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under the hood

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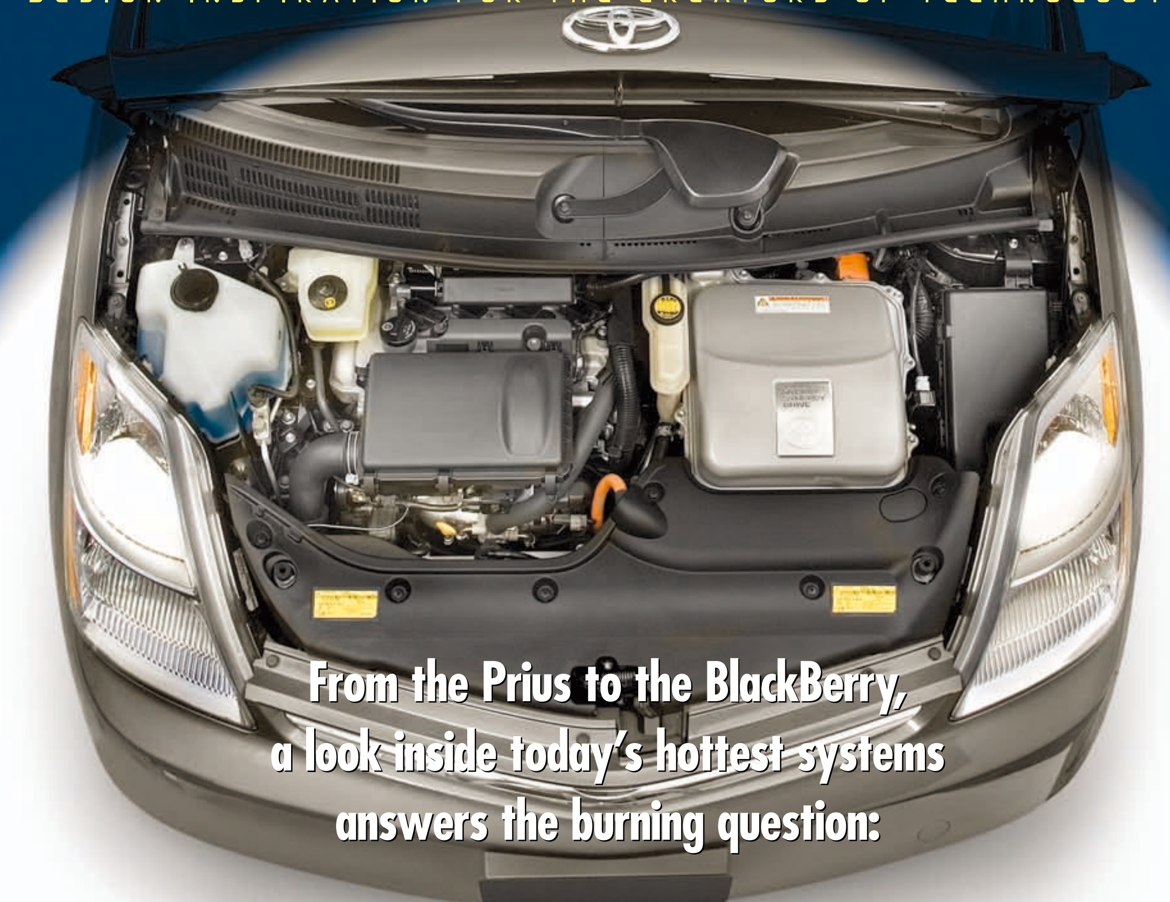
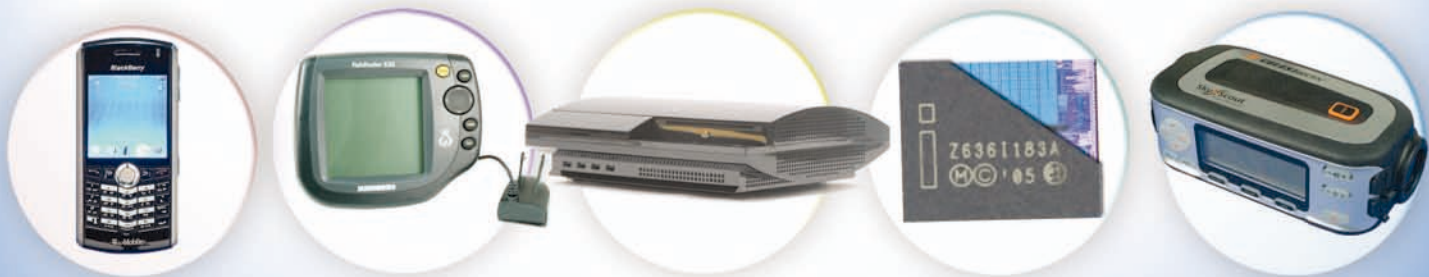


From the Prius to the BlackBerry, a look inside today's hottest systems answers the burning question:

HOW'D THEY DO THAT?



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under the hood

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Tried-and-true design concepts drive Prius

By Al Steier and Rick DeMeis

From energy efficiency to navigation and entertainment to safety, the Toyota Prius hybrid represents the cutting edge of automobile design. So, naturally, we had to buy one and tear it to pieces. What we found was at once expected and surprising. Use this cover feature to find out how to blend proven design techniques and components with the latest in network control, power management, analog and digital design, and consumer electronics.

ONLINE

View the related OnDemand seminar, "Toyota Prius exposed," discussing the design of the skid-control module, airbag controller and the display system, at www.techonline.com/underthehood, search article ID: 199200803

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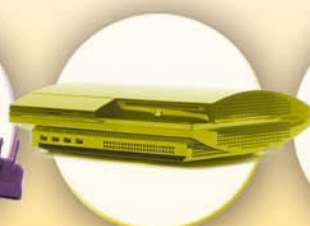
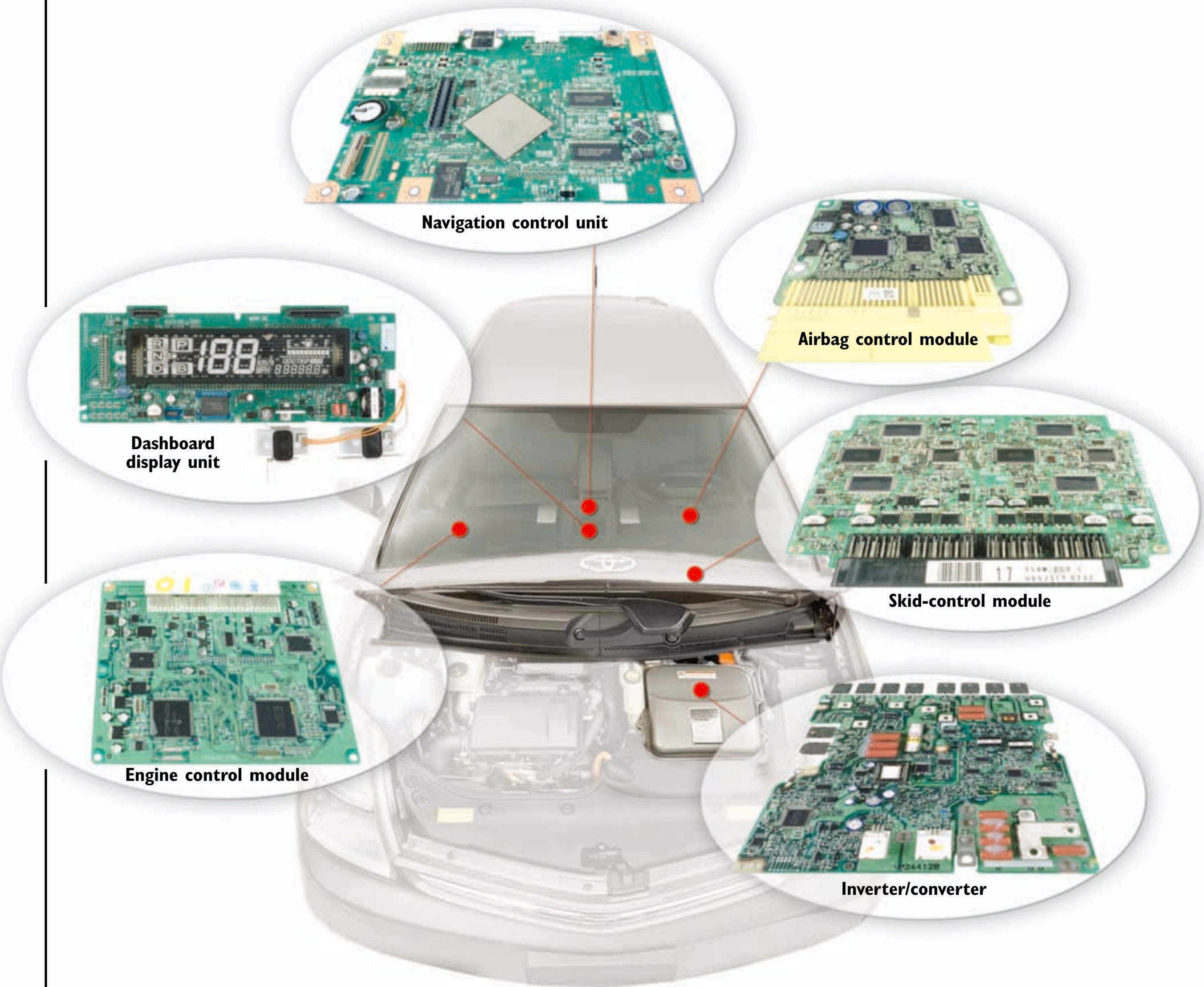




Tried-and-true design concepts drive Prius

By Al Steier
and Rick DeMeis

Upon tearing apart a Toyota Prius—spanking new from the dealer—what strikes an engineer's eye is that this first parallel drive train gas/electric hybrid car is more like other modern vehicles than not. Ignore the large nickel-metal hydride battery tucked out of sight behind the rear seat; filter out the associated starter-motor-like heavy-gage high-voltage orange cables running along the frame to carry current to and from the electric traction motor for power and regenerative braking. Now you have a system that seems "conventional," despite the optimized hybrid-power-train architecture.

The Prius overall appears to follow the Toyota build philosophy: standard modules, bits and pieces—from electronics to doors and other components—that readily fit in place, enabling the same vehicle model to be built to the same quality standard anywhere in the world.

Like any modern vehicle, the Prius packs numerous electronic subsystems. Six, however, stood out: the inverter/converter, the user-interface/dash module, the engine control module, the navigation/display system, the airbag control module and the anti-skid system. The functionality, placement, electronic content and packaging of those subsystems represent the cutting edge not only in terms of technology but also in the context of reliability and power management.

Architecture

The Prius uses a parallel gasoline/electric power train, which means the car can run on electric power alone at low speeds (and shut off the gas engine at stops), accounting for its high city mileage. The architecture incorporates two motor generators mounted within the transaxle. One MG starts the car and recharges the high-voltage nickel metal hydride battery. The other MG boosts the internal-combustion engine's output and, conversely, regeneratively brakes the car to reclaim energy back into the battery and optimize brake effectiveness. Under heavy load, output from the first motor generator is sent to the second, adding to traction power.

When running, the Prius drives similarly to a conventional car but with better low-speed acceleration from the MGs' torque.

Inverter/converter

Obviously, the module of most interest is the one critical in making a hybrid car unique: the inverter/converter. This unit—placed atop the transaxle—is the electrical-system "switching yard," providing voltage control and switching dc to dc, dc to ac (for the motor drive) and ac to dc (to charge the battery with the gasoline engine and during regenerative braking).

The system voltage values that the inverter/converter must handle include 201 V from the NiMH battery and 500 Vac system max for the two motor generators in the transaxle. The circuit board is pressed into a substantial

IN BRIEF

While we were only able to look at a portion of the overall Prius electronics content, the teardown yielded some pretty clear top-level conclusions.

First, the Toyota Prius is a fantastic piece of engineering designed to reduce the financial burden at the pump and to recover energy efficiently. By combining a small gas engine with an electric drive train and regenerative braking, Toyota has successfully targeted consumers looking to lower their "carbon footprint."

From a technical perspective, we found that cautious design was the engineering principle, particularly for mission- and safety-critical subsystems. While component selection, electronics packaging and device complexity all became more state-of-the-art as modules for infotainment were opened up, what's known to work (including 10-year-old microprocessor designs) gets a long lifetime in the Toyota design environment. Embedded memory likewise is preferred for control systems; discrete memory packages appeared in the touchscreen interface and navigation modules alone.

Finally, the teardown brought into stark relief the highly distributed nature of auto electronics. Dozens of MPUs are sprinkled wherever the local needs of electronics demand, communicating over several buses and cooperating to affect vehicle control, power train management, user interface and safety functions.

—David Carey, Portelligent

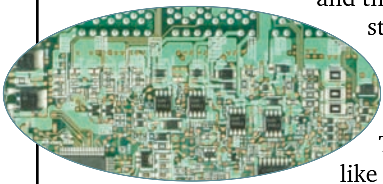
VIDEO

To view a video of this teardown, compressing seven hours into one minute of streaming video, go to www.techonline.com/underthehood, search article ID: 199201709

ALSO ONLINE

Automotive DesignLine editor Rick DeMeis took the Toyota Prius for a real-world drive to see how it performs—and how 'green' it really is. He also compared it with the Toyota Highlander hybrid. Test-drive his findings at *www.automotivedesignline.com,* search article ID: 199200607

Also, to view teardowns of the Prius' skid-control module, airbag controller and dashboard display system, go to *www.techonline.com/underthehood*

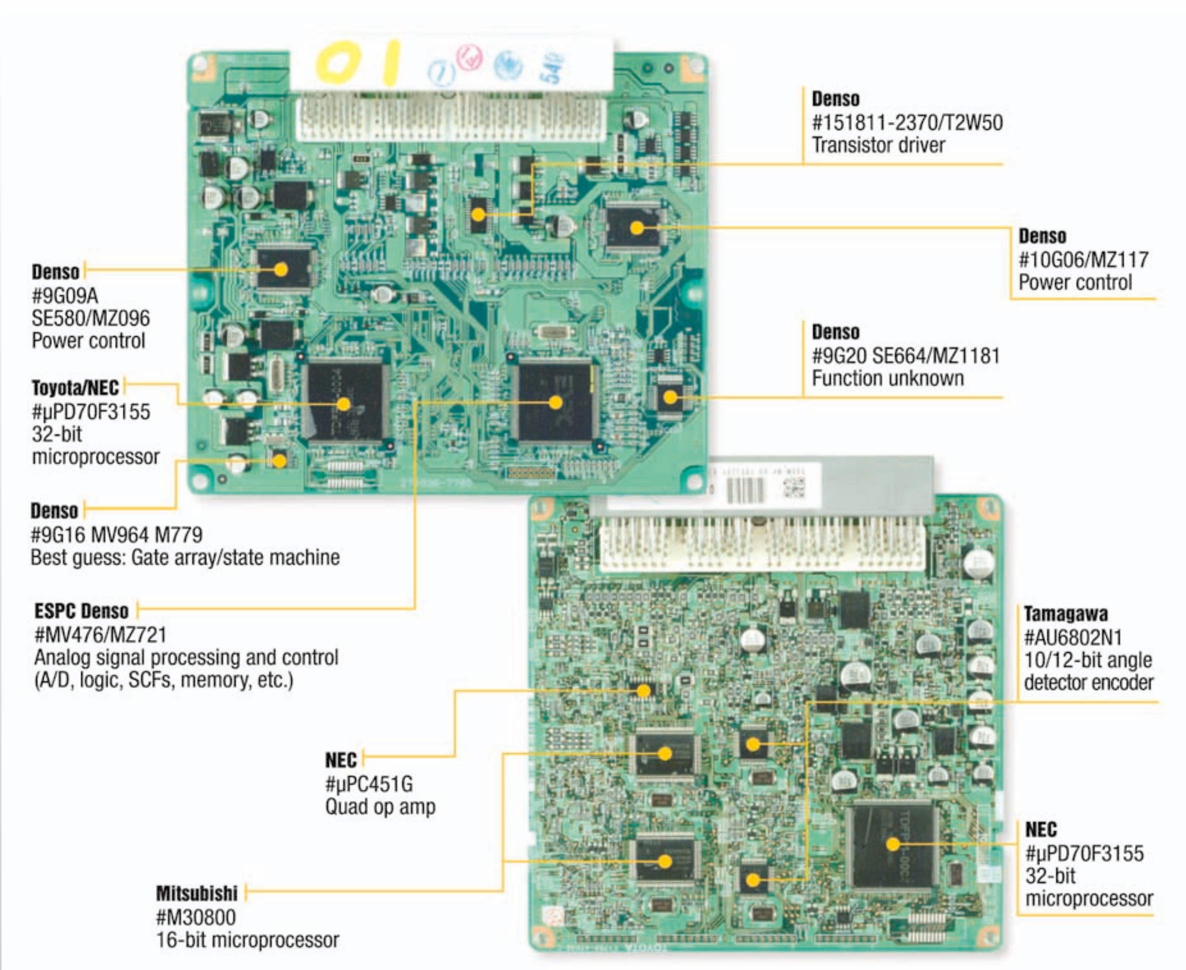


aluminum casting that acts as a heat sink, and the assembly is closed by a stamped steel cover. Within the module are robust relays and bus bars.

Engine control module

The ECM looks and functions much like those in conventional cars when providing gasoline engine control (such as modulating the timing and width of fuel injector pulses) and monitoring engine and emissions sensors (including cam, crank and O_2 sensors). But in a hybrid, it must also interface with other modules, such as the inverter/converter, to allow running on all-electric power at low speeds and to use the gas engine to recharge the battery pack.

Placed under the instrument panel cover, behind the glove box (and attached on a common bracket with the climate control



Controllers keep dual motors humming

Toyota's Prius in many respects can be considered to have two engine controllers: one for the traditional, 1.5-liter gasoline engine and another for the electric motors used to power the car alternatively.

Starting with the petrol-powered side of the equation, the engine control module (ECM) must constantly monitor a number of input sensors to assess the state of the engine and its own primary inputs of fuel, air and fire. Airflow monitoring occurs by way of an optical chopper sensor whose output frequency is proportional to flow rate. An engineered vortex in the intake plenum creates a wake in which a mirrored vane flutters faster or slower depending on airflow, with the vane forming the mirrored reflector of the chopper. An oxy-

>>12

module), the engine control module is difficult to access. Such positioning, however, gets the unit out of the harsh under-hood environment, with its higher temperatures, potential moisture and higher electromagnetic interference. (In addition, since the module is difficult to reach, mechanics may be less inclined to replace this costly component first when troubleshooting problems.)

The Prius drives like a regular car but offers better low-speed acceleration.

Center-stack display

The touchscreen at the top of the center stack is one of two key driver interfaces, along with the interface/dash module. In addition to providing navigation information and input to navigation functions, the display allows control of the audio system and climate control, as well as updating the driver on the status of the hybrid system and in which mode it is running. The latter feature fascinates new hybrid operators—sometimes to the point of distraction—as they try to squeeze out maximum mileage and track which mode they are in by watching the current flows on the schematic.

The navigation system is connected to a DVD player under the driver's seat. The data storage device holds nav system map data that is read in conjunction with the real-time GPS satellite location to yield the guidance information displayed on the screen. The location of the GPS antenna is not obvious; it may be located behind the touchscreen mod-

<< **10 ECM** gen sensor that monitors for proper air/fuel mixture is used as the input to detect either rich or lean conditions. Crankshaft and camshaft position, vehicle speed, throttle position, engine/intake-air temperature, knock detect and other engine conditions are among the additional inputs to the ECM.

Output functions of the ECM are primarily used to affect airflow, fuel injector delivery, intake valve closure angle and spark timing as a means to close the control loop in the engine, maintain optimal power delivery and minimize emissions. Injector solenoids are pulse-width-modulated to control fuel delivery volume and timing. Separately, the spark timing is driven to control detonation precisely. Ignition timing is retarded when the piezoelectric knock sensor input indicates pre-detonation. Further efficiency refinement is achieved by extending the intake valve opening (Atkinson Cycle operation) to reduce displacement effectively, since the intake valves remain open partway into the compression stroke.

The hybrid vehicle engine control unit (HVECU) manages control of the electrical drive plant. Heavy communication with the ECM coordinates the relative contributions of gas power, electric power or, in many cases, the combined efforts of the two systems to provide propulsion.

As with the ECM, the HVECU has its own set of inputs and outputs to implement a closed-loop control system. Much of the HVECU interaction occurs with the two motor generator units of the Prius (MG1 and MG2), which provide drive or recovered energy (the latter during regenerative braking). Here, a motor speed/position sensor in the MG1 and MG2 are used as inputs to the HVECU, along with shift-level position and even accelerator pedal position.

While the inverter/converter unit (ICU) handles all of the electrical conversion in the system, the HVECU is instrumental in the control of the ICU, whose operation is responsible for energy delivery and recovery to and from MG1 and MG2.

The ECM and HVECU share common attributes in their implementation. Although both are housed inside the car cabin, their physical construction reflects an emphasis on reliability, with sturdy housings and protective coatings on the entire circuit board assemblies. The quad flat packs and other peripheral-leaded IC device packaging used throughout both engine control boards boasts a long record of reliability. Without an emphasis on miniaturization, "what we know works" seems to drive technical choices.

The two engine control modules use a common Toyota-branded NEC μPD70F3155 32-bit microprocessor as the primary source of computing power. Neither the ECM nor the HVECU contain discrete memory components; the NEC processor die contains both the volatile working memory and the nonvolatile ROM used to store control code.

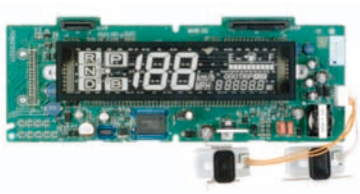
The rest of the ECM components are custom to the module manufacturer, Denso, and most appear visually to implement mixed-signal interfaces at the inputs and outputs where sensors must be digitized and actuators driven.

A more complex set of ICs supports the NEC microprocessor on the HVECU. Two Mitsubishi 16-bit microprocessors are each paired with a Tamagawa AU6802N1 angle encoder and a custom Toshiba analog device, perhaps corresponding to the MG1 and MG2 input interfaces. Another pair of Mitsubishi 16-bit controllers in the HVECU probably manages communications with the ICU, ECM and skid-control module.

Custom Denso and Toyota chips found in the motor control and engine control modules speak to the design's unique requirements for mixed-signal interfaces.

It's also worth noting that the Mitsubishi controllers have die-level copyrights dating back as far as 1995—further evidence of the measured pace of change and conservative design practices found in the mission-critical elements of automotive electronics.

— David Carey



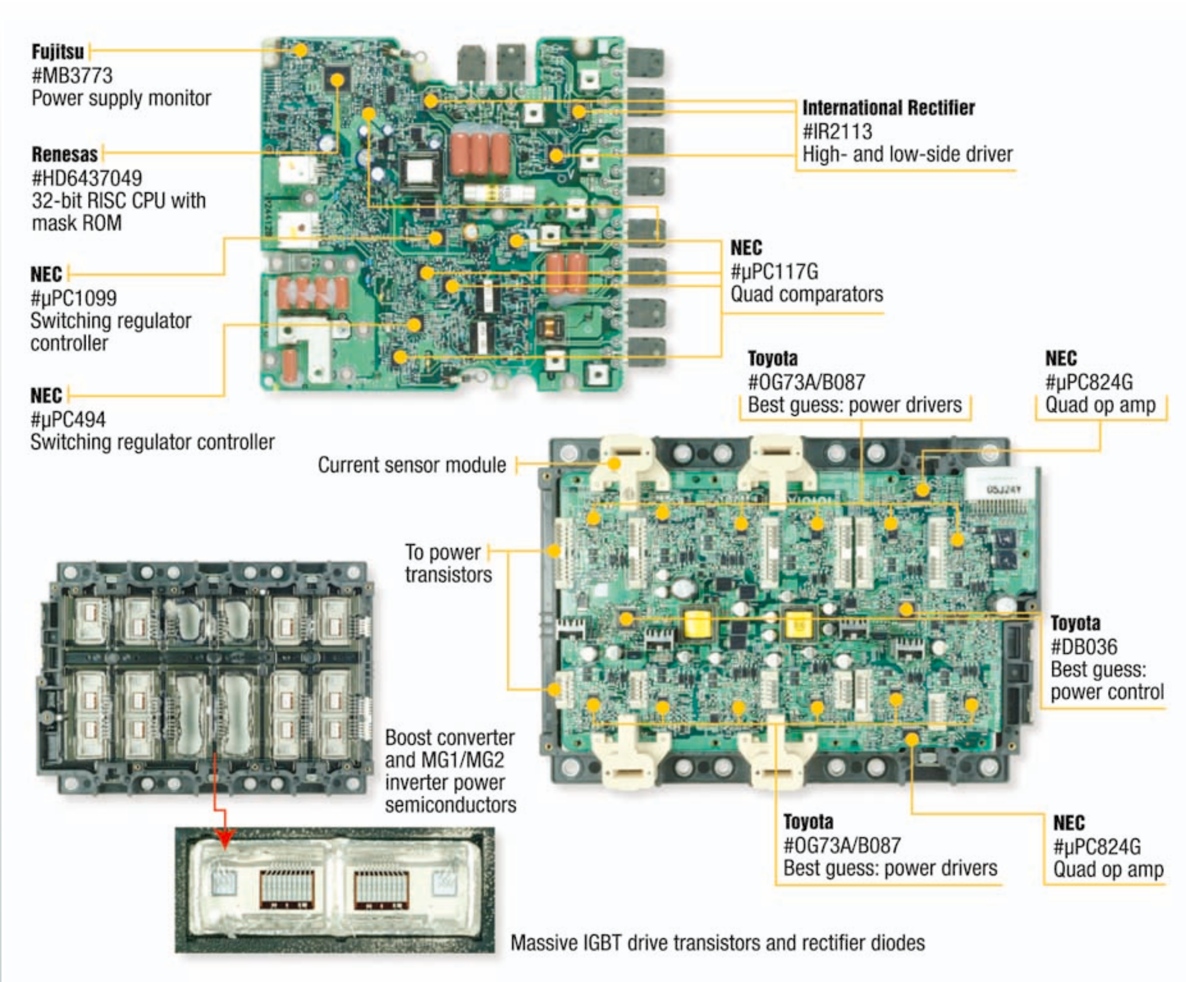
ule to enable a good sky view through the windshield.

The radio is integral to the center stack as well, with control via the touchscreen. The lighting implementation for the radio, however, was not obvious.

All in all, the stack comprises basic, easy-to-assemble technology with few fasteners. That facilitates assembly, which in turn minimizes costs as well as the opportunities for problems (and associated warranty work).

User interface/dash module

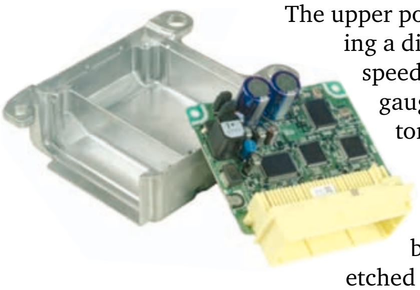
Just below the center windshield is a display module that gives the driver speed and odometer readings; provides gear, turn and high-beam indicators; and contains system status and warning lights. Its location serves as a quasi-heads-up display that comfortably



Inverter/converter: Prius' power broker

The inverter/converter unit (ICU) is the ringmaster of all of the electrical conversion in the Prius. The hybrid's two motor generator units have distinct roles: MG1 recharges the high-voltage (approximately 200-V) nickel metal hydride battery pack located in the rear of the car and also applies direct power to drive the MG2 assembly. MG1 additionally serves as the electric motor used to start the gas engine portion of the power train. MG2 is the primary electric drive motor when energized and performs the reverse function to serve as the power generator during regenerative braking.

Both MG1 and MG2 are permanent-magnet three-phase devices, providing torque when driven by ac power or providing ac output >>16



allows drivers to focus on the road.

The upper portion of the display, comprising a digital electroluminescent speedometer, odometer, fuel gauge and gear position indicator, is separate from the warning and status indicators positioned below. The latter are LED-backlit behind a black polycarbonate laser-etched panel.

On other cars, such a display would usually be one large assembly. Here, the large size of each of the displays (23 x 10 cm for the speedometer cluster and 20 cm wide for the warning lights) probably dictated the dual-display configuration. The two displays are individually prewired and then electrically connected to the vehicle main wiring harness via inline connectors pressed together during the module assembly. Flex circuits serve as the interconnects between the circuit boards and the displays.

Airbag control module

The airbag module governs selective deploy-

<<14 PRIUS ICU when rotated from outside sources (either the gas engine or the wheel rotation during braking).

To create the three-phase power for the motors, the dc battery source must first be stepped from 200 to 500 Vdc via a boost converter. A bank of insulated-gate bipolar transistors (IGBTs) with parallel diodes is mounted in bare-die form to a thermal plate, with connection to an ICU control board by way of feed connectors and ultraheavy-gauge aluminum wedge bonds for power interconnect.

With a boosted dc voltage available, the inverter is responsible for delivering the three-phase power needed in the MG1 and MG2 assemblies when they are used as motors. As in the boost converter, IGBTs are used for power modulation in the inverter. Again, a dedicated assembly plate supporting unpackaged transistor slices is used, with similar interconnect to the same controller board to which the boost converter is linked. The entire transistor/diode array assembly used by the boost converter and inverter is encapsulated in a gooey sea of protective silicone gel. Four of the six legs of the inverter have small current monitor assemblies to keep tabs on power delivery to and from MG1 and MG2.

This same power semiconductor plate used for the inverter supports a set of diodes, again mounted as bare chips, with one diode parallel to each of the IGBTs. The diodes are used during regenerative braking to rectify the ac output of the MG1 and MG2 assemblies so that after filtering and regulation (using the boost converter circuit in reverse), the recovered energy resupplies the high-voltage battery pack.

The Prius also uses an electric air-conditioning compressor motor so that cabin cooling is maintained even when running in electric mode only. A second dc/ac inverter, with circuits located on a second ICU controller circuit board ringed with TO-packaged IGBTs, is deployed to power the electric A/C compressor from the HV battery pack. The A/C inverter IGBT packages are bolted to one face of the substantial heat-sinking enclosure of the ICU. More on that shortly.

Since the Prius still needs a conventional electrical system to operate instrumentation, cabin lighting and the like, the ICU also supports step-down conversion from the 200-V NiMH battery to the 12-V subsystem, where a conventional lead-acid battery is used. Circuits for the dc/dc converter share space on the same circuit board that is believed to house the A/C compressor inverter, and TO-packaged devices are again bolted to the cooling plate of the overall ICU assembly.

The boost converter, MG1 and MG2 inverter, dc/dc converter and A/C compressor inverter all operate under the direction of the hybrid vehicle engine control unit.

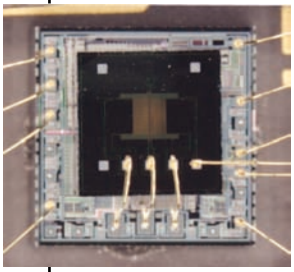
With the large currents involved throughout the ICU, cooling of power semiconductor devices is paramount. The two sets of power components—both bare direct-mount slices and the TO-packaged parts—are mounted back to back on the metal case of the ICU. Heat transfer is achieved by way of a dedicated liquid cooling loop that runs through the ICU casing and is shared with the two MG assemblies.

Semiconductor content is critical in the ICU, but with the exception of a control 32-bit CPU from Renesas (the HD6437049), the IC content largely comprises switcher and inverter control components. An NEC μPC1099 switching regulator controller and NEC μPC494 inverter controller join with Toyota custom power control devices and a number of transistor drivers for implementing the active circuits. Toshiba GT30J324 and Renesas 2SK1517 N-Ch MOSFETs constitute the array of TO-packaged transistors, and Toyota custom IGBTs and diodes are used on the bare-chip power semiconductor plate referenced earlier.

Inductors, transformers, filter capacitors and a host of other passives complete the component set used in this impressive example of power engineering.

Much as the airflow, injectors, spark plugs and valves are the controlled aspects of the gas engine, the dc/ac, ac/dc and dc/dc converters are the managed elements of the electric drive train. Batteries and motors serve as rough parallels to the gas and mechanical pistons of the engine, and by teaming through the ECM and HVECU, the two systems create a fuel-efficient source of power to get you down the road.

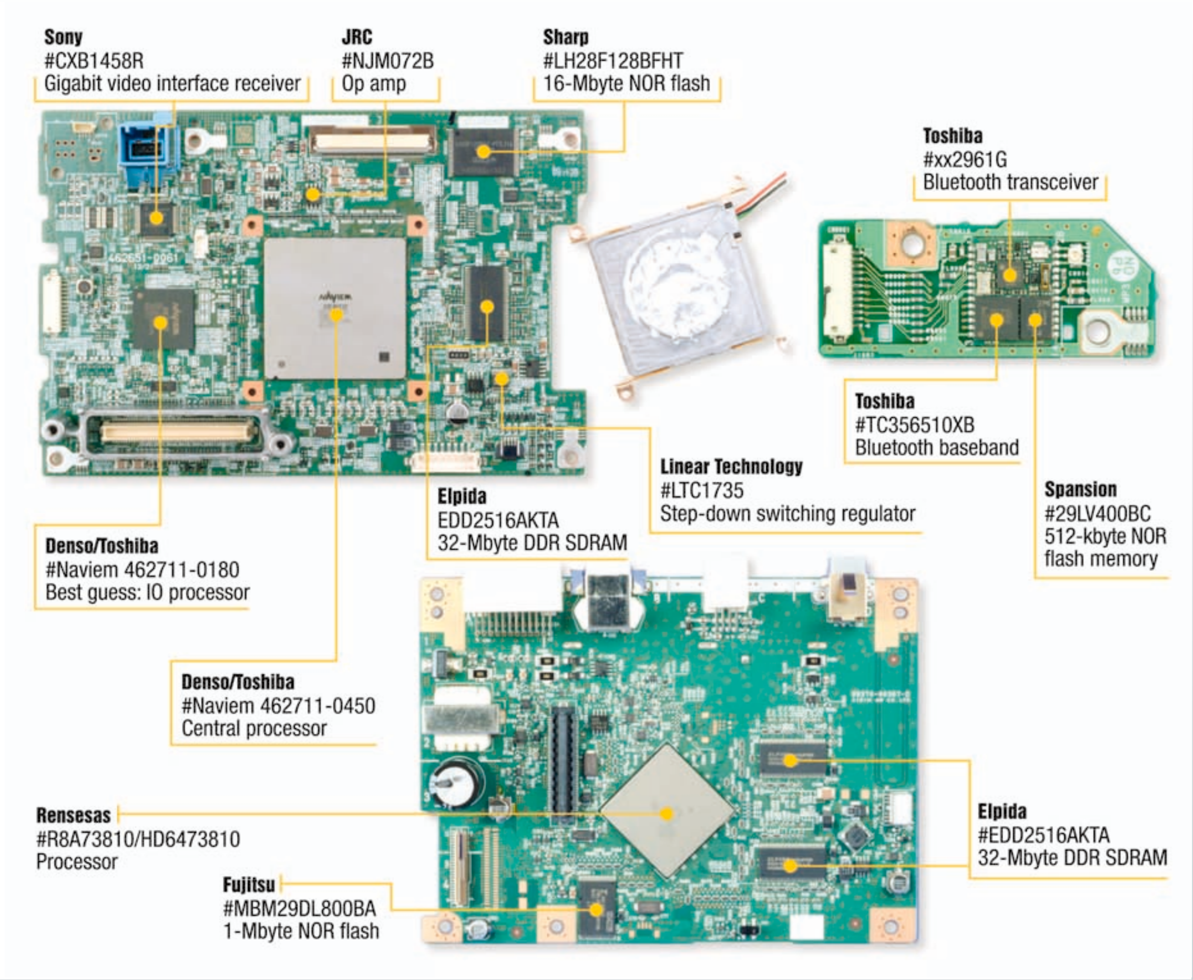
— *David Carey*



ment of the various airbags (front, side, side-curtain and belt pretensioners) in a crash. Inspection of this unit reveals that the front airbags are dual-stage devices with two inflation rates, depending on crash severity.

The module is centrally hard-mounted on a spring steel bracket to the body directly below the instrument panel center stack. Located at the centerline position is a piezoelectric sensor, one of many on the vehicle (such as at the front corners and side pillars) for crash detection. Because this location is right below a set of cup holders, a clear, vinyl-like cover is glued to the module's die-cast aluminum housing to prevent liquid intrusion.

Closer inspection of the airbag control uncovers standard yellow connectors, denoting safety system circuits. All airbag squib-firing circuits have shorting bars to short the



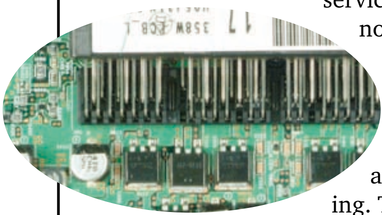
Navigation unit bridges automotive, CE

With increasing frequency, car buyers are spending big for the convenience of in-car navigation. Not unusual for factory-optioned navigation, the Prius' GPS-based mapping and guidance system adds almost $2,000 to the sticker price.

As a practical matter, what the driver perceives as the navigation "system" is really a composition of two distinct subsystems, one the GPS navigation unit itself and the other a visual interface by which the driver can see and interact with mapping functions.

The Prius' visual user interface (VUI) comes by way of a Toshiba liquid-crystal display and associated electronics located middash. The touch-screen LCD panel is an important and standard part of any Prius bought today (it's present even if the >>20

connectors when they are disconnected for service so that an electrostatic discharge cannot fire off a bag.



One of the skid control's main inputs is a yaw sensor, placed toward the rear.

Stability control module

By selectively braking individual wheels, this module mitigates skids and understeer during severe maneuvering. The module is directly above the throttle (gas) pedal. But one of its key inputs is a yaw sensor placed about a foot toward the rear of the car from the airbag module position. This spot is roughly at the center of gravity of the car and determines rotation (yaw) about the vertical axis.

Other inputs to the module include steering wheel angle (driver input), speed, brake inputs and wheel speed (from the antilock-braking system sensors, via the ABS controller).

The stability control module has an unusual two-piece case. One half is a die-cast housing whose chief feature is the many metal "posts" on its surface; they appear to be related to heat rejection. The other half of the case is sheet metal and includes the unit's mounting brackets. But the circuit board inside this case is only attached at the ends to bosses that are placed well away from post-studded areas of the case. Perhaps the housing was adapted from another unit that had more-critical heat issues. The stability control module circuit board has "typical" ICs and passives, with no sensors on the board.

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Rick DeMeis is editor of Techonline's Automotive Designline *(www.automotivedesignline.com)*.

<<18 **NAV UNIT** navigation option is not chosen), serving as the interface for energy monitoring, climate control and car audio. The trend in cars and aircraft today is to migrate much of the traditional gauge and button user interfaces to a centralized "glass cockpit," and the Prius is no exception.

Communication with the engine control module (ECM), hybrid vehicle engine control unit (HVECU) and other convenience control subsystems occurs within the VUI, allowing the touch panel to serve many roles, depending on the selected use mode (activated via the buttons to either side of the LCD). While speed, gear, fuel-level and odometer functions are delivered via a vacuum-fluorescent display (VFD) assembly, the bulk of interaction in the Prius comes through the VUI.

A pair of components based on the multi-OS-capable Naviem partnership between Denso and Toshiba creates the master graphical display and control interface. Joining with the Naviem devices are 32 Mbytes of NOR flash from Sharp and 64 Mbytes of DDR SDRAM from Elpida to create what can be considered the general-purpose compute system responsible for touchscreen and monitoring and command I/O. The VUI box is cooled by a pair of fans, hinting at the processor horsepower within.

Pony up the extra money for the navigation unit (NU), and the MAP/Voice and DEST mode buttons become active alongside the standard VUI mode selects. With the navigation option, a box housing the navigation-specific electronics and accompanying DVD-ROM drive for map data gets installed under the driver's seat at build time. The factory navigation unit supports more than just mapping information, however. Voice recognition allows hands-free address and navigation command entry, and voice prompts provide spoken driving directions, among other functions.

The navigation subsystem is standalone, other than the visual interface. To complete the connection to the VUI for visual aspects of operation, a Sony CXB1457R Gigabit Video Interface transmitter pipes data up to the VUI for display. A corresponding Sony CXB1458R Gigabit Video Interface receiver is found within the VUI box to bring in navigation unit information for that.

A GPS antenna installed under the dash cover is positioned to allow line of sight to GPS satellites through the front windshield, and a coax cable then snakes its way back to the under-seat navigation box. The RF front end for GPS constitutes quite a small portion of the navigation electronics, based here on a Panasonic AN18401A downconverter to get to a de-modulated GPS input signal. From there, a sizable Renesas HD6473810 processor is responsible for all of the GPS baseband work needed to calculate the present position for joining with local mapping data. But GPS data crunching is only part of the required processor function, since all of the voice recognition and voice prompting are also done in the NU.

Within the NU, 96 Mbytes of total DDR SDRAM is found spread across three 32-Mbyte Elpida chips, and 1 Mbyte of Spansion NOR flash serves for local code store. Both the NU and VUI are among the few modules in the Prius that use sizable stores of discrete memory. Likewise, IC packaging steps up to high-pin-count BGA devices from the QFP packaging found in the more conservatively designed modules.

The mix of cabin-internal use environments, more-modern design and less-mission-critical attributes for the NU and VUI probably contributes to the latter's closer engineering resemblance to traditional consumer electronics (CE). Indeed, it is in infotainment where we see much of the growth in automotive electronics and convergence with the gadgetry we're accustomed to seeing outside the car.

— *David Carey*