Computing for the Next-Generation Automobile

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Innovative computational technologies developed by automotive companies and research institutes in Japan are making cars greener, smarter, and more connected.

Following the magnitude 9.0 earthquake that hit northeastern Japan on 11 March 2011, the ground transportation network in the affected areas largely fell apart. To rescue people and deliver aid from other parts of Japan and the rest of the world, officials urgently needed to find alternate routes through a disaster area that stretched hundreds of kilometers.

Honda, the inventor of the in-car navigation system, had pioneered this type of work using technology that provides information on passable routes generated from individual vehicles through Internavi Premium Club, a telematics service. Acting as probes, each car periodically sends its location, driving direction, and velocity to the Internavi center. If a driver encounters a situation that makes it necessary to take another route, the system identifies the road that the vehicle has just left as being impassable. After privacy filtering, the system superimposes the aggregated intelligence on a map, displaying the passable routes on each car navigation system's screen. This feature also helped many drivers escape the damaged roads that resulted after an earthquake hit the northwest coast of Japan in July 2007.

Immediately after the March 2011 quake, Toyota and Nissan teamed up with Honda and Google to share information about passable routes collected from their own telematics services. On 19 March, they jointly launched a service that offered passable routes via Google Maps—depicted as the bold blue lines in Figure 1.

These collaborative efforts are examples of how combining advances in computing technology and automotive technology can have a beneficial effect when applied to help people recover from emergency situations.

NEXT-GENERATION VEHICLES

As society has changed, requirements for automotive functions have likewise changed—often dramatically. As recent reports indicate,[1] we can expect many more changes in the coming years, focusing on three trends: making automobiles greener, making them smarter, and merging transportation and information networks.

Going greener

By 2020, more than 2 billion automobiles will be on our roads, with Asia serving as the fastest growing sector of the global automotive market.[2] As concerns about global warming and fossil fuel depletion continue to increase, countries around the world are focusing their efforts on reducing automobile emissions and fuel consumption.

To address these concerns, automotive companies are focusing on developing efficient computer-controlled combustion engines. Alternative engine technologies offer a potential solution, specifically electric vehicles (EVs), hybrid vehicles (HVs), and fuel cell (FC) engines.[3] Table 1 identifies representative HV and EV brands marketed in Japan along with their evolution over the past 15 years.

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Toyota introduced its Prius to the market in 1997, offering the first mass-produced vehicle with a hybrid architecture that bridged the conventional combustion engine and the electric motor. Development of the Prius began with Globe 21, a project initiated in 1993. At the time, Japanese consumers preferred bigger luxury cars, but Toyota's engineers were concerned about the automobile's future and wanted to produce a new automotive technology paradigm for the 21st century.

The Prius has evolved over three generations, the most recent of which was introduced in 2009, featuring high fuel efficiency—32.6 km/liter in the Japanese-standard JC08 mode and 50 mpg according to the US EPA combined estimate. The Prius was the best-selling car in Japan from 2009 to 2011. In 2011, HVs accounted for 17.1 percent of all new passenger car sales in Japan, up 4.8 percent from 2010. For Toyota alone, HVs accounted for 36.1 percent of sales in 2011.

Nissan and Mitsubishi have taken the lead in EVs, with Leaf and i-MiEV, respectively. After a series of open experiments from 2007 to 2009 in Japan, Europe, and the US, Toyota put the Prius PHV on the market in 2012 as a hybrid between HV and EV technology. With the technology having reached a certain maturity, we can expect to see a wide variety of HV, PHV, and EV options from major automotive companies worldwide.

HVs and PHVs draw maximum fuel efficiency through sophisticated computer control of the combustion engine, electric motor, and regenerative braking systems that recapture a car's kinetic energy and convert it into electricity that recharges the car's batteries. In particular, HVs and PHVs depend on precise control of software to balance power. Figure 2 shows three basic HV architectural styles: *series*, *parallel*, and *series-parallel*. Each architectural style has its advantages and disadvantages.

The series architecture has no direct connection from engine to wheel. Some EVs have adopted the series architecture, in which the motor drives the wheels, and the engine (usually a small one) generates electricity.

Figure 1. Google Maps depiction of Northern Honshu Island's passable traffic routes on 2 April 2011.

In the parallel architecture, the engine and motor drive the wheels in parallel. The motor improves fuel efficiency and regenerates electricity when the car is braking. A computer balances the power between the engine and motor. Many HVs incorporate this motor-assisted engine architecture, including Honda Insight, Honda Fit, and Nissan Fuga.

The series-parallel architecture integrates the series and parallel architectures for improved fuel efficiency and performance. Balancing the engine, motor, and regenerative braking systems requires more sophisticated computer control. Toyota adopted this architecture for its Toyota Hybrid System II (THS II), which drove the development of the Prius and other Toyota HVs.[4] As Figure 3 shows, the hybrid control computer in the THS II architecture works collaboratively with the computers for engine control, transmission control, the battery, and the electronically controlled brake (ECB) system.

The PHV is considered a hybrid between the HV and EV because it adds a charging capability for the HV battery.

Table 1. Japanese hybrid, plug-in hybrid, and electric vehicles.

Vehicle type	~1999	2000–2004	2005–2009	2010+
Hybrid	Toyota Prius (1st generation, 1997) Honda Insight (1st generation, 1999)	Toyota Prius (2nd generation, 2003) Honda Civic Hybrid (2001)	Toyota Prius (3rd generation, 2009) Toyota Camry Hybrid (2006) Lexus LS600h (2008) Lexus HS250h (2009) Honda Insight (2nd generation, 2009)	Toyota Prius α (Prius V in US) (2011) Toyota Aqua (Prius c in US) (2012) Honda Fit Hybrid (2010) Nissan Fuga Hybrid (2010)
Plug-in hybrid				Toyota Prius PHV (2012)
Electric			Mitsubishi i-MiEV (2009)	Nissan Leaf (2010)

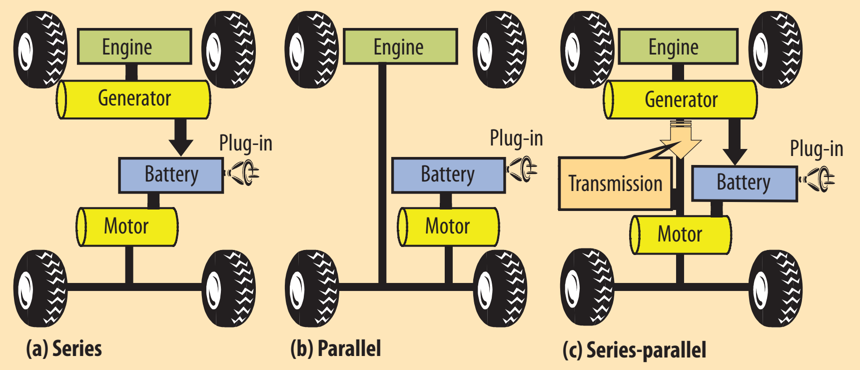

Figure 2. Three hybrid vehicle architectural styles: (a) series—there is no direct connection from engine to wheel; (b) parallel—both the engine and the motor drive the wheels; and (c) series-parallel—the series and parallel architectures are integrated for better fuel efficiency and performance.

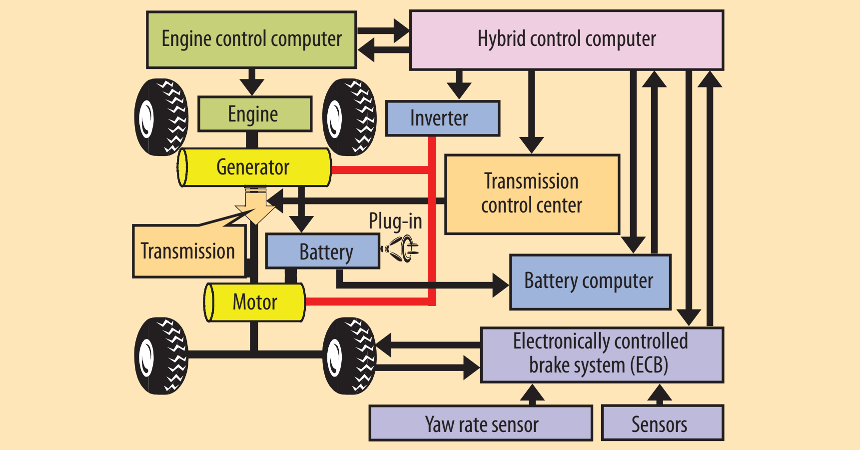

Figure 3. Prius integrated THS II control architecture.

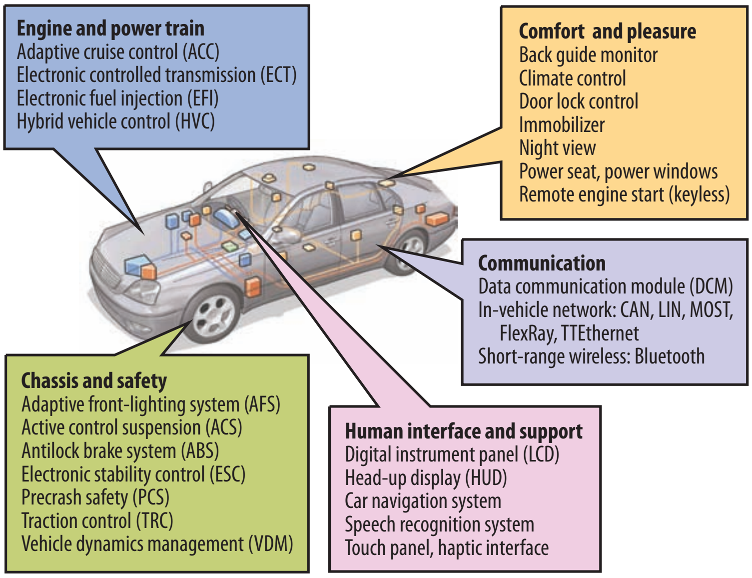

Figure 4. Vehicle computer systems. The electronic control unit deployment typically consists of between 5 and 10 million lines of embedded code; a navigation system adds another 5 to 10 million lines of code.

After plugging a PHV into a power source at home to charge it, the driver can travel a certain distance without using the engine—approximately 11 miles (17.6 km) according to the US EPA estimate for the Prius PHV, for example. Interestingly, the technology works both ways: the PHV and EV can provide electricity to a house. A fully charged Nissan Leaf can provide enough electricity to power the average Japanese house for two days.

Both EVs and PHVs are expected to play an important role in the smart grid's future, but we have a long way to go: plugging vehicles into the power grid can affect the entire grid's usage patterns and stability. Smarter control of vehicular electricity must work with both the home energy management system (HEMS) and the smart grid. Many open experiments are being conducted across Japan on this research topic.

Getting smarter

Most vehicles today come with more than 50 embedded computer components, called *electronic control units* (ECUs). Figure 4 shows an ECU deployment in a vehicle, which typically has between 5 and 10 million lines of embedded code. A car navigation system with rich functionality will add another 5 to 10 million lines of code. Code size has rapidly increased in the past decade due to ever-increasing demands for software systems in automobiles. Software engineering will be the key to improving the quality and productivity of future vehicles.[5,6]

Automotive software engineering presents immense challenges. Among them, safety is the most critical, involving every aspect of driving. As Figure 5 shows, driving has two safety modes: *passive* and *active*. Passive safety mitigates the damage incurred in an accident, whereas active safety is intended to avoid an accident. Most current recent research activities focus on active safety.

For stability, some governments mandate that new cars must have

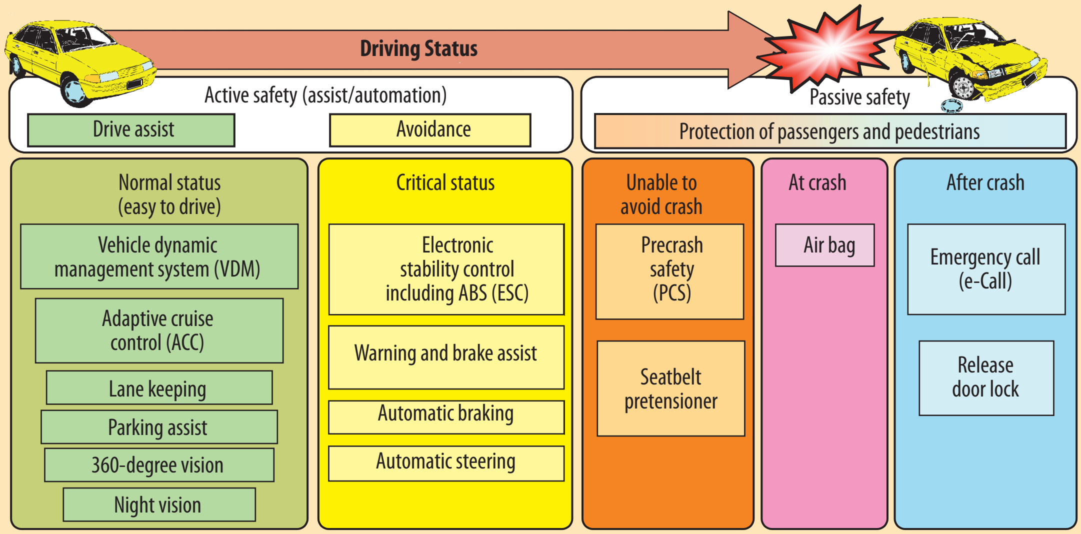

Figure 5. Active safety versus passive safety. Passive safety mitigates the damage incurred in an accident, whereas active safety is intended to avoid an accident.

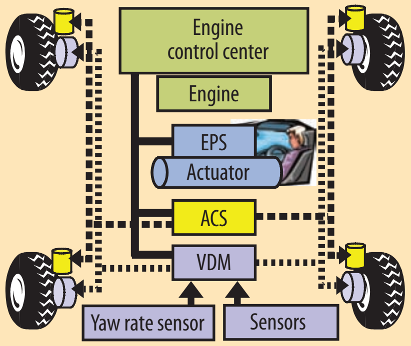

Figure 6. Vehicle dynamics management architecture. The VDM works collaboratively with multiple computers embedded in the ESC, engine control, electronic power steering (EPS), and adaptive control suspension (ACS) systems.

electronic stability control because statistics prove that ESC significantly reduces traffic accidents. ESC integrates the antilock braking system (ABS) and traction control (TC) to provide stability while braking.

However, computational problems can arise—for example, the ABS can manipulate each wheel independently, but controlling each wheel affects the entire car's behavior, which in turn affects the feedback to the ABS.[7] Suppose a driver applies the brakes while traveling on a road that is partially wet. One wheel might be on a wet patch, while the other three wheels are on dry sections, which could cause the vehicle to skid uncontrollably.

A vehicle dynamics management (VDM) system is an ESC advancement intended to improve safety, stability, and passenger comfort under adverse driving conditions. VDM controls the four wheels individually for driving and braking based on information gathered from various sensors detecting a vehicle's attitude, velocity, and acceleration, as well as the conditions between the tire and the road surface. As Figure 6 shows, VDM works collaboratively with multiple computers embedded in the ESC, engine control, electronic power steering (EPS), and adaptive control suspension (ACS) systems.

The vehicle dynamics integrated management (VDIM) system is a VDM implementation for Lexus and premium Toyota sedans. According to the "ball in a bowl" control principle, VDIM provides an envelope for maneuvering to keep the car stable.[8]

The ultimate goal for vehicle safety is collision avoidance. Most collision avoidance systems employ either radar or cameras to identify obstacles. For example, Volvo's City Safety automatic braking system uses laser radar to stop a vehicle traveling at up to 15 km/h. Subaru introduced the first driving assistance system in 1999. In 2008, this evolved to the EyeSight system, which can stop a vehicle automatically via a stereo camera mounted inside the front window. EyeSight version 2, introduced in 2010, can stop a vehicle traveling at up to 30 km/h. A 3D image processor analyzes the images that two cameras capture and estimates the distance to the obstacle. If the vehicle cannot avoid a collision, the safety system works collaboratively with computers in the ESC, engine control, and transmission control systems to stop the vehicle smoothly.

Although software provides advanced safety functionalities, the increasing code size and complexity introduce risks.[9] Researchers at Nanzan University revealed complex interactions among distributed ECUs collaboratively working for VDM.[7] The interactions are twofold: one is the direct interaction among distributed ECUs through in-vehicle

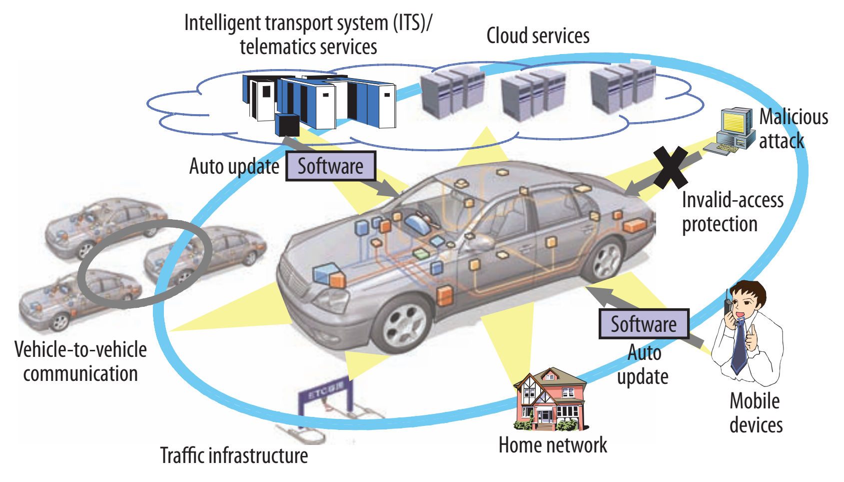

Figure 7. Automotive cloud services system. The service-oriented ACSS software architecture collaborates with the cloud, providing context-aware services to automobiles via real-time analytics.

Figure 8. Concept vehicle i-unit in demonstration (front) and Prius PHV (back) in Toyota Kaikan Museum.

networks, and the other is indirect interaction among ECUs through the physical vehicle.

Suppose an ECU controls actuators that change the state of some vehicle parts, such as the brakes, and sensors then detect the status changes. The complexity of such interactions can make the vehicle behave inappropriately, for example, inconsistent control of the ABS or inadequate assistance for braking while driving on a hill. Thus, automobile manufacturers might need to develop an understanding of the complexity of automotive software as a type of cyberphysical system or system of systems.

To address this type of concern, after six years of development, researchers published ISO 26262, a new functional safety standard specific to automobiles, in November 2011. The standard recommends various software development techniques depending on safety requirements.

Merging networks

Most people prefer to be connected to the Web at any given time,[10] but being online while driving a car is not a safe activity. To offer connection while maintaining hands-free attention to the road, automobiles are increasingly being equipped with a *data communication module*, a small box with a mobile phone capability. Through the DCM, vehicles can exchange information with the intelligent transport system (ITS) and telematics service center to obtain traffic information and commercial services, respectively.

Toyota, Honda, and Nissan initiated their G-Book, Internavi Premium Club, and Car Wings telematics services in 1997. Since then, researchers have developed many new services for smarter navigation, real-time map updates, driver safety support systems (DSSSs), and remote control services from mobile devices and smartphones. Introduced in 2011, DSSS can work with the ITS to provide context-aware information based on location, traffic, and driving status. For example, it can warn the driver when the car is approaching an accident-prone area as identified from accident statistics.

Cloud computing is expected to play a pivotal role in future automotive telematics services, as illustrated in Figure 7. The automotive cloud services system is an automotive service-oriented software architecture that collaborates with the cloud.[11] Cloud computing is particularly suitable for providing context-aware services to automobiles via real-time analytics. Not surprisingly, Toyota recently announced that it will launch global cloud services for its G-Book telematics services. Soon, your car will be able to send you tweets updating its status and share traffic information with other drivers.

But improved connectivity also raises security risks, which is becoming a central concern in automotive telematics services as well as in-vehicle computing systems.

INCREASING COMPLEXITY

EV drivers need to know the location of charging stations within their driving distance. The Nissan Leaf provides this information through its car navigation system, which identifies reachable charging stations based on the remaining amount of battery and the vehicle's location information, as acquired from telematics services.[12,13] The computer even suggests fuel-efficient driving patterns based on statistics.

Introducing more functions like this will increase the complexity of automotive user interfaces—for example, the number of switches on the steering wheel or dashboard, and the amount of information displayed. This complexity puts a burden on drivers, especially senior citizens. As the population continues to age, this will become a growing concern.

THE FUTURE IS NOW

On 7 and 8 March 2011, just three days before the earthquake in Japan, attendees at a workshop in Nagoya met to discuss the future direction of automotive software engineering (www.nise.org/IAS-ASE-2011). Afterward, a group of workshop participants visited the Toyota Kaikan Museum, a technical showcase located in a suburb of Nagoya. A demonstration of i-unit—a working concept of personal mobility, shown in Figure 8—attracted many visitors.

It is doubtful that automobile exteriors will change to the i-unit level, but we need to reengineer the systems under the hood as our population and climate continue to change.

The automotive industry has become a multidisciplinary field. It was once a mechanical industry, but now it is a computer, software, communication, and power industry as well. With the heavy demand on automotive software to deliver better safety, decreased emissions, improved fuel consumption, full-connectedness, and ease of use, we can expect the size and complexity of software embedded in automobiles to increase exponentially. It is time for software engineers to work together with automotive engineers. ■

Acknowledgments

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