Autonomous longitudinal control for a Network Assisted Vehicle

Tim Edwards, Pawel Jaworski and Maria Loukadaki

MIRA Ltd, Watling Street, Nuneaton, Warwickshire, CV10 0TU, UNITED KINGDOM
Phone: +44 24 7635 5484
Fax: +44 24 7635 8484
E-mail: tim.edwards@mira.co.uk

The Network Assisted Vehicle is a semi-autonomous vehicle that is tightly integrated with the innovITS ADVANCE City Circuit test facility. The vehicle incorporates a low cost speed control system that utilizes a pre-existing adaptive cruise control system. A radio interface allows synchronization with an off-board control facility that can adjust the vehicle speed demand around other events on the track. This paper describes the design and evaluation of both the lower level on-board speed control system and the higher level off-board algorithm.

1. INTRODUCTION

Test scenarios for current generation Advanced Driver Assistance Systems (ADAS) commonly feature a second car in addition to the vehicle under test. This could be to simulate, in a controlled way, a lead vehicle (for Adaptive Cruise Control (ACC) or Forward Collision Warning [1]) or an overtaking vehicle (for a Blind Spot Information System or Lane Change Support [2]). As ADAS and Intelligent Transportation Systems (ITS) evolve, mass production vehicles continue to extend the range and accuracy of their hazard detection and communication systems. It is therefore reasonable to expect that test scenarios will become more complex and involve additional traffic.

2. NETWORK ASSISTED VEHICLE

The Network Assisted Vehicle (NAV) is a novel semi-autonomous vehicle designed specifically for proving ground test applications (shown in Fig. 1). To be able to build on test scenarios and add additional traffic the NAV design was required to be scalable and portable. This is achieved by minimising the complexity of the on-board control systems and moving the main control decisions off-board so that multiple events can be synchronised.

The unusual vehicle concept is the result of a very specific set of requirements. Unlike the majority of autonomous and semi-autonomous vehicles NAV is only required to operate in a well defined environment (the innovITS ADVANCE city circuit test facility), with a trained driver and restricted access to additional traffic. Furthermore, this environment is already well equipped with measurement systems, wireless communications infrastructure and a centralised control system. Using these external systems reduces the amount of expensive equipment required in each vehicle.

Fig. 1 The Network Assisted Vehicle prototype

The NAV architecture has been described previously [3]. To meet the requirements of complex, multi-vehicle, test scenarios the majority of the control decisions are calculated off-board. NAV reports its position to a centralised control system wirelessly, and the controller sends back new demands according to the scenario. The on-board systems always retain responsibility for the safety of the system, so that any delays, or failures, in the off-board controller or communications systems are not able to result in unsafe vehicle behaviour.

There are two operating modes defined for NAV; a route following mode, that uses only the on-board controller, and an off-board control mode. In route following mode NAV reproduces a pre-defined speed profile based only on position. In this mode NAV does not require any infrastructure so it can be used to automate general proving ground drive cycles. In off-board control mode the NAV target speed can be adjusted dynamically to maintain a position or speed relative to another event or vehicle.
3. ON-BOARD (LOW LEVEL) CONTROLLER

A requirement of the NAV design was that on-board systems should be portable and low cost. To achieve this goal a novel approach was applied to control the vehicle’s speed. A CAN Signal Injection system (CSI) was designed to manipulate messages on the vehicle CAN bus and override inputs to the existing ACC system [4]. This approach, although inexpensive and fairly simple to implement, does impose severe constraints on the available control actions. The ACC system can only accept a new command at 200ms intervals. The following ACC commands were available over CAN:

- Increase the target speed by 5mph (8km/h)
- Decrease the target speed by 5mph
- Leave the target speed unchanged

3.1 On-board Controller Design

The incremental nature of the available control actions made it necessary to adopt an incremental approach when designing the NAV controller. A fuzzy logic design based on [5] was used.

![NAV on-board control loop](image)

The control loop is illustrated in Fig. 2. The controller uses the following fuzzy expressions:

\[
\Delta V = V_{\text{curr}} - V_{\text{ref}} \quad (1)
\]

IF \( \Delta V \) LESS THAN null THEN increase set speed

IF \( \Delta V \) MORE THAN null THEN decrease set speed

\[
\Delta Q = V_{\text{acc}} - V_{\text{ref}} \quad (2)
\]

IF \( \Delta Q \) LESS THAN null THEN increase set speed

IF \( \Delta Q \) MORE THAN null THEN decrease set speed

Where \( V_{\text{curr}} \) is the current vehicle speed, \( V_{\text{ref}} \) is the target speed (shown as Speed Demand in Fig. 2) and \( V_{\text{acc}} \) is the ACC Setting (the quantised target speed allowed by the ACC system).

The degree of membership describes the correctness of a fuzzy expression in terms of a confidence value ranging from 0 to 100%. It is obtained by using an appropriate membership function for each expression, as shown in Fig. 3. Behaviour of the membership functions can be adjusted using the tuning parameter \( d_{\text{sat}} \). Membership degrees are referred to as \( \Delta V^+, \Delta V^-, \Delta Q^+ \) and \( \Delta Q^- \) with respect to the membership functions that defined them (See equations (1) and (2)). The membership functions are defined such that one of the membership degrees in a pair is always equal to zero.

![Example membership function with tunable parameter](image)

The output value, \( X \), of the fuzzy expression evaluation represents the desire to change speed, and is obtained by summing the products of each membership function with an appropriate sign.

\[
X = \Delta V^+ + \Delta Q^+ - \Delta V^- - \Delta Q^- \quad (3)
\]

Positive values of \( X \) indicate a desire to increase speed and negative values mean that the speed should be reduced. In order to determine the control signal that will be sent to the ACC the \( X \) variable is normalized as follows:

\[
X_{\text{norm}} = \frac{\Delta V^+ + \Delta Q^+ - \Delta V^- - \Delta Q^-}{\Delta V^+ + \Delta Q^+ + \Delta V^- + \Delta Q^-} \quad (4)
\]

Normalisation ensures that the values of \( X \) always vary between -1 and 1. The process of determining the control action from the normalised \( X \) is demonstrated in Fig. 4.

![On-board control action generation](image)

Parameters \( T_d \) and \( T_s \) determine the deceleration and acceleration thresholds respectively. The increase speed command is sent to the ACC when \( X_{\text{norm}} \) is greater than \( T_s \) and the decrease command when it is smaller than \( T_d \). The speed remains unchanged when neither of those conditions are met.

3.2 On-board Controller Implementation

A failure of the speed control system has potentially seriously safety implications. Hazard and Operability analysis (HAZOP) was conducted early in the NAV project to identify the critical modules and interfaces. The fail-safe condition is always to disable the NAV electronics and return full control to the driver. All the identified hazards could be mitigated against by the driver, either by applying the brakes (which disables ACC) or isolating the power to the NAV electronics. However, the on-board controller and CSI systems were identified as critical modules that must have
independent fault-detection and fail-safe behaviours.

To meet the safety requirements the on-board controller was built using a deterministic Time-Triggered Cooperative Scheduler (TTCS) [6] on an Infineon XE164FM microcontroller. The system was developed in accordance with the MISRA (Motor Industry Software Reliability Association) Development Guidelines for Vehicle Based Software, and in particular the Guidelines for the Use of the C Language in Critical Systems [7].

Fig. 5 shows the full detail of the external interfaces to and from the controller. The Situation Awareness Module (SAM) provides a single interface for all vehicle data, including inputs from the driver and external vehicles and infrastructure (when the radio communications interface is active).

![On-board controller interfaces](image)

Fig. 5 On-board controller interfaces

The controller separates the core control actions (sample, compute, actuate) into time triggered tasks to minimise timing jitter in the control loop and to ensure quick detection of fault conditions. The SAM module is a complex Linux based system and so the controller input task is particularly sensitive to the timing and consistency of messages from the SAM. If a fault is detected the controller instructs the CSI to isolate the NAV electronics from the vehicle CAN bus, and the controller notifies the SAM of the fault condition, which in turn displays the fault information on the driver HMI (Human Machine Interface).

### 3.3 On-board Controller Performance

The range of acceleration that can be achieved with this implementation is limited by the performance of the original cruise control system. A series of step input tests from 50km/h to 100km/h, and back to 50km/h, were used to quantify this performance. Results showed acceleration in the range of -1.2m/s² to 1.4m/s².

The on-board speed controller has been extensively tested on the MIRA proving ground using NAV. Speed profiles have been defined for 3 test tracks including the innovITS ADVANCE City Circuit. Actual performance against a pre-defined speed profile, and even at steady state, is variable due partly to the resolution of the ACC control inputs but also due to variables outside the direct influence of the controller, such as the automatic gear box.

Fig. 6 shows a target speed profile against the actual achieved speed. The gear selected by the automatic transmission is also shown below. In this plot there are three significant events where a gear change caused a large deviation from the target speed, these can be seen at approximately 30, 80 and 110 seconds. After the gear drops down at 80s, to allow for more acceleration, a noticeable lag against the target speed is introduced. On the subsequent deceleration the gear is kept high for some time. The gearbox selects a lower gear just as the target speed levels out causing a large overshoot.

The main steady-state section of this data (55 to 75 seconds) shows stable performance but at a fixed offset of ~2km/h. This offset remains constant because it lies in the “No Change” region of the control action calculation (as shown in Fig. 4). In this test Td and Ta were both tuned to 20%. Attempting to reduce this offset further can introduce oscillation due to the large, slow, step changes acceptable to the ACC.

![Actual vehicle speed against demand](image)

Fig. 6 Actual vehicle speed against demand

Clearly there are significant variations between the target and actual speed but when routes are repeated the pass-to-pass variations tend to be small. This means that repeatable drive cycles can be achieved.

![Pass-to-pass variation in route following mode](image)

Fig. 7 Pass-to-pass variation in route following mode

Fig. 7 shows the results for multiple tests of the same route. 3 tests were conducted on the same day and in the same conditions. These are shown as solid lines and can be seen to be tightly matched. The test was repeated 2 weeks later and the results are shown with a
A VEC dashed line. Small differences, such as the weather conditions, can affect multiple variables including tyre grip and GPS accuracy, the result is that the test starts with a close match to previous results but deceleration is slower around the 20 and 48 second marks. This introduces more overshoot, the speed then resumes following the route profile but it is now lagging behind previous tests.

3.4 On-board Controller Optimisation

The performance of the low level, on-board, speed control interface is currently constrained by the ACC interface that it operates around. The response to step changes in speed demand experience some latency and variation due to the automatic gearbox and steady-state performance is variable depending on how closely it is aligned with one of the quantised ACC target speeds. Another recent study demonstrated a similar control strategy on a hybrid-electric vehicle (HEV) with continuous electric transmission eliminating the gear change issue [8].

There is scope to improve the maximum vehicle deceleration with the current implementation. The original vehicle ACC systems supports automatic braking, with up to the 30% of the manual braking capacity [9], equivalent to approximately -2m/s². This is triggered when the target separation distance from the preceding vehicle can no longer be achieved. The existing NAV electronics are able to simulate this event, in a controlled way, to achieve this harder deceleration on-demand.

4. OFF-BOARD SPEED CONTROL

In the previous section we described a speed control system for following pre-defined route profiles. However, the on-board controller is isolated from the source of speed demands. Using a wireless communications interface (to the SAM, shown in Fig. 5) external speed demands can be set dynamically. The SAM also provides isolation from the physical interface. To date, 3 different wireless interfaces have been trialled, WiFi (802.11b/g), Mesh4G and 802.11p.

speed commands. The main features of the architecture are shown in Fig. 8. All vehicles that join a test scenario must at least be equipped with a mobile module that includes a GPS receiver and compatible radio.

Two scenarios are described in this paper. The longitudinal following scenario has been demonstrated on the MIRA proving ground using V2V communications. The lateral crossing scenario is a complex test planned as future work, which would fully utilise the V2I communications and central controller.

4.1 Longitudinal following

The longitudinal following scenario is common to a range of test specifications for ADAS such as ACC, Forward Collision Warning (FCW) and Autonomous Emergency Braking (AEB). Tests for other systems such as Blind Spot Monitoring and Lane Change Assist are very similar but with the two vehicles in adjacent lanes.

A FCW scenario is illustrated in Fig. 9. The vehicle under test is commonly referred to as the subject vehicle, (SV). The SV is driven manually against a test scenario description. A second vehicle, in this case NAV, will adjust its speed profile to give a repeatable behaviour relative to the SV.

In this scenario the NAV speed, VNAV, remains constant until the SV reaches a defined separation distance, dtarget. This triggers a constant deceleration from NAV which should exercise the FCW system under test in a repeatable way. A surrogate vehicle (or soft target) is often used in these tests to reduce the risk of a real collision.

![Fig. 9 Forward collision warning scenario](image_url)

Fig. 9 Forward collision warning scenario

![Fig. 10 Vehicle-to-vehicle speed demands](image_url)

Fig. 10 Vehicle-to-vehicle speed demands
A soft target system for NAV is currently in development; in its absence a proof of concept study has shown V2V speed profile matching. The current speed of a secondary vehicle is sent to NAV, the controller adopts this as the new target speed.

The results, shown in Fig. 10, show the speed demand from the secondary vehicle against the actual speed of NAV. Sampling and transmitting the speed demand causes the discrete step changes that can be seen. The NAV speed lags behind demand but follows the trend well. The on-board controller still has to contend with gear change effects (such as that at 105 seconds) but the system can be seen to recover quickly.

4.2 Lateral crossing

Testing a collision warning system at an intersection requires a complex lateral crossing scenario, as illustrated in Fig. 11. This is planned as future work. As the SV approaches the intersection NAV must drive across in front of its path with the same speed and headway distance each time the test is run. Using V2I communications, and the off-board control architecture, the NAV speed can be adjusted before the vehicles are in direct communications range of each other. It may also be desirable to synchronise a prescribed traffic light sequence with the vehicles.

The NAV speed control problem here can be broken into two stages. There is a short section where the speed profile is predefined, shown here as 3 route points r1, r2 and r3. This section is controlled by the on-board controller, as before, to ensure repeatable behaviour in every test. Up to this point the speed is set dynamically, by the off-board controller, so that NAV reaches the route start point at the correct time, \( t_{f_{cw}} \), in relation to the SV.

5. CONCLUSIONS

The Network Assisted Vehicle project has demonstrated a novel design pattern that can achieve a simple, low cost autonomous longitudinal control solution. Crucially this design pattern utilises an off-board control architecture that can support multiple vehicles with tight synchronisation.

The use cases for NAV were defined based on test specifications for ADAS and ITS applications. This first NAV prototype fully achieves the requirements for some of test scenarios and it has also been useful to general proving ground drive cycle automation. Further work is underway to improve performance, and in particular the maximum deceleration.

Safety considerations are a significant aspect of any ADAS test. The NAV control systems have been carefully designed against the industry best practices to ensure reliable hazard mitigation. The next step is to introduce soft targets (or surrogate vehicles) that will be towed or carried by NAV in real track tests. This allows near-miss scenarios to be conducted on the track with the risk of a real vehicle-to-vehicle impact.

A new project, called Network Guided Vehicle (NGV), is also underway which extends the NAV concept to also feature autonomous lateral control.

REFERENCES