RUGGED BY DESIGN:

Engineering automated driving systems for safety

White Paper by:

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Modern autonomous vehicle system designs benefit from reliable, safety-critical electronics built on proven, trusted military and aerospace systems engineering standards and practices.

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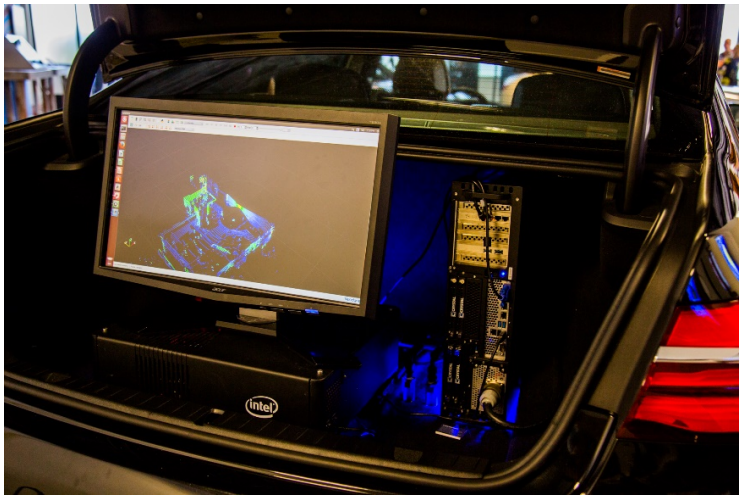
Autonomous vehicles (AVs) including fast-growing fleets of self-driving cars and trucks are poised to revolutionize transportation. The global automotive industry is on the cusp of significant change, enabled by innovative automated driving system (ADS) and autonomous vehicle (AV) technologies in a fast-growing market estimated to reach $7 trillion by 2050; yet, widespread deployment hinges almost entirely on safety.

A single ADS mishap can have far-reaching implications, adversely affecting the acceptance and adoption of autonomous vehicles worldwide. Destruction of property and loss of life caused by any manner of ADS failure will not be tolerated by the public, regulatory bodies, transportation officials, or lawmakers – all of whom seek assurances from automotive manufacturers that the vehicles, including all essential systems, can be trusted to perform reliably no matter what they might encounter on the road.

Predictable, repeatable performance over time is integral to safety, which in turn builds trust. A single unfortunate event could slow, set back, or even bring an abrupt end to the advancement, adoption, and acceptance of autonomous driving systems and threaten the entire, global autonomous vehicle industry. Automated driving system failures are not an option and must be avoided, using systems specifically designed to be durable, offer high availability, and perform reliably in various operational environments throughout their life cycle.

ADS ANATOMY

“The amount of technology required to bring fully driverless vehicles is staggering,” Intel CEO Brian Krzanich admits. “Vehicles require sensors to pick up lidar, sonar, radar, and optical signals; hubs to gather millions of data points; in-car microprocessors and high-speed connectivity to capture, process, and transport data.”

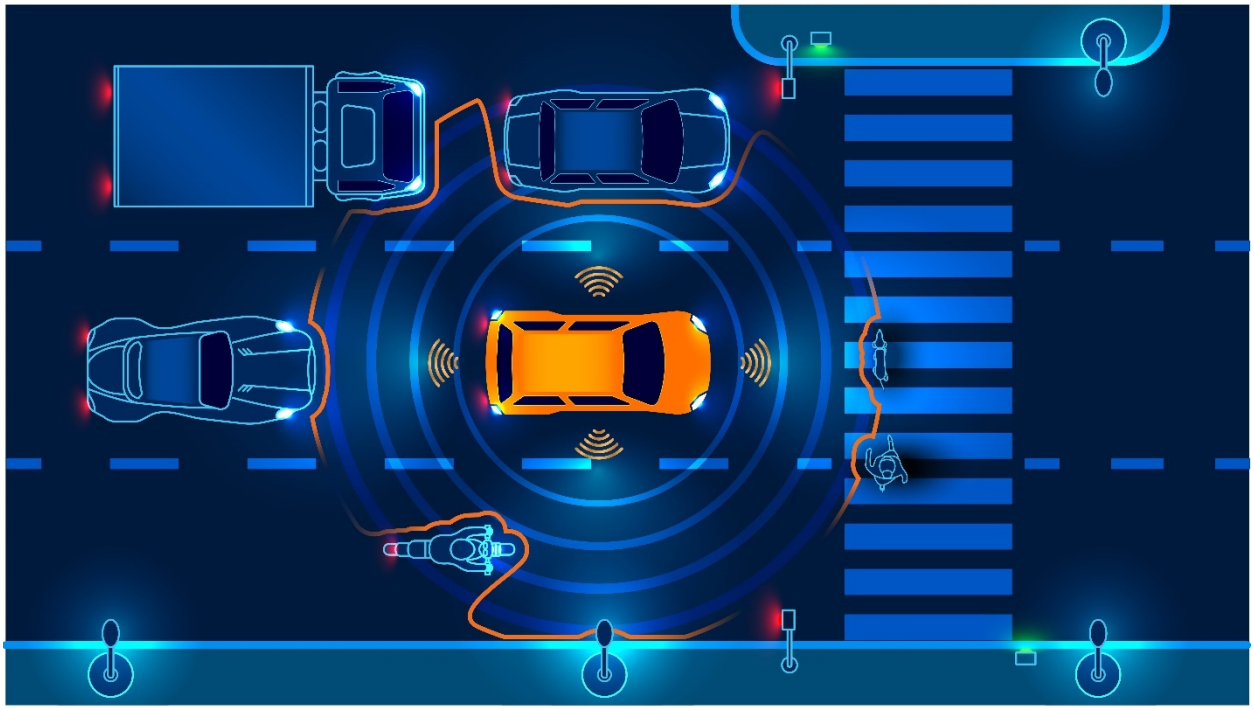


An autonomous vehicle is a complex piece of machinery encompassing a wealth of disparate electronic, electro-optic, and compute components and systems, including a combination of central processing units (CPUs), graphics processing units (GPUs), and field-programmable gate arrays (FPGAs), that must all work in tandem.

The autonomous vehicle is replete with cameras and sensors capturing volumes of data, estimated at 4 Terabytes per day, which places greater demands on compute capabilities. At the heart of this intricate driverless vehicle ecosystem sits one of the most critical elements: the embedded computer. Tasked with sensor fusion, machine learning, data collection, and data processing responsibilities, the onboard system paints a virtual picture of the operational environment through which it then navigates safely and efficiently.

UNPREDICTABLE ENVIRONMENTS

Self-driving cars and trucks are easily the most sophisticated and complex mobile platforms, outside the military, to hit public streets – largely unpredictable environments. Onboard systems must always be ready to identify and avoid hazards in their path. When a child runs into the street, for example, the embedded computer must respond in a fraction of a second to avoid disaster. To ensure safety, it must be highly reliable, available when needed, and capable of processing sensor data and executing commands instantaneously –faster than the human brain.



If any individual in-vehicle system is not immediately responsive and available when needed to make a potentially lifesaving, split-second decision, that vehicle can pose a very real threat to its inhabitants and everyone else on the road. As a result, not just any computer or electronics system will do; safety-critical applications call for rugged, reliable systems designed to meet or even exceed operational and environmental demands. In contrast, average consumer- and enterprise-level systems not designed for or capable of withstanding extended use in challenging or harsh environments do fail; it could just be a matter of when and what damage will result. For this and other reasons, a growing number of safety-critical

solutions throughout commercial and industrial markets rely on military-grade rugged computer and electronics systems. Indeed, the office-grade equipment installed in early ADS vehicles has not provided sufficient reliability to enable data collection or prototype capabilities.

BEST PACTICES AND GUIDANCE

Transportation safety experts are encouraging autonomous vehicle and automated driving system manufacturers to benefit from lessons learned in various parallel markets including military and aerospace. Best practices include SAE standards as well as systems engineering practices successfully employed for decades in aerospace and defense programs, according to the latest guidance from both the U.S. Department of Transportation (DoT) and the National Highway Traffic Safety Administration (NHTSA).

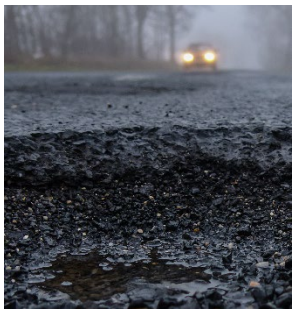
DoT officials issued *Automated Driving Systems 2.0: A Vision for Safety*, voluntary guidance that encourages best practices and prioritizes safety to help pave the way for the safe deployment of advanced driver assistance technologies. In it, officials encourage technology companies working on ADS "to adopt voluntary guidance, best practices, design principles, and standards developed by established and accredited standards-developing organizations, as well as standards and processes available from other industries such as aviation, space, and the military."

Military and aerospace vehicles and vehicle-based electronics are renowned the world over for being built to work reliably, without fail, over a long operational life in even the most challenging applications, rough terrains, and extreme environments. The Boeing B-52 Bomber military aircraft, for example, is currently in its sixth decade of operational service to U.S. and allied forces, contributing to national security and providing immediate nuclear and conventional global strike capabilities. Similarly, National Aeronautics and Space Administration (NASA) scientists recently fired up the thrusters on the Voyager 1 spacecraft, which is still operating reliably in space more than 40 years into its mission.

Today's savvy automotive and automated driving system manufacturers recognize the value that longtime, trusted military and aerospace suppliers bring to the AV market: field-tested and proven technologies, experience, and expertise. Therefore, many are proactively seeking out

and partnering with technology companies that have widespread experience delivering rugged computer and electronics systems designed to meet strict standards and operational requirements, and built to last in a variety of demanding applications and challenging environments. The level of compute and sensor capabilities on a mobile platform is new to the automotive market but not necessarily foreign to the aerospace industry.

OPERATIONAL DOMAIN



Transportation safety specialists stress the importance of designing and developing ADS from the start with not only industry standards and lessons learned in mind, but also the environment in which the systems will operate. Automated driving systems should be tailored specifically to the environmental conditions in which the systems are expected to operate. Military and aerospace vehicles and their critical onboard electronics and computer systems have long been designed and developed for their specific operational environment, from the desert to frozen tundra and the furthest reaches of space. There is a natural parallel from one market to the next.

The DoT's *A Vision for Safety 2.0* guidance expressly encourages ADS manufacturers "to follow a robust design and validation process based on a systems-engineering approach with the goal of designing ADSs free of unreasonable safety risks. The overall process should adopt and follow industry standards, such as the functional safety process standard for road vehicles, and collectively cover the entire operational design domain." The operational design domain is defined as the specific operating environment(s) in which the automated system is designed to properly operate, including but not limited to roadway types, speed range, and environmental conditions such as weather.

Military and aerospace organizations, including the U.S. Department of Defense (DoD) and NASA, learned decades ago that average computer and electronics systems would soon become ineffective, work only sporadically, or completely fail to function in the field. Consumer- and enterprise-level systems are largely designed to operate in climate-controlled, protected office environments and, when deployed in the field, typically cannot withstand and will succumb to various environmental elements, such as: shock and vibration, hot and cold temperature extremes, dust and dirt, water and humidity, and snow and ice. It stands to reason that modern ADS and AV solutions must also be designed to withstand impacts from potholes, washboard roads, and collisions – which traditional computer and electronic systems cannot tolerate.

MISSION- AND SAFETY-CRITICAL SYSTEMS

To help avoid system failures in the field due to environmental hazards, a majority of military and aerospace programs require systems to meet a variety of important standards, such as MIL-STD-810, Environmental Engineering Considerations and Laboratory Tests. The MIL-STD-810 U.S. military standard calls on manufacturers to tailor a device's environmental design to the conditions that it will experience throughout its service life, and to test the device using methods that replicate the effects of environments on the equipment.

Similarly, the NHTSA in its *Assessment of Safety Standards for Automotive Electronic Control Systems* encourages the use of MIL-STD-882E, Department of Defense Standard Practice - System Safety, is a systems engineering safety standard approved for use by all U.S. military departments and defense agencies, and a required practice for military automotive design. The military standard provides for the identification of environmental requirements and hazards, and the elimination or mitigation of those hazards, using environmental hazard analysis data, risk assessments, mishaps, and lessons learned from legacy and similar systems.

These and other important standards and requirements were designed specifically for military equipment but are also applicable to and employed for commercial devices. They are particularly important to ensure mission-critical and safety-critical devices – equipment upon which the success of missions or the safety of human lives depend – can withstand and continue working reliably in the face of harsh environments, ranging from the battlefield to the farthest reaches of space.

Commercial automated driving systems are largely considered to be both mission-critical, in the case of a large unmanned truck navigating the nation's highways to transport cargo, and safety-critical, as self-driving cars traverse busy city streets with pedestrian crosswalks to deliver travelers to their destinations. It is little wonder, then, why transportation safety experts find military and aerospace systems engineering standards and practices pertinent to ADS. Using a robust quality certification framework such as AS9100 for Aerospace applications is directly applicable to the ADS - mission and safety critical systems for autonomous vehicles.

RELIABILITY RESEARCH

The NHTSA, in its mission to save lives, prevent injuries, and reduce economic costs due to road traffic crashes, established the Automotive Electronics Reliability Research Program to ensure "the safety and reliability of emerging safety-critical electronic control systems in motor vehicles. Its electronics reliability research includes methods and standards within and outside the automotive industry for assessing, identifying, and mitigating potential and new hazards that may arise from the increasing use of electronics and electronic control systems in the design of modern automobiles."

NHTSA in its safety standards assessment and automotive electronics reliability research further recommends ISO 26262 Road Vehicles – Functional Safety as a "comprehensive

automotive safety standard that addresses the functional safety of the growing number of electrical/electronic and software-intensive features in today's road vehicles." ISO 26262 is an adaptation of the International Electrotechnical Commission (IEC) 61508 standard that requires system designers and developers to consider all environmental factors – including shock, vibration, temperature, and electromagnetic interference (EMI) – that could result in an unsafe situation for the equipment.

These and other environmental factors threaten computer and electronics reliability, which is inextricably linked to safety. Mission- and safety-critical projects, therefore, require computer and electronics systems to be protected from the elements. The most effective, efficient, and economical way to ensure high reliability, particularly for ADS expected to function daily on everything from highways to city streets to the roughest back roads in all kinds of weather, arguably is: to use computer and electronics systems that are built to be rugged and reliable from design and development, through meticulous manufacturing and testing, for deployment in modern autonomous vehicles of all types in various locales.

RUGGED PREREQUISITE

Autonomous vehicle systems should be engineered from the start to be rugged, helping to ensure they work reliably over a long operational life in environments that are inhospitable to common computer and electronics devices. All rugged systems are not alike, however. It is advantageous to adopt rugged products that have been built from the ground up to last, extensively tested and proven to meet or exceed industry standards and delivered and backed by a provider with a long, successful track record of delivering rugged, highly reliable systems.

Crystal Group Inc., a leading designer/manufacturer of rugged computer hardware in Hiawatha, Iowa, has delivered field-tested and proven rugged, reliable, and robust commercial and custom-engineered computer and electronics systems for a variety of mission- and safety-critical aerospace, defense, industrial, and commercial applications for over 35 years. The company's rugged servers, workstations, displays, and embedded computers are employed on more than 500 military programs to date, including many vehicle electronics, unmanned, and autonomous systems and platforms.

Crystal Group engineers its products from the ground up to be rugged, work reliably, and to last – even in the roughest terrains, toughest applications, and most extreme environments. Many of its systems meet or exceed already strict military requirements and industry standards, such as those promoted by transportation safety professionals.

Company engineers employ system design and development techniques tailored to help extend operational life, boost performance, and increase safety and reliability. Crystal Group provides some of the most rugged and reliable products on the market today through a combination of key techniques, including:

- Stabilizing components that are susceptible to damage from shock and vibration
- Increasing air flow or liquid cooling to hot components
- Using open architecture technologies, rugged enclosures and transit cases, and quality materials and components
- Improving the conductive and convective heat transfer mechanisms of components to extend the thermal limits of commercial motherboards
- Offering industry-leading technologies, warranties and support

CHASSIS CONSIDERATIONS

The average electronics enclosure may be suitable for stationary, temperature-controlled office environments, but they have proven time and time again to be inadequate for various mobile and harsh-environment applications. Whereas the average chassis can expose critical electronics to the elements, Crystal Group's rugged chassis protects components and systems from water and humidity, dust and dirt, temperature extremes, electromagnetic interference (EMI), and other damaging conditions.

Crystal Group's all-aluminum rugged chassis boasts side walls constructed from thick 6000-series aircraft aluminum, support structures inside and on the front and rear plates made from milled plate stock, and a base plate structurally bonded and mechanically fastened to the side walls. The all-aluminum construction helps to limit weight, improves thermal conductivity and vibration performance, enhances electrical conductivity for EMI, and is designed to meet stringent military and automotive standards.

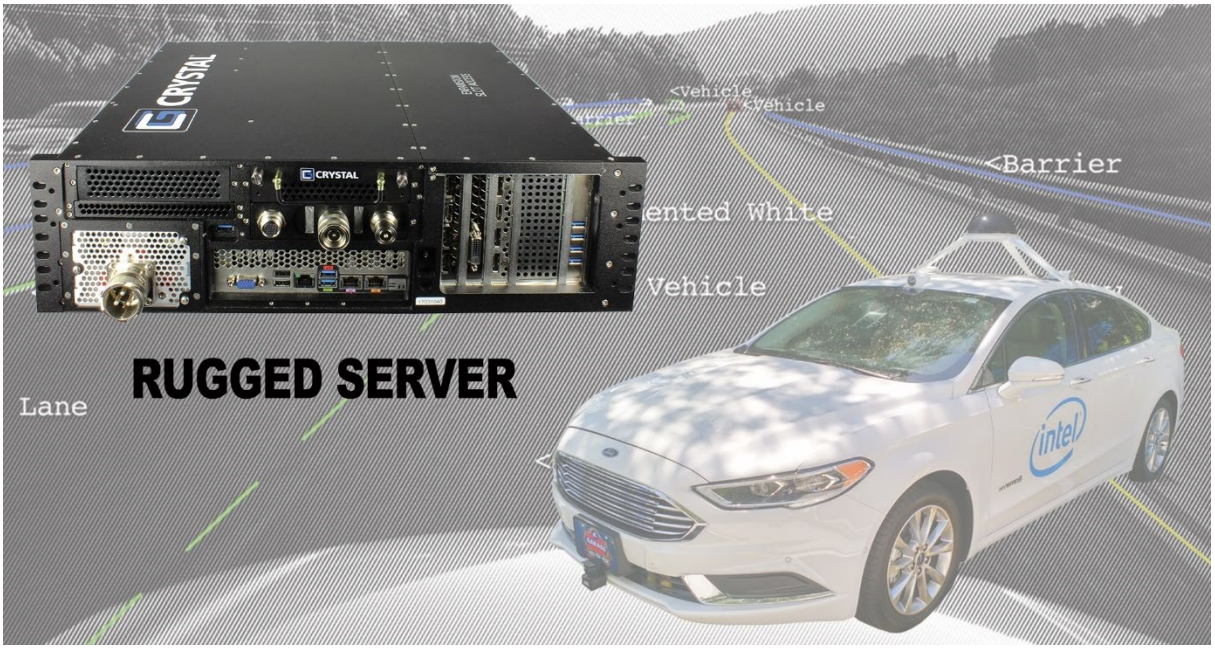
Noise reduction is accomplished by using liquid cooling techniques providing exception thermal management as well as low cabin noise. The structural integrity of the system is enhanced by using very thick sections for the side rails, front and rear end plates, and center brackets/braces with screws attaching structural components. The net result is a robust system that not only survives high vibration and shock, but also doesn't rattle when subjected to external excitation.

Coatings on the company's enclosures help maintain the electrical conductivity of the chassis, create low-impedance interfaces, and provide protection from both corrosion and EMI. Conformal coatings on all printed circuit boards (PCBs) and surfaces help prevent moisture

penetration and mitigate the effects of shock and vibration, to help protect critical components from becoming unseated when the vehicle hits a pothole or travels down a washboard road.

AUTONOMOUS INNOVATION

Traditional commercial computer hardware cannot withstand everyday road conditions, such as potholes, collisions, and extreme temperatures, which could render the ADS unreliable and potentially result in unsafe or even life-threatening situations. Crystal Group's ruggedization techniques combine to deliver highly reliable systems to boost the safety of virtually any autonomous vehicle application. Major automotive manufacturers and top technology firms have already partnered with Crystal Group to tap the company's expertise in and portfolio of rugged and reliable systems for use in autonomous vehicles and automated driving systems. To date, Crystal Group has successfully passed numerous in-vehicle crash safety tests.



Technology leader Intel Corporation recognized early on the value that military-grade, ruggedized computer and electronic systems, and partners who engineer and manufacture them, bring to the autonomous vehicle market. Intel teamed with long time partner, Crystal Group, to engineer, manufacture, and test a rugged and reliable first-generation high-performance computer crafted specifically for use in a wide variety of autonomous vehicles and automated driving systems across military, industrial, and commercial markets.

SPEED TO MARKET

Decades of experience engineering rugged computers and electronics for autonomous and other advanced vehicles and systems culminate in Crystal Group's second generation Rugged Intelligence Appliance (RIA™) line of rugged solutions for autonomous vehicles and

automated driving systems. Advancements include liquid cooling options, low noise, reduced footprint and weight, increased processing, and 9VDC to 32VDC power.

Crystal Group's Rugged Intelligence Appliance (RIA) line, including the AVC0161 high-performance rugged computer, is specifically designed to accelerate AV and ADS projects and help engineers bring their innovations to market faster. The Crystal Group AVC0161 combines impressive compute power, data-handling capabilities, and storage capacity in a compact, rugged solution capable of withstanding harsh environmental conditions, including potholes, collisions, and extreme temperatures that are likely to cause traditional systems to fail.

Crystal Group RIA AVC0161

The Crystal Group AVC0161 provides the horsepower AV and ADS projects need, combining robust I/O, multiple GPU capacity, dual Intel® Xeon® Scalable Processors, sophisticated thermal management, and other high-quality components stabilized in a rugged, aluminum enclosure measuring just 6.5 x 14.1 x 15.6 inches and weighing 35 pounds. Providing superior performance per watt, the high-performance rugged server can operate off a 12-volt (12V) car battery. Other systems on the market require costly and space-consuming power supplies for DC power.

Crystal Group RIA systems are built for safety and reliability, tapping over 30 years of experience tailoring high-performance, fail-safe rugged hardware for hundreds of military and aerospace missions, as well as challenging industrial, critical infrastructure, and commercial programs, including some of the most advanced autonomous vehicles. The system is scalable and customizable to meet growing demands and accommodate future upgrades. Additional compute and storage capacity can be added with predictable results. Customized options and

rack integration services are available to quickly take advantage of the latest technology advances and speed the pace of development.

Crystal Group's vehicle-specific development kits and customization services further streamline AV and ADS workflows with compute, display, networking, and other components essential for autonomous vehicle platforms. The Crystal Group ADS development kits are designed to provide optimal performance under even the most severe environmental conditions with robust input/output (I/O), multiple GPU capacity, sophisticated thermal management, and low power consumption – all critical elements of an efficient, flexible, and easily deployable computer and electronics system.

Crystal Group's RIA product line, the AVC0161, and vehicle-specific development kits deliver speed, agility, and quality in a single, turnkey package, and help to increase speed to market with Crystal Group's fast response time and expert technical support.

HIGH RELAIABILITY FOR SAFETY

"From reducing crash-related deaths and injuries, to improving access to transportation, to reducing traffic congestion and vehicle emissions, automated vehicles hold significant potential to increase productivity and improve the quality of life for millions of people," *A Vision for Safety 2.0* explains. Motor vehicle-related crashes on U.S. highways claimed 37,461 lives in 2016, DoT research indicates, noting that 94 percent of serious crashes are due to human error, dangerous choices or errors people make behind the wheel.

"Technology can save lives," transportation safety officials affirm, with the help of highly reliable, fail-safe automated driving systems tailored to fit the application and the environment. "Thanks to a convergence of technological advances," *A Vision for Safety 2.0* reads, "the promise of safer automated driving systems is closer to becoming a reality."

Self-driving cars bring the promise of greater energy conservation, lower emissions, added convenience, and roads that are both safer and less congested. To fully realize this vision, automotive manufacturers and autonomous vehicle makers are opting to benefit from established standards and lessons learned in mission- and safety-critical military and aerospace programs, and through collaboration with experienced, trusted industry partners with proven, field-tested, military-grade products, services, and technologies designed to help manufacturers of autonomous vehicles and automated driving systems bring their innovations to market faster with the added confidence that comes with rugged, reliable systems built to last in even the most extreme environments.

ABOUT THE AUTHOR

Jim Shaw is the Executive Vice President of Engineering at Crystal Group. Since 2006, Jim has led the engineering department and the new product development team.

Jim's revolutionary design prowess led to the birth of the rugged series (RS) chassis for the military and industrial computing markets. During Jim's tenure at Crystal Group the company has expanded its rugged product lines with embedded, storage, displays, switches, carbon fiber options, and custom power supply designs.

Jim holds a Bachelor of Science degree in Mechanical Engineering from Iowa State University and a Master of Business Administration from the University of Iowa. Prior to joining Crystal Group, Jim held a management position in engineering at Rockwell Collins, located in Cedar Rapids, Iowa. While at Rockwell Collins, he was honored three times as an Engineer of the Year nominee for his work in high performance electronics packaging. He has authored or co-authored eight international patents.

ABOUT CRYSTAL GROUP, INC.

Crystal Group, Inc. a technology leader in rugged computer hardware, specializes in the design and manufacture of custom and commercial rugged servers, embedded computing, networking devices, displays, power supplies, and data storage for high reliability in harsh environments. An employee-owned small business founded in 1987, Crystal Group provides the defense, government and industrial markets with in-house customization, engineering, integration, configuration management, product lifecycle planning, warranty, and support services.

Crystal Group products meet or exceed IEEE, IEC, and military standards, including MIL-STD-810, 167-1, 461, and MIL-S-901; are backed by an industry-leading, 5-plus-year warranty with in-house support; and are manufactured in the company's Hiawatha, Iowa, USA, facility certified to ISO 9001:2015/AS9100D quality management standards.

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