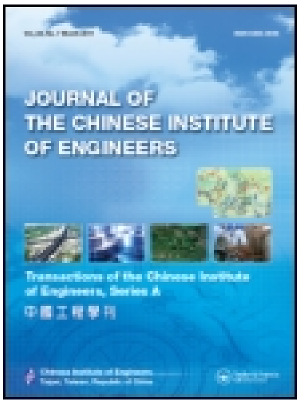

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THE DESIGN OF AN INTELLIGENT REAL-TIME AUTONOMOUS VEHICLE, TAIWAN *i*TS-1

Bing-Fei Wu*, Chao-Jung Chen, Hsin-Han Chiang, Hsin-Yuan Peng, Jau-Woei Perng, Li-Shian Ma and Tsu-Tian Lee

ABSTRACT

Developed at National Chiao Tung University, TAIWAN *i*TS-1 is the first smart car with active safety systems and comfortable autonomous driving in Taiwan. An adaptive vision-based lane detection algorithm was proposed to help the lateral control unit to keep the car in its lane safely. It also carries a DSP system to generate warning signals for unintentional roadway departures. A laser radar measures the distance between the preceding car and TAIWAN *i*TS-1. With this information, the longitudinal control unit performs intelligent cruise control and stop-and-go functions. The remote control function is realized on TAIWAN *i*TS-1 for safety testing and military applications. Unlike most smart car studies, this paper considers not only driving safety demands but also non-driving security. An active mobile surveillance system will inform the car owner when the car is illegally broken into, anytime and anywhere. For drivers and passengers, the perception of comfort is achieved by intelligent vehicle dynamic control. All functions integrated into TAIWAN *i*TS-1 have been tested repeatedly on National Highway 3 and Expressway 68 in the Hsinchu area and the system's robustness has been successfully demonstrated in these real-road experiments.

Key Words: smart car, lane departure, cruise control, stop-and-go

I. INTRODUCTION

The purpose of intelligent transportation systems (ITS) is to increase transportation safety and efficiency by integrating human beings, vehicles, roadways and call-centers. In (Huang *et al*., 2000), traffic capacity was increased from 2,000 vph (vehicles per hour) per lane to 5,000 vph per lane when autonomous vehicle systems were included in advanced safety vehicle (ASV) developments. Fig. 1 shows the worldwide representative smart car researches, including the Navlab-11 at Carnegie Mellon University (CMU), Ohio State University (OSU) and California Partners for Advanced Transit and Highways project (PATH) in U.S.A., VaMoRs-P at the University of Bundeswehr Munchen (UBM) in Germany, ARGO at Parma University in Italy, THMR-V at Tsinhua University in China (Kai and Kezhong, 2003) and TAIWAN *i*TS-1 at National Chiao-Tung University (NCTU) in Taiwan.

In these autonomous systems, vehicle handling and sensing related techniques have been extensively developed to enhance safety and convenience, reduce emissions and fuel consumption, and increase the traffic capacity of existing roadways.

The vision-based rapidly adaptive lateral position handling system (Pomerleau, 1995, Pomreleau, 1997) was developed on the Navlab-5 vehicle. A template matching approach was used to determine the lane curvature and lateral offsets of the vehicle for the lane keeping system. Since 1984, the CMU Navlab group has built a series of robot cars, vans, SUVs and buses. The latest one is Navlab-11 which is a robot Jeep Wrangler equipped with a wide variety of sensors for short-range and mid-range obstacle detection. An adaptive network fuzzy inference system (ANFIN) was also presented by Mar and Lin (2001) to control vehicle speed. In that investigation, the distance and speed related to the car ahead were measured by a radar sensor. The initial membership functions and 25 rules of ANFIN were constructed

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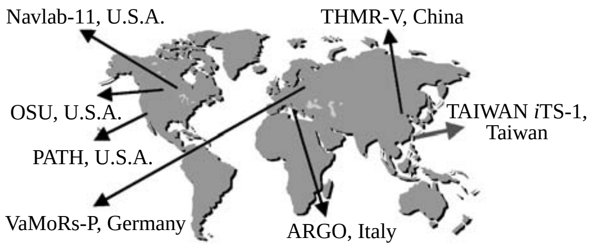


Fig. 1 Worldwide representative smart car researches

by a fuzzy inference system. The ANFIN-based controller enables safe, reasonable and comfortable autonomous driving. The second order sliding mode control was used in the study (Nouveliere and Mammar, 2003) to implement a stop-and-go (S&G) system in a real car. A model match control (MMC) based on sliding mode control was applied to S&G presented by Bin *et al*. (2004). This MMC was more robust than those based on conventional PID controllers.

In the U.S.A., a famous PATH program (Hessburg and Tomizuka, 1994) demonstrated an infrastructure-based approach. It used a reference and sensing system comprising discrete magnetic markers set in the roadway, forming a predetermined path, and a magnetometer attached to the front of the experimental car. During this project, supported by HONDA Research and Design North America Inc., a vision program for lane-keeping control was also developed at Berkeley university of California in 1997.

Since 1960, OSU has proposed a long-range program on various aspects of automated highway operations. The most extensive automated highway system (AHS), especially for vehicle guidance and control, began at OSU in 1964 and continues to the present. The principal emphasis is the design and development of reference systems and controllers for longitudinal and lateral vehicle control. The OSU Center for Intelligent Transportation Research has developed three smart vehicles with advanced cruise control, automated steering control for lane keeping, and autonomous behaviors including automated lane-change and stopping in reaction to other vehicles. Various sensors have been used for the autonomous vehicles, which are provided by Honda Research and Development with steer-by-wire and drive-by-wire throttle and brake control capabilities. A radar reflective stripe system and a vision system are loaded for lane position sensing, and a scanning laser range finder for the detection of objects ahead of the subject vehicle. Supporting sensors, including side looking radars and an angular rate gyroscope, are also employed to assess a number of vehicle measurements. Whenever multiple sensors are available, data fusion and fault detection maximize functionality without driver involvement. As a result, autonomous vehicles developed by OSU were successfully demonstrated at the National Automated Highway System Consortium (NAHSC) 1997 Technical Feasibility Demonstration in a scenario involving mixed autonomous and manually driven vehicles interacting in a fully autonomous manner at highway speeds (Fenton and Mayhan, 1991, Hatipolglu *et al*. 2003).

ARGO, an experimental autonomous vehicle, was developed at the Department of Information Engineering at the University of Parma, Italy. ARGO uses a vision-based system for extracting road and environmental information from acquired images. As a result of this research, the Generic Obstacle and Lane Detection (GOLD) system (Bertozzi and Broggi, 1998) was integrated into ARGO's autonomous driving system. GOLD system uses data on the positions of obstacles and road geometry to drive the steering wheel actuator. It also combines vehicle motion data, such as lateral offset and yaw, with the upcoming road curvature to determine the centerline of the road at a reference distance ahead of ARGO. The system then turns the steering wheel to guide ARGO toward the target point. During testing in the MilleMiglia in the Automatico tour, ARGO drove autonomously for approximately 2,000 km on public roads in real traffic conditions. Several lane-change operations were also made from the right lane to the center lane and vice versa. This tour demonstrated GOLD's abilities in different terrains (tunnels, bridges and different asphalt patches), weather, and traffic conditions. Finally, other enhancements have been undertaken for future ARGO developments presented in Broggi *et al*. (2000), Bertozzi *et al*. (1997), Bertozzi and Broggi (1997) and Broggi *et al*. (1999), including a vision algorithm for handling general road slop and developing control mechanisms suitable for higher velocity driving.

In Germany, the autonomous road vehicle named VaMoRs, was developed at UBM (Graefe and Kuhnert, 1992). This vehicle consists of a 5 ton van containing sensors for vehicle velocity, yaw rate, and accelerations; the vision system comprises two monochrome video cameras for a short focal length wide view and a telescopic view, respectively. The real-time image processing and feature extraction is computed on a BVV 2 multi-processor computer, while the control and high level computer vision is executed on an IBM IC computer. VaMoRs navigates by comparing the external real-world feature image to a predicted feature image derived from an internal 4-D model of the real-world. Many times a second the two feature images are compared and the differences are used to adjust the internal model of the world, so that changes in the external world can be closely

Table 1 The summary of the achievements of worldwide smart car researches

Functions	Navlab-11 (USA)	OSU (USA)	PATH (USA)	VaMoRs-P (Germany)	ARGO (Italy)	THMR-V (China)	TAIWAN *i*TS-1 (Taiwan)
Lane departure warning	√		√	√			√
Lane-keeping	√	√	√	√	√	√	√
Car-following		√	√	√		√	√
Stop-and-go	√						√
Lane changing	√	√	√		√		Ongoing
Integrated longitudinal and lateral control	√	√	√	√			√
Remote control						√	√
Active embedded car surveillance system							√
Driver comfort			√	√			√

followed. The state of the environment is then known via the internal model with regard to objects identification and position, while the state of VaMoRs is known via its motion sensors and control actuator positions. By combining these known states with the physical laws of motion, control signals can then be generated. VaMoRs is capable of driving at its top speed of 98 km/h on an open freeway, and up to 50 km/h on an unpainted road.

Developed by Tsinghua University in China, the intelligent vehicle named THMR-V is an SUV of the prototype SXZ6510. THMR-V is equipped with color CCD cameras, laser radars, GPS, magnetic compasses, optical encoders, etc. Besides, it also consists of an intelligent level, a coordinated level and an executive level. All the images are sampled by the camera on the top of THMR-V, and then the vision system processes the image sequences and generates the vehicle control commands to the electric motors that drive the steering wheel, the throttle, and the brake mechanism. With a speed of 20 ms/frame for image processing, THMR-V can reach a maximal speed of 150 km/h and an average speed of more than 100 km/h.

The first Taiwan smart car, TAIWAN *i*TS-1 as shown in Fig. 2 (Wu *et al*. 2004b), was developed by the Department of Electrical and Control Engineering at NCTU. TAIWAN *i*TS-1 is the prototype of a Mitsubishi SAVRIN sedan donated by China Motors Corporation. In order to provide reliable information, the car is well-equipped with data acquiring units, vehicle dynamic sensors, vehicle operating actuators and central processing systems.

A vision-based real-time lane detection system (Wu *et al*., 2004a; Wu *et al*., 2005a) for lane departure warning system (LDWS) and a lane keeping system (LKS) are available for TAIWAN *i*TS-1 (Wu *et al*., 2005c). The lateral control system steers the vehicle toward the desired trajectory on the road. The vision-based system and the vehicle state sensors provide this control system sufficient information to perform lateral motion control. The longitudinal control system mainly depends on forward distance measurements from the laser radar and the current speed of the host vehicle. Using this information, it will generate commands for the throttle and brake actuators in the autonomous adaptive cruise control (AACC) and the stop-and-go (S&G) systems. Table 1 summarizes the achievements of worldwide smart car researches (as shown in Fig. 1).

Fig. 2 TAIWAN *i*TS-1

It is observed that TAIWAN *i*TS-1 not only considers driving safety functions such as lane keeping, car following, lane-change, and stop-and-go, but also performs comfortable driving and active vehicle surveillance. The proposed intelligent car surveillance system (Wu *et al*. 2005b) on TAIWAN *i*TS-1 is an innovative idea which carries out mobile surveillance tasks without extra Internet Services Provider (ISP) constraints. Car owners can obtain immediate car status reports shown on their mobile phones. The details will be addressed in Section VII. The remote

Table 2 The specification of TAIWAN *i*TS-1

MITSUBISHI SAVRIN 2.4	
Engine Type	L4 DOHC 16V VVT+DDM
Exhaust	2400 c.c.
Horsepower (hp/rpm)	150/6250
Torsion (kgm/rpm)	19.2/3000
Transmission	INVECS-II SPORT-MODE 4 A/T
Weight	1640 kg

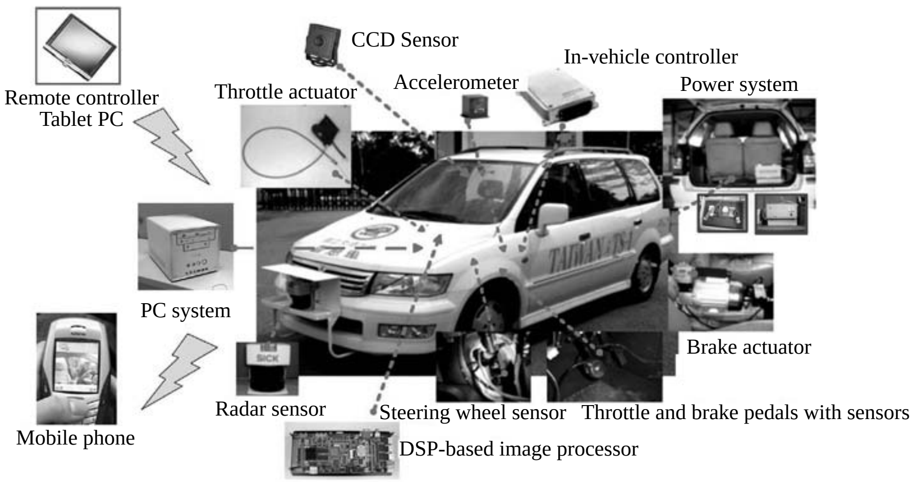


Fig. 3 TAIWAN *i*TS-1's equipments

control function enables TAIWAN *i*TS-1 to speed up and slow in response to the tablet PC and PDA through wireless communications. Due to the page-limits of this journal, this part will not be completely described in this article.

This paper is organized as follows : Section II shows the overview of TAIWAN *i*TS-1. The LDWS, the automated LKS, the AACC system, the automated S&G system and the active mobile car surveillance system are addressed sequentially from Section III to Section VII. Section VIII gives conclusions and future work.

II. THE OVERVIEW OF TAIWAN *i*TS-1

As shown in Fig. 3, TAIWAN *i*TS-1 is equipped with data acquiring sensors, motion sensors, actuators and controllers. The prototype specifications of TAIWAN *i*TS-1 are listed in Table 2. The CCD sensor grabs the raw image data; the radar sensor provides the forward-distance measurements with respect to the object ahead; the yaw rate, velocity sensors, and accelerometer perceive the real-time dynamic states of TAIWAN *i*TS-1; the steering wheel, brake pedal, and throttle pedal position sensors feed back the actuators' status to the in-vehicle controller. This in-vehicle controller will generate signals to the actuators based on the sensing and feedback information. The descriptions and specifications including data acquiring sensors, signal processors, and motion sensors are collated in Table 3.

III. LANE DEPARTURE WARNING SYSTEM

The lane departure warning system (LDWS) is a vision-based system which indicates unintentional roadway departures to avoid running off the road and sideswipe collisions, because drivers may lose their concentration when they are drowsy or talking on a cell phone. The proposed LDWS detects lane markings on the road and estimates the car's position within its lane by using a monochromatic CCD camera as shown in Fig. 4 mounted behind the windshield.

Raw image data from this camera is sent to the DSP-based image processor for real-time recognition. The recognition speed can achieve more than 35 frames per second with QVGA size. This system works well in sunny, cloudy, and rainy weather conditions, day or night. Different types of lane markings can be detected, such as solid, dashed, double, yellow, etc. The LDWS is qualified for highway, urban, and tunnel applications at all vehicle speeds.

Table 3 The equipment list in TAIWAN *i*TS-1

Data acquiring sensors	
CCD	Monochromatic, DC12V
Radar sensor	Laser range finder (Max. Dist. 100m)
Signal Processors	
In-vehicle controller	MicroAutoBox – dSpace
DSP processing unit	DM642 – 600M Hz, 32MB RAM
PC system	AMD 1.53G Hz CPU, 512MB RAM
Motion Sensors	
Actuator sensors	Motor position sensors
Yaw rate sensor	CRS-03 (29 ×18 ×29 mm)
Accelerometer	CXL01LF1 (19 ×48 ×26 mm)
Velocity sensor	Vehicle tachometer

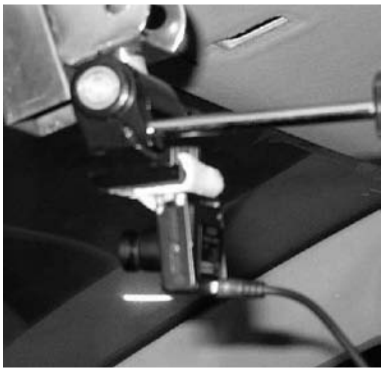


Fig. 4 The monochromatic CCD mounted behind the windshield

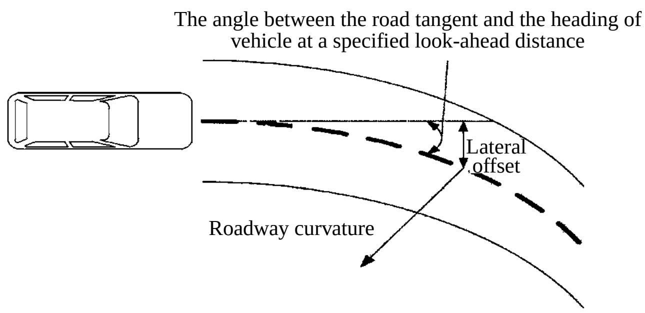


Fig. 5 The definition of the three estimated parameters

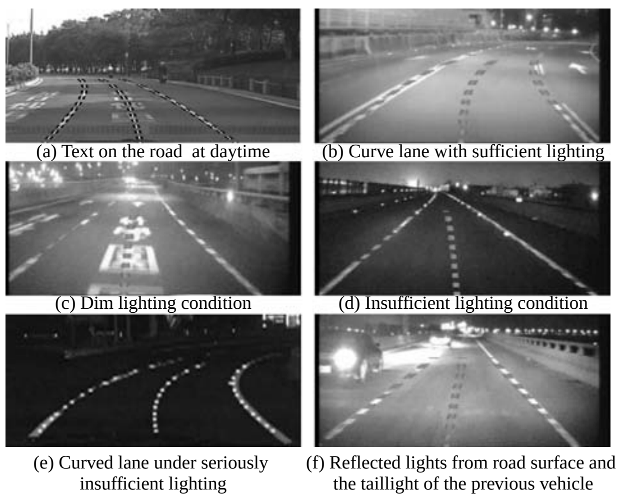


Fig. 6 Lane detection results under difficult road conditions

Lane detection and position estimation are the two key functions of the LDWS. The proposed lane detection algorithm uses a two-stage process to enhance efficiency. The first stage is for images where no previous information of lane marking pixels or lane trends exists. The second stage works on the images when the lane marking pixels and lane trends have been detected at the previous stage. When it appears that the lane cannot be successfully identified, the first stage runs again. The first stage is a full range search of the selected area. The detected lane marking pixels are approached as a second order polynomial and the lane's curvature is taken as the lane trend information on the image plane. In the second detection stage, the search area is smaller than the one in the first stage because the detected lane information from the first stage is available for reference. Three parameters, lateral offset, roadway curvature and the angle between the road tangent and the vehicle heading at a specified look-ahead distance, are defined and estimated, as shown in Fig. 5.

The LDWS system performs well even with poor roadway markings and conditions, such as strong shadows, text on the road, harsh lighting, reflected light from the road surface and other vehicles. Fig. 6 shows detection results for these difficult conditions. Fig. 6(a) is the result in the urban area and Fig. 6(b) to Fig. 6(f) are ones on highways and expressways.

The adaptive detection algorithm also works well inside tunnels and in heavy rains, as shown in Fig. 7. In rainy cases, TAIWAN *i*TS-1 overcomes

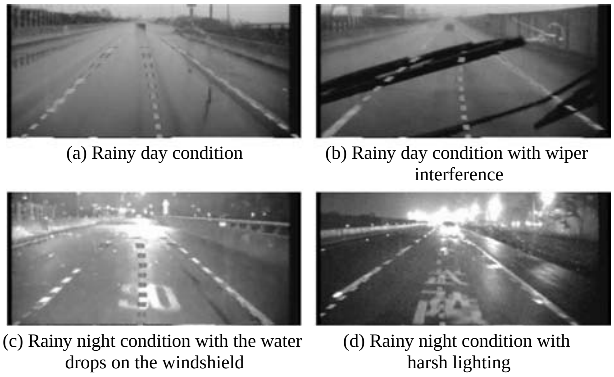


Fig. 7 The lane detection results under rainy day and night conditions

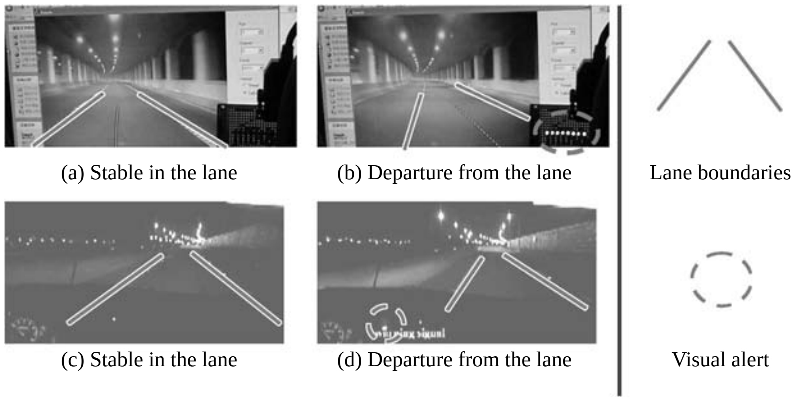


Fig. 8 The visual alerts to the drivers when departure appears

the influences of wipers and water drops on the windshield. When it appears that the vehicle intends to depart from its lane, as shown in Fig. 8(b) and Fig. 8(d), visual and audible warning signals alert the driver to take corrective action. As shown in Fig. 8(a) and Fig. 8(c), TAIWAN *i*TS-1 keeps stable in the lane. The red lines, marked manually, indicate the desired path in the lane. It is observed that TAIWAN *i*TS-1 departs from its lane in Fig. 8(b) and Fig. 8(d). The visual alarm is activated since the turn signal is un-triggered.

IV. AUTOMATED LANE KEEPING SYSTEM

The objective of the lane keeping system design is to track the centerline of the lane with the steering wheel. Fig. 9 depicts the hardware of the proposed automated LKS, which comprises a vision system, state sensors, a lateral control system, and a motor driver with necessary attachments. The vision system, which is a computer-based one, captures real-time road images and then determines the centerline, lateral offset and the angle between the road tangent and the vehicle heading at a specified look-ahead distance.

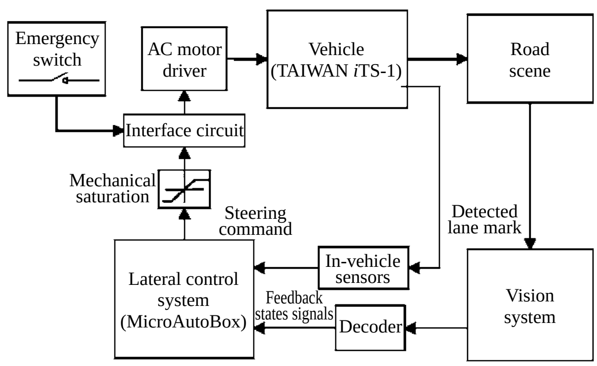


Fig. 9 The automated lane-keeping system architecture

Measurements made from the vision system and the in-vehicle sensors are fed into the lateral control system, which is implemented on a real-time MicroAutoBox. The lateral control system routes the feedback signals from the vision system and sensors to the local controller of the AC servo motor. Afterward, the desired steering command is then transmitted to the motor to drive the steering wheel via the interface circuit.

The proposed automated LKS is designed based

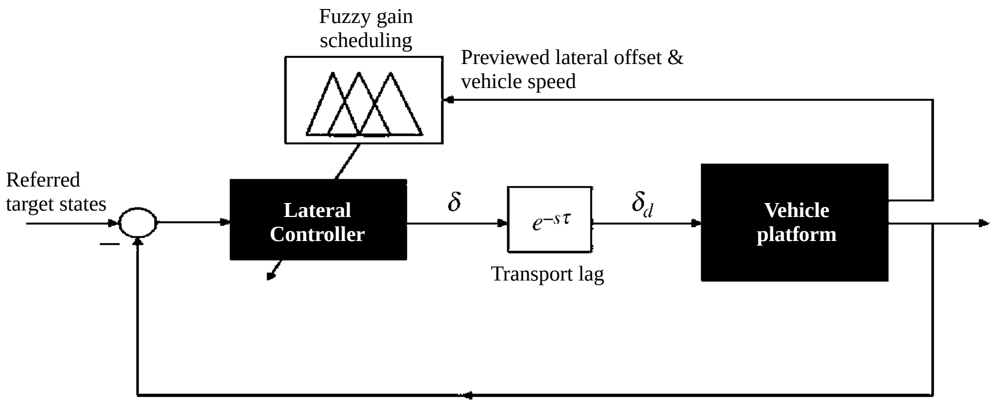


Fig. 10 Closed-loop structure of the automated lane keeping system

on human driving behavior. Many automobile navigation developments have been made, but few studies in real-time implementation deal with the steering tasks of human driving. It is assumed that human drivers can see the desired path (or lane) ahead, just like the previewed lateral offset and heading angle provided by the vision system. Drivers then take action based on visual feedback to bring the vehicle's future path in line with the desired future path; besides, it has been found that human drivers actually use feedback signals other than lateral offset to stabilize the vehicle. Therefore, in-vehicle sensors including the accelerometer and the yaw rate sensor are utilized to create the perception or feeling of the human driving experience. Transport lag between the signal process and the controlling action of the actuator can represent the neural delay of human beings. As a result, the lateral control system designed in this study executes real-time lane-keeping on highways using visual data captured from a monochromatic CCD camera mounted behind the windshield and dynamic state information provided by the in-vehicle sensors.

Many studies have confirmed that drivers exhibit adaptive behavior while steering. Therefore, this work proposes a fuzzy gain scheduling (FGS) strategy based on a soft computing technique to achieve satisfactory results and ensure human-like driving behavior by the automated driving control. The aim of FGS is to compensate for static feedback control and adjust the steering by considering the lateral offset and instantaneous speed of the vehicle. The rule base of FGS involves parameters that define membership functions and consequent expressions, which are designed to establish a closed-loop driving system based on the crossover model principle (Hess and Modjtahedzadeh, 1990). This eliminates the need for manual tuning by trial and error. The closed-loop structure of the lane keeping system is shown in Fig. 10.

The utility of this system was verified on standard test tracks at the Automotive Research & Testing Center (ARTC) and on real roads, on National Highway 3 and Expressway 68 in Taiwan. The real-car experiments were repeated at the Coastdown Test Track (CTT) and Noise Vibration and Harshness Surface Test Track (NVHSTT) at ARTC. The demonstration at CTT, shown in Fig. 11, was successful at a speed of 145 km/h. The testing at NVHSTT was achieved at a speed of 120 km/h. In these real-car tests at the two tracks, TAIWAN *i*TS-1 autonomously follows the center line of the tracks even when lane markings on one side disappear for a while.

Fig. 11 Real car experiments at ARTC with the speed of 145 km/h

As to the experiments on Expressway 68 and National Highway 3, TAIWAN *i*TS-1 kept in its lane automatically. The experimental route on Expressway 68 is from Chutung to Nanliao (C2N) and the one on National Highway 3 is from Hsianshan to Kuqnhsi (H2K). Fig. 12 is an aerial photograph of the routes for real-car lane-keeping experiments, where A and B, marked in white refer to C2N and H2K, respectively.

The proposed automated LKS has been verified on these two routes on sunny and cloudy days, with complicated road environments, such as heavy traffic, poor road markings and text within a lane. Due to the traffic rules in Taiwan, the highest vehicle speeds of TAIWAN *i*TS-1 in these tests were 80 km/h. The

Table 4 The summary of the test environments and weather conditions

Testing road \ Weather	Sunny	Cloudy	Night
CTT	0 ~ 145 km/h	0 ~ 145 km/h	0 ~ 90 km/h
NVHSTT	0 ~ 120 km/h	0 ~ 120 km/h	0 ~ 90 km/h
C2N	60 ~ 80 km/h	60 ~ 80 km/h	N/A
H2K	80 ~ 100 km/h	80 ~ 100 km/h	80 ~ 90 km/h

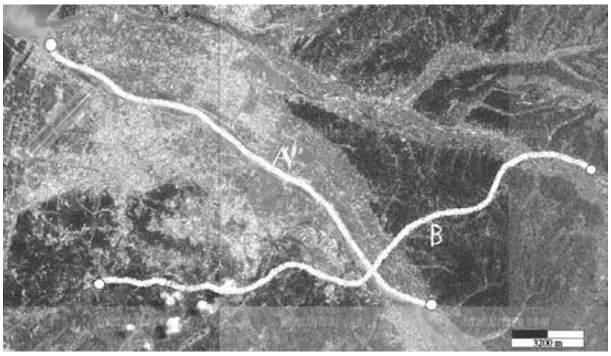
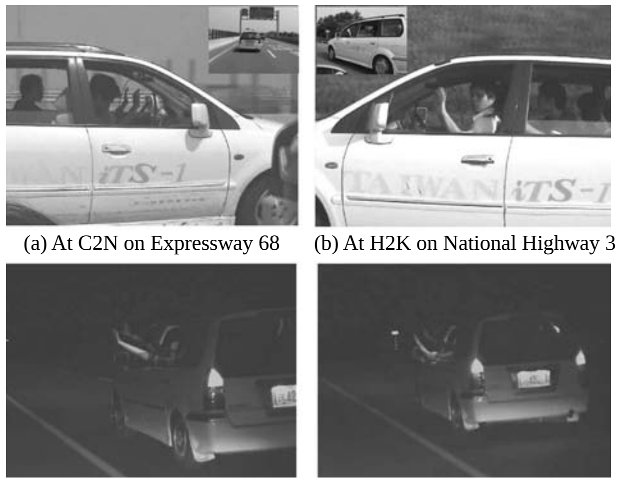


Fig. 12 The aerial photography of the experimental routes for the automated lane keeping



(a) At C2N on Expressway 68 (b) At H2K on National Highway 3

(c) The night experiment at NVHSTT in ARTC (d) With single-side lane marking available at NVHSTT in ARTC

Fig. 13 Real car experiments

system is not, however, limited to this speed. Fig. 13(a) shows our experiment using the inside lane on Expressway 68 and a replication on National Highway 3 in the outside lane, as shown in Fig. 13(b). The demonstrations at night were run at CTT, NVHSTT and H2K under 90 km/h with dim or insufficient lighting conditions. At CTT and NVHSTT, TAIWAN *i*TS-1 completed the lane-keeping trials without lights except for headlights, as shown in Fig. 13(c). We want to point out that TAIWAN *i*TS-1 accomplished its lane keeping trails when only one-side lane marking was available at night, as shown in Fig. 13(d). Table 4 summarizes the testing environments and weather conditions. As observed, TAIWAN *i*TS-1 performed well in the lane-keeping task on highways and expressways and the system robustness was also demonstrated on sunny and cloudy days and at night at high speed.

V. AUTOMATED ADAPTIVE CRUISE CONTROL SYSTEM

The objective of the AACC system is to adjust speed and inter-vehicle distance with respect to the preceding vehicle. The longitudinal control system depends on forward distance measurements from the laser radar and the current speed of the host vehicle to generate commands for the throttle and brake actuators. The configuration of the longitudinal control system is depicted in Fig. 14. Sensed signals from the laser range finder, the velocity sensor, and the angle position sensors for the throttle pedal and brake pedal, are fed into the in-vehicle controller to achieve the desired speed tracking and safety space maintenance by controlling the acceleration and braking. The throttle pedal is adjusted by the DC-motor. For the brake actuator, an electronic cylinder pump is used to push and ease the brake pedal directly.

Both speed control and distance control are involved in this system design. More specially, the control system works in two modes, namely, with and without a vehicle in front. There exists transitional switch logic between these two modes, velocity and distance, for vehicle cut-in and cut-out situations. Moreover, the safety and comfort of humans are taken into consideration at the core of the AACC system design.

The structure of the AACC can be divided into the supervisory control and the regulation control, respectively. The supervisory control contains the switch logic between different operation modes by recognizing the specifying inputs. With the measurements from the on-board sensors and the commands of the human driver, the supervisory control also could cooperate with the information from roadway infrastructure and other vehicles by the communication device. In

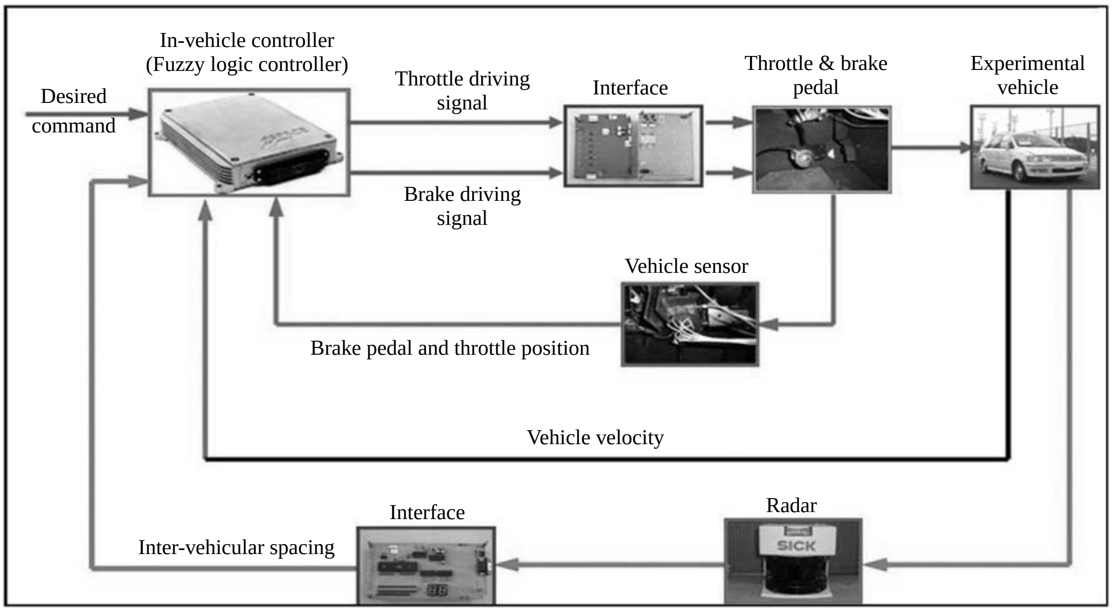


Fig. 14 Overall longitudinal control system configuration

this paper, there is no vehicle-to-vehicle (v-v) communication. The function of this communicating scheme is the continuum in our system development. If a valid target is detected during the controlling process, then supervisory control chooses the distance tracking mode. A valid target is defined as a preceding vehicle in the same lane whose speed is lower than the host vehicle's current speed. The fixed headway time strategy is employed in the distance tracking mode such that the desired safety distance depends on the host vehicle's current speed. It should be noted that many studies have proven traffic safety and smoothness benefits using this strategy. According to the specification of ISO 15622 for ACC systems, the safety headway time is within the range from 1.5 to 2.2 s. In our AACC system, the headway time can be set as 1 s to exhibit the precise performance during the distance tracking mode for car-following. As to the ride comfort consideration, a saturated sliding mode controller (Chang *et al.*, 2006) is designed to constrain the desired velocity variation of the vehicle. This result is examined by the international standard ISO 2631 which defines the means to evaluate vibration with respect to responses of human drivers and passengers. The acceleration of the AACC is limited to 0.2g (g is 9.8 m/s^2), and the resulting ride quality agrees with the "No discomfort" rank of ISO 2631.

The regulation control is responsible to guarantee the host vehicle follows the desired velocity commands by the supervisory control. The vehicle longitudinal dynamics can be described by a set of systems composed of various linear and nonlinear subsystems, e.g., engine, automatic transmission in the gear box, brake system, the rubber tires with respect to roads, and etc. Indeed, control designing based on this complicated model is very difficult. Conventional methods to perform ACC based on analytical control generate good results but with high design and computational costs. To oppose the ill-conditioned and complex model of vehicle longitudinal dynamics, the fuzzy logic control (FLC) technique is employed in the regulation control design. Moreover, FLC can also allow an approximate human reasoning and an intuitive control structure (Sugeno, 1985) such that a human-like speed control can be achieved.

There are many advantages to this control structure in comparison with other existing ACC systems. One remarkable point is that the supervisory control can be designed without much consideration for the regulation control which is developed specifically for the vehicle. Therefore, the supervisory control is essentially robust designed such that it can be transferred to another vehicle with only minor modification. As to the employment of FLC, the regulation control relieves the limitation of those commercial ACC systems which operate effectively above 30-40 km/h but fail at lower speeds. Not only can the proposed AACC system perform the longitudinal automation at high speeds, but is also suited to low-speed driving in heavy traffic situations.

To demonstrate the validity of the proposed AACC system, many experiments were successfully conducted at C2N on Expressway 68. Without a vehicle in the feasible radar field, the host vehicle will track the desired speed input from the human driver.

(a) Valid target is detected (b) Throttle and brake are actuated automatically (c) Keeps a fixed headway distance, 10 m, under 70 km/h

Fig. 15 Distance tracking of the AACC system on Expressway 68

Once a preceding vehicle with a slower speed is detected by the laser radar, the AACC system then controls the vehicle to maintain a safe headway distance based on the current driving speed, as shown in Fig. 15. When the preceding vehicle changes lanes, the host vehicle accelerates to the previous speed setting.

The proposed AACC system can assist the driver to maintain a safe distance, which is determined from the current velocity, to the vehicle ahead at speeds between 20 km/h and the maximum speed of the vehicle. Besides, the AACC system can switch autonomously to assist the driver to maintain velocity while the preceding vehicle is far away. In conclusion, the workload of driving at high speeds can be reduced by the AACC system.

The designs of the automated LKS and the AACC system are introduced separately. The validity of each system has been demonstrated in the previous sections. The integration of the automated LKS and AACC systems is ongoing, but so far some results have given us confidence in the eventual results. In Fig. 16(a), the scenario for unmanned-driving is demonstrated in an urban-road environment, where lanes are maintained at speeds from 0 to 30 km/h. Moreover, on Expressway 68 the full automation has also been shown to achieve the integration of the LKS and the AACC system. As shown in Fig. 16(b), the steering wheel, throttle and brake pedal are actuated autonomously without the human driver's intervention. Consequently, not only the lane-keeping mission but also the adaptive cruise control is carried out simultaneously.

VI. AUTOMATED STOP-AND-GO SYSTEM

The overall structure of the proposed automated S&G system is shown in Fig. 17. Due to the nonlinearity of vehicle dynamics integration such as the engine, power transmission, brake system and drive train, a fuzzy logic control (FLC) technique is employed in the core design of the automated S&G system. This design handles unknown vehicle models and guards against uncertainties arising from the vehicle body

(a) Unmanned driving scenario (b) Full automation on Expressway 68

Fig. 16 Demonstration of the integrated lateral and longitudinal control

and external environments. In addition, linguistic rules in the fuzzy control law can also produce driving behavior more like human behavior (Sugeno, 1985). Two separate FLCs with proportional-integral-derivative (PID) gains for throttle and brake, respectively, are designed to achieve safe distance and the desired velocity tracking. These PID gains with fuzzy inference rules can be tuned by engineering judgment to imitate human driving characteristics (Wu *et al*., 2006d); also, the approaches as examples of adaptive or learning schemes can be utilized to improve the controlling performance. The required acceleration and deceleration are limited to 0.2g and 0.3g respectively. Therefore, the ride comfort for the driver and passengers can also be achieved and the results can also meet by the international standard ISO 2631.

Unlike the ACC systems, so far there is no international standard for the specification of safe distances for S&G systems. In this work, the desired driving speed is initially commanded by the driver, and the stopping distance with respect to the preceding vehicle is set as lengths of passenger vehicles (about 5 m).

The feasible velocity for the S&G system is 25 km/h, which is a normal circumstance in an urban area with heavy traffic. If the sensed distance is smaller than the desired stop distance, the S&G controller actives the brakes and releases the throttle pedal; otherwise, the throttle control is activated and brake pedal is released. In comparison with other S&G systems, this

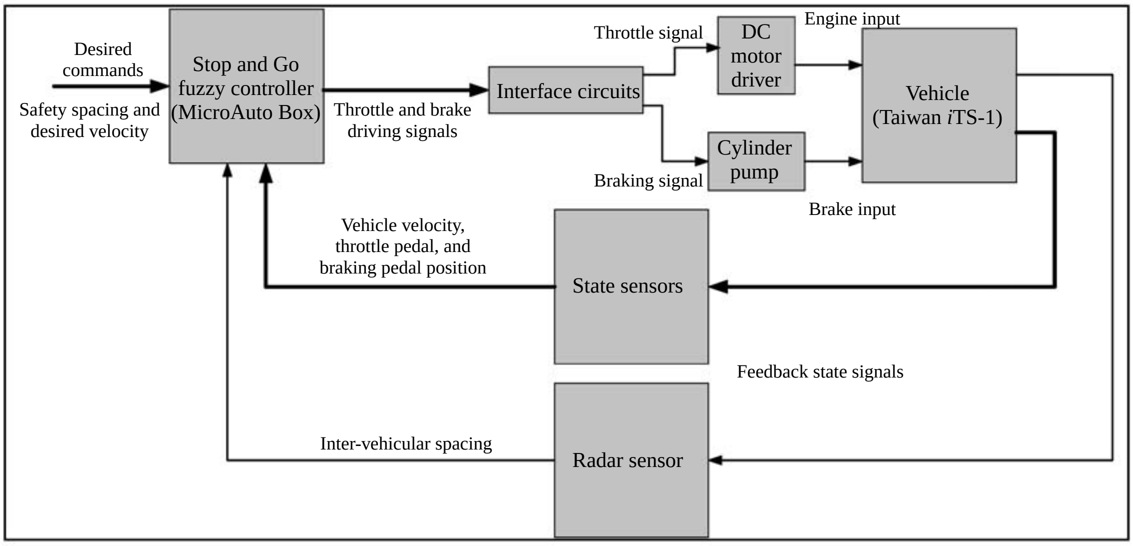


Fig.17 The overall structure of the automated stop-and-go system

proposed automated S&G system also performs collision avoidance for obstacles or pedestrians. Not only the preceding vehicle, but also forward obstacles and pedestrians should also be detected, especially when these targets appear on the driving course of the vehicle. If the forward radar senses an obstacle ahead, the S&G system will stop the vehicle and keep a safe distance from the obstacle (or pedestrian) ahead. When the obstacle (or pedestrian) leaves, the vehicle goes forward and reaches the previous velocity. Note that the absence of an obstacle (or pedestrian) is determined by the fact that it will not be within the radar scanning field.

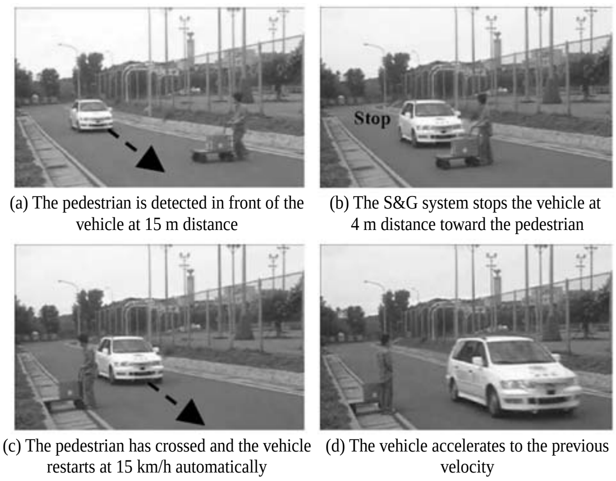
To exhibit the validity of the automated S&G system, the following three experimental scenarios were demonstrated at a public parking lot.

1. Scenario 1: Pedestrian Crossing

In this scenario, the experimental vehicle approached at a velocity of 15 km/h. When the pedestrian was detected in front of vehicle at a distance of 15 m, the throttle pedal was released. The braking control system was then activated, bringing the vehicle to stop at a distance 4 m in front of the pedestrian. After the pedestrian crossed the road, the experimental car resumed acceleration toward the previous velocity, as shown in Fig. 18.

2. Scenario 2: Stop in front of Obstacle

In this scenario, an obstacle (or stopped vehicle) appeared in front of the host vehicle. The S&G system started braking at 14 m behind the vehicle and stopped the vehicle 7 m behind the preceding car (obstacle), as shown in Fig. 19.



(a) The pedestrian is detected in front of the vehicle at 15 m distance
(b) The S&G system stops the vehicle at 4 m distance toward the pedestrian
(c) The pedestrian has crossed and the vehicle restarts at 15 km/h automatically
(d) The vehicle accelerates to the previous velocity

Fig. 18 The Scenario 1 S&G system test

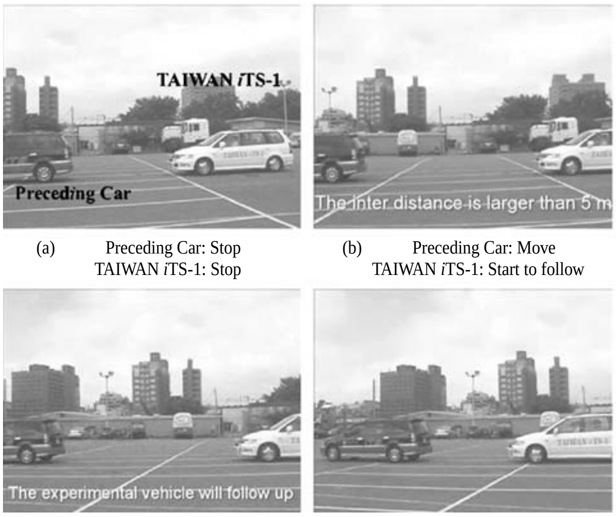
3. Scenario 3: Stop & Go

This scenario simulated a traffic jam. In this scenario, the preceding vehicle moved at a speed 5 km/h for a period of time, then stopped completely. After a few seconds, the preceding vehicle continued to move and stop. The automated S&G system in the host vehicle controlled the throttle and brake pedals to maintain a safe distance between the host vehicle and the preceding vehicle, as shown in Fig. 20.

In summary, the ultimate objective of the automated S&G system is to reduce the driver's mental fatigue and to increase traffic capacity. These successful

(a) Started to brake the vehicle at a 14 m distance behind the preceding car (b) Stopped the vehicle at a 7 m distance behind the preceding car

Fig. 19 The Scenario 2 S&G system test



(a) Preceding Car: Stop TAIWAN *i*TS-1: Stop
(b) Preceding Car: Move TAIWAN *i*TS-1: Start to follow
(c) Preceding Car: Stop TAIWAN *i*TS-1: Follow up
(d) Preceding Car: Stop TAIWAN *i*TS-1: Stop

Fig. 20 The Scenario 3 S&G system test

results indicate a brand-new milestone for advanced research and development in intelligent vehicle design and the promotion of related industry.

VII. ACTIVE MOBILE CAR SURVEILLANCE SYSTEM

The active mobile car surveillance system (AMCSS) is a surveillance function of TAIWAN *i*TS-1. AMCSS can transmit real-time images and the vehicle's position to users, letting them know the current situation by use of their mobile devices anytime and anywhere. An embedded system and mobile devices cooperate to perform this mobile surveillance function. When the sensors mounted in the vehicle sense any illegal motions, AMCSS will be triggered to start capturing and storing images in a CompactFlash card. The illegal motions will be detected by infrared, microwave or image sensors. In AMCSS, a trigger I/O is reserved for this add-on signal. Simultaneously, AMCSS sends a warning message to the car owner. Users can receive AMCSS's notification immediately and take any necessary actions, e.g. reporting to the police or double checking their car's situation. The

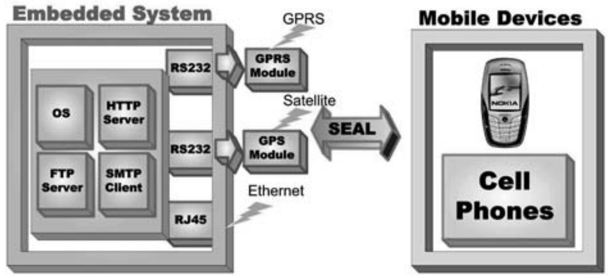


Fig. 21 The overall architecture of AMCSS

(a) The operation of the Java Applet (b) The screen on the mobile phone

Fig. 22 AMCSS system's experimental results

primary function of this system is not only the message, but also the encrypted real-time images transmitted to the users' mobile devices via a software encryption algorithm (SEAL) encryption. Users can determine whether the alert is erroneous or not.

The overall AMCSS architecture is shown in Fig. 21. AMCSS is based on an embedded system which has its own operating system (OS) and several network applications. An SMTP client, an FTP server, an HTTP server and two wireless communication modules, GPRS and GPS, are integrated together in this embedded server. AMCSS can acquire its global position via the GPS module and access the internet with the GPRS module when no wired internet connection is available. μclinux was chosen as the embedded OS.

A Java applet programmed for mobile phones enables users to see real-time images through a GPRS protocol. The images are transmitted from the alarm-triggered AMCSS. After receiving a short warning message, users can run the Java applet on mobile phones and see the images on the phone screen. The images have a 176 by 144 frame size. Fig. 22(a) shows the operation of the Java applet. The images refresh continuously. The applet was successfully run on a Nokia 6600 mobile phone with its supports, GPRS, MIDP and Symbian operation system.

The actual average bandwidth of GPRS is approximately 8-10K bits per second for data downloading.

The average encrypted JPEG image size is approximately 1K Bytes. Therefore, a mobile phone can download, decrypt and decode compressed image data from the MCSS in less than 3 seconds. The processing time will be reduced if GPRS gains a wider bandwidth. As shown in Fig. 22(b), the top of the screen shows the date and time of the captured picture, and the two buttons on the bottom of the screen are "Option" and "Exit" in Chinese.

AMCSS is a completely mobile surveillance systems solution. It can also be used in parcel service company fleets. The call center manager can check the drivers' condition anytime and anywhere to help avoid accidents or theft. AMCSS is also a good solution for bank security trucks.

VIII. CONCLUSIONS AND FUTURE WORK

TAIWAN *i*TS-1 is the first smart car in Taiwan. The functions described above have been demonstrated and video taped by the Taiwan press under real road conditions. The related video clips of these functions' demos and the media reports are available on http://cssp.cn.nctu.edu.tw. The lane departure warning, automated lane keeping, and adaptive cruise control systems were verified at H2K on National Highway 3 and C2N on Expressway 68. The presented LDWS gives drivers accurate warnings when it appears that their vehicles are departing from their lanes in day light or at night with sunny or rainy conditions. Even when road markings are flawed, the LDWS still performs well. The proposed lane keeping and adaptive cruise control functions have been repeatedly tested under real road conditions. It should be mentioned that the comfort of drivers and passengers was considered in the vehicle autonomous control design, and smooth driving behavior is achieved. The S&G and remote control experiments were carried out in a public parking lot on the campus at NCTU. The S&G system is expected to be applied to traffic jam conditions, letting drivers utilize their time more efficiently on the way home. The remote control function is planned for safety testing and military applications. In national defense roles, casualties can be significantly cut by using this system. The active mobile car surveillance system is an innovative idea that provides non-driving security for vehicles. This compensates for the lack found in most research and experiments on smart cars, which focus only on safety while driving. AMCSS gives users real-time information and images of their cars to assist in problem identification and emergency response.

The preliminary function verifications of TAIWAN *i*TS-1 have been successfully completed and future development is underway. Human-like driving behavior is desired in the vehicle control logics. Intelligent automatic mode switching is also necessary because traffic conditions do not remain constant in traveling. In particular, the control system must integrate the vision system, the radar system and the vehicle sensors. Integrating vision and radar detection can compensate for the weaknesses of these systems, making each better. Moreover, the vision-radar detection system is expected to expand the current one-lane detection to multi-lane detection. This multi-lane vision-radar system gives lane information and the location of the preceding vehicle. Likewise, detections at the side and rear of the vehicle are on-going, which will let TAIWAN *i*TS-1 know its complete surrounding conditions for omni-directional autonomous driving. Moreover, some difficult problems due to the road complexities like entry/exit segments on highways and intersections on urban roads are still under investigation. To solve these difficulties, a combination of location sensor techniques like GPS and map navigation might be one good solution.

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