The Embedded Driving-assistance System on Taiwan iTS-1

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Abstract—Vehicle automation is an important research topic of advanced vehicle systems (AVS). Taiwan iTS-1 is the first smart car with autonomous driving in Taiwan. In this paper, an embedded driving-assistance system is presented. The definition of hierarchical-control structure is necessary in the system to deal with sensorial inputs and environmental and procedural knowledge to manage vehicle actuators in order to accomplish various driving tasks. Upper-level control perceives road environment and determines the proper and safe operation modes including lane-keeping, lane-change, cruise control, adaptive cruise control, and stop-and-go. In each mode, the desired-velocity and reference-trajectory are primarily determined, and then are forwarded to vehicle-body control. To incorporate well driver behavior into our system, vehicle-body control utilizes the fuzzy control technique to manage the fundamental actuators of vehicle, steering wheel, throttle, and brake, to adapt to the desired command (velocity and trajectory). The core controller is built-in on a DSP-based embedded computing platform. The aim of our system is to provide the driving-assistance in the same way human drivers do.

Keywords—Driving-assistance, vehicle automation, automotive, embedded system, intelligent transportation systems (ITS).

I. INTRODUCTION

Thanks to the wake of the electronic and information technology evolutions, vehicles are expected to increase their capabilities of interacting with drivers. The development in automated driving endows vehicles to relieve drivers from undesired routines of driving task. A number of research programs have been aiming to develop various advanced technologies for driving-assistance systems in the world.

Partners for Advanced Transit and Highways (PATH) program developed an infrastructure-based lane embedded with discrete magnetic markers so that automatic vehicles can circulate autonomously and form platoons [1]. The Navigation Laboratory (NavLab) at Carnegie Mellon University demonstrated automated steering control by artificial-vision and neural-network-based control techniques [2]. A navigation system for autonomous lane-keeping and lane-change on their test-bed vehicles (Honda Accord LX) was developed by a team in the Ohio State University (OSU) [3]. Dickmanns’ team at University of Bundeswehr in Germany developed an artificial-vision-based automatic driving system installed in a van with automated actuators. It can drive at speeds up to 130 km/h on highway [4]. Alberto Broggi’s team developed the ARGO vehicle at Parma University. ARGO executed an automatic artificial-vision-based steering mission over 2000 km on highway [5]. In AUTOPIA program two Citroen Berlingo vans, which are equipped with fuzzy-logic-based control system for mimicking human driving behavior, carried out driving and route-tracking tasks under urban-like environments [6]. Tsugawa’s team in Japan demonstrated their intelligent vehicles with fully automatic driving on normal roads by global positioning system (GPS) and inter-vehicle communications [7]. In China, a digital-driving system which is particularly based on modeling of driver behavior is proposed by the Beijing Institute of Technology [8].

The traffic on real highways remains complex and difficult to be managed such that different functions are required to be performed as well as vehicle control which is necessary to design the decision and the control for an automated vehicle from a safe viewpoint. In this paper, we propose a hierarchical-control autonomy structure in Taiwan iTS-1 to achieve integrated longitudinal and lateral control on highway and urban-road environments. The upper-level control analyzes the traffic situation and determines a driving mode among several developed modes, while the vehicle-body control executes the real-time control signal based on the determined driving mode. The good driving task depends on the well logical reasoning in underlying systems and dealing with uncertainty related to environment perception. Therefore, it motivates to integrate aspects of human intelligence and behaviors into the vehicle-body control so that driving actuators can be managed in a way similar to drivers. Instead of using the mathematical representation of the systems, the behavior and experience of human drivers can be built into the system through fuzzy reasoning which is undeniably a useful feature for emulating the human reactions. Classical approaches frequently fail to yield appropriate models of complex processes, while fuzzy control technique provides an alternative tool for dealing with vehicle and its subsystem complexity. In this way, the controller at vehicle-body level has the same structure across different driving modes at upper-level; besides, the upper-level control is modular and
extensible for accommodating to evolutionary modification by easily adding supplementary modes into the decision, and incorporating additional real-time information into the control.

II. THE VEHICLE OVERVIEW

Figure 1 illustrates the components in Taiwan iTS-1 which are supported by add-on hardware devices and processing software in order to fulfill driving-assistance in steering-, throttle-, and brake-control.

A. Sensor Installation

Two internal state sensors, namely the speedometer and an inertia measurements unit (IMU), are used to sense the vehicle’s velocity, acceleration and angular rate, respectively. Besides, the utilized primary sensors include a real-time kinematical differential GPS (RTK-DGPS), an image processor with a monochromatic CCD camera, and a laser range finder. Both the vision system and RTK-DGPS can provide lateral information such as the deviation from the centerline and the orientation with respect to a reference trajectory. The vision system is a look-ahead sensor while RTK-DGPS is a look-down sensor, and the fundamental difference between these two sensors is the difference in the range of the lateral information. The vision detects the lane-markings ahead of the subject-vehicle, and provides the look-ahead relative positions of the vehicle with respect to the lane center [9, 10][12]. Based on RTK-DGPS, the relative position data are compared with a digital map on which the target route has been previously specified to be tracked. The main sensor for vehicle forward motion is the range finder which provides the current headway distance between the subject-vehicle and a preceding-vehicle in the same lane.

B. Vehicle Control Actuator Installation

An AC servomotor is installed in the steering wheel (SW) column to enable automatic steering. The angle of SW is measured by a steering angle sensor which is set around the axis of SW. A throttle valve is driven by a mounted DC servomotor avoiding any change to vehicle’s internal-components. A throttle position sensor (TPS) is composed of an A/D converter encoding an analog voltage into a normalized digital signal. The brake pedal is automated by using a DC servomotor which is connected to a brailed steel cable via an electromagnet. Its position is measured in terms of voltage variation output from a linear position transducer.

C. Vehicle Embedded System

The real-time software for driving-assistance function is developed by using C programming language under the embedded platform TMS320F2812. This embedded system processes the signals transmitted from sensors, and compute the controlling commands to the throttle-, brake-, and SW-actuators. Besides, the driver-compatible intelligence and behavior is also provided for speed and steering control for various driving conditions. The driver-vehicle interface provides the current status of vehicle, and the warning data about forward obstacle and lane-departure coming from the range finder and the vision system, respectively.

III. DRIVING-ASSISTANCE SYSTEM DESIGN

A. Modeling for Taiwan iTS-1

The longitudinal and the lateral dynamics can be separated if the moving velocity does not vary too much. If roll movement is neglected, the vehicle lateral dynamics can be well represented by the so-called “bicycle model”. The bicycle model which dominates the lateral and yaw dynamics is useful in designing the steering controller to stabilize the vehicle keeping within the lane. To validate the bicycle model with the lateral vehicle dynamics of Taiwan iTS-1 is critical to obtain precise tracking results of steering control. The SW angle can be expressed as a product of the steering ratio and the front-wheel angle. Due to the fact that turning compliance...
and steering torque gradients vary with increasing steering angles and load on the front tires, tire pressure, coefficient of friction, etc., in general, this ratio is not a fixed value. However, the constant ratio can be practically used for control design. The steering ratio can then be adjusted slightly to yield a response from SW command to lateral acceleration and yaw rate that is approximate to the real vehicle platform.

The true vehicle dynamics is unfortunately complicated and includes high nonlinearity in the interaction between propulsion, roadway interface, and aerodynamics. However, the vehicle longitudinal dynamics under non-braking conditions can be represented by one nonlinear model in the form of third-order transfer function. This model is employed in this chapter to describe the nonlinearity in velocity dependent dynamics between the voltage applied on throttle valve and the forward velocity of the vehicle. The velocity dependent parameters are accomplished via a closed-loop model-matching technique such that the responses of the model are matched to those obtained from corresponding real vehicle wherein the same driving controller is employed in the real vehicle. The identification procedure is repeated several times for each specified command velocity for the vehicle until the consistent response is obtained. Note that the driving controller set in the configuration of closed-loop model can be chosen different so as to the model parameters are demonstrated to be independent of the specific controller choice.

B. Vehicle Control

A two-level hierarchical architecture as shown in Fig. 2 to achieve automated driving or driver assistance in a highway/freeway and urban-road environment. Mimicking human driver observing the traffic situation and the course of the road, the upper-level control determines the driving modes, namely lane-keeping (LK), lane-change (LC), cruise control (CC), adaptive cruise control (ACC), and stop-and-go. This level is concerned with ensuring that the system fits the suitable driving to the existing road-condition and the traffic. After determination of driving mode, the upper-level control then provides the vehicle-body control with the reference velocity (for CC, ACC, and stop-and-go) and the reference trajectory (for LK and LC).

In this two levels “controller/vehicle” system, a division into longitudinal and lateral control is made. The upper-level control requires good knowledge about road-environment, while the vehicle-body control focuses on providing driver-comparable control behavior in carrying out the control of throttle pedal, brake pedal, and SW angle. The upper-level control is responsible for calculating the reference values of velocity (for CC, ACC, and stop-and-go) and trajectory (for LK and LC) for the longitudinal controller and lateral controller, respectively. The reference velocity changes frequently and is rather dependent upon the road traffic. The objective for the longitudinal controller is to keep the reference velocity as exactly as possible. The general task for the lateral controller is to keep the lateral error to zero, i.e., the reference trajectory is the centerline of the road. While LC mode is activated, the reference trajectory will be previously calculated in terms of desired values of lateral offset such that the vehicle can be steered from the current lane to an adjacent lane [10]. It should be noted that either the upper-level control or the vehicle-body control is designed to be adaptive with vehicle states such as current velocity, real-time lateral error, and headway distance. In practice human drivers also perform several driving tasks which are adaptive to these vehicle states.

The steering control is in charge of tracking accuracy of the reference trajectories including straights, curves, and lane-changes, and ride comfort requirements at all possible vehicle speeds, regardless of environmental uncertainties such as road adhesion, preview errors from vision system, road curvature variations, actuator bandwidth and transport lag, vehicle dynamic changes, soft suspension modes, and all reasonable sensor and vehicle noises. A virtual look-ahead lane-keeping control with a fuzzy gain scheduling (FGS) based adaptive scheme [9, 10] is proposed and implemented by using the following form

\[
\text{Steer} = -\Delta_k K_{p,x}
\]  

(1)
where $x$ represents the state vector which consists of lateral velocity, yaw rate, look-ahead lateral deviation and look-ahead orientation angle which can be provided from the vision system. $K_{fb}$ is the feedback control gain which is designed to guarantee the stability of the closed-loop system under the highest vehicle speed and the transport lag coming from the two latencies which are processing delay from the vision system and hysteresis in servo motor actuation; $\Delta_{s}$ is the FGS-based adaptive gain. Although the static feedback control strategy suffices to meet the requirements of vehicle lateral control, it is sensitive to the parameters of the system, such as vehicle mass, cornering stiffness, and road curvature, and thus solid reflected by feedback signals. The desire to steer the vehicle in a more human fashion and to provide a smooth steering control process, motivates the adoption of a fuzzy inference scheme as part of the lateral controller designing strategy. The proposed FGS consists of a single parameter that changes the magnitude of controller gain in such a way that the inference gain decreases with increasing speed and look-ahead lateral deviation [9, 10]. Many control algorithms propose an additional feedforward control based on curvature preview information to improve the transient behavior during changes of curvature. Although the curvature information at a look-ahead distance is useful to improve the steering performance while entering/existing curves, it is difficult to obtain the precise information of road curvature in practice. Fortunately, this change in curvature ahead can be anticipated by the varying look-ahead lateral offset such that FGS is able to compensate the effect from unknown curvature information: if the look-ahead lateral offset increases, then the steering control should be increased. This scheme also provides the steering controller that achieves an overall tradeoff among robustness, tightness, and comfort.

The reference speed is calculated by a two-stage approach. The desired acceleration of each operation mode is determined by means of sliding mode control (SMC) in the first stage [10], and then is converted to the desired velocity in the second stage. This velocity is then issued to vehicle-body control. We here use a desired velocity, instead of the subject-vehicle’s velocity can be measured directly. Moreover, high-frequency noise problems from sensed velocity differential can be avoided. In the first stage, we adopt the sliding mode control technique to design the corresponding control laws for various driving modes. In the second stage, the conversion from the desired acceleration ($a_{cr}$ and $a_{bc}$) into the desired velocity ($V_c$) takes the form as following (2)

$$V_c(k+1) = \min\left\{\left(1-Tk_{cc} W_c(k) + Tk_{bc} V_c(k) + a_{cr}(k)\right), \left(1-Tk_{bc} W_c(k) + Tk_{cc} V_c(k) + a_{bc}(k)\right)\right\}$$

(2)

where $V_c$ is the current speed of vehicle and $T$ is the sampling period of embedded platform. The filtering gain can be chosen differently, namely $k_{cc}$ for CC mode and $k_{bc}$ for car-following situation including both ACC and stop-and-go mode. The subject-vehicle drives in CC mode in general. It will automatically switch to ACC mode or stop-and-go mode once a preceding vehicle is detected in the same lane. This concept is identical to the Gipps model [11] which is demonstrated to be capable of longitudinal human driving characteristics: the first half tends to accelerate to the desired velocity, while the second half tends to keep a safe distance from the preceding-vehicle.

Under different types of engine, automatic transmission in the gear box and brake system in each vehicle, a normal driver can still operate the throttle and brake systems easily to reach the suitable speed. In view of this, the design concept to throttle/brake actuation brings from the human-driving behavior. By importing the human-driving experience into fuzzy rule, not only avoid the difficulty for control designing based on such complicated mathematical model, but we also make the system satisfy the humanlike driving behavior. As to the switching strategy to implement the integrated control between throttle and brake, it should be noted that the normalized universe of discourse of the driving voltage is absolutely positive and negative voltages can not provide inverse torques from the throttle motor. Therefore, the negative voltage can be output into the brake driver for deceleration control. In other words, the throttle/brake fuzzy controller is designed to provide a positive voltage with regard to acceleration for the throttle driver while provide a negative voltage with regard to deceleration for the brake motor. By using an inverse operation, the negative voltage can be inverted to the brake motor. Due to this nature of input voltage to motor drivers, the switch between the throttle and brake control can be directly constructed.

By receiving the throttle-, brake-position, and SW-angle commands from the vehicle-body control, a proportional-integrate-differential (PID) controller is utilized to manage the AC-motor attached to the SW column, and another two PID controllers are used to drive DC-motors to adjust the throttle degree and the brake position. This architecture, based on the cascade-control paradigm [10], is particularly useful to get over time-delay from controlling signals to action signals: rapid control can be achieved by intermediate signals which will provide faster response than the control signals.

IV. PERFORMANCE RESULTS

In this section, we present some examples that show the performance of our developed embedded driving-assistance system installed in Taiwan TS-1. The first experiment demonstrates the LK and LC operation mode. The CC, ACC, and Stop-and-go mode are demonstrated in the second experiment.

Figure 3 shows the frame grabbed from the vision system in the operation from LK to LC and back to LK mode. The lane-marking data will be lost due to the fact that the vision system cannot catch lane-marking in the lane-to-lane transition, as shown in the circled two plots of Fig. 3. When the vehicle moved to an adjacent lane, the vision system re-caught the lane-marking and thus the system returned to LK mode. The example lane-change control at speed around 56 km/h is shown in Fig. 4. The LC mode started at 12 s, and the SW was then controlled by the lane-change controller instead of the lane-keeping controller. During the period of lane-change (from 12 s to 18 s), initially the lateral offset will increase since the vehicle steered to the boundary of road. While the vision
Fig. 3. Lane-marking detection in the lane-change scenario from the display of vision system.

Fig. 4. The transition between LK mode and turn-left LC mode.

The system cannot catch the lane-marking, the lateral offset data hold a maximum value of 200 cm (between 14 s and 16 s). After the lane-change command was completed at 18 s, the SW returned to the lane-keeping controller and the subject-vehicle kept the centerline of road. Here the command signal indicated from dSPACE MABX is in LK mode and it provides the comparison with the controlling of LC mode.

The second experiment represents the typical traffic jam scenario in which the vehicle continues stopping and starting. The system adapts the subject-vehicle’s speed to follow a preceding vehicle which is driven manually, stopping when necessary and keeping a safe distance even when circulating at low speeds. As shown in Fig. 5, the initial condition of this scenario is that both the preceding- and subject-vehicles are stationary in the same lane with over 50 m apart and facing in the same direction. Here the maximum speed of CC mode is set as 30 km/h, 2 s for the headway time, and 4 m for the minimum stopping distance which is the typical length of a vehicle. The subject-vehicle starts driving along its lane at 5 s, with initial CC mode. As the subject-vehicle approaches to a stopping preceding-vehicle, the headway distance decreases, and the system switches to the stop-and-go mode, adjusting the speed to keep a safe distance. As the headway distance decreases, the throttle degree is also gradually released. Around 28 s, the headway distance begins to be smaller than the safe distance, and thus the desired speed is less than the vehicle speed. At this point, the system applies the brake to slow down the vehicle, and the vehicle continues reducing speed until its headway distance reaches the minimum stopping distance 4 m from 32 s to 38 s. The preceding-vehicle then starts moving, followed by the subject-vehicle. This throttle/brake control behavior is very similar to human driving: The driver accelerates until a front car appears in the driving lane, then releases the degree on the throttle to slightly reduce speed and, if this reduction is not enough, applies the brake until the car stops without collision to the front car. This experiment reproduces the case of typical stop-and-go situation: the preceding vehicle is stationary and the following vehicle approaches the preceding one at high speed; this
situation is very common at the tail end of a traffic jam and causes a lot of rear-end crashes.

V. CONCLUSIONS

An Embedded driving-assistance system with multi-mode operation is proposed in this paper. The control system is constructed in a hierarchical autonomy structure to achieve integrated longitudinal and lateral motion control. Upper-level control determines the reference velocity and the reference trajectory of each driving mode. Vehicle-body control is designed on the basis of the fuzzy control technique for managing the vehicle’s throttle-, brake- and SW-motor in such way to mimic a human driver. By means of the embedded DSP platform, and self-installed sensors and actuators, this system is implemented on an experimental vehicle, Taiwan iTS-1. The experimental results in real-traffic environments show that Taiwan iTS-1 not only performs well in expressway/highway for CC, ACC, LK, and LC mode, but also extends the low speed capability in the urban-road for stop-and-go mode.

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