and congested networks. Furthermore, real-time GNSS denial is available based on simulated city infrastructure configured for individual vehicles, replicating the effects of features such as tall buildings, tunnels and GPS jammers.[14]

City Circuit monitoring systems allow the facility to operate as an outdoor laboratory. RTK-GPS reference stations allow vehicles to be tracked with +/− 1 cm accuracy, and an always-on Mesh network connects test vehicles with the facility infrastructure for data collection and the triggering of synchronised events. A novel prototype 3D motion capture system is installed at a large intersection that can track objects, such as pedestrian dummies, with high precision and at a fast frame rate.

Developing Unmanned Ground Vehicle Systems for Unstructured Environments

HORIBA MIRA has extensive experience in the development of autonomous unmanned and tele-operated vehicles for both civil and defence applications. Since 2002, HORIBA MIRA have led the way in the development and delivery of advanced UGVs featuring the proven and award winning MIRA Autonomous Control Equipment (MACE) technology - the system which provides the basis for all HORIBA MIRA's UGV vehicle conversions.
Further enhancements to this UGV technology continue to be made through HORIBA MIRA's Autonomy Development Programme (ADP). New technologies, software and algorithms are integrated and tested on the third-generation off-highway research vehicle MACE III which is based on a Land Rover Defender chassis using in-house designed actuators to convert the vehicle to Drive-by-Wire (DBW). It is fitted with three forward and one rearward facing driving camera to allow monitoring and real time tele-operation. The platform is also equipped with an integrated Global Positioning System (GPS) and Inertial Navigation System (INS) with wheel angular position encoder input. A mesh network radio system provides communications with the vehicle and an E-Stop system provides a safe and high-integrity way of remotely stopping the vehicle in an emergency.

MACE adopts a Perception / Reasoning / Motion Architecture (see Figure 4). Each element is typically hosted on its own computer platform. The Perception computer takes input from the vehicle sensors such as Light Detection And Ranging (LIDAR), GNSS, wheel encoders and cameras, and builds an understanding of the world around the vehicle. The virtual world is made available to the reasoning computer which also takes inputs from the operator control station and combines this with on-board mission plans and known route networks to decide on a vehicle trajectory. The trajectory is then passed to the motion computer which in turn generates control demands for the vehicle DBW systems. The vehicle can be tele-operated from a local operator control station (see Figure 5) over a radio link or placed into an autonomous mode where it can be tasked from anywhere in the world over a secure internet connection.

The tele-operation terminal or Operator Control Station (OCS) is hosted either on a PC or rugged laptop. For tele-operation either a hand controller with joysticks or a steering wheel and pedals are connected to the computer. The OCS also interfaces to an E-Stop button and a mesh radio network node for communications with the vehicle. Live camera views allow the UGV to be monitored or controlled in real-time. A user-configurable speed profile

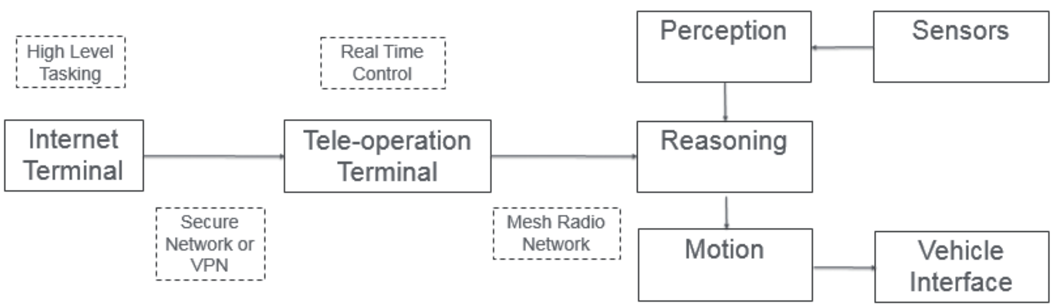

Figure 4 UGV System Architecture – Perception/Reasoning/Motion

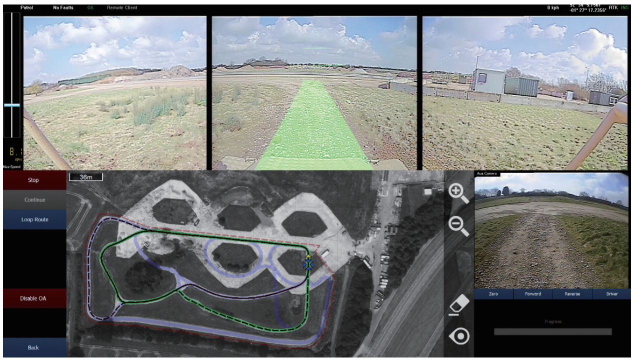

Figure 5 Operator Control Station primary display. The predicted path of the vehicle is shown as a green path in the centre monitor.

allows maximum autonomous driving speed to be set, an overhead map view allows the position of the vehicle to be shown and routes to be created or selected for autonomous operation. A “tentacle” shows the predicted path of the vehicle (see Figure 6) and if any obstacles are detected then the system can take appropriate action. The obstacle detection system makes it virtually impossible for the vehicle to collide with any object or drive onto any untraversable terrain either when it is being tele-operated or autonomously driven.

A system of LIDARs is used to map the terrain around the vehicle and to detect and avoid obstacles in real time. There is a horizontal LIDAR mounted on the front and rear bumpers providing a safety skirt around the vehicle and a “push broom” LIDAR mounted on the roll cage which is able to generate 3D terrain information as the vehicle moves forward. The primary sensor mounted on top of the vehicle’s roll cage is a Velodyne HDL 32 spinning LIDAR which has a range of 70 m around the vehicle.

The LIDARs produce a huge amount of information which is time-synchronised and fused with the other vehicle sensors in a time synchronisation hub. The hub makes the synchronised data available to the Perception computer which runs software algorithms to turn the huge amount of LIDAR data into a scrolling obstacle map used to navigate the vehicle through the terrain.

The obstacle map is made up of cells which represent three dimensional voxels typically 0.2m square. An algorithm is run on the LIDAR data corresponding to each cell and the result is a value per cell representing the traversability of the terrain. The system then looks ahead at the vehicles predicted trajectory and checks to see that there are no obstacles in the path. In the obstacle map display obstacles are coloured red and terrain that can be traversed at full speed is coloured white. Yellow and orange cells represent terrain that can be driven but at a reduced speed.

Figure 6 Snapshot from the Obstacle Map showing the MACE III Vehicle (Blue Rectangle) predicted trajectory (Green Tentacle), traversable terrain (White, Yellow and Orange) and obstacles (Red).

The usual UGV operating environment is challenging for radio links. Tele-operation of the UGVs requires robust data links, with relatively high bandwidth in order to provide sufficient video resolution, frame rate, and low latency in order to reduce operator work load and to enable control at relatively high speeds. ADP research has developed a system which can deliver the equivalent of 4 PAL (720 × 576) video camera streams over a mesh network with a glass-to-glass latency of approximately 100ms. Glass-to-glass latency refers to the amount of time it takes between something being seen at the vehicle cameras lens (glass) and appearing on the operator control station screen (glass). A mesh network approach allows the communications data link to achieve coverage beyond the line of sight by hopping across radio nodes in the network. Each additional hop the video and control signals have to make adds only 10ms additional latency. The radio data link uses Forward Error Encoding (FEC) and Coded Orthogonal Frequency Division Multiplexing (COFDM) to achieve a robust link between the vehicle and control station. The FEC essentially provides an efficient way of sending the same data more than once and the COFDM transmits that data across different frequencies in order to maximise the chance of the data being received.

Current UGV research being carried out includes work on machine perception and image processing to allow the UGVs to navigate and operate without being reliant on Global Navigation Satellite System (GNSS). The work includes road edge detection and tracking in unstructured environments where computer vision cameras look ahead of the vehicle and using image processing techniques to look for edges of an off-road track. The approach uses an image processing pipeline to identify off-road track edge candidates and assigns the candidates to a particle filter which then tracks the road edge. The goal is to be able to follow a track network without using GNSS. Other new research being performed includes using convolutional neural networks and deep learning techniques with computer vision to recognise landmarks for navigation and also identify traversable terrain.

The range of application areas for UGV technology is continuing to expand. For example, HORIBA MIRA is leading research into Intelligent Autonomous Digital Construction Machines through a UK government funded collaborative research project. The purpose of the project is to research future construction techniques involving a combination of automation, information technology and machine guidance.

The UGV Proving Ground

The purpose-built UGV proving ground at HORIBA MIRA's main site is used extensively for UGV systems development for off-road environments. The facility includes approximately 4 km of off-road test tracks with various features designed to allow engineers to push these vehicles to their limits. Key features include: test hills, positive and negative obstacles, complex bend radii, non-line of sight testing and a fully integrated, elevated control room with line of sight of the whole UGV proving ground.

Conclusions

Achieving autonomous driving and the encompassing C-ITS will bring remarkable benefits. The complexity of such vehicles as well as the foreseeable growth in the number of interconnected subsystems in ITS-enabled vehicles calls for developments in procedures, tools and facilities to test and assess the vehicles and ITS infrastructure under a sufficiently comprehensive set of conditions. The HORIBA MIRA R&D portfolio addresses some of the key development and testing challenges required to eventually achieve a deep penetration level of vehicles with high-automation features and the supporting ITS technologies.

For the structured environment case the emphasis is on the longer term research challenge of developing systems for cooperative automated driving, whereas the emphasis for the unstructured environment case is on the shorter term development challenge of engineering unmanned vehicles that can be safely and reliably deployed in demanding off-road environments.

The development of the real-time simulation tools addresses the need for more virtual techniques for test and validation in the longer term. The development of the Cooperative Driving Simulation and Robotics testbed allows for rapid iterations and benchmarking of CAVs through Robot Hardware-in-the-Loop. Vehicle Hardware-In-the-Loop simulations demonstrate the validity of the simulation and robot models through the use of the NGV and the City Circuit.

In the area of unstructured environment automated driving, the development and client use of advanced UGVs and vehicle conversions featuring the MACE technology demonstrates a proven HORIBA MIRA technology. Further enhancements continue to be made and new technologies, software and algorithms are typically integrated and tested on the latest-generation, off-highway research vehicle MACE III and the UGV proving ground.

Future Works

Building on the existing work outlined in this paper HORIBA MIRA is embarking on a number of routes to further expand the current scope of its research in autonomous vehicles.

More in-depth communications Simulation and Modelling capability is to be developed and integrated into the CTMS to better understand the effects of communications related issues in ITS application. New algorithms for cooperative driving and traffic management will also be the subject of future research. These will be developed and tested initially using the cooperative robots and then tested at full scale.

To cope with more complex and realistic conditions during automated vehicle system tests the availability of sensor models and automated vehicle features in the simulation platform will be further expanded.

For unstructured environments, improvements to the UGV operator control stations are planned to increase system productivity, for example in construction applications. Ultimately these will realise the goal of simultaneous multi-vehicle control from a single operator station. To facilitate this the system will be developed to allow the scheduling of autonomous vehicle tasks and the control of vehicles over the Internet.

Further work is also planned on UGV obstacle mapping and terrain classification systems to enable vehicles to be able to react appropriately to dynamic obstacles and to allow increased vehicle autonomy on more complex off-road routes.

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