Virtualization Coming to Autos

One Processor, Multiple Operating Systems

For the last couple of years carmakers and tier-one suppliers have been researching the feasibility of using hardware virtualization technology as a way to run multiple software applications and multiple operating systems side-by-side on one single- or multi-core processor. The most obvious benefit would be integration—eliminating one or more processors from an ECU or consolidating multiple ECUs into one.

A second important benefit is maintaining a higher level of security for vehicle systems. The outside world is kept separate from the vehicle by means of a microkernel (also called a separation kernel), which operates as an intermediary between the applications and the microprocessor itself.

Integration enabled by virtualization while maintaining safe separation between applications of varying criticality

At least one carmaker has completed its research and is headed to production with a virtualization implementation that combines a Linux and an AUTOSAR solution on a single chip. “We actually go into series mass production in the second quarter of 2013 with our virtualization solution,” said OpenSynergy’s general manager, Stefaan Sonck Thiebaut.

In this telematics solution, Linux is used to talk to the outside world; AUTOSAR talks to the vehicle. Because it needs to be able to immediately link to the vehicle’s CAN network, the AUTOSAR part must boot up in just a few hundred milliseconds, even though it’s running on the same processor as Linux, which takes longer to boot up. The carmaker reduces system complexity and saves cost by using one chip instead of two.

“Five years ago, we were the first company to suggest using virtualization and microkernel technology to solve some critical automotive problems,” said Mr. Thiebaut. “Back in 2007 we had to do a lot of evangelizing, but now carmakers and tier ones looking for a virtualization solution are contacting us regularly.”

OpenSynergy, based in Berlin, Germany, is presently working on eight or nine automotive virtualization projects including some proof-of-concept projects. Before coming to OpenSynergy, Mr. Thiebaut worked at Carmeq, the engineering services subsidiary of Volkswagen Group.

Virtualization software for non-automotive markets where the technology is already mainstream accounts for 20% of Green Hills Software’s revenues. “Every data center on planet Earth has it,” said Dave Kleidermacher, the company’s chief technical officer. “Eventually every car made will benefit from virtualization. … Carmakers have been kicking the tires on virtualization for a couple of years. Now we have begun to see requests for proposals from companies who make virtualization part of their requirements.”

Gordon Jones, vice president and general manager for the Integrity® Secure Virtualization products at Green Hills,
Virtualization...

With future vehicles linked increasingly to cloud services, Mr. Walkembach believes that security needs to be a core issue, every bit as important to the vehicle as quality. “It is not just about one component, or one ECU or the IVI system. What’s needed is a complete security solution for the whole car,” he cautioned.

According to Green Hills Software’s Mr. Kleidermacher, “Hypervisor is a general term for anything that can host a virtual machine, whereas a separation-kernel-based [or microkernel] solution is a specific type of hypervisor.”

Seeing an analogy to the universal adoption of virtualization in the server world, Mr. Kleidermacher believes that in ten years virtualization will be ubiquitous in the auto industry as well.

“Virtualization for servers started coming out in the year 2000. But it didn’t really pick up steam and take over until Intel VT came out. Intel VT is the hardware acceleration for virtualization that hypervisors like ours use. Well suited to cars, Intel’s Atom processor now has Intel VT. ARM also has something very similar to VT called ARM VE (virtualization extension).”

Security

Wind River delivers virtualization using its hypervisor, which sits atop a board support package, the basic software the processor needs to run, explained Franz Walkembach, senior product manager of automotive solutions at Wind River. “On top of the hypervisor we can run full operating systems, so a full Android stack with its own software kernel, a full VxWorks real-time OS stack, which has its own kernel, as well as an AUTOSAR stack in a third partition, for example.

“You transfer messages between operating systems through the hypervisor. If information is coming from a partition that is trusted, then the hypervisor directly passes it through. But if the information comes from an untrusted partition, then the hypervisor can block it,” he said.

Wind River’s hypervisor has just 6,000 lines of code and requires a memory footprint of only a couple of thousand kilobytes.

Mr. Walkembach believes that hypervisors will play a role in maintaining the vehicle’s security from hackers and unknown Internet sources. He envisions infotainment system partitions based on threat.

For example, one partition could be reserved for use cases that are the least trustworthy such as third party applications: “In the no-trust partition, where consumer-type functions can be downloaded, you might run an Android-based, fully open-source operating system. In the fully trusted partition you can run an AUTOSAR or CAN stack that’s linked to the vehicle’s safety features, which must run on their own without any lockdown or stopping.

“In another partition you can run a real-time OS such as Wind River VxWorks to run the other OEM and tier-one applications.”

Infotainment Consolidation

Most of the requirements for virtualization are coming from engineers working in the infotainment domain, where connectivity and safety features as well as drivers for the center-stack, cluster and head-up displays, are increasingly being consolidated.

Virtualization can provide certifiably safe separation as safety systems are placed side by side with low-risk systems, or open-source software is run alongside legacy software. Telematics systems that access vehicle networks, for example for remote diagnostics or to lock or unlock doors, can safely run alongside commercial apps and Internet-based features such as music streaming.

“Multiple things are driving virtualization in automotive,” pointed out Green Hills vice president of business development, Dan Mender, “including improved processor performance and capability. The acceptance of open-source code by the auto industry is another factor, as is the demand for consumer electronics functionality in the car. Carmakers want to provide it, but these applications must perform competently and not be at all distracting to drivers. They are mixing risk criticality and they don’t want software code that they didn’t write and don’t trust accessing critical areas of the vehicle.”

To provide safety and security, the virtualization software controls what messages can be sent and where according to how the systems are partitioned.

Benefits and Use Cases of Integration via Virtualization

◆ Partitioning of infotainment system
◆ Enabling fast boots for the backup camera and cluster
◆ Consolidation of cluster, HUD and center stack electronics
◆ Reuse: run legacy OS with Linux, Android, Genivi, Windows or QNX operating systems on the same chip
◆ Maintain unified architecture from low-to high-end model lineup while scaling up processors and adding other operating systems

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research firm GiK found that 94% of respondents agreed that HUDs make the driving experience more pleasurable and 95% of them would recommend HUDs to a friend. The BMW HUDs are windshield types. Forty-one percent of respondents said the lack of a HUD feature would negatively impact the choice of their next vehicle.

Besides making driving more comfortable, head-up displays make driving safer. “HUDs are all about keeping eyes on the road,” said Ray Kiefer, General Motors Technical Fellow for crash avoidance systems. “In tests we found that looking at a digital speedometer projected on a HUD saves about 130 milliseconds compared with its head down location in the instrument cluster. HUDs help avoid rear-end crashes, which account for about 30% of all crashes.” One of the first carmakers to put HUDs into production, GM already offers HUDs on six models—Camaro, Corvette, Cadillac XTS, Cadillac ATS, GMC Acadia and Buick LaCrosse—with many more in the pipeline.

Head-up displays are available from nine carmakers today and by 2016 will be offered by 14. Because they are costly they are almost always associated with luxury and near luxury vehicles. At the OE level, HUDs range in price from $150 to $250 each, not including the extra cost of the windshield, which must be modified to accommodate the windshield HUD. “The windshield gets a special inner layer to wind the HUD. The bigger the telescope the better the view you are going to get. It’s best to avoid designing too much magnification into the HUD unit, as the inconsistencies and complex curvatures of the windshield will begin to play a bigger role in the optical system.”

Lasers
HUD developers have been considering a number of substitute display technologies to see what might take HUDs to the next generation—laser, digital micro-mirror device (DMD) and liquid crystal on silicon (LCOS) technologies. Among these options laser-based technology seems to be getting the most attention.

Delphi, which has been in and out of the HUD business twice since the late 1980s, says it is developing laser-based, full-color HUDs that will be ready in time for the 2017 model year. “Laser projection gives you a bigger display, so you can put more information up on the windscreen,” said Glen DeVos, vice president of engineering for Delphi Electronics and Safety. “You get brighter images without generating a lot of heat. And you can simplify the optics, which reduces the size of the HUD package.”

Delphi is pursuing two laser-based approaches. “Digital light processing (DLP) lasers actually scan every pixel within the frame one line at a time. We are also looking at vector technology where, rather than scanning the whole rectangle, the laser draws only the images, as though you are drawing with a pen. The advantage to that is you can get much higher [light] intensity and it is faster because you are not scanning as many pixels,” explained Mr. DeVos. Delphi has prototypes of its laser projectors in the lab and plans to have vehicle-based HUD demonstrators within 12 months. Among the challenges that must be overcome with lasers is their lack of robustness in high and low temperatures and a tendency to produce images that are speckled with dots.

Continental’s Mr. Richter isn’t so keen on laser technology, because of the speckling problem and because “the color green has too limited a lifetime for an automotive solution. Rather, digital micro-mirror device technology is the best way to achieve increased image size,” he said.

Augmented Reality
If larger HUD images were feasible, carmakers could use HUDs to implement augmented reality concepts that overlay the driver’s view of the road ahead with images that support safe driving. For ex-
The Company Profile... ESG Group

ESG Group
Headquarters: Frankfurter Ring 211, 80807 Munich, Germany; Phone: 49 (89) 92 16-0; www.esg.de
2011 Sales: €237.5 million
R&D Expenditures: 16% of sales
Regions Supported: U.S., France, Germany and China
Employees: 1,452 at year end 2011
Sales per Employee: €135,830
Products: Engineering services, process and technology consulting primarily for the automotive and aerospace industries

2011 Automotive Sales: €92.5 million
Automotive Sales by Product: Embedded E/E system development, integration and test, 67%; IT system development and test, 33%
2011 Automotive R&D: 1.6% of sales
Automotive Employees: 681 as of year end 2011; 786 at present
2011 Automotive Sales per Employee: €135,830

ESG's expansion into the automotive market accelerated in 1998, when many carmakers lacked the expertise and resources to develop and integrate increasingly complex vehicle software and electronics systems.

Automotive Business
Since 2007, ESG's automotive sales have been growing at just over 7% per year. The company expects automotive sales to increase by at least 10% per year over the next five year period, a few percentage points better than expected growth of the market it serves.

In order to better leverage international growth, since January 2012 the automotive business is organized as a global division of ESG. The global automotive division is headed by Hans-Georg Frischkorn, who joined ESG in January 2012, and Robert Morgner, who has been part of the automotive leadership since 2006.

Mr. Frischkorn brings a wealth of experience in automotive electronics and software. As a computer scientist, he spent 17 years with IBM in software development and marketing to automotive customers. After two years as a consultant with McKinsey & Co., Mr. Frischkorn went to BMW for the next nine years, becoming senior vice president for systems architecture and integration. During that time he was instrumental in founding both the AUTOSAR and FlexRay standards and was a strong proponent of top-down systems engineering.

In 2006, he became the executive director of global electrical systems, controls and software at General Motors, where he served for five years. Just prior to joining ESG, Mr. Frischkorn was managing director of technology and environment for the VDA in Germany, responsible for research, engineering, logistics, quality and electric vehicles.

"I knew ESG from my years at BMW," Mr. Frischkorn said. "I thought even at the time it was a great company, develop-
ing technological innovations that provided additional customer value especially in software intensive contact systems.” Mr. Frischkorn also employed ESG’s services on behalf of General Motors.

ESG is proud of its proven ability to set up shop quickly in a new country to serve local customers, as it has done in France, China and the United States. In 2008, ESG had a small operation in the U.S. with 10-15 German engineers working on some small BMW projects. That year the company won a contract to develop the 12-volt electrical system for the Fisker Karma range-extended plug-in EV.

Steve Polakowski was recruited from Magna International in 2009 to head the expanding U.S. operations. In 2010, ESG acquired Automotive System Integrators (ASI), a specialist in E/E systems engineering with roughly twice as many employees as ESG had in the U.S.

Mr. Polakowski, president of ESG Automotive in Troy, Michigan, has approximately 140 employees in the U.S. facility and co-located with customers. Globally, 90% of ESG staff are employed at customers’ facilities.

“Our average experience level is eight to ten years. We have very knowledgeable people; they know vehicle systems, on top of the fundamental E/E sciences,” Mr. Polakowski noted.

ESG Group has developed an engineering staff that brings a mix of computer science, electrical/electronics and some mechanical engineering backgrounds. Mr. Frischkorn describes them as “highly qualified, passionate about innovative technology and able to work with state of the art development tools and processes.” Most have Master’s degrees or the equivalent but the staff also includes some Ph.D. level experts. Engineers from both the automotive and aerospace divisions frequently work together on in-house research or customers’ projects, when the need arises. For large, complex projects ESG may employ a peer review process, where the lead engineering team will present its work in progress to other experts and project leaders within the company whose feedback or new ideas could benefit the project.

In the next three to five years, ESG will be looking to further expand its footprint, specifically in Korea and India. Mr. Frischkorn noted, however, that in Asia, employing outside engineering service providers is not yet a widely accepted practice among carmakers. In May 2012, ESG established a wholly owned subsidiary company in Shanghai.

ESG Strengths

“Our strength is understanding what an OEM wants to get done and helping them develop customized solutions to meet their specific challenges and needs. We are not about off-the-shelf products or services, but about customer-specific solutions,” stated Mr. Frischkorn.

◆ Technology Transfer

As head of ESG’s automotive business, Mr. Frischkorn has some blunt advice for the automotive industry as it moves from a component-oriented development paradigm toward true systems engineering in all vehicle domains: “Do it faster.” ESG has more than 40 years of experience working with the aerospace industry in highly complex, safety-critical systems development and integration. One of the company’s core strengths is the ability to leverage that experience in the automotive market.

Despite a spotty industry record of successful transfers of technology from aerospace to automotive, Mr. Frischkorn continued on following page
ESG Group

pointed out that rather than thinking in terms of transferring individual components or technologies, the likelihood of success is far greater for transferring not only systems engineering expertise, but also architectural concepts and processes. He suggested the example of the highly successful drone programs underway in aviation as a possible source of technology for autonomous vehicle programs. “The individual sensors or actuators the drones use are not relevant for technology transfer. But if you look at the architecture, how you do mission control for such vehicles from an architectural viewpoint, then I think the transfer becomes very, very relevant.”

Mr. Polakowski noted that ESG is also bringing its aerospace experience in head up displays and HMI to automotive solutions. He is seeing more automotive HUD project proposals after a several-year lull, and ESG currently is working on HUDs for two external clients.

“HMI is huge, probably foremost on every OE’s mind right now,” Mr. Polakowski said. “They are asking how to minimize driver distraction and put the right information in the right place at the right time. Think of the volume of information being presented to a pilot. There is some exciting technology and work being done in aerospace that has a great transferability to the automotive side.” ESG is working on project proposals to determine the cognitive effectiveness of HMI design.

In addition to working with app developers and service providers to adapt their functions for the vehicle, ESG provides personalization of graphical user interfaces, customizing how information is presented on infotainment systems, for instance, menu structures. ESG also performs device interoperability testing.

◆ Innovation
Separate from client engagements, ESG aerospace and automotive divisions work jointly on R&D projects to not only improve the company’s skills and know-how, but also to look at areas where a technology transfer may be possible, or where jointly developed projects might serve both industries. One example of that type of project was an integrated modular architecture that would be relevant in both automotive and aerospace. Another research project created a prototype high-bandwidth camera system.

Architecture
David Brodie, manager of systems engineering, shed more light on ESG’s architecture development programs. “We have our own roadmap. A year and a half ago we put out our vision of the move toward autonomous driving — what would a vehicle architecture for autonomous driving look like if we designed it from scratch? The problem today is vehicles are built by mechanical engineers who focus on individual subsystems, for instance adaptive cruise control or a rearview camera. That results in a set of parallel, vertically integrated systems. You have multiple systems doing the same job, maybe analyzing the same data. In an all-new architecture, sensor fusion and integration would play a bigger part. We would use information from all the sensors to build a model of the environment for the vehicle. We are working now on a conceptual framework from which we can make new service offerings or architecture offerings.”

Mr. Frischkorn has long been a proponent of domain architecture, where multiple ECUs can be replaced by three to five centralized domain controllers, at least a chassis controller, a body controller and one powertrain controller.

Infotainment is another domain; safety might be separate or part of the chassis domain. Vehicle domains could ultimately be linked through an Ethernet backbone, initially complemented by CAN and LIN networks.

Driver Assistance
ESG is currently working on an innovation project focused on online calibration of cameras for driver assistance systems. ESG describes online calibration as “fully automatic establishment of the camera’s orientation in terms of the vehicle.” Typically, vehicle-mounted cameras are calibrated when the car is still on the production line, but over time and with usage, the cameras can become misaligned.

Mr. Brodie explained that rather than using road markings to recalibrate the orientation, as some systems on the market do, ESG developed an algorithm based on a concept called structure from motion, which analyzes a sequence of images of a fixed object in the environment to determine the position of the camera relative to the vehicle. ESG has developed a prototype product and is in active discussions to bring the software to market.

Connectivity—New Architecture Is Needed
While Genivi is an important initiative in developing infotainment standards, Mr. Frischkorn noted, “The
industry is lacking architecture for the connected space. How does the vehicle talk to its environment, to other vehicles, to the infrastructure, to the telematics world? There we are still in almost an architectural chaos. ... A lot of the headache in the industry is about managing the complexity that results from looking only at the car, instead of looking at the car as it is linked to its environment.”

He believes much work remains to be done in the area of developing connectivity standards beyond data transmission protocols such as CAN, FlexRay or Ethernet. “In the classic telematics world, for example, we have an understanding of which protocols to use to transmit information about a traffic jam, but that is only a small part of the information,” he said. There are no standards for delivering information about phases of traffic lights, or public transportation schedules or airport delays, for instance.

To solve the challenges of the truly connected car—one connected to a telematics backbone, to the world of services, to other vehicles and the infrastructure—Mr. Frischkorn said the industry needs to move to cloud architecture because it addresses service-based architecture. “A service like ‘tell me more about the traffic situation’ will become a service request to the cloud. In a service-based architecture, you standardize not on the level of bus protocols or data items, but on standardized functions or requests or services,” he explained. “This is about what abstraction layer you want to standardize. The more abstract you get in your definition of data, the more you go to what we’re calling here a service-based architecture.”

See the graphic on page 6 for a description of the evolutionary development of vehicle architectures.

E-Mobility

When ESG acquired ASI in 2010, much of ASI’s electrical systems integration business was with Chrysler. The founders and management of ASI, Bob George, Aneil Shah and Gary Aldrich, are all former Chrysler EE.

“ASI was working on a variety of projects for Chrysler, from requirements to test services, design release functions and test and verification. That gave us a big foothold at Chrysler,” said Mr. Polakowski.

ESG Automotive Inc. is providing electrical system integration, adaptation and test services for a small Chrysler program to develop an all-electric version of the Fiat 500. ESG is working on both the 12-volt side and the high voltage wiring. Approximately 19 ESG engineers have been on the program with Chrysler in Auburn Hills.

“We also have a lot of business with battery makers. We are working with four of the lithium-ion battery suppliers in North America,” said Mr. Polakowski. “We have done work on everything from functional safety and high-voltage wire harness design, to BMW (battery management system) testing and high-voltage training. And we’ve done work for drive motor controls and algorithm development for a couple of different start-ups.”

ESG provided electrical system development work for the Fisker Karma, beginning in 2008, and is still engaged with the carmaker. After its well-publicized battery problems, the Karma was recently criticized again by Consumer Reports magazine for, among other things, intermittent glitches related to gauges, warning lights, power windows and radio. “These are issues and improvements the component suppliers are working on,” Mr. Polakowski replied. “We are supporting Fisker as the systems and diagnostics group, doing what the OE would do on the architecture side and certain requirements specifications.”

Processes and Tools

ESC supports its customers in designing, optimizing and documenting their development processes using industry standards such as CMMI (Capability Maturity Model Integration), Automotive SPICE or V-Model XT.

“While CMMI is not total systems engineering, I believe it is a good base. It addresses most of the key process areas that are important to systems engineering,” Mr. Frischkorn said. “Doing true requirements management and requirements engineering is the start of that process. Keeping requirements up to date over the life of the product, ensuring traceability from system to subsystem to component requirements, traceability from requirements to test execution and tracking test results—I think that is very, very important.”

ESG has longstanding, successful working relationships with automotive OEMs who view it as a classic engineering support company, capable of providing reliable project management and testing services. But Mr. Brodie wants to be certain that customers such as BMW also recognize the full range of ESG’s expertise: “We want to provide our customers the competencies other engineering services companies don’t have: architectural knowledge, functional knowledge about ADAS, functional knowledge about domain platform architectures that we have in our aviation division. I would love them to see us as an innovator.”

The Company Profile Continued

ESG Automotive Customers

| #1 BMW | Nissan | Autoliv |
| #2 GM/Opel | Porsche | Borg Warner |
| #3 Volkswagen Group | PSA Peugeot Citroën | Bosch |
| #4 Chrysler | Renault | Cobasys |
| Other OEMs | RUF Automobile | Continental |
| (Alphabetically) | Saab | Delphi |
| DAF Trucks | Smart | Denso |
| Daimler | Volvo | Gentex |
| Fisker | Suppliers | Harman |
| Ford | (Alphabetically) | Hella |
| Jaguar | A123 | Johnson Controls |

ESG Memberships

- AUTOSAR
- Car2Car Consortium (C2C)
- FlexRay Consortium
- GENIVI Alliance
- ISO Group
- System@tic
As of January 1, 2012, Dice Electronics became a strategic partner of Audiovox Electronics Corp., a wholly owned subsidiary of VOXX International. With the new partnership Audiovox received exclusive, global distribution rights to Dice Electronics’ branded aftermarket products, which now go by the brand name Audiovox Driven by Dice.

According to Mr. Witt, a key advantage Dice has in the smartphone integration market is the flexible, robust, software-driven architecture on which it builds its kits, such as the top of the line MediaBridge. Another is its custom-designed, proprietary chipset supplied by Rohm Semiconductor and Micro Analog. “Because the hardware is software-controlled,” Mr. Witt said, “Dice can adapt quickly to any of the changes that may be driven by Apple releasing a new iOS, for example, or Bluetooth being updated by the Bluetooth SIG. Our core intellectual know-how is this software.”

Three days after the introduction of iPhone 5, Dice announced its products’ compatibility with the new phones and iOS 6. In August, Dice completed a firmware update to MediaBridge that enabled full integration of Apple’s Siri voice interface with OEM-installed radios in cars without Bluetooth. The company also offers a Siri integration platform for cars already Bluetooth-equipped. “When we did our Siri announcement we had four car companies, who were not in the original nine that were publicized by Apple, call us within 24 hours. We’re doing feasibility studies for three of them,” Mr. Witt said.

While Dice Electronics is a very small company with only eight engineers, it claims to offer OEMs an affordable alternative to traditional Tier-one solutions for device integration, which take far more time to develop and implement.

Dice’s MediaBridge module platform, at $200 (factory cost in low unit volumes), provides full USB digital audio and USB command and control. According to Mr. Witt, the module includes Bluetooth for Handsfree profile, Bluetooth A2DP (Advanced Audio Distribution Profile) for audio streaming and Bluetooth AVRCP (Audio/Video Remote Control Profile) for command and control. MediaBridge does not support video but displays text metadata on whatever display is available in the car. MediaBridge is compatible with select models of Acura, Audi, BMW, Honda, Infiniti, Lexus, Mini, Nissan, Scion, Toyota and Volkswagen vehicles. Dice Electronics can be port-, dealer- or factory-installed or purchased through the aftermarket. The aftermarket version retail price is $300.

Dice also offers an analog, non-USB platform at $150 (factory), and a platform that uses FM modulation to get into the audio system. More detailed information is available from Steve Witt, who can be reached at switt@diceelectronics.com or (562) 275-8849. ◆

HUDs...

ample, in fog, the unseen edge of the road could be highlighted. Or the turn-by-turn direction could be superimposed on the scene.

“Augmented reality could mean placing a warning on top of reality,” explained Kenneth Murphy, a senior engineering manager at Nippon Seiki. “Imagine a pedestrian stepping in front of your vehicle. Instead of putting the warning in the same place every time in the cluster, the augmented reality warning would appear above the actual pedestrian.”

The appeal of “next-generation, head-up displays that combine night vision, navigation, and sensor-based technologies to allow a driver to view information such as virtual road lines in foggy conditions, highlighting of barely visible pedestrians or objects, and speed limit warnings,” was confirmed this past April by a J.D. Power and Associates study that surveyed 17,400 vehicle owners to measure interest and purchasing intent for 18 new features. Sixty-nine percent of respondents said they would “definitely” or “probably” purchase next-generation head-up displays with their next vehicle. Next-generation head-up displays came in third. Though when respondents learned that the price of such a feature was $1,300, the feature dropped to twelfth place with only 29% saying they would definitely or probably purchase the feature.

 “[Current generation] HUD sales are going to pick up,” said Denso’s Mr. Patton. “In the past it was a gadget, not a necessary device. HUDs are becoming an integral part of the HMI package, along with the other visual displays, haptics and voice and gesture recognition.” ◆