We get technical

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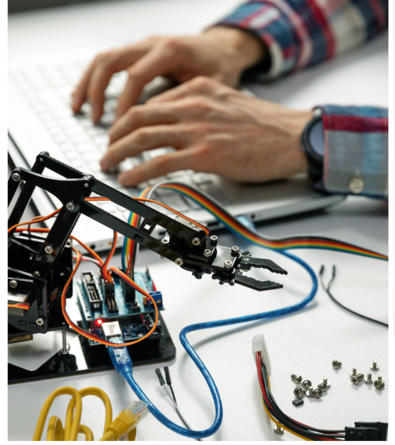



contents

Editor's note

Welcome to the DigiKey eMagazine Volume 22 – Robotics.

In this issue, we explore the technologies and engineering breakthroughs powering the next generation of robotic systems across industrial, service, and collaborative environments.

We begin with a look at the Agilex 3 product family from Altera, highlighting how its high-performance processing and adaptability are helping developers build smarter, faster robotics solutions. Samtec walks us through their connectivity innovations that address the unique challenges in robotic and industrial systems, where precision and reliability are non-negotiable.

STMicroelectronics dives into strategies for building flexible robotic designs, essential for developers facing constantly shifting performance demands. TE Connectivity follows with an exploration of smart navigation, safety, and control in service robotics – key factors in ensuring both effectiveness and trust in human-robot interactions.

In the power domain, we examine component-based distributed power architectures that bring scalability and efficiency to robotics. As safety grows increasingly critical in collaborative environments, we offer practical guidance on selecting and integrating multi-dimensional safety systems to protect workers while enabling seamless co-existence with cobots.

Finally, we delve into the core of motion and control with a detailed look at fast, precise, and low-power position sensing, a technology at the heart of responsive and intelligent robotic behavior.

Whether you're designing robotic platforms, specifying components, or architecting systems for the future, we hope this volume offers valuable insights and inspiration. The world of robotics is not just about machines – it's about building intelligent, collaborative systems that move our industries, and our lives, forward.

Agilex 3 FPGAs & SoCs: engineering solutions for power-conscious, cost-effective embedded systems

Embedded system designs require solutions that balance high performance with power and cost constraints. Unfortunately, standard FPGA architectures often require designers to compromise between power efficiency and computational capability. Altera's Agilex 3 FPGA and SoC family addresses these challenges with purpose-built features that are optimized for embedded, edge, and industrial applications. They introduce targeted innovations with devices spanning from 25,000 to 135,000 logic elements while maintaining architectural benefits across the full range. The integration of AI acceleration, advanced security features, and processing capabilities, results in a platform suited for applications where every milliwatt and cost consideration matters.

Advanced HyperFlex foundation

Agilex 3 leverages a HyperFlex FPGA architecture, achieving substantial performance gains through fundamental improvements in timing management and routing effectiveness. This foundation delivers fabric performance improvements up to 1.9 times, while reducing total power consumption by up to 38% compared to earlier solutions. These improvements result from core architectural changes that minimize critical path latencies and streamline routing complexity.

Agilex 3 devices demonstrate exceptional integration capabilities, supporting up to 135,000 logic elements within packages measuring 12 mm x 12 mm. Their variable pitch BGA packaging strategy preserves high I/O density while conforming to conventional PCB design standards, facilitating easy deployment in space-constrained applications without requiring specialized production techniques. With fabric operation reaching 345 MHz, the Agilex 3 series delivers exceptional computational performance for real-time processing while preserving the power efficiency needed for both thermal and battery constraints. The operational speed reflects engineering choices that balance processing power with energy usage, enabling sophisticated algorithm implementation within practical power limitations.

AI processing integration

The Agilex 3's design embeds AI Tensor Blocks throughout the FPGA fabric, establishing a processing environment capable of handling standard digital signal processing as well as AI computations. These blocks can switch between DSP and Tensor operations, delivering a key adaptability that removes the need for additional acceleration hardware. The AI Tensor Blocks can perform matrix calculations efficiently, executing dot products within single clock cycles using various data formats such as fixed-point, INT8, FP16, FP19, FP32, BFLOAT16, and INT9.

Combined with up to 368 configurable 18 x 19 multipliers, this architecture achieves a peak theoretical throughput of 2.54 TOPS for INT8 processing. This processing density simplifies system design and reduces component costs by incorporating specialized capabilities that would otherwise require additional hardware. It also benefits edge implementations requiring simultaneous real-time sensor processing or intelligent analysis. The 'frictionless' switching between signal processing and ML functions in one device enables design methodologies that would be challenging with separate processing components.

Image source: Altera

Advanced connectivity architecture

Agilex 3 devices offer robust communication capabilities via built-in transceivers operating at speeds up to 12.5 Gbps across four channels. These transceivers feature hardened PCIe 3.0 and 10 Gigabit Ethernet IP blocks, providing direct high-speed communication without external interface hardware. The consolidation reduces system complexity while maintaining reliable data transmission for applications including industrial automation, video processing, and measurement instrumentation.

Memory interfacing uses LPDDR4 implementation which supports transfer rates up to 2,133 Mbps, offering sufficient bandwidth for embedded implementations while emphasizing power usage. This memory selection shows an emphasis on power-sensitive applications where battery performance and thermal control

Tight fabric coupling allows flexible workload distribution, allowing processor-intensive operations to shift between software and hardware execution based on immediate performance needs.

outweigh maximum memory throughput.

For imaging and display implementations, MIPI D-PHY v2.1 offers direct sensor and display connectivity at speeds reaching 2.5 Gbps per lane across fourteen lanes. This functionality serves medical imaging, surveillance, and consumer electronics processing of high-resolution visual data. Integrated MIPI interfaces remove external bridge requirements, decreasing costs and enhancing signal quality through reduced interconnect distances. The adaptable I/O design also incorporates 1.25 Gbps LVDS and additional high-speed differential interfaces for direct industrial sensor/communication system connections. This flexibility accommodates designs requiring diverse external component interfacing without extra conversion hardware.

Embedded processing architecture

The integrated processing system features dual-core Arm Cortex-A55 processors running at frequencies up to 800 MHz, establishing linked hardware-software operations optimized for mixed computing applications. This integration facilitates coordination between software and hardware processing components which is usually challenging using separate devices connected via external links.

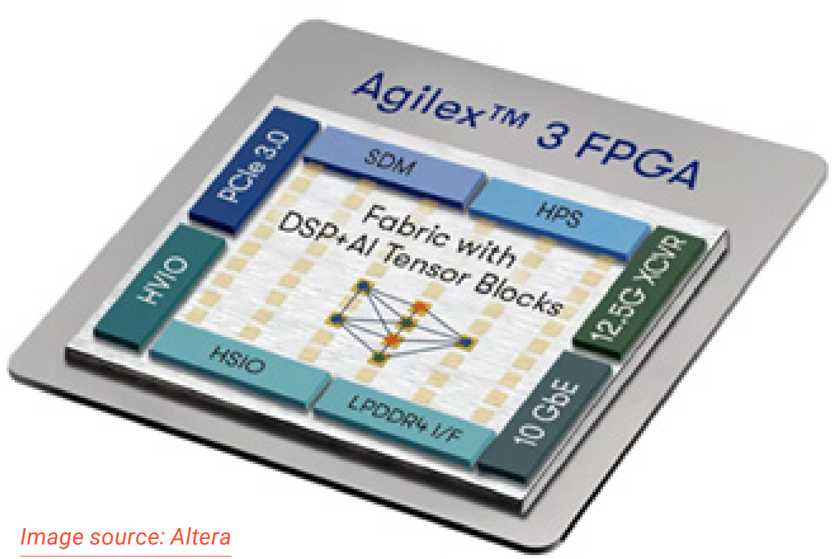


Image source: Altera

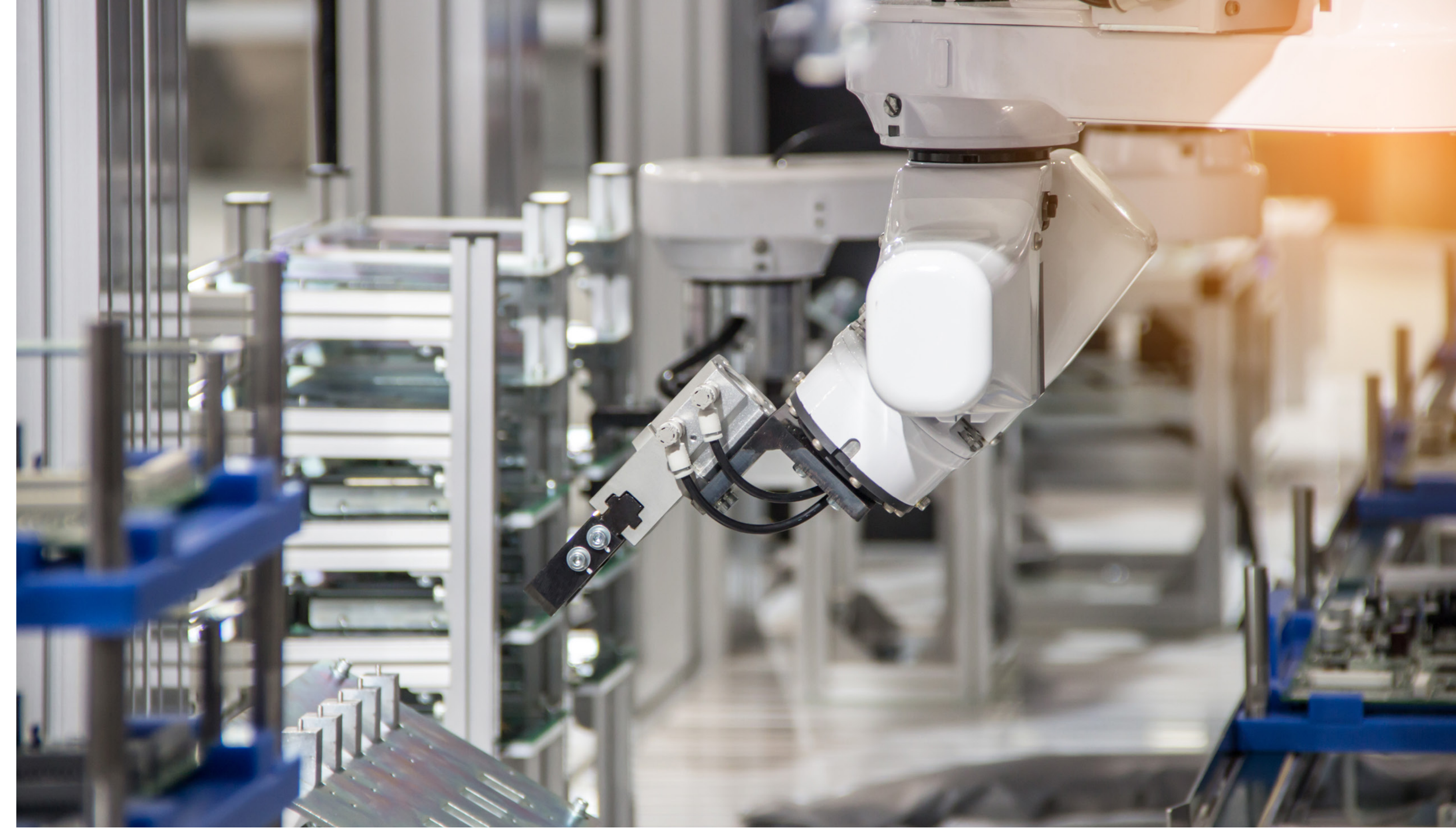
The Agilex 3 processor implementation provides computing capacity for real-time operating environments, communication protocols, and application software while maintaining power efficiency required for embedded deployments. Tight fabric coupling allows flexible workload distribution, allowing processor-intensive operations to shift between software and hardware execution based on immediate performance needs.

Comprehensive power control features ensure precise device power management through independent power and clock domains. Engineers can tune power consumption according to immediate processing demands, which is crucial for battery-operated applications where efficiency directly influences operational duration and system dependability.

Security and management systems

The Agilex 3 series includes a Secure Device Manager (SDM) with extensive security capabilities that cater to increased security demands in embedded and edge computing environments. Authenticated boot features ensure that only verified software and FPGA configurations load during system startup, which is essential for industrial control, medical equipment, and infrastructure applications where unauthorized code poses serious hazards.

Management capabilities also include thorough monitoring and control features supporting system diagnostics and maintenance planning. The SDM also offers access to temperature measurement, voltage monitoring, and additional diagnostic functions for health assessment and maintenance scheduling. These capabilities can be beneficial for industrial deployments where unexpected downtime creates substantial operational and economic consequences.



Growth and migration planning

The Agilex 3 series provides a platform for expandable system development through design compatibility with enhanced Agilex 5 devices. This compatibility allows engineers to initiate development with cost-effective Agilex 3 devices, then subsequently transition to enhanced performance solutions as needs develop, without major design modifications. Package compatibility across the logic density spectrum (25,000 to 135,000 logic elements) also supports board designs accommodating various device options, delivering flexibility for product management and cost optimization.

Conclusion

Agilex 3 FPGA and SoCs achieve high performance without sacrificing power efficiency or cost effectiveness. Their Hyperflex architecture delivers performance gains and reduces the power consumption in a wide range of embedded designs. Additionally, the integration of AI Tensor Blocks with DSP capabilities, hardened high-speed connectivity, and dual processors creates a unified platform that eliminates the need for multiple discrete components.

To find an Agilex 3 product your next design, visit Agilex 3 on DigiKey.

An industrial robot on a factory floor. Image source: Adobe Stock

samtec

Industrial and robotic interconnects: Samtec's solutions for harsh environment connectivity

Industrial automation and robotics systems operate in environments that can quickly destroy standard electronic connectors. Factory floors, for instance, subject equipment to vibrations, temperature extremes, chemical exposure, and physical abuse that could cause connection failures within months of deployment. In robotic applications, these issues can be severe as connectors are subjected to millions of motion cycles which can degrade critical electrical pathways over time.

Samtec's solution to these issues is purpose-engineered connector and cable solutions that address the demands of industrial and robotic applications. Its specialized product families prioritize long-term reliability, environmental resilience, and preserving high-performance

signal integrity. Samtec's solutions include rugged board-to-board connectors designed for factory automation systems, as well as flexible cable assemblies suitable for multi-axis robotic joints that operate continuously.

Advanced contact technology for extended life

Reliability of industrial connectors depends on contact design, and typical solutions often fail under the harsh conditions of industrial environments. To address this issue, Samtec's Tiger Eye connectors use a multi-finger contact system that offers redundant connection points to increase their life cycle. A 3-finger beryllium copper contact design distributes mechanical stress across multiple contact points, reducing wear and extending operational life beyond 1,000 mating cycles. This contact architecture is ideal for robotic systems where connectors are frequently mated/unmated during maintenance procedures.

For applications requiring ingress protection, AccliMate sealed connectors meet IP67 and IP68 ratings for dust and water protection

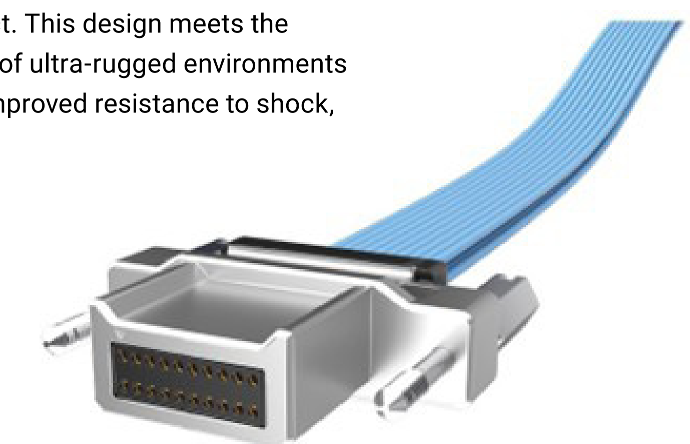
The smooth contact surface minimizes insertion force and provides a reliable electrical connection for precise systems and sensitive sensor interfaces. Their micro-slot tail design also enhances solder joint strength, addressing mechanical stress that can accumulate over extended operational cycles.

For applications requiring even higher performance, Samtec's Edge Rate contact system balances electrical performance with higher mechanical robustness. These contacts feature broad-milled surfaces rather than standard stamped edges to reduce crosstalk and improve signal integrity at data rates of 56 Gbps PAM4 (28 Gbps NRZ). Similarly, Samtec's URSA I/O utilizes hyperboloid-type contacts providing four points of electrical contact. This design meets the needs of ultra-rugged environments with improved resistance to shock, vibration, and corrosion while maintaining low contact resistance.

Environmental resilience through rigorous testing

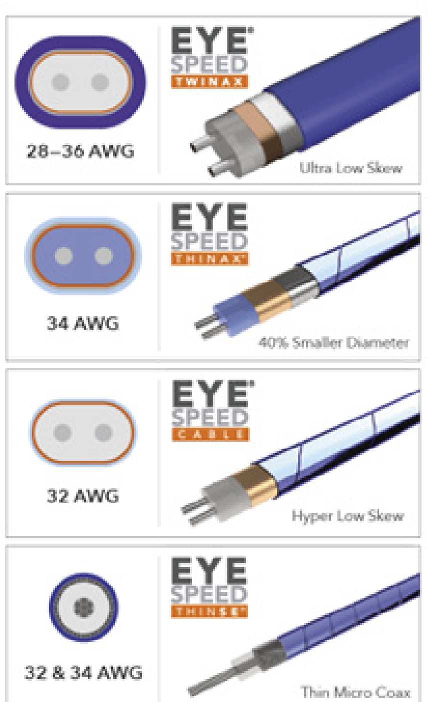
Samtec's Severe Environment Testing (SET) subjects products to conditions that simulate decades of field exposure, including temperature cycling from -65 to +125°C for up to 500 cycles, mechanical shock testing at 40 G peak acceleration, and random vibration testing at frequency ranges from 5 to 2000 Hz.

The Extended Life Product program provides additional testing for long-term deployments through 10-year Mixed Flowing Gas testing that evaluates contact



Samtec's URSA I/O. Image source: Samtec resistance stability under corrosive atmospheric conditions. This protocol simulates the effects of industrial pollutants, salt sprays, and other environmental contaminants that can degrade performance over time.

For applications requiring ingress protection, AcliMate sealed connectors meet IP67 and IP68 ratings for dust and water protection. These bayonet-sealed circular cable assemblies maintain reliable connectivity in washdown environments and outdoor robotics applications where moisture ingress could quickly cause issues. The sealing systems utilize O-ring designs and environmentally stable materials that resist degradation from UV exposure and chemical cleaning agents.



High-speed signal integrity solutions

Industrial automation and robotics systems rely on high-bandwidth connectivity for real-time control, sensor fusion, and AI processing. Samtec FireFly optical transceivers meet these requirements by delivering data rates up to 28 Gbps per lane in a compact 0.63 square inch footprint, achieving 265Gbps per square inch density for space-constrained applications. The system's interchangeable copper and optical capability allows designers to optimize for cost/performance and maintain consistent connector footprints across designs.

Samtec's Eye Speed cable technology achieves ultra-low skew performance with a max. intra-pair skew of 3.5 picoseconds per meter for standard versions, and 1.75 picoseconds per meter for Hyper Low Skew variants. This precision is essential in applications requiring synchronization between servo motors or sensor arrays, as even slight timing variations can degrade system performance or cause instability.

Samtec meets high-density interconnect requirements through its NovaRay micro rugged backplane systems that accommodate up to 128 differential pairs in a single connector while supporting 128 Gbps PAM4 performance. The fully shielded differential pair

AcliMate sealed USB Type-C cable assembly plug. Image source: Samtec

design helps to minimize crosstalk and is applicable in blind-mate applications in industrial equipment where precise connector alignment can be challenging.

Addressing robotic motion and power requirements

Robotic systems have specialized connectivity demands that standard connectors simply do not meet. For example, continuous movements across multiple axes cause repetitive stress patterns that can lead to cable failures within months of deployment. Samtec addresses this challenge with discrete wire cable designs incorporating Teflon fluoropolymer construction and specialized outer jackets engineered for extreme flex endurance.

Similarly, managing power delivery in space-constrained robotic designs requires innovative approaches to current density and thermal performance.

Samtec's mPOWER Ultra Micro power connectors. Image source: Samtec

Samtec's mPOWER Ultra Micro Power Connectors achieve 18 Ampere current handling within a 2.00 mm pitch configuration. In robotics applications where microsecond timing variations can impact surgical outcomes, (e.g., medical systems) Samtec's Tiger Eye multi-contact design ensures the consistent resistance characteristics for servo control accuracy, while meeting Extended Life Product standards for sterilization compatibility.

Engineering system-level integration

Beyond individual component selection, industrial connectors can benefit from board-level optimizations and enhanced thermal management. Samtec's Flyover allows signals to be routed above standard PCB substrates, which reduces dielectric losses and minimizes layer stack complexity. This methodology is ideal in compact controller designs where PCB space constraints impact manufacturing costs and thermal performance.

Heat dissipation can also be challenging as robotic systems are integrating more processing power into smaller dimensions. Samtec's passive cable solutions are designed to minimize thermal stress on system electronics with heat management features that prevent localized hot spots in high-current applications. Their wide operating temperature range from -40 to +85°C allow these products to function reliably in diverse environmental conditions.

Electromagnetic compatibility (EMC) is another frequent concern in industrial environments as high-power machinery can generate significant interference. Samtec's solutions offer complete shield continuity using 360-degree cable protection to maintain signal integrity, while metal housing construction provides additional isolation for critical control circuits. The URSA series incorporates braided metal jackets specifically designed for applications where electromagnetic interference can compromise system operation.

Conclusion

Samtec's industrial and robotics interconnect solutions are a focused engineering approach that resolve several automation system connectivity challenges. Their advanced contact mechanics, environmental validation, and high-bandwidth signal integrity helps to meet the demands of robotic applications. Samtec's focus on longer operational life, durability, and electrical performance consistency offers a good foundation for developing systems that can operate reliably in the harsh conditions where industrial and robotic equipment function.

Building a flexible design for today's robotic applications

A common pain point for designers building robotic systems is combining various hardware modules while figuring out how to make them communicate effectively. The usual piecemeal approach can eat up valuable time and prevent developers from focusing on understanding core concepts behind successful robotic systems. Both professional engineers and robotics enthusiasts encounter these same integration headaches.

Think about designing an autonomous floor cleaner or yard maintenance robot. The project requires integrating distance sensors for collision prevention, vision systems for pathfinding, motion sensors for position tracking, motor drivers for locomotion, as well as AI software for intelligent behavior. Each of the components requires specific knowledge, and designing a unified system requires comprehensive architectural knowledge.

A complete working robot out of the box

The STEVAL-ROBKIT1 (Figure 1) from STMicroelectronics takes a unique approach to deliver a fully functional robotic platform ready for immediate use. Rather than spending time integrating basic hardware, developers can start out with a working robot with autonomous capabilities.

This evaluation kit includes everything needed for autonomous operation (e.g., drive motors, wheels, vision hardware, and control circuitry) pre-configured and ready to run. The included software offers intelligent navigation features, like boundary detection, collision avoidance, and environmental mapping. Having this working foundation allows developers to head into advanced robotics concepts instead of wrestling with basic setup tasks. Development teams can benefit from this plug-and-play system for faster prototype creation and proof-of-concept testing. Engineers can tweak existing code, integrate additional sensors, or fine-tune control algorithms while building on a stable, proven platform.

Development teams can benefit from this plug-and-play system for faster prototype creation and proof-of-concept testing.

The system employs a three-board layout that logically divides core robotic operations while preserving system coherence. Central processing is executed on a primary board containing a STM32H725 controller, which also handles sensor fusion, executing intelligent algorithms, managing communications, and directing overall system behavior. Motor control also gets a dedicated board powered by an STM32G071 microcontroller. This modular design ensures the robots maintain smooth motion control while the main processor handles intensive tasks and highlights an embedded system design where critical, real-time tasks run independently from general processing.

Additionally, a specialized imaging module combines Time-of-Flight (ToF) measurement with camera functionality for vision capabilities. This configuration shows how robots can achieve spatial awareness using multiple sensing methods. The design also proves microcontrollers can effectively handle vision tasks without requiring separate application processors.

Advanced sensing and built-in intelligence

STEVAL-ROBKIT1 allows robots to achieve environmental awareness using a ToF distance sensor, which performs range measurements that allow robots to detect obstacles and avoid falls. Developers can study exactly how distance readings convert into navigation decisions and protective behaviors. Visual perception comes from an integrated monochrome camera that works alongside the distance sensor, enabling critical features like object identification, waypoint recognition and vision-based navigation. For motion tracking, a 6-axis IMU (Inertial Measurement Unit) monitors orientation and movement. This sensor feeds essential data for navigation accuracy and movement stability. Additionally, an integrated magnetometer adds directional awareness, improving the robot's ability to maintain course and navigate reliably.

STEVAL-ROBKIT1's software comes with ready-to-use navigation algorithms for converting sensor readings into intelligent movement patterns. Developers can use these algorithms for boundary detection, obstacle navigation, route planning, etc. Machine Learning frameworks built into the system allows users to experiment with AI-driven behaviors or create their own algorithms based on integrated navigation and safety features.

The STEVAL-ROBKIT1 also offers Bluetooth Low Energy connectivity for mobile control and system monitoring via its BlueNRG-M2SA module. BLE allows robots to connect with mobile devices for remote operation and tracking, enabling control beyond the direct visual range. Users can use it to modify the robot's operational parameters and track performance metrics using mobile interfaces, which improves the overall ease of use.

Expansion and customization options

A 40-pin expansion header matching Raspberry Pi GPIO standards makes it possible to add extra sensors, actuators and custom hardware without needing specialized interface boards. This standardized interface can allow robotics platforms to evolve to meet other needs while preserving core capabilities.

Figure 1: The STEVAL-ROBKIT1 from STMicroelectronics.
Image source: STMicroelectronics

For sound features, the STEVAL-ROBKIT1 includes both input and output using an onboard microphone and buzzer system. The microphone supports voice commands or sound-based interactions, while the buzzer delivers alerts and status signals. Visual indicators using LEDs or manual controls through buttons can also provide direct feedback and operation modes. For example, LEDs can indicate operational states, sensor status and overall system health, allowing developers to understand robot behavior during testing during development work or regular use.

Key applications

The STEVAL-ROBKIT1 platform allows developers to explore diverse robotic applications by providing basic building blocks that scale across consumer products, commercial systems, and specialized industrial equipment. Understanding how these core technologies adapt to specific use cases accelerates development from concept to implementation.

Residential automation systems

Robotic vacuums are some of the most practical use cases for STEVAL-ROBKIT1's sensing technologies. For example, ToF measurements can accurately calculate distances to walls and furniture, while vision processing identifies docking stations or navigational landmarks. The platform's inertial measurement capabilities are also applicable for maintaining cleaning patterns and estimating coverage areas. Similarly, autonomous lawn care products can use its navigational foundations to address outdoor challenges. Magnetic field sensing is useful in boundary wire detection and maintaining cutting patterns across sloped surfaces. Though commercial mowers typically operate at power levels higher than the platform, all the basic motor control strategies for load-adaptive speed regulation are directly applicable.

Education and entertainment

Interactive toy developers can use the STEVAL-ROBKIT1's accessible hardware interfaces and wireless connectivity options, such as BLE to create smartphone-controlled experiences where physical robot actions correlate with digital content. Similarly, designers can utilize the platform for educational projects. For example, students can observe relationships between sensor inputs and behavioral outputs to understand how software transforms measurements into purposeful actions. Audio interfaces support voice interaction experiments, while visual indicators can provide feedback during programming exercises.

Conclusion

STEVAL-ROBKIT1 offers engineers, students, and hobbyists direct access to the integrated systems that power autonomous robots. By removing integration obstacles, developers can now focus on their design rather than dealing with basic technical challenges. This approach speeds up both the learning and product development process.

Moreover, the educational benefits go beyond basic component demos to provide practical experience that enables users to develop a solid understanding of how sensors, processors, and actuators work in tandem to create autonomous behaviors. Overall, this solution tackles the complexity that often slows robotic system development.

To explore more on this Robotics Eval Platform, please see the video below and visit STEVAL-ROBKIT1.

Industrial service robotics: smart navigation, safety and control with TE Connectivity's connector solutions

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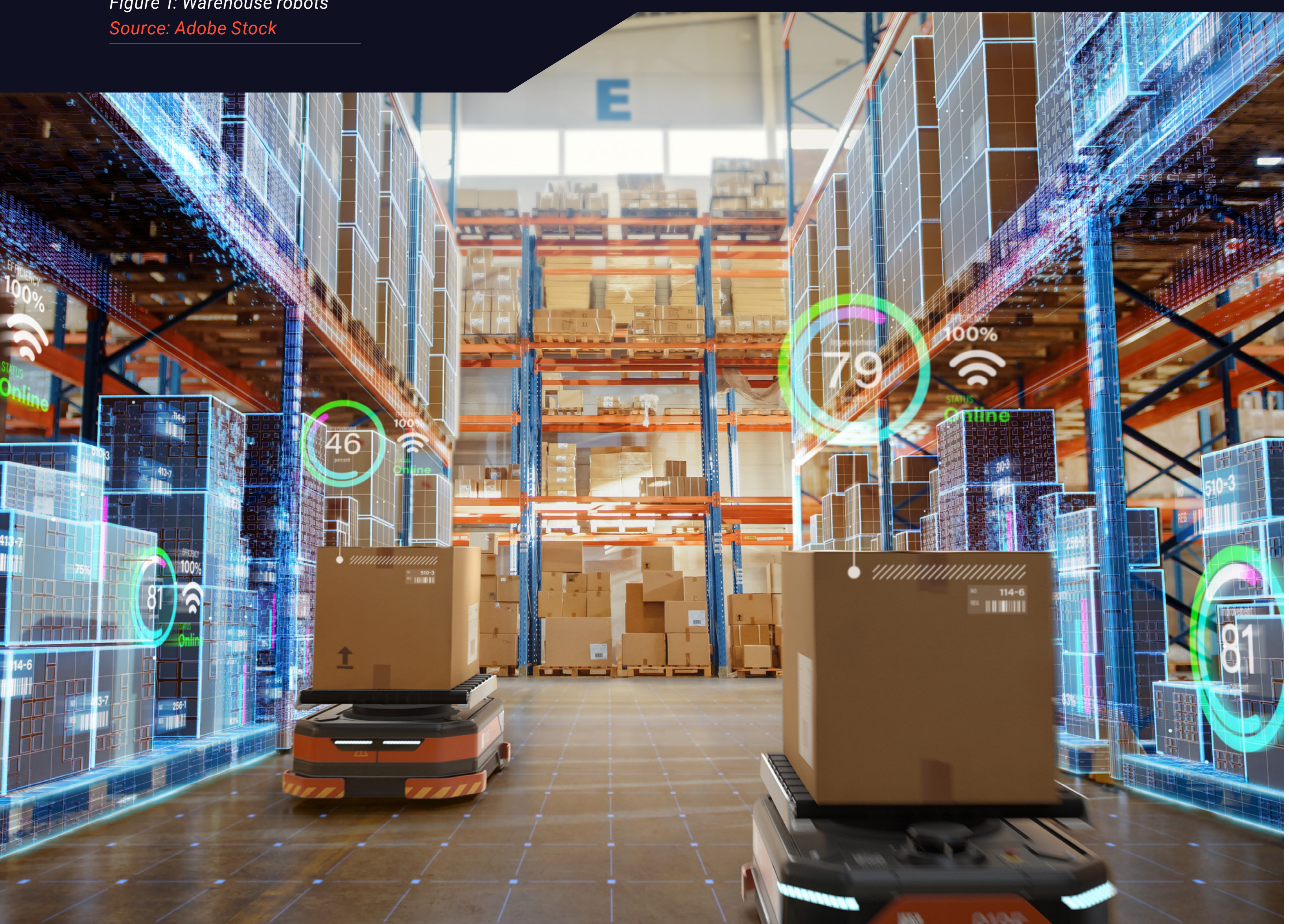
Figure 1: Warehouse robots
Source: Adobe Stock



Industrial service robots (Figure 1) are improving productivity and efficiency in manufacturing, logistics, and automated warehouses in multiple industries. While these robots boast vast networks of sensors, processors, actuators, and communication systems all working together to achieve autonomous operation, a critical, yet often overlooked component is connector solutions that enable them to function in industrial environments. TE Connectivity's interconnect solutions address the reliability challenges manufacturers face when building industrial service robots as off-the-shelf connectors typically fail to meet requirements for miniaturization, durability, and performance.

Enabling autonomous movement and situational awareness

Navigation and safety systems in service robots use arrays of sensors like LiDAR, ultrasonic detectors, vision cameras, and inertial measurement units to achieve holistic environmental awareness. A key requirement is for each sensor to continuously generate data streams to be transmitted without loss or corruption to CPU for real-time analysis and decision-making. The ERNI MicroCon Series connector (Figure 2) fully meets the requirements with its industry-leading 0.8 mm pitch and sturdy, robust construction that allows designers to have the dense sensor integration necessary for environmental monitoring. The miniaturized 0.8 mm pitch spacing delivers space savings compared to 1.27 mm alternatives, which enables robot designers to integrate additional sensors into limited spaces.

The MicroCon's dual-beam female contact design provides exceptional reliability for sensor connections via its 1.9 mm wipe length for consistent electrical connectivity under continuous vibrations. Additionally, the wider contact surface in the dual-beam design, helps to minimize contact resistance variations that can potentially introduce noise to sensitive sensor signals. The connectors support data transmission rates of up to 3 Gbit/s, suitable for high-resolution camera systems and advanced LiDAR units that generate massive data volumes. Operating temperature range is from -55 to +125°C ensuring reliable performance whether the robot operates in sub-zero temperature environments or near industrial heat sources.

Safety systems in service robots also need fail-safe connectivity to maintain signal integrity under adverse operating conditions. The MicroCon's blind-mate pre-centering capability with ±0.7 mm misalignment tolerance is especially useful in modular robot designs where sensor modules require frequent replacement for maintenance or reconfiguration.

Figure 2: The ERNI MicroCon series
Source: TE Connectivity

Central control units: supporting precise command and coordination

In the control units of industrial service robots, power distribution efficiency and high-density signal routing capabilities are critical. These systems are responsible for coordinating motor controllers, processing sensor inputs, managing communication interfaces, and maintaining real-time control loops using battery power or industrial power supplies. Entrelec DBL Power Distribution Blocks can be integrated to optimize power management in control units. These blocks utilize a 3-in-1 configuration system that consolidates a single-pole splitter, multi-pole splitter, and grouping configurations into a single product family. With current ratings ranging from 80 A to 550 A, DBL blocks can meet a broad range of power needs of industrial service robots, from

Safety systems in service robots also need fail-safe connectivity to maintain signal integrity under adverse operating conditions.

low-power sensor circuits to high-current motor drives. Moreover, a 1500 VDC capability aligns with the latest high-voltage battery systems/industrial power supplies, while a 100 kA short-circuit rating offers exceptional safety margins to protect sensitive electronics from system faults.

For efficient signal distribution within robotic central control units, TE Connectivity offers its AMPMODU family of connectors (Figure 3). These products feature a 0.025” square post design with dual-beam contacts that provide mechanical robustness for connections subjected to heavy vibration while maintaining the electrical performance required for high-speed digital signals.

Operating temperatures from -65 to +105°C accommodate thermal extremes in industrial facilities without compromising connection integrity. The AMPMODU connectors are offered in pitch options from 1mm to 3.96 mm. High-speed processor interconnects can benefit from the 1mm centerline option with significant space savings compared to 2.54 mm connectors, while power and low-speed control signals can utilize larger pitches for easier assembly and higher current capacity. This flexibility allows control unit designers to optimize board layouts for both electrical performance and manufacturing efficiency.

Figure 4: TE Connectivity’s Industrial Mini I/O connectors Source: TE Connectivity

Delivering high-speed, durable connections

TE Connectivity’s Industrial Mini I/O connectors (Figure 4) address key limitations of RJ45 connectors with unique designs that achieve considerable size reduction while maintaining mechanical and electrical performance. For example, the Mini I/O uses a ‘fighting snake’ contact design with dual contact points that maintain connectivity and redundancy even when subjected to extreme vibration levels up to 50g encountered in mobile robotic applications.

With data rates from 10 Mbps to 10 Gbps, the Mini I/O system can be utilized in both legacy fieldbus protocols and newer Time-sensitive Networking (TSN) implementations. Power over Ethernet (PoE) capability can also simplify wiring architectures to further reduce the weight of robots. Moreover, Mini I/O connectors are designed using 360-degree metal shielding for electromagnetic interference protection in industrial environments where variable frequency drives, welding equipment, and other high-power systems can generate electrical noise that could otherwise corrupt data transmissions.

Mini I/O connectors feature a hermaphroditic contact layout with spring action on plug and receptacle sides that ensures consistent performance throughout the connector’s lifecycle of 5,000 to 10,000 mating cycles. This durability can be valuable in robots that dock repeatedly for charging or data transfer, as RJ45 connectors typically fail after hundreds of cycles. The 98N cable pull force rating prevents accidental disconnections during robot movement, while the compact form factor enables multiple network interfaces within limited panel space.

The Dynamic Mini (Figure 5), with a 1.8 mm pitch, is suitable for extremely high-density connections for serial communication buses that link up distributed sensor nodes and actuator controllers. It uses a 3-point contact system with 0.38 µm gold plating which offers low contact resistance over millions of operational cycles.

For internal communication between distributed control modules, TE Connectivity’s Dynamic family covers 3 A signal connections up to 100 A power links. Operating specifications from -55 to 105°C with vibration and shock resistance provide reliable operation throughout the robot’s operational lifetime.

Future-ready connectivity for evolving robotics trends

As service robots achieve full autonomy with enhanced capabilities and deeper integration with IIoT systems, connectivity will only become more demanding. For example, integrating 5G communication capabilities into industrial robots will require connector solutions capable of supporting the high-frequency signals and antenna connections for wireless operation. Emerging technologies like Single-Pair Ethernet will enhance robot networking by delivering high-speed communications over simplified cabling. TE Connectivity is positioned to support these emerging standards while maintaining backward compatibility with existing protocols.

Edge computing implementations that place artificial intelligence processing directly within robots demand exceptional signal integrity for high-speed processor interconnects. The AMPMODU and MicroCon systems’ proven performance at multi-gigabit data rates ensures readiness for these computational advances. As robots become more intelligent and autonomous, the reliability and performance of their

interconnection infrastructure becomes even more critical to overall system functionality.

Conclusion

Industrial service robots are some of the most demanding applications for durable connector technology, combining requirements for miniaturization, durability, signal integrity, and power handling that push traditional solutions beyond their limits. TE Connectivity’s comprehensive portfolio of specialized connectors including the ERNI MicroCon, Entrelec DBL blocks, etc., provide reliable connections in a broad range of robotic applications for multiple industries.

For more information on TE Connectivity’s robotics connectivity solutions, visit DigiKey’s TE Connectivity Robotics page.

Engineering silence: the telephone and the negative feedback amplifier

Written by: David Ray, Cyber City Circuits

The telephone is 150 years old and has undergone many different incarnations. From Elisha Gray's first version, playing the violin over telegraph lines to modern smartphone computers that no longer need a line to charge. At every step, innovations in the telephone have driven technological advancements. Innovations in transmission lines, switchboards, touch-tone systems, audio filters, FSK modems, and more. Just like when they stretched telegraph lines across the ocean, pulling telephone lines across the country also led to new and unique problems emerging along the way.

Harold S Black while testing his new system in 1930.

This is the story of distortion and noise and how a man named Harold Black solved it.

Western Electric and the telephone

Elisha Gray first invented the telephone in 1875. His company, Western Electric Manufacturing Company in Chicago, had worked in the telegraph industry for years, manufacturing all kinds of equipment. Gray retired from his administrative duties at Western Electric the year before to focus on his own research.

He began holding demonstrations in January 1875. Various tunes, including 'Yankee Doodle', 'Robin Adair', 'Auld Lang Syne', and others, were transmitted a mile and heard by a room full of ladies and gentlemen as loudly and tunefully as if they had been in the same room where they were played. These demonstrations were nationwide news. Everyone was excited about the prospect of actual voice communication, but Gray's telephone could only transmit music from an instrument, like the violin.

Alexander Graham Bell, a Scottish immigrant, was a dedicated servant to those who suffered from deafness and hearing loss. He and his engineer, Thomas Watson, worked for months to develop a method for the deaf to communicate using the telegraph or a similar device. Working on this problem, Bell and Watson had developed a way to send a voice message over telegraph wires and files, for which they were granted a patent in March 1876, fifteen months after Gray first demonstrated his telephone. Within a few weeks of applying,

Elisha Gray and his first telephone.

Bell was awarded the patent for the telephone.

Around the same time, Gray sold his interest in the Western Electric Manufacturing Company to the telegraph giant, Western Union. Now owning the patent applications and caveats filed by Gray, Western Union sued Bell Telephone over this patent dispute. Western Union lost the lawsuit and, as part of the judgment, was forced to exit the telephone industry altogether, selling Western Electric to Bell Telephone. Western Electric became the manufacturing division of Bell Telephone for the next fifty years, and many of the world's great innovations came out of the team at Western Electric.

Retro Electro fun fact: the official story goes that Gray filed for a patent on his telephone within moments of Bell, but Bell's application was awarded while Gray's was not because Bell's was earlier in the day. Newspapers would allege, a decade later, that Bell bribed the patent examiner, Mr. Wilber, with a $100 bill (half of a month's pay for an examiner) for his 'favoritism' in this matter.

The proliferation of telephones throughout the developed parts of this country was very quick. It soon surpassed telegraph line production, and Bell Telephone was at the center of it all.

Long-distance phone calls

Eventually, phone lines would stretch across the country, including the transcontinental telephone line (1914), which had amplifier stations all along the way. Every ten to twenty miles, there would be a repeater station. As with the transatlantic cable, once the telephone was used over long distances, new problems began to appear.

- Signal attenuation – as the electrical signals traveled through the telephone lines, they experienced attenuation, requiring the use of many amplifier stations and, in some cases, manned relay stations
- Noise from the repeaters – each repeater was designed around high-voltage vacuum tubes, and each one carried with it some intrinsic thermal noise or 'hiss.' Each station would amplify the noise from every station before it, and eventually, the noise would rival the intended voice signal, making it unintelligible. The distortion in a string of amplifiers would increase in direct proportion to the number of amplifiers
- Poor quality telephone lines

Bell and Watson] Caption: Alexander Graham Bell (Left) with his engineer Thomas Watson (Right).

– while every effort would be made to make the best cable, transmission line theory was still poorly understood. Quality was all over the place

- Impedance mismatch – inconsistent quality caused signal reflections, propagation delays, and a noticeable echo. Stations attempted to remedy this by using long adjustable coils to help balance the lines. An operator had to monitor the resistance on the lines and adjust the coil and the amplifier's gain accordingly
- Environmental noise – in addition to thermal noise and the vacuum tube 'hiss,' weather conditions significantly affected phone signal quality. Lightning strikes would produce loud bursts of noise, which would be amplified through the repeater stations. Ice buildup on the lines would consistently disrupt the impedance, requiring continuous adjustment of loading coils

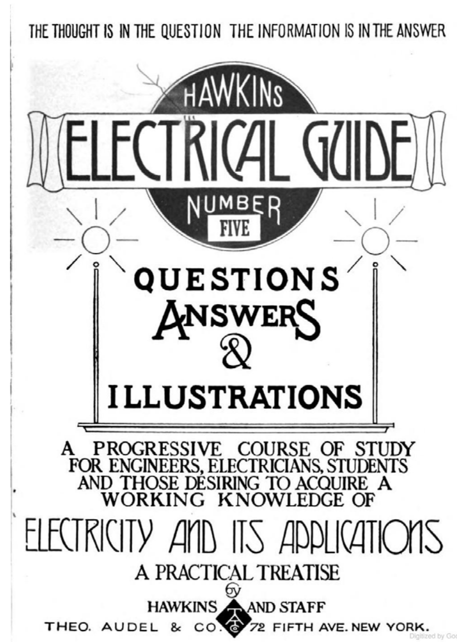
Retro Electro fun fact:
as this is going on, at the same time Frank J Sprague was perfecting is electric traction motor, bringing electric mass transportation to reality. Learn more in the Retro Electro article, Frank J Sprague and the Richmond Union Passenger Railway. (https://www.digikey.com/en/emedia/emagazine/2024/transportation?page=9)

…and every imperfection in the audio quality had to be amplified with the intended signal.

Harold S. Black

Harold Stephen Black was born on April 14, 1898. His father worked at a 'shirt shop' and had an eighth-grade education. His mother was a Stenographer. As a teenager, he bought a series of books on the subject of electricity. The Hawkins Electrical Guide, published between 1914 and 1917 by Nehemiah Hawkins, was a comprehensive and accessible series of small volumes designed to teach readers about electricity and its practical applications. Spanning numerous concise books, the guide covered a wide range of electrical topics, from basic principles of electricity, wiring, lighting, and circuits to detailed explanations of electric motors, generators, batteries, telegraphy, telephony, and electrical measurement instruments. Each volume was full of diagrams and technical drawings, making complex concepts understandable to many people, including teenage hobbyists of the day, like Harold Black.

Starting in 1914, with these books, he started gathering 'electrical things' from the local town dump in the attic of the house they were renting. He tells of when he was 16, he built a microphone out of some scrap wood and some carbon that he pulled out of an old battery. He



The Hawkins Electrical Guide series of books was very influential to engineers and hobbyists of the day.

ran wires across the street to the neighbor's house, and he said that he could hear everything in their house, even the ticking of a watch. Soon, the father came home and saw it, ripping it out of the window and destroying the microphone. His first telecommunications system didn't last very long.

Joining Western Electric

After high school, he attended Worcester Polytechnic Institute (WPI), where he earned a degree in electrical engineering in 1921. Western Electric's Systems Engineering Laboratory at 463 West Street, New York, soon hired him, starting at $32 a week. He was assigned to a team that was trying to solve issues surrounding long-distance calling and the transcontinental telephone line. This is a problem they had already been trying to solve for nearly a decade when he joined.

In an interview, he tells the secret of his success at Western Electric. Frustrated after being passed over for a raise following his first three months at West Street Labs, Harold Black briefly considered quitting, only to decide the next morning that "I am going to go to work and learn everything that I can about the business." He realized that everything an engineer did had to be documented in a memorandum, and all of those were archived.

To that end, each Sunday, he would visit the archive with a special pass from the guards. He methodically read the firm's archival memoranda, dating back to his birth year, 1898, absorbing technical reports and organizational histories that spanned all twelve floors of 463 West Street. While smoking in the archives was not permitted for obvious reasons, he would repeatedly get caught smoking his pipe while reading. After being written up for it four times by the guards, he was allowed to spend his time reading in one of the higher supervisors' offices, where smoking was permitted. This gave him additional access to a wide range of new information.

The offices at 463 West Street in New York City.

The problem of developing a perfect amplifier

In 1921, the new goal was to make transcontinental telephony practical. The first transcontinental telephone call was made in January 1915, which included President Woodrow Wilson. The quality of this call was terrible by any measure. The attenuation over the thousands of miles of copper forced each side to yell into the microphone, in hopes that it would make it through to the other side. The voices were described as hollow and 'metallic.' The higher frequencies in the voice were lost. There was a significant delay and echo, making the conversation difficult and disjointed. The many repeaters between the participants amplified all of the noise and distortion along the way. Every time someone spoke, there was a rise and fall in background static, so bad it was described as "like a distant train whistle over a stormy sea."

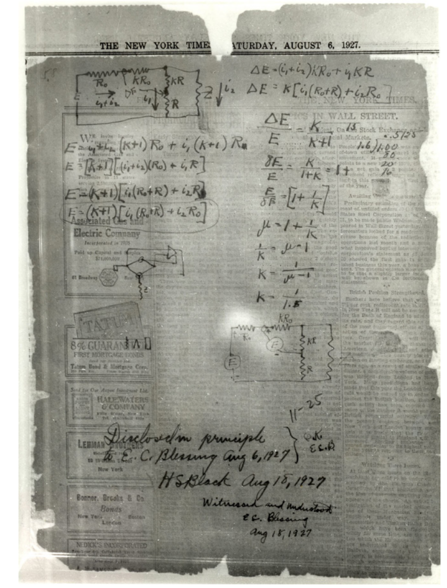
The repeater amplifier problem was considered unsolvable to everyone because nobody knew how to make the amplifier linear or stable enough. For years, the only approach to a solution was to try to make a perfect 'linear' vacuum tube. All this research later proved that it is impossible.

Retro Electro fun fact: while the reader can find 'AA,' 'C,' and 'D' batteries at the local hardware store, 'A' and 'B' batteries are absent. 'B' batteries were used in early vacuum tube equipment to provide a plate voltage of up to ninety volts, while an 'A' battery was used to supply high current to heat the filaments in the tubes.

First principles

After working on this problem for over a year, Black was plainly stumped. The unsolvable problem. Then, in March of 1923, Black attended a lecture by mathematician and electrical engineer Charles Steinmetz. Black arrived early to get a seat in the front row. Steinmetz arrived 20 minutes late, walking down the aisle with enormous applause and an even larger cigar hanging out of his mouth. Black recounts this lecture by saying that "***I no longer remember the subject, but I do remember the clarity and logic of his presentation and how quickly and directly he reached the final conclusion of his talk.***"

Black was so impressed by this approach that he went home and restated his amplifier in a new way. Removing all of the superfluous requirements of gain and distortion rejection. He framed his new problem simply as "remove all distortion products from the amplifier output." The amplifier output consisted of two different parts: the wanted signal or intelligence and the unwanted distortion. Anything that was not part of the desired signal was now considered distortion. Now to "isolate and then eliminate this distortion."



The newspaper that Black wrote out the solution he received 'in a flash'

He now considered that if he reduced an amplified output signal from an amplifier to the same amplitude as the input signal and then subtracted the input signal from the adjusted output, the only thing that would remain would be the distortion from the amplifier. He could take this distortion, using a separate amplifier, amplify it, then subtract it from the original amplifier output, thereby relieving the system of the distortion. Surely this felt like the perfect solution at the time, but it was still far from it. He designed a 'feed-forward amplifier' with this solution, but every hour, twenty-four hours a day, a technician had to make adjustments to the vacuum tube's current. Then, four times a day, someone had to adjust the voltages of the 'B' battery. Ultimately, these solutions were too complicated and complex to be practical.

Retro Electro fun fact: this is the underlying concept that makes modern operational amplifiers (Op-Amps) work.

In a flash

Then, after four years of trial and error, while riding the ferry to the city from his home in New Jersey, it came to him 'in a flash.' He realized that if he fed the amplifier output back into the input, but 180 degrees out of phase, he would have what he had been wanting. "A means to cancel out the distortion in the output." He took what paper he had with him, that day's copy of the New York Times, and scrawled out the diagrams and formulas needed for the negative feedback amplifier. As soon as the ferry stopped, he ran to the West Street Labs (by then renamed to Bell Labs) and had it witnessed by Earl C. Blessing.

Few people had faith that it could work. Feeding the output of an amplifier back into the input just sounds like loud noise. Consider what happens when a microphone is placed near a guitar amplifier. Quickly, the signal will 'self-oscillate' and it will start wailing a high-frequency ear-bursting whine. This skepticism of the concept would follow him for the next several years.

Within a few weeks. He had a working model that gave a reduction in distortion of 100,000 to 1 in a single amplifier module, finally solving the task he had been assigned six years earlier. These results were quickly signed and sent off to Bell Labs' patent lawyer, Harry A. Burgess.

In January 1928, Bell Labs began developing a new system for transcontinental cables. This became the first application of the invention. Each amplifier was

The Negative Feedback Amplifier works by feeding the output through a 'feedback circuit' back into the input of the amplifier.

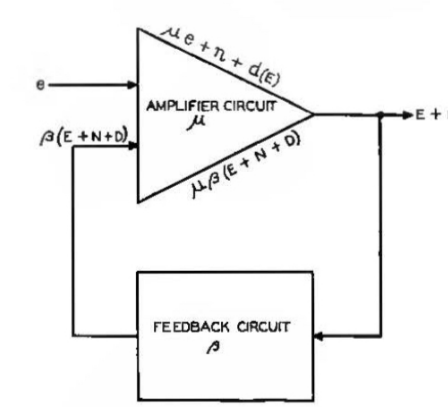


Fig. 1—Amplifier system with feedback.
e—Signal input voltage.
μ—Propagation of amplifier circuit.
μe—Signal output voltage without feedback.
n—Noise output voltage without feedback.
$d(E)$—Distortion output voltage without feedback.
β—Propagation of feedback circuit.
E—Signal output voltage with feedback.
N—Noise output voltage with feedback.
D—Distortion output voltage with feedback.

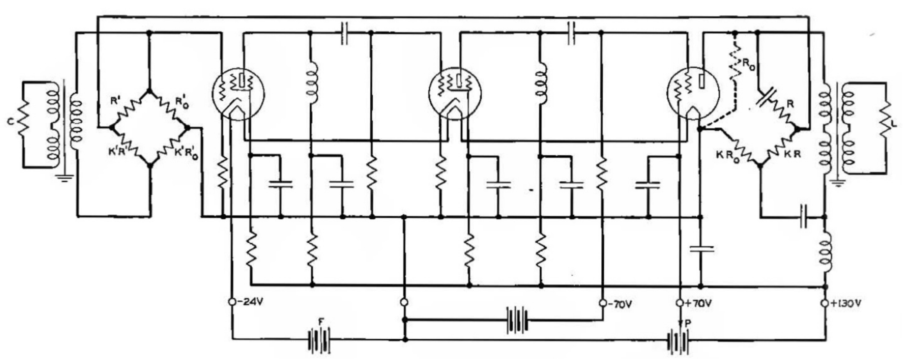


Fig. 2—Circuit of a negative feedback amplifier.

expected to transmit up to nine different voice channels over a single pair of 16-gauge wire in a twenty-five-mile-long underground cable between repeater stations. Once word of this started spreading at Bell Labs, the higher-ups at the company objected, claiming it was impossible for it to actually work. Instead, Black was instructed to design more traditional Colpitts push-pull amplifiers that could meet the requirements, and he did.

Rarely discouraged, behind the scenes, he started designing six different models of his negative feedback amplifier, in addition to the other work. When he was able to demonstrate that these new amplifiers could easily meet the requirements of the proposed system, the management was satisfied, and he didn't hear anything else about using the Colpitts amplifiers.

A couple of years later, his new system was ready for a field test. They built seventy-eight new negative feedback amplifiers and took them to the labs at Morristown, NJ. Here, they used a twenty-five-mile-long stretch of cable, made up of sixty-eight pairs, each expected to carry nine voice channels. With this cable, looping back on itself with every pair, they were able to simulate communication over a 7,650-mile distance, which resulted in excellent voice quality.

Patent troubles

Even though the patent application was sent off to the US Patent Office in 1928, it would be over nine years before the patent was issued. The main reason for this is that it was already well established that you cannot tie the output of an amplifier back into its input and achieve a gain of more than one. The concept of negative feedback was totally unknown. The patent examiners would cite numerous technical journals showing that it's impossible that it could work. In England, Black says in an article, his "patent application was treated in the same manner as one for a perpetual motion machine."

The patent was long. It had 75 different figures and diagrams, nine pages of 126 different claims, and 42 pages of text. Since the concept of negative feedback was brand new, much of the patent was spent trying to teach the concept, making it difficult and time-consuming to go through.

Eventually, Bell Labs was able to overcome these problems by demonstrating that 70 amplifiers were currently functioning successfully in the telephone building at Morristown, New Jersey.

The issue with patents is that they are only as good as the holder's ability to defend them

Bell Labs v Zenith

The issue with patents is that they are only as good as the holder's ability to defend them. Bell Laboratories aggressively enforced the negative-feedback amplifier patent against Zenith Radio Corp. beginning in 1948. Bell Labs alleged that Zenith's FM and AM receiver designs incorporated feedback loops that infringed Black's patent. Black was deposed and testified extensively over multiple sessions between 1948 and 1953, explaining both the genesis of his inverted-feedback concept and the technical distinctions between his licensed implementations and Zenith's circuits. The litigation ultimately led Zenith to negotiate a licensing agreement with Bell Labs, under which Zenith paid royalties for use of the negative-feedback technique in its high-fidelity receivers.

Harold Black in 1981

Legacy

Nearly one hundred years later, the negative feedback amplifier concepts can be found in everything. It is used in Op-Amps, EVs, space satellites, cell phones, guitar amps, cruise missiles, prosthetic limbs, and in thousands of other applications. In this way, Harold S. Black is an inventor on the tier of Lord Kelvin, Hans Camenzind, and Philo Farnsworth.

After more than four decades at Bell Labs, Black joined General Precision Corporation in 1963 as a Principal Research Scientist. Beginning in 1966, he transitioned to work as an independent communications consultant. By that time, Dr. Black had amassed 62 U.S. patents and 271 additional patents across 32 countries. In addition to numerous technical papers, he authored the seminal text Modulation Theory in 1953. In recognition of his contributions, Worcester Polytechnic Institute awarded him an honorary Doctor of Engineering degree in 1955.

Suggested reading

1. The Bell Telephone: Patent Nonsense? (Washington Post, Feb 20, 2008) https://www.washingtonpost.com/wp-dyn/content/article/2008/02/19/AR2008021902596.html?sub=AR
2. The 'Musical Telegraph' or 'Electro-Harmonic Telegraph', Elisha Gray. USA, 1874 https://120years.net/the-musical-telegraphelisha-greyusa1876/
3. The Telephone Gambit: Chasing Alexander Graham Bell's Secret by Seth Shulman
4. Harold S. Black, an oral history conducted in 1977 by Michael Wolff, IEEE History Center, Piscataway, NJ, USA. https://ethw.org/Oral-History:Harold_S._Black
5. Harold Black and the Negative Feedback Amplifier by Robert Kline https://brewer.ece.gatech.edu/ece3043/FBBlack.pdf
6. Inventing the Negative Feedback Amplifier – IEEE Xplore (December 1977) https://wiki.epfl.ch/me412-emem-2020/documents/06501721.pdf
7. Stabilized Feedback Amplifiers – The Bell System Technical Journal https://convexoptimization.com/TOOLS/Black.pdf
8. Harold S Black Patents (Google Patents) https://patents.google.com/?inventor=Harold+S+Black&sort=old https://patentimages.storage.googleapis.com/b8/63/f0/e6bfd23228c3e1/US2102671.pdf
9. Modulation Theory by Harold S. Black https://babel.hathitrust.org/cgi/pt?id=mdp.39015002077488&seq=9

January 1875

Elisha Gray holds public demonstrations of his liquid-transmitter telephone, broadcasting tunes like 'Yankee Doodle' over a one-mile line, generating nationwide excitement.

March 1876

Alexander Graham Bell and Thomas Watson file a complete patent application for Bell's telephone; Bell's patent is granted within weeks.

Elisha Gray sells his interests in Western Electric Manufacturing Company to Western Union.

1879

Western Union sues Bell Telephone in the Gray–Bell dispute but ultimately loses, formally beginning the Bell Telephone Monopoly.

Western Union sells Western Electric to Bell Telephone.

January 1915

First transcontinental telephone call.

July 5, 1921

Harold Black joins Western Electric's West Street Labs, earning $32 per week.

March 16–17, 1923

Inspired by Charles Steinmetz's lecture, Black sketches and tests feed-forward amplifier prototypes.

1925

Western Electric and the West Street Labs are rebranded as Bell Laboratories.

August 2, 1927

Aboard the Lackawanna Ferry, Black conceives the negative-feedback amplifier—scribbling inverted-feedback loop diagrams on a New York Times newspaper.

January 1928

Bell Labs begins developing a new transcontinental cable-carrier system using Black's feedback amplifiers to carry nine voice channels over a single wire pair spaced 25 miles apart.

August 8, 1928

U.S. patent application filed for Black's negative-feedback amplifier.

1930

Morristown field trial simulates a 7,650-mile-long connection link, delivering excellent voice quality.

December 21, 1937

U.S. Patent No. 2,102,671 for the negative-feedback amplifier is finally issued after a nine-year examination.

1948–1953

Bell Labs sues Zenith Radio Corp. for infringing Black's feedback amplifier patent.

1953

Black publishes Modulation Theory, a definitive textbook on communications and modulation techniques.

December 11, 1983

Harold S. Black passes away in Summit, New Jersey, at age 85—leaving a legacy of 62 U.S. patents and 271 international patents across 32 countries.

Unlocking the potential of 48 V systems with Allegro Solutions

By Electronic Specifier

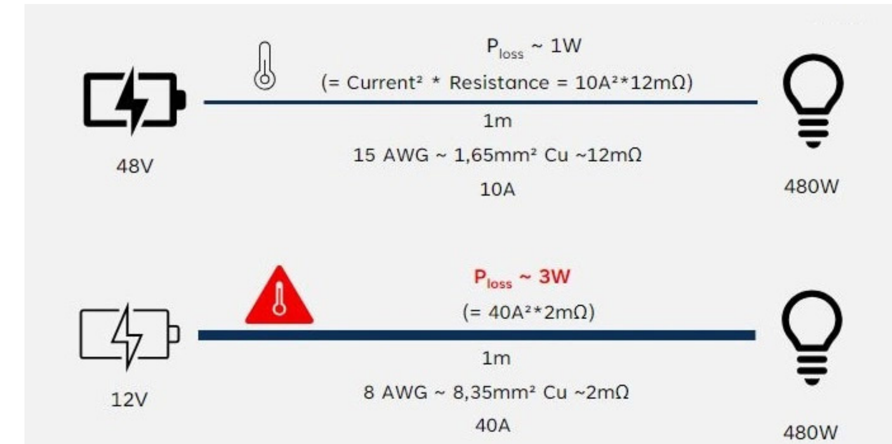


Figure 1: Power loss comparison between a 48 V system and a 12 V system. Image source: Allegro

The demand for efficiency and cost-effectiveness in electrical systems is driving the adoption of 48 V systems across industries. These higher voltage systems provide a more optimal alternative to conventional 12 or 24 V architectures, especially where higher power delivery is crucial. Industrial automation and telecommunications leverage 48 V to power motors, actuators, and other high-power equipment.

The advantages of using 48 V systems include:

- Drive larger loads: unlike 12 V systems, which struggle to meet modern power requirements
- Lower currents: higher voltage reduces current requirements fourfold
- Reduced power loss: lower currents mean less power loss, less heat to dissipate, and higher efficiency; operating at a higher voltage, Allegro's 48 V solutions drastically reduce energy loss compared to conventional 12 V systems
- Higher power density: Allegro's highly integrated 48 V solutions enable higher power density space compared to competitive solutions, translating to further driving range and lower energy loss in clean energy systems
- Lighter cabling: thinner cables lower costs and reduce weight and space,
- lower current requirements of 48V systems, coupled with Allegro's innovative design approaches, allow for thinner and lighter wiring harnesses and fewer overall components

History of power distribution systems

The 6 V power distribution system became a practical standard for ignition and lighting in early automobiles, largely influenced by the widespread use of batteries at the time. Its simplicity and ease of use made it a popular choice.

Although 24 V systems were initially trialed – for example, in the 1912 Cadillac with its electric starter – the 6 V system quickly gained dominance for most automotive electrical functions.

As automotive technology progressed, the demand for electrical accessories such as radios, heaters, and later, power windows, began to grow. This placed greater strain on the electrical system, highlighting the limitations of the 6 V setup. A 12 V system offered a key advantage: for the same power output, it required only half the current, which reduced the risk of overheating and allowed for the use of lighter, more manageable wiring.

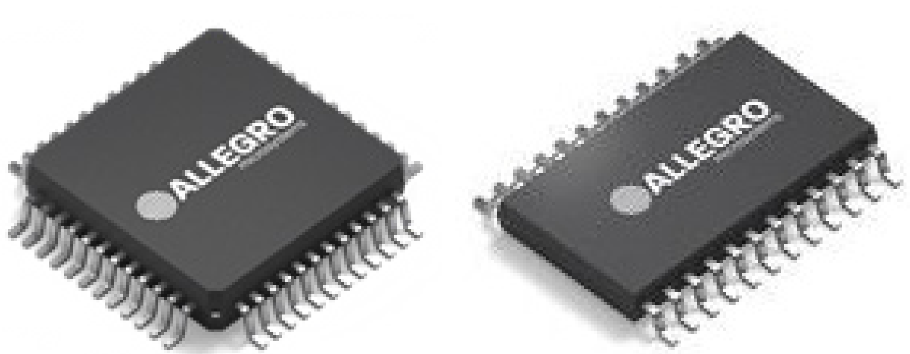
The development of reliable 12 V lead-acid batteries and alternators further supported the transition. With these components becoming easier to produce and more cost-effective, the 12 V system became the new standard. This led to the design and widespread adoption of compatible electrical parts, including lighting and motors that operated more efficiently at the higher voltage.

Struggles of traditional systems

Modern power demands cannot be met with traditional 12 V systems, currently the mainstay of power delivery. The limitations of 12 V systems become clear when considering factors like power loss and cable thickness.

As power demands increase, so do the currents within a 12 V system in a linear fashion (P = V * I). This results in higher power losses along any wiring from the supply source to the load ($P_{loss} = I^2 * R$) (Figure 1).

These power losses manifest as unwanted heat and reduced system efficiency. Also, managing higher currents requires thicker and heavier cables which adds weight and cost to system designs.



AMT49100 3-Phase BLDC Gate Driver (Figure 2, left)
A89503 Half-Bridge Gate Driver (Figure 2, right)

48 V systems highlights

1. It is safer to handle than the higher voltage of 110 – 240 VAC typically used in homes and businesses because it is a low voltage, meaning it is less likely to cause electrical shock or injury and use lower current for the same power output.
2. It provides more power output and torque for a given motor size, enabling higher performance and acceleration. Also, it can effectively recover kinetic energy during braking and deceleration, storing it for later use in additional torque or to power other vehicle systems.
3. It is more 'mobile' compared to 12 or 24 V systems, especially in applications where space and weight are important, and it requires fewer wires and less current to transmit the same amount of power, which can be advantageous in mobile environments such as RVs or campers.
4. The portable 48 V battery pack has emerged as an excellent solution to meet the power needs during camping trips. It is usually encased in a lightweight material, enabling campers to bring along electrical equipment such as lights, small refrigerators, and charging stations for their mobile devices.
5. It offers energy savings by reducing wiring material and labor costs, improving fuel efficiency, and enhancing overall system performance. This allows for thinner wires to carry reduced current compared to 12 V systems, leading to lower resistive losses and heat generation.
6. It enables space savings in various applications due to their higher voltage and lower current requirements. This allows for smaller conductors, more compact components, and increased power density, especially when compared to 12 V systems.

Industrial automation equipment

48 V systems are increasingly used in industrial automation and robotics, offering higher power and improved safety over lower voltage systems. This includes components like motors, sensors, and gate drivers that are designed to handle the higher voltage and power demands of industrial applications.

The lower currents present in these systems reduce heat generation and potential fire hazards. Compared to higher voltage systems, 48 V systems requires less insulation, which can be a factor in compact designs. As they fall below the 60 V safety limit, they are often considered SELV (Safety

ACS37220 Low-Resistance Current Sensor (Figure 3, left)
ACS724 and ACS725 Isolated Current Sensor (Figure 3, right)

Extra Low Voltage), meaning they are designed to be safe for direct contact with unshielded equipment.

48 V systems offer enhanced efficiency and precision by reducing energy loss, enabling faster control, and allowing for smaller, lighter equipment, increased dexterity, and improved thermal management.

48 V solutions with high efficiency and maximum performance

Allegro offers a broad array of sensor and power IC products ready for use in the design of 48 V systems across a myriad of robotic applications.

The reduced power loss with Allegro's 48 V solutions translates to a tangible increase in fuel economy for mild hybrids, significantly extending the range for all electrified vehicles and improving energy conversion efficiency in solar inverters.

Motor and gate-drive units

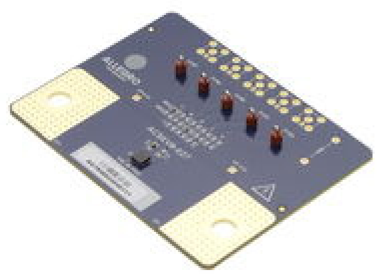
Allegro's motor and gate drivers provide precise and efficient control for 48 V motors and actuators used in automotive and industrial automation, improving productivity and reliability.

Their integrated current sensor IC supports high-voltage applications, while the digital position sensors deliver robustness and reliability to complement the motor drivers.

- AMT49100: 3-Phase BLDC Gate Driver, 3x Integrated Low-side CSAs, True 48V capability, SIL-3 Compliance
- A89503: Half-Bridge Gate Driver, Integrated Low-Side Current Sensor, True 48V capability, SIL-2 Compliance
- A89500: Joint Brake Half-Bridge Gate Driver, True 48V capability, Functional Safety Quality Managed (FS-QM)

Current sensors with functional isolators

- ACS37220: low resistance, high power density 200A current



sensor in QFN Package
- ACS37041: +/- 2.8% sensitivity error, 7.6 bits resolution, is a small leaded magnetic current sensor for cost-optimized applications
- ACS724 and ACS725: high-accuracy, isolated current sensor ICs with stray field rejection

Isolated gate drive units
- AHV85000: primary side of GaN FET isolated gate driver chipset with power-thru integrated isolated bias supply
- AHV85111: self-powered single-channel isolated GaNFET gate driver with regulated bipolar output drive

Autonomous Mobile Robots (AMRs)

AMRs navigate dynamic environments for logistics and inspection, demanding precise motion, robust battery management, and reliable obstacle detection.

Allegro's integrated motor drivers, magnetic sensors for positioning and load sensing, and efficient power management ICs enhance AMR performance, optimize energy usage, and ensure operational safety in diverse settings.
- AAS33001: Motor Position Sensor for precise wheel/lift motor control with easy integration and on-chip misalignment calibration.
- ACS71240: Current Sensor that enables efficient battery life with low-cost, low-loss current sensing for motors.

Collaborative robots (Cobots)

Cobots work safely with humans, requiring precise motion, advanced safety features (SIL-2/3), and efficient power for articulated joints.

Allegro's true 48V gate drivers, high-resolution position sensors, and accurate current sensors enable robust joint performance, dependable braking, and optimized power management for reliable human-robot collaboration
- AMT49100: 3-Phase BLDC Gate Driver with true 48V capability, integrated CSAs, and SIL-3 for safe servo motor control
- CT310: TMR Bridge Angle Sensor with high-resolution (13-14 bit) analog output for precise motor commutation and joint feedback

Humanoids

Humanoid robots aim for human-like motion and interaction, demanding sophisticated actuation, dynamic balance, and complex perception.

Allegro's advanced servo motor control, versatile multi-axis position sensing, and efficient power management technologies are fundamental for the intricate mechanics and demanding performance required by the numerous joints in Humanoid robots.
- AMT49100: 3-Phase BLDC Gate Driver with SIL-3 compliant 48V motor driving for precise control of multiple high-performance joints
- A31301: Multi-Axis Position Sensor with user-selectable axes for flexible, precise angle sensing in complex, space-constrained joints

Evaluation boards
- ACSEVB-EZ7-37220-100B3: evaluation board for the ACS37220 current sensor
- APEK49101KJP-A-03-T: evaluation board for the AMT49101 ASIL BLDC MOSFET gate driver
- APEK89500GEJ-01-T: evaluation board for the A89500 fast switching 100 V half-bridge MOSFET driver
- APEK85111KNH-02-T-MH: evaluation board for AHV85111 self-powered single-channel isolated GaN FET gate driver

Why stop at 48 V?

The primary factor behind this limit was the safety standards that had to be met. Organizations such as UL and NFPA classified voltages below 60 V as Safety Extra Low Voltage (SELV), considering them safe for human contact with unshielded equipment.

Systems operating above 48 V required more robust components and engineering to ensure adequate insulation and isolation, which increased overall cost and complexity.

Although 48 V systems could be cost-effective, higher voltage systems often involved greater initial expenses due to the need for specialized components and wiring. Their design tended to be more complex, and implementation could be more costly, as specialized parts were either more expensive or demanded more intricate manufacturing processes.

Powering the artificial intelligence revolution

Delivering low-latency AI responses requires substantial computing power, which significantly increases data center energy demands. To improve efficiency and reduce cooling requirements, data centers are transitioning from 12 to 48 V power systems.

Innovations in power supply design support this shift, with future developments aimed at enhancing power supply performance and density. Consequently, data centers need to be equipped with high-performance servers, advanced cooling systems, and robust power infrastructure to manage the workload effectively.

Data center operators are increasingly adopting energy-efficient technologies such as liquid cooling, renewable energy sources, and server virtualization to reduce their carbon footprint and lower operating costs.

Conclusion

The shift from 12 to 48 V systems is driven by the need for improved efficiency and reduced cooling requirements. In industrial automation, these systems offer higher power and enhanced safety compared to lower voltage options.

Components such as motors, sensors, and gate drivers are designed specifically for 48 V systems, with a focus on safety, power output, mobility, and cost savings.

With a wide range of 48 V products, Allegro delivers solutions that enable higher integration, as well as space and energy savings, allowing you to concentrate on your application.

Written by Electronic Specifier

Smart GNSS antennas: a better way to design positioning, navigation and timing into your project

Calian's Dual-Band High-Performance Global Navigation Satellite Systems (GNSS) Antennas offer a plug-and-play solution that supports future-proofing for Positioning, Navigation, and Timing (PNT) enhancements via a digital interface. These antennas are designed to adapt easily to evolving PNT requirements, ensuring long-term usability and streamlined integration.

This article focuses on specific models within the range: the TW5384 (Figure 1, left), TW5386, TW5387, TW5390, TW5790, TW5794, TW5394, and the HCS885XF (Figure 1, right). It outlines the performance improvements these products deliver, along with the key features that make them reliable and competitive choices within the GNSS antenna market.

Successful GNSS

The use of GNSS to provide PNT has become widespread across countless types of systems. Its success has made GNSS a foundational element in virtually all mobility applications – a sector that continues to grow rapidly.

In most designs, this capability is implemented by pairing a GNSS receiver module – such as the u-blox F9 series – with a high-performance GNSS antenna. The receiver is typically mounted on the system's control board and connected to the external antenna using standard connectors and coaxial cable.

While this setup has proven highly effective for single-band GNSS applications with modest accuracy requirements, developers often underestimate the increased complexity involved when transitioning to PNT solutions that demand centimeter-level precision.

Figure 1: TW5384 Smart GNSS Antenna w/ u-blox ZED-F9P series receiver (left), and the HCS885XF Smart GNSS Antenna w/ u-blox NEO-F9P series receiver (right). Image source: Calian

Expert-level solutions

Cm-level positioning is susceptible to in-band frequency interference from common system elements such as high-speed buses and other RF emitters. Smaller design teams don't have the expertise to deal with the performance degradation that can occur.

With these accuracy requirements rapidly expanding, designers without experience are poorly equipped to anticipate the effect it can have on their projects. Smart GNSS antennas not only mitigate this problem, they also provide a pathway to easy system upgrades when new PNT technologies come online.

Calian's smart antennas are designed and manufactured to meet high standards of performance and reliability. They are ready to use straight out of the box, providing impressive accuracy – typically less than 50cm – without the need for augmentation. This level of precision is achieved through the integration of a high-quality antenna and receiver.

For applications requiring even greater accuracy, augmentation can offer significant benefits. Calian supports this through its software development kits (SDKs), which enable developers to enhance system performance and unlock advanced positioning capabilities.

Navigating with precision

Calian's high-precision integrated smart GNSS antennas combine advanced antenna technology with high-end GNSS receivers, offering a reliable solution for demanding positioning and timing applications. These antennas address key RF design challenges – such as multi-constellation, multi-frequency compatibility, and interference mitigation – that can otherwise compromise GNSS performance.

With Calian's smart GNSS antennas, developers can concentrate on timing or positioning needs while customizing elements of their system, including interface options, mechanical components, mounting styles, and the addition of inertial measurement units (IMUs) for enhanced performance in dense urban environments.

The multi-band, high-precision solutions support centimeter-level accuracy through compatibility with both local base/rover corrections and commercial Real-Time Kinematic (RTK) services from various vendors. Integrated IMUs help reduce the impact of severe multipath effects, enabling robust performance even in challenging GNSS conditions.

Software Development Kits

Calian's Smart GNSS SDKs offer a plug-and-play evaluation platform for its Smart Antennas, designed to streamline development and integration. The SDKs include tools such as TruPrecision software, a short-term complimentary augmentation subscription, and straightforward PC connectivity via USB.

The TW5794 **Smart GNSS Antenna SDK** (TP5794SDK) provides a ready-to-use solution for achieving precise heading in robotics applications. It is based on Tallysman's TW5794 Smart GNSS Precise Heading Antenna,

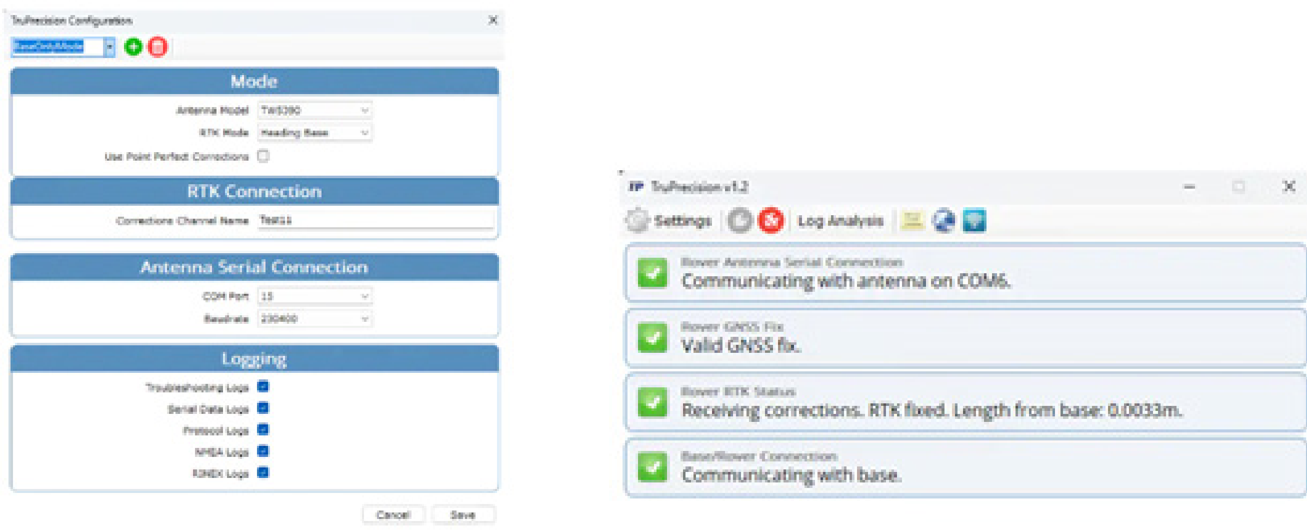


Figure 2: An example application using the TruPrecision SDK for Windows. Image source: Calian

delivering accurate performance with minimal setup.

The HCS885XF **Smart GNSS Helical SDK** is a lightweight, low-power L1/L5 antenna solution optimized for handheld devices, robotics, and drones. It leverages the L5 enhanced signal architecture to offer improved standard positioning accuracy and effective mitigation of multi-path errors. Operating within the ITU/ARNS aviation band, it benefits from regulatory protection against interference.

The **TruPrecision SDK application** (Figure 2), developed for Windows, allows automatic streaming of RTK corrections and decryption keys to both the TW5794 and HCS885XF Smart Antennas. The system connects via a USB cable, which provides a Virtual COM Port. This enables developers to link their existing applications directly to the high-precision, corrected GNSS position data output from the Calian Tallysman Smart GNSS Antennas.

Calian gives you the tools to manage these products, including configurator downloads, manuals, its full TruPrecision application, and complementary trials of the following corrections services:

- u-blox PointPerfect Augmentation Service (60 days)
- Swift Navigation Skylark Cx Precise Positioning Corrections (6 months)
- Point One Navigation Polaris RTK Corrections (2 weeks)

Maximizing GNSS signal clarity

Antennas play a critical role in GNSS systems by reducing interference and preserving signal integrity – factors that are essential for achieving accurate positioning. The primary function of a GNSS antenna is to deliver as clean a signal as possible to the receiver.

However, the signal path from the antenna element to the receiver can introduce systematic errors, particularly in traditional setups where the antenna is positioned some distance away from the receiver. This separation exposes the signal to local system impairments and potential degradation.

The transition to carrier-phase precise positioning systems, especially those using integrated L-Band augmentation, demands a more detailed and refined approach to GNSS system design. In such systems, maintaining the integrity of the GNSS signal throughout the signal chain is crucial for sustaining carrier phase lock, preventing cycle slips, and ensuring reliable convergence in difficult operating environments.

Given that GNSS signals are low in amplitude and easily disrupted, the most effective strategy is to design the system around a well-characterized set of physical and electrical parameters. This careful design approach helps preserve signal quality from antenna to receiver, enabling higher precision and stability.

Streamlining accuracy

The most effective GNSS solution minimizes the opportunity for signal degradation by limiting the variables between the analog GNSS signal and its digital geo-location output to a defined, controlled set.

Calian addressed this by integrating high-performance antennas with leading commercial GNSS receivers within a single, native mechanical package. This integration reduces signal path complexity and ensures consistency in performance. The combined antenna-receiver system connects to the target application via a 'fit for purpose' interface, with options including:

- RS422/485
- RS232
- USB2.0 Type A
- USB2.0 Type A with BLE and Wi-Fi
- CAN BusAutomotive Ethernet 100BaseT1

Calian's augmented smart antenna solutions feature support for PPP (Precise Point Positioning) and PPP-RTK, using u-blox's F9x GNSS receivers and DSx satellite-based correction receivers. This configuration offers high-accuracy positioning with a streamlined integration process, tailored to meet the needs of precision-focused applications.

TruPrecision testing

TruPrecision and the accompanying SDKs were developed to simplify the evaluation of precision heading and positioning in autonomous applications. Each SDK and antenna combination is tailored to support specific testing scenarios, including PPP and PPP-RTK correction performance, as well as Base/Rover configurations for centimeter-level accuracy.

Key SDK options include:

- 33-TP5390SDK-0: required for testing PPP-RTK over L-Band and IP-based networks
- 33-TP5384SDK-0: designed for use as the Base unit in Base/Rover configurations for precision heading
- Antenna options: compatible antenna models for direct integration include the TW5384, TW5390, TW5790, and TW5386, each selected based on specific functional requirements

Calian Smart Antennas with RS-485 interfaces can be quickly connected to a PC using the USB converter supplied in the SDK. The TruPrecision Windows application provides a straightforward interface for configuration, enabling streamlined testing and validation of high-precision GNSS capabilities.

Conclusion

Calian's smart GNSS antennas were developed to address complex GNSS systems' engineering challenges, allowing developers to concentrate on their core application requirements. Traditionally, designers need to pair a high-performance GNSS antenna with a suitable receiver module, such as the u-blox F9 series, which adds design and integration complexity.

Calian streamlines this process by offering integrated antenna-receiver solutions, along with software development kits (SDKs) that support advanced testing capabilities. The SDKs make it straightforward to evaluate PPP and PPP-RTK correction and augmentation performance.

To support this, the TruPrecision software provides an intuitive interface for configuring the system and simplifies RTK performance testing. It also enhances development workflows through user-friendly tools that support collaboration and system optimization.

Why and how to use a component-based distributed power architecture for robotics

Written by Jeff Shepard

The use of battery-powered robots is growing across applications such as factory automation, agriculture, campus and consumer delivery, and warehouse inventory management. For maximum operating time between charges, designers of these battery systems have always needed to be concerned about power conversion efficiency, as well as size and weight.

However, these concerns have become more critical as load capacities continue to increase and sensing and safety features such as vision, ranging, proximity, location, among others, add design complexity and physical weight. At the same time, the additional electronics processing required also consumes more power.

To maximize battery life in the face of these additional challenges, designers can turn to a component-based distributed power delivery architecture to power the motors, CPUs and other subsystems. In such an approach, each individual DC/DC power conversion component can be placed at the point of load (PoL) To maximize battery life in the face of these additional challenges, designers can turn to a component-based distributed power delivery architecture to power the motors, CPUs and other subsystems. In such an approach, each individual DC/DC power conversion component can be placed at the point of load (PoL) and optimized for high efficiency, small size (high power density) and overall performance. This approach can result in a lighter overall power system, enabling further performance gains for battery-powered robotic systems. Flexibility is also enhanced since power conversion components can be paralleled to easily scale as robotic power demands increase, and they also allow for the same power architecture to be deployed across a platform of various-sized robotic systems.

This article briefly outlines the power needs of several robotics applications including agricultural harvesting, campus and consumer delivery, and warehouse inventory movement. It will then review the benefits of using a component-based distributed power delivery architecture, and then introduce example DC/DC converter solutions from Vicor, along with evaluation boards and associated software to help designers get started.

Power requirements for robots

The power requirements for specific types of robots are determined by the application:

- ***Agricultural harvesting robots:*** plant, maintain, and harvest produce (fruits, vegetables, grains) using automated vehicle guidance along with visual recognition and multiple environmental and soil analysis sensors. These large robotic vehicles are typically powered from a high-voltage DC source of 400 volts or more
- ***Delivery robots:*** last-mile consumer or campus delivery of various items. While payloads vary in size and weight, these robots are typically powered by 48 to 100 volt batteries and have longer run time requirements than the warehouse inventory moving class of robots
- ***Warehouse inventory moving robots:*** provide inventory

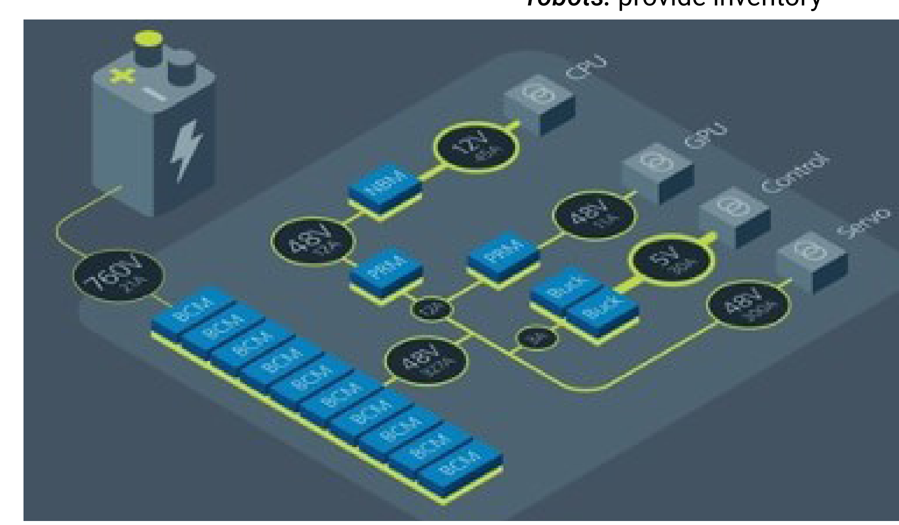


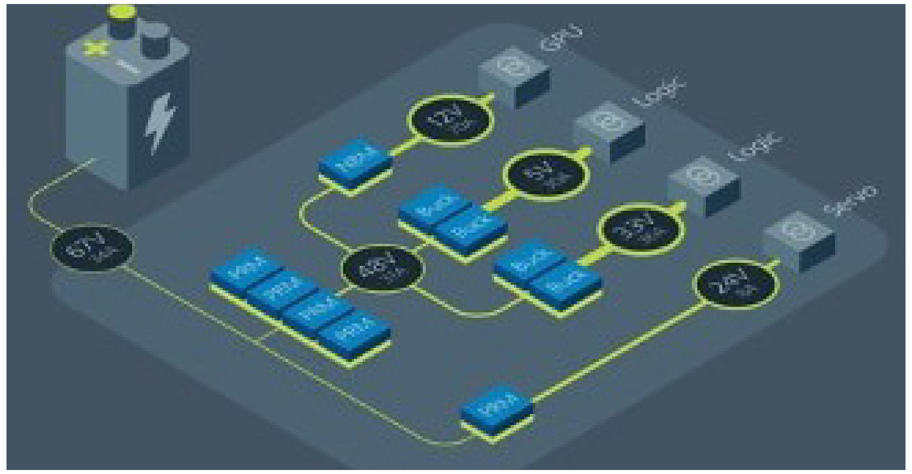
Figure 1: This PDN for 15.4kW agricultural harvesting robots comprises a 760 volt distribution bus supporting a network of lower voltage converters (DCMs, PRMs, NBMs, and buck. Image source: Vicor

management and order fulfillment tasks within large warehouse environments. This robot class is typically powered from a 24 to 72 volt battery source with opportunity charging performed on an as-needed basis

Component-based distributed power architectures for robotics

This section reviews four examples of component-based distributed power architectures for robots ranging from a 15.9 kilowatt (kW) system for agricultural harvesting robots with a 760 volt battery pack down to a 1.2kW system for warehouse inventory movement robots using a 48 volt battery pack. A common feature in three of these applications is a relatively high voltage main bus that distributes power throughout the robot, followed by one or more voltage step-down sections that deliver the needed power to the subsystems. A high-voltage power distribution bus results in improved efficiency and lower power distribution currents which allows the use of smaller, lighter and less expensive power cables. The fourth application shows the simplification that can result in smaller robots that use 48 volt battery systems.

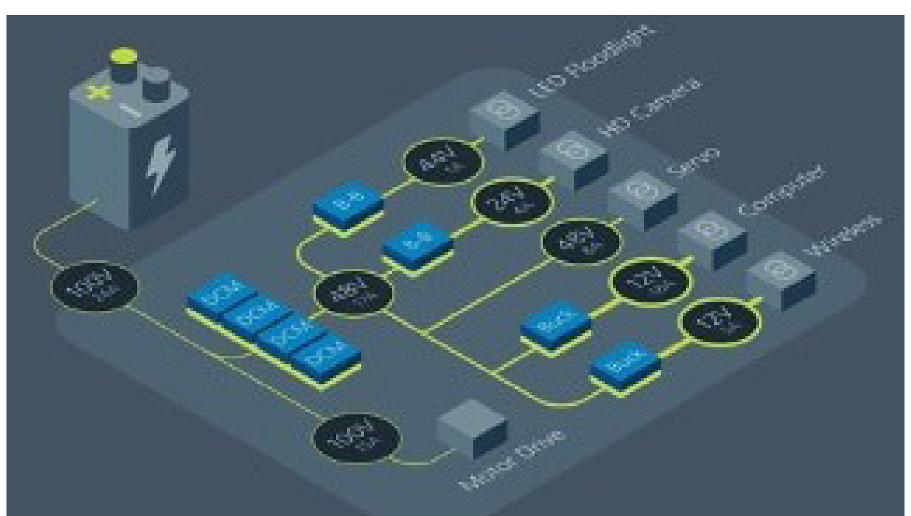
Figure 3: The PDN for warehouse robots combines a 67 volt main power bus and a 48 volt intermediate power distribution bus. Image source: Vicor



The power delivery network (PDN) for agricultural harvesting robots comprises a 760 volt main power bus (Figure 1). This is supported by a series of fixed ratio (unregulated) isolated DC-DC converters (shown as BCM modules on left) with an output voltage of 1/16 of the input voltage. These converters are used in parallel, enabling the system to be resized according to the needs of the specific design.

Further into the network, a series of fixed ratio (NBM, upper middle) and regulated buck-boost (PRMs, center) and buck converters (bottom) power downstream, lower voltage rails as needed. In this design, the servo is driven directly from the 48 volt intermediate power bus with no additional DC-DC conversion.

The PDN for campus and consumer delivery robots shows the simplification that can result in medium power systems by employing a lower main power bus voltage (in this case, 100 volts), and adding regulation to the isolated DC-DC converters (DCMs) on the main power distribution bus to produce the 48 volt intermediate bus voltage (Figure 2).



This approach enables the use of non-isolated buck-boost and buck DC/DC converters to power the various subsystems. In addition, the use of a lower voltage for the main power bus enables the motor drive to connect directly to the main bus, while the servo can connect directly to the 48 volt intermediate bus. Smaller campus and consumer delivery robots may incorporate a 24 volt intermediate bus voltage and either 24 or 48 volt servos, but the overall architecture is similar.

The PDN for warehouse robots using a 67 volt battery pack highlights the use of buck-boost non-isolated DC-DC converters (PRMs) on the main power bus (Figure 3). These converters provide efficiencies of 96% to 98% and can be paralleled for higher power needs. This architecture also features a fixed ratio, non-isolated DC/DC converter (NBM) to power the GPU, and non-isolated regulated buck converters powering the logic sections.

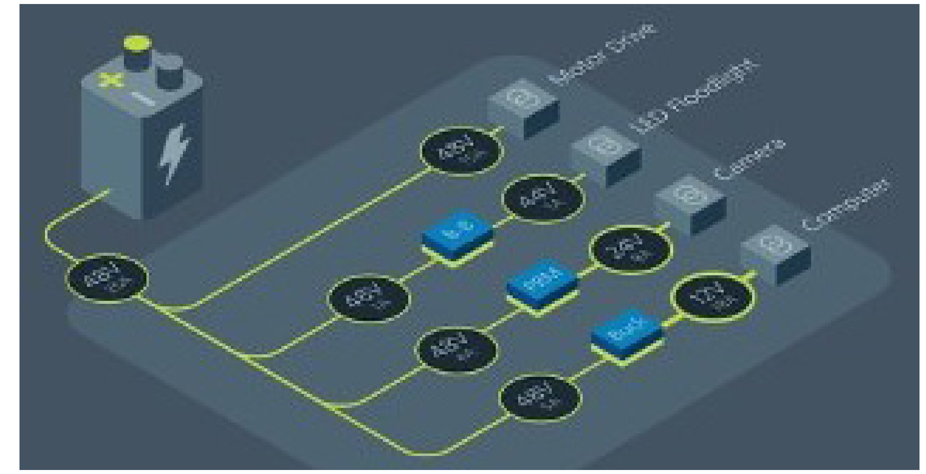


Figure 4: The PDN for warehouse robots using a 48 volt battery pack eliminates the need for an intermediate power bus, greatly simplifying the design. Image source: Vicor

For smaller robot designs using a 48 volt battery there is no need to generate an intermediate bus voltage, simplifying the design (Figure 4). The loads are powered directly from the battery voltage by direct conversion using various non-isolated DC/DC converters. The elimination of the intermediate bus in the power train increases system efficiency and reduces power system weight and cost.

A high-voltage power distribution bus results in improved efficiency and lower power distribution currents which allows use of smaller, lighter and cheaper power cables.

Distributed power architecture design considerations

As shown above, designers must make numerous power system choices to optimize a component-based PDN for robotics. There is no 'one size fits all' approach. In general, larger robots benefit from higher battery voltages which can result in higher power distribution efficiencies and smaller, lighter power distribution buses.

The use of isolated versus non-isolated DC/DC converters is an important consideration when optimizing overall system efficiency and minimizing costs. The closer the DC-DC converter is to a low-voltage load the more likely it is that the optimal choice will be a lower cost, non-isolated power component, increasing overall PDN efficiency. When appropriate, the use of lower cost fixed-ratio (unregulated) DC/DC converters

can also contribute to higher PDN efficiencies.

Vicor offers DC/DC converters that are capable of supporting designers' needs in a wide range of component-based distributed power delivery architectures, including the four outlined above. The following discussion focuses on specific devices that can be used in a power delivery system similar to the one described for campus and consumer delivery robots, as shown in Figure 2.

DC/DC converters for robot power systems

The DCM3623TA5N53B4T70 is an example of a DCM isolated and regulated DC/DC converter that can produce the 48 volt intermediate bus voltage from 100 volt battery power (Figure 5). This converter uses zero voltage switching (ZVS) technology to deliver a 90.7% peak efficiency and a 653 watts per cubic inch power density. It provides 3,000 volts dc isolation between the input and output.

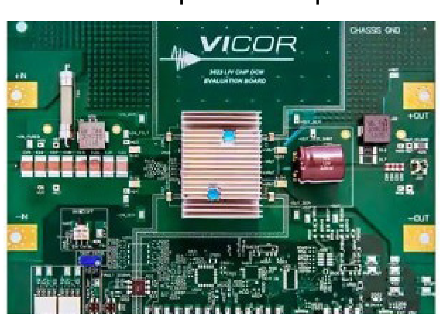


Figure 6: The DCM3623EA5N53B4T70 evaluation board enables designers to explore the capabilities of the DCM3623TA5N53B4T70 DC/DC converter. Image source: Vicor

Leveraging the thermal and density benefits of Vicor's Converter-housed-in-Package (ChiP) packaging technology, the DCM module offers flexible thermal management options with very low top and bottom side thermal impedances. ChiP-based power components enable designers to achieve cost-effective power system solutions with previously unattainable system size, weight and efficiency attributes, quickly and predictably.

To start exploring the capabilities of the DCM3623TA5N53B4T70, designers can use the DCM3623EA5N53B4T70 evaluation board (Figure 6). The DCM evaluation board can be configured for various enabling and fault monitoring schemes, as well as to exercise various modes of trimming depending upon the application requirements.

The DCM3623EA5N53B4T70 can be used to evaluate DCMs in either a stand-alone configuration, or as an array of modules. It also supports evaluation of various enable, trim and fault monitoring options:

Enable options:

- On-board mechanical switch (default)
- External control

Trim options:

- Fixed trim operation (default): the TR pin is permitted to float at initial startup. The DCM disables output trimming and the output trim is programmed to the nominal rated VOUT
- Variable trim operation, on-board variable resistor: The trim pin voltage is ratiometric, with a rheostat working against a pull-up resistor inside the DCM to VCC
- Variable trim operation, off-board control: The trim pin voltage is controlled via external programming control, which is referenced to the –IN of each specific DCM in the system

Fault monitor options:

- On-board LED: the FT pin drives a visible LED for visual feedback on fault status
- On-board optocoupler: the FT pin drives an on-board optocoupler to bring fault status across the primary-secondary isolation boundary

Vicor's PI3740-00 buck-boost DC/DC converter can be used to produce 44 volt and 24 volt power for LED floodlights and high-definition (HD) cameras,

Figure 7: The PI3740-00 buck-boost DC/DC converter SiP can be used to power LED floodlights and HD cameras in the PDN for campus and delivery robots. Image source: Vicor

respectively. It is a high efficiency, wide input and output range ZVS converter. This high-density system-in-package (SiP) integrates a controller, power switches, and support components (Figure 7). It features a peak efficiency up to 96%, as well as good light-load efficiency.

The PI3740-00 requires an external inductor, resistive divider, and minimal capacitors to form a complete buck-boost regulator. The 1 megahertz (MHz) switching frequency reduces the size of the external filtering components, improves power density, and enables fast dynamic response to line and load transients.

To kickstart design with the PI3740-00, Vicor provides the PI3740-00-EVAL1 to evaluate the PI3740-00 in constant voltage applications where VOUT is above 8 volts. The board operates from an input voltage between 8 and 60 volts dc and supports output voltages up to 50 volts dc. Features of this eval board include:

Figure 8: The PI3526-00-LGIZ buck regulator from Vicor can be used to provide the 12 volt power required by a computer and wireless subsystems in the PDN for campus and delivery robots. Image source: Vicor

- Input and output lugs for source and load connections
- Location to place a through-hole input aluminum electrolytic capacitor
- Input source filter
- Oscilloscope probe jack for accurate, high-frequency output and input voltage measurements
- Signal pin test points and wire connectors
- Kelvin voltage test points and sockets for all of the PI3740 pins
- Jumper selectable high-side/low-side current sensing
- Jumper selectable float voltage

Finally, the PI3526-00-LGIZ buck regulator from Vicor can be used to provide 12 volt power for a computer and wireless subsystems in the PDN (Figure 8). This DC/DC converter provides efficiency up to 98%, and support for user-adjustable soft start and tracking that includes fast and slow current-limit capabilities. These ZVS regulators integrate the controller, power switches, and support components in a SiP configuration.

The PI3526-00-EVAL1 evaluation board from Vicor can be configured to experiment with the PI3526-00-LGIZ buck regulator in a stand-alone or a remote sense configuration. Sockets are provided to permit quick probing and placement of a bulk input capacitor. The evaluation board provides lugs, bottom layer banana jack footprints for input and output connections, signal connectors and test points, and Kelvin Johnson-Jacks for accurate power node voltage measurements.

Conclusion

Robotic system power conversion needs become more challenging as load capacities, visual recognition, and user functionality increase the complexity of robots. Existing power solutions can suffer from performance limitations in terms of size, efficiency, weight and scalability, making them less suitable for robotics applications. For robotics applications, designers can turn to component-based distributed power delivery architectures to power the motors, CPUs and other systems.

As shown, this approach can result in a lighter weight power system, enabling further performance gains for battery-powered robotics. Flexibility is also enhanced as power conversion components can be paralleled to easily scale as power demands increase, allowing the same power architecture to be deployed across a platform of various sized robotic systems.

Suggested reading

1. Reducing Robot Risk: How to Design a Safe Industrial Environment
2. Use Compact Industrial Robots to Make Any Shop More Productive

How to select and integrate multi-dimensional safety systems to protect workers from cobots

Written by Jeff Shepard

Safety is essential when deploying collaborative robots (cobots), autonomous mobile robots (AMRs), and autonomous guided vehicles (AGVs) in factories and logistics facilities. It's also complex and multi-dimensional.

Machine movements need to be monitored and controlled per International Organization for Standardization (ISO) 13849, International Electrotechnical Commission (IEC) 62061 and IEC 61800-5-2 that provide safety requirements and guidance on the principles for the design and integration of safety-related parts of control systems (SRP/CS).

Ensuring the safe operation of cobots, AMRs, AGVs, and similar equipment often requires the establishment of a layered safety envelope with multiple fields from initial detection and warning of approaching objects to identify when an object breaches a hazardous zone and stops the machine.

A modular safety controller system can add another layer of analysis and protection. Efficient and quick fault analysis can be an important consideration when dealing with protective field interruptions and unexpected tripping of a scanner. That can require a second sensor to monitor the protective field of the primary sensor.

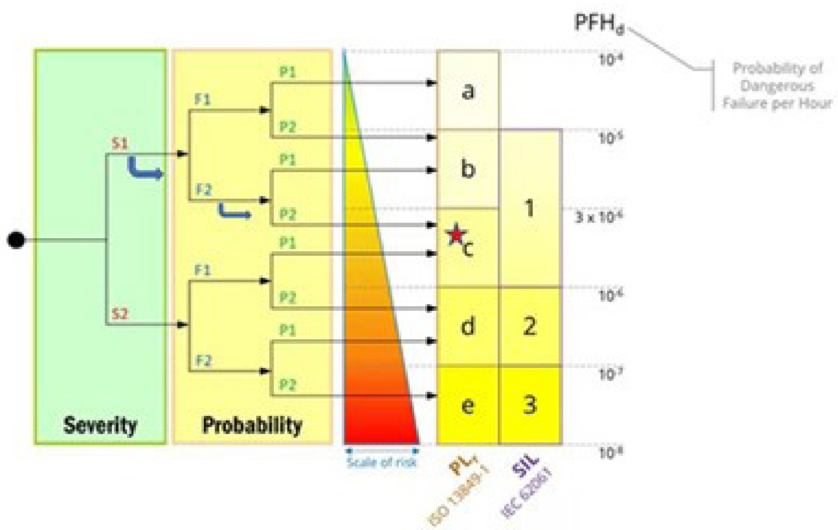


Figure 1: Derivation of PLr levels in ISO 13849 and corresponding SILs in IEC 62061. Both standards are based on the concept of dangerous failure per hour (PFHd).
Image source: SICK

This article starts with a brief refresher on the requirements of ISO 13849, IEC 62061, and IEC 61800-5-2 and a review of the basics of two-dimensional (2D) light detection and ranging (LiDAR) safety laser scanners. It then provides a deeper dive into how layered safety envelopes can be implemented to protect people from cobots, AMRs, AGVs, and similar equipment.

Included is a review of the use and integration of 2D LiDAR sensors and a look at the benefits of combining those sensors with a modular programmable safety controller to provide an additional dimension of safety, plus the use of an event camera to enable fault analysis of unexpected interruptions of protective fields. Exemplary devices from SICK are included.

IEC 61508 is the foundational standard for 'Functional Safety of Electrical/Electronic/Programmable Electronic Safety-related Systems (E/E/PE, or E/E/PES)' and applies to all industries. In addition, there are industry and application-specific subsections and variants.

IEC 62061, 'Safety of machinery: Functional safety of electrical, electronic and programmable electronic control systems', is the machinery-specific variant of IEC 61508. IEC 61800-5-2, 'Adjustable speed electrical power drive systems – Part 5-2: Safety requirements – Functional,' is also related to IEC 61508 and is a standard for the design and development of adjustable speed drive systems.

ISO 13849 was developed independently and not derived from IEC 61508. Both are concerned with functional safety. IEC 61800-5-2 uses Safety Integrity Levels (SILs) to define safety requirements, while ISO 13849 defines the Required Performance Level (PLr).

ISO 13849 and IEC 61508 are based on the concept of the probability of dangerous failure per hour (PFHd). The ISO 13849 functional safety analysis considers three factors: the severity of a possible injury, the frequency or exposure to a hazard, and the potential of limiting the hazard and avoiding harm (Figure 1):

Severity of injury

- S1: Slight (normally reversible injury)
- S2: Serious (normally irreversible or death)

Frequency and/or exposure to hazard

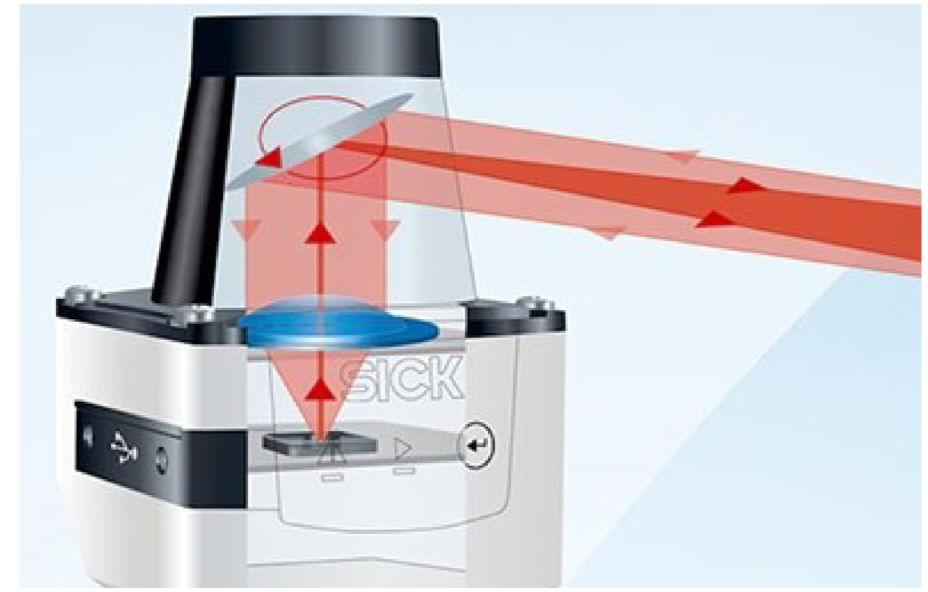
- F1: Seldom-to-less-often and/or exposure time is short
- F2: Frequent-to-continuous and/or exposure time is long

Possibility of avoiding hazard or limiting harm

- P1: Possible under specific conditions
- P2: Hardly possible

How does LiDAR work?

Certification to PLb according to ISO 13849 is required for the use of 2D LiDAR safety sensors in personal protection applications. The TiM 2D LiDAR sensor family includes models meeting that requirement. 2D LiDAR sensors



scan their surroundings using optical time-of-flight (ToF) technology. ToF is implemented by sending laser pulses using a rotating mirror and detecting the reflected light. The longer it takes for the reflected light to arrive back at the sensor, the further away the object.

The time measurement combined with the strength of the returned signal enables the sensor to calculate the position of multiple objects with millimeter accuracy. The resulting picture of the surroundings is updated up to 15 times every second (Figure 2). It can support real-time navigation, orientation, control, and safety functions.

TiM 2D LiDAR sensors detect objects in defined areas (fields) to be monitored. Depending on the model, they have a scanning range of up to 25 m and a working range of up to 270°.

The return pulse data from the laser is processed using high-definition distance measurement (HDDM) or HDDM+ technology. HDDM achieves a very high measurement accuracy at short distances and is suitable for fine positioning in applications like docking. HDDM+ processes edge reflections particularly well, making it best suited for localization and anti-collision applications in dynamic environments.

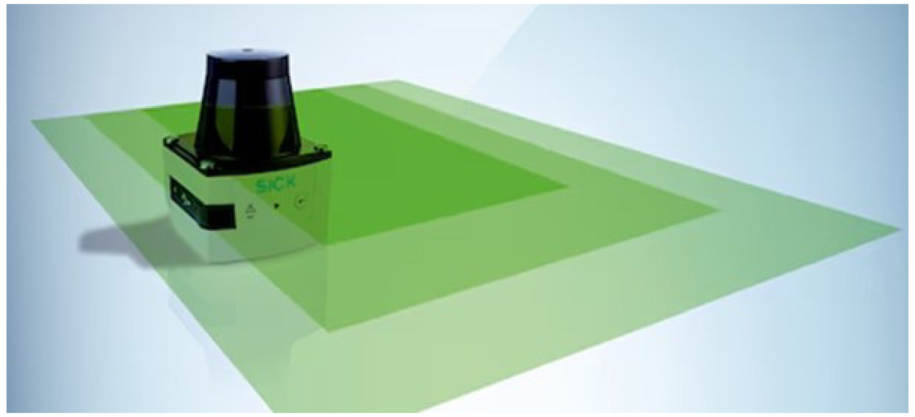
The time measurement combined with the strength of the returned signal enables the sensor to calculate the position of multiple objects with millimeter accuracy.

In both cases, the patented HDDM/HDDM+ multi-pulse technology enables TiM 2D LiDAR sensors to detect the entire scanning range without gaps, ensuring consistent measurement precision, and they can handle different surfaces and remission factors.

Types TiM1xx, TiM3xx, and TiM7xx detect whether objects are in a pre-defined field. Sixteen field sets, each with three preconfigured fields, support quick adaptation during operation (Figure 3). Individual field geometries can be specified, or reference contour fields can be defined for static contour monitoring. Digital filters, masked areas, and response times can also be defined to maximize performance even in the presence of heavy rain, snow, or dust.

Models that provide field evaluation data or field evaluation and measurement data are available. Field evaluation sensors only determine the presence of an object, while field evaluation and measurement data can be used to provide an accurate picture of a scanned surface.

In addition to distance data, TiM 2D LiDAR sensors are available that also provide angular data and a



received signal strength indicator (RSSI) output. This expanded data set can be especially useful for collision avoidance and navigation for AMRs in changing environments.

Safety LiDARs, adding the first protective layers

The TiM 2D LiDAR family has safety-related variants, the TiM361S (field evaluation) and TiM781S (field evaluation and measurement data output), that meet the requirements of PL_b and can be used for both stationary and mobile applications. They can be used for personal protection in access monitoring for industrial cobots and on mobile platforms like AMRs and AGVs.

- Type TIM361S-2134101, model number 1090608, is suited for indoor use with a detection range of 0.05 to 10 m and HDDM technology
- Type TIM781S-2174104, model number 1096363, is also suited for indoor use with a detection range of 0.05 to 25 m and HDDM+ technology

Simplified integration

TiM 2D LiDAR sensors are designed to simplify integration. With an enclosing rating of up to IP67, neither dust nor moisture can enter the housing. They are highly immune to bright ambient lighting up to 80,000 lx. Their rugged design meets the vibration resistance requirements of IEC 60068-2-6 and the shock resistance requirements of IEC 60068-2-27. Their ruggedness can be enhanced when needed using damped mountings of protective plates.

The compact design, light weight, and low power consumption of TiM 2D LiDAR sensors make them well-suited for mobile platforms. The Type TIM361S-2134101 and Type TIM781S-2174104 both weigh only 250g, have a typical power consumption of 4W, and measure 60mm long x 60mm wide x 86mm high.

Safety controllers add another layer

LiDAR laser scanners detect hazards and send alerts, while a modular safety controller can add another layer of safety to a protection system. For example, the Flexi Soft safety controller is a modular system that can be connected to various sensors and switching elements, including laser scanners. It's rated SIL3 according to IEC 61508 and PLe with a PFHd of 1.07 x 10-9 according to ISO 13849.

A basic system consists of at least two modules (Figure 4):

1. The CPU0, like model 1043783, is the central logic unit where signals from sensors like LiDAR are analyzed and evaluated, offloading safety analysis from the central machine controller. The output of the CPU0 connects with a higher level machine control, such as a programmable logic controller (PLC), where safety functions are implemented
2. The XTIO I/O expansion module, such as model 1044125, is required to connect laser scanners to the system. One XTIO I/O expansion module is necessary for every two laser scanners, as each laser scanner uses three switching inputs. The controller can operate up to 12 I/O modules

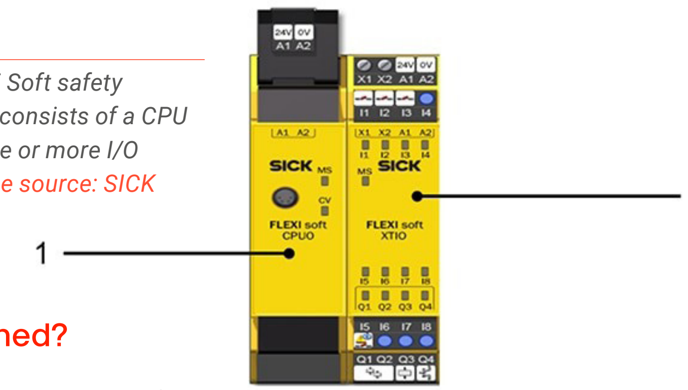


Figure 4: The Flexi Soft safety controller system consists of a CPU module (1) and one or more I/O modules (2). Image source: SICK

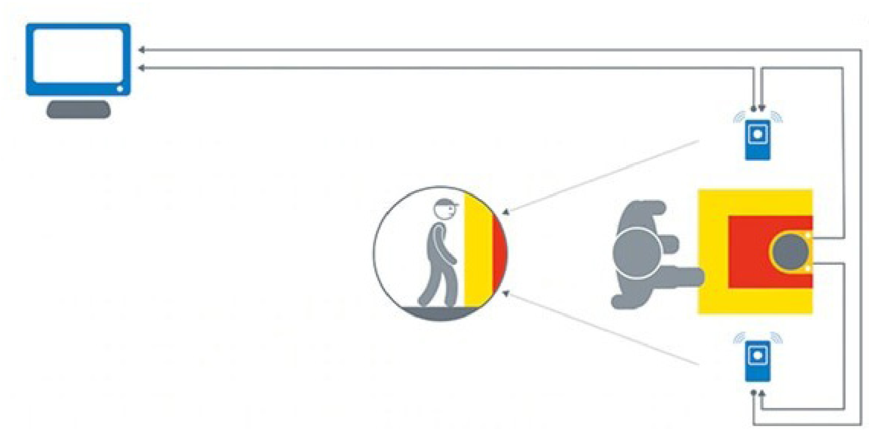
What happened?

An important element in a safety system can be the ability to analyze and understand the root cause of any faults, answering the question, 'What happened to cause the safety laser scanner to trigger?' An event camera, EventCam from SICK, is specifically designed to detect and analyze sporadic faults in industrial settings.

EventCam is self-contained with optics, illumination, electronics, and memory and can be integrated into mobile or stationary systems. The cast aluminum housing is IP65-rated and can be mounted in various positions. EventCam can be connected to an automation system like a safety controller or directly to a sensor.

Once an error has been reported, EventCam begins storing single frames or video sequences. The internal ring memory can store up to 240 seconds before and 100 seconds after an event. In high-definition (HD) mode, it can record up to 25 seconds before and 15 seconds after. The video frames per second (fps) rate ranges from 13 to 65, depending on the required resolution.

EventCam can also be useful when commissioning new machines or processes. It can monitor an unsupervised test run like a multi-hour or multi-day continuous test and quickly identify error sources. Multiple EventCams can monitor a single process, providing visual information from several angles at once for a deeper and more thorough analysis of errors (Figure 5).



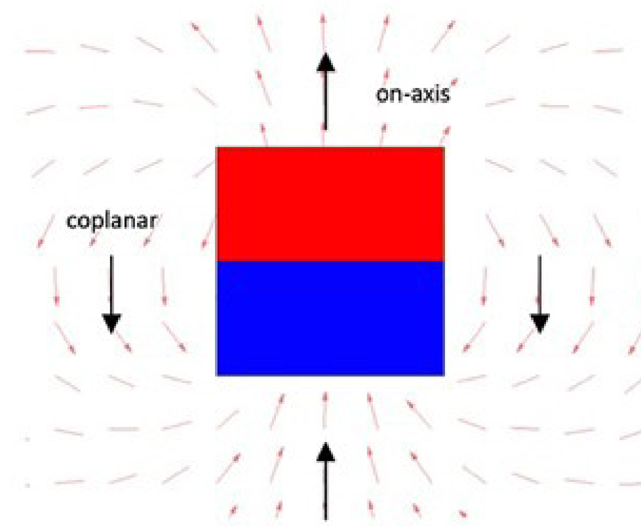
EventCam is offered in two variants. Model 1102028 has a working range of 0.4 m to 0.6 m and can be suitable for use with stationary cobots with relatively small protective spaces. Model 1093139 has a working range of 0.8 to 6 m and can accommodate larger protective spaces encountered with bigger cobots, AMRs, and AGVs.

Summary

2D LiDAR sensors like the TiM family from SICK can provide the first line of defense in a safety system for cobots, AMRs, AGVs, and similar machines. They provide a series of protective fields to monitor the approach of people. The addition of a safety controller can support intrusion analysis and enhance system performance. Finally, one or more EventCams can monitor the primary 2D LiDAR sensor to help identify the root cause of any sporadic tripping.

How to achieve fast, precise, and low power position sensing for real-time control

Written by Jeff Shepard



The use of three-dimensional (3D) position sensing for real-time control is growing across a variety of Industry 4.0 applications, ranging from industrial robots and automated systems to robot vacuums and security. 3D Hall effect position sensors are a good option for these applications as they provide high repeatability and reliability, and can also be used with windows, doors and enclosures for intrusion or magnetic tampering detection.

Still, designing an effective and safe 3D sensing system using a Hall effect sensor can be a complex and time-consuming process. The Hall effect sensor needs to interface with a microcontroller (MCU) powerful enough to act as an angle calculation engine and to perform measurement averaging, as well as gain and offset compensation to determine magnet orientations and 3D positions. The MCU also needs to handle a variety of diagnostics including monitoring the magnetic field, system temperature, communication, continuity, internal signal path, and the power supply.

In addition to hardware design, software development can be complex and time-consuming, further delaying time to market.

To address these challenges, designers can use integrated Hall effect 3D position sensor ICs with an internal calculation engine. These ICs simplify software design and reduce the system processor’s load by as much as 25%, enabling the use of a low-cost, general-purpose MCU. They can also provide fast sample rates and low latency for accurate real-time control. In battery-powered devices, 3D Hall effect position sensors can be operated with duty cycles of 5 Hertz (Hz) or less to minimize power consumption. In addition, integrated functions and diagnostics maximize design flexibility and system safety and reliability.

This article reviews the fundamentals of 3D Hall effect position sensors and describes their use in robotics, tamper detection, human interface controls, and gimbal motor systems. It then presents examples of high-precision, linear 3D Hall effect position sensors from Texas Instruments, along with associated evaluation boards and implementation guidance to speed the development process.

What are 3D Hall effect sensors?

3D Hall effect sensors can gather information about the complete magnetic field, enabling the use of distance and angular measurements for position determination in 3D environments. The two most common placements for these sensors are on-axis and coplanar with the magnetic polarization (Figure 1). When placed on the axis of polarization, the field provides a unidirectional input to the sensor that can be used for position determination. Coplanar placement produces a field vector that is parallel to the magnet face regardless of the range to the sensor, also enabling position and

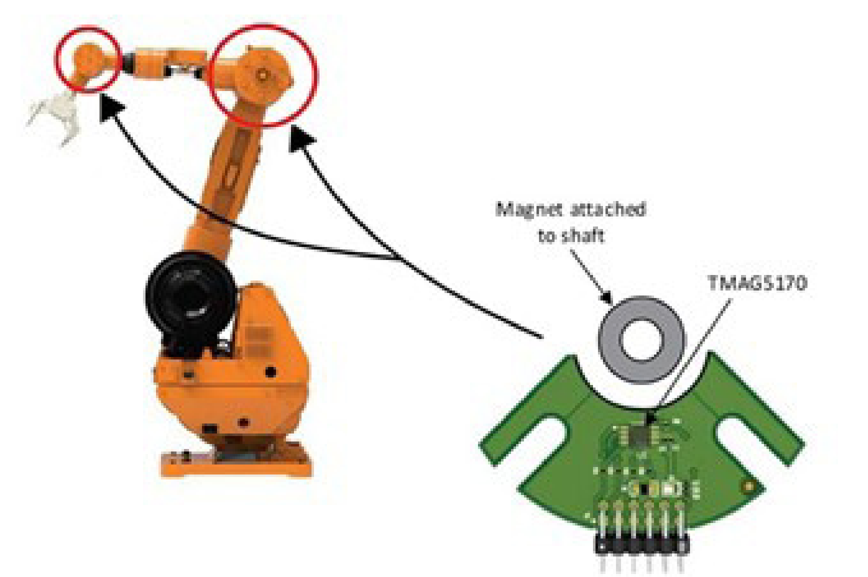


Figure 2: Integrated 3D Hall effect sensors can measure shaft rotation in robots and other Industry 4.0 applications. Image source: Texas Instruments

angle determination.

Industry 4.0 systems such as robots need multi-axis motion sensing to measure the angle of robotic arms, or at each wheel of mobile robots to support navigation and precise movement throughout a facility. Integrated 3D Hall effect sensors are well-suited for these tasks since they are not susceptible to moisture or dirt. Coplanar measurements provide highly accurate magnetic field measurements of rotating shafts (Figure 2).

Secure enclosures such as electricity and gas meters, automatic teller machines (ATMs), enterprise servers and electronic point of sales equipment can use on-axis field measurements to detect intrusions (Figure 3). When the case is opened, the flux density (B) sensed by the 3D Hall effect sensor decreases until it falls below the flux release point (BRP) specification of the Hall switch, at which time the sensor sends out an alert. When the case is closed, the magnetic flux density must be large enough relative to the BRP to prevent false alerts. Since a magnet's flux density tends to decrease as its temperature increases, the use of a 3D Hall effect sensor with temperature compensation capability can improve system reliability for enclosures used in industrial or outdoor environments.

Human interfaces and controls in home appliances, test and measurement equipment, and personal electronics can benefit from the use of all three axes of motion. A sensor can monitor motion in the X and Y planes to identify rotation of a dial and can identify when the dial is pushed by monitoring a large shift in the X and Y magnetic axes. Monitoring the Z-axis enables the system to identify misalignments and send alerts for wear or damage that the dial may need preventative maintenance.

Gimbal motor systems in handheld camera stabilizers and drones benefit from the use of 3D Hall effect sensors with selectable magnetic field sensitivity ranges and other programmable parameters to provide angle measurements to an MCU (Figure 4). The MCU continuously adjusts the motor position as needed to stabilize the platform. A sensor that can accurately and precisely measure angles in on and off-axis positions provides mechanical design flexibility.

Out-of-plane measurements often cause different magnetic field strengths (gains) and different offsets in different axes, which can cause angle calculation errors. The use of a 3D Hall sensor with gain and offset corrections supports flexibility when placing the sensor relative to the magnet, ensuring the most accurate angle calculations.

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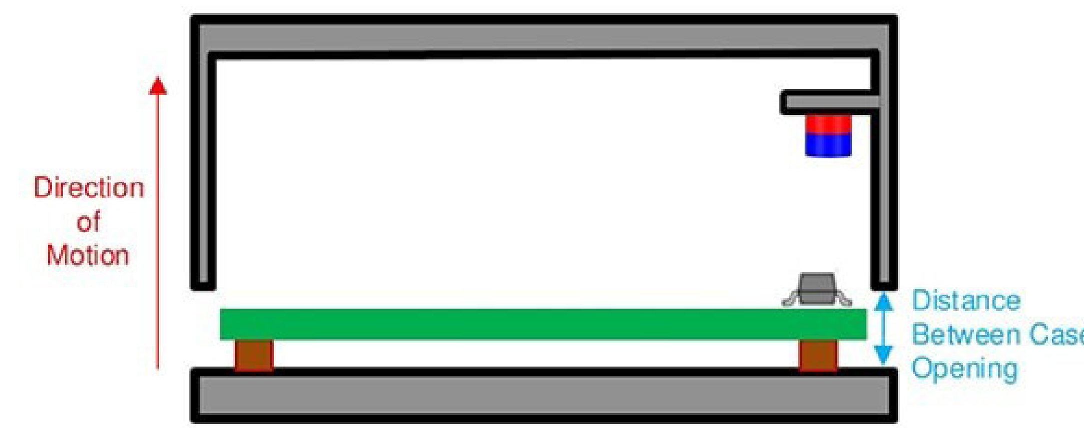

Flexible 3D Hall effect sensors

Texas instruments offers designers a selection of three-axis linear Hall effect sensors including the TMAG5170 family of high precision 3D linear Hall effect sensors with a 10 megahertz (MHz) serial peripheral interface (SPI) and cyclic redundancy check (CRC), and; The TMAG5273 family of low power linear 3D Hall effect sensors with an I²C interface and CRC.

TMAG5170 devices are optimized for fast and accurate position sensing and include: linear measurement total error of ±2.6% (maximum at 25°C); sensitivity temperature drift of ±2.8% (maximum), and; 20 kilosamples per second (Ksps) conversion rate for a single axis. TMAG7273 devices feature low power modes including: 2.3 milliampere (mA) active mode current; 1 microampere (µA) wake-up and sleep mode current, and; 5 nanoampere (nA) sleep mode current. These ICs include four primary functional blocks (Figure 5):

- The Power Management & Oscillator block includes undervoltage and overvoltage detection, biasing, and oscillators
- Hall sensors and associated biasing with multiplexers, noise filters, temperature sensing, integrator circuit, and an analog-to-digital converter (ADC) make up the Sensing and Temperature Measurement block
- The communication control circuitry, electrostatic discharge (ESD) protection, input/output (I/O) functions, and CRC are included in the Interface Block
- The Digital Core contains diagnostic circuitry for mandatory and user-enabled diagnostic checks, other housekeeping functions, and an integrated angle calculation engine that provides 360° angular position information for both on-axis and off-axis angle measurements

The TMAG5170 devices are delivered in an 8 pin VSSOP package measuring 3.00 x 3.00 millimeters (mm) and are specified over an ambient temperature range of −40 to +150°C. The TMAG5170A1 includes sensitivity ranges of ±25 millitesla (mT), ±50 mT, and ±100 mT, while the TMAG5170A2 supports ±75 mT, ±150 mT, and ±300 mT.

The low-power TMAG5273 family uses 6 pin DBV packages measuring 2.90 x 1.60mm and is specified over an ambient temperature range of −40 to +125°C. It's also offered in two different models; The TMAG5273A1 with sensitivity ranges of ±40 mT and ±80 mT, and the TMAG5273A2

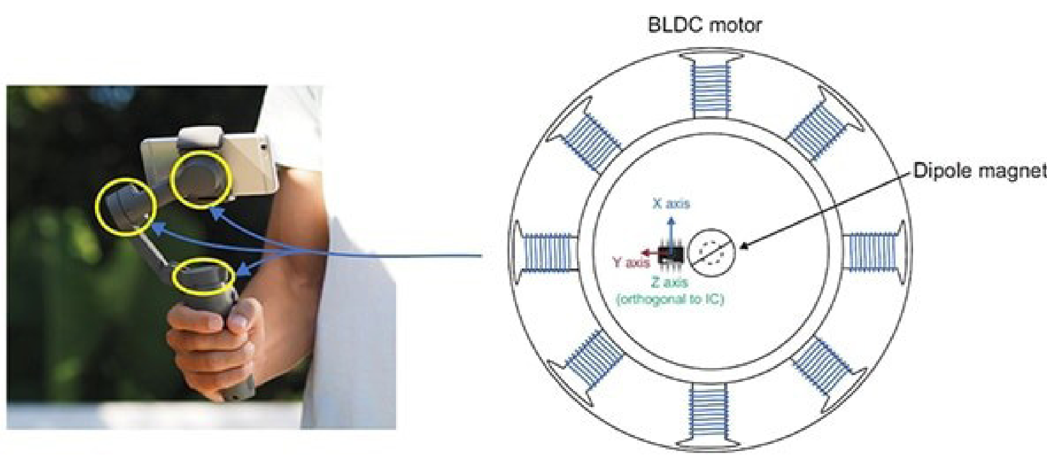

Figure 4: Gimbal motors in handheld camera platforms and drones benefit from 3D Hall effect sensors with selectable magnetic field sensitivity ranges. Image source: Texas Instruments

that supports ±133 mT and ±266 mT.

Two user-selected magnetic axes are used for angle calculations. The impact of system mechanical error sources is minimized through magnetic gain and offset corrections. The onboard temperature compensation function can be used to independently compensate for temperature changes in the magnet or the sensor. These 3D Hall effect sensors can be configured through the communications interface to enable user-controlled combinations of magnetic axes and temperature measurements. The ALERT pin on the TMAG5170, or the INT pin on the TMAG5273, can be used by an MCU to trigger a new sensor conversion.

Eval boards aid in getting started

Texas Instruments also offers two eval boards, one for the TMAG5170 series and one for the TMAG5273 series, to allow basic functional evaluations (Figure 6). The TMAG5170EVM includes both the TMAG5170A1 and the TMAG5170A2 models on a snap-apart pc board. The TMAG5273EVM has the TMAG5273A1 and TMAG5273A2 models on a snap-apart pc board. They include a sensor control board that interfaces with the graphic user interface (GUI) to view and save measurements and read and write registers. The 3D printed rotate & push module is used to test common functions of angular measurement.

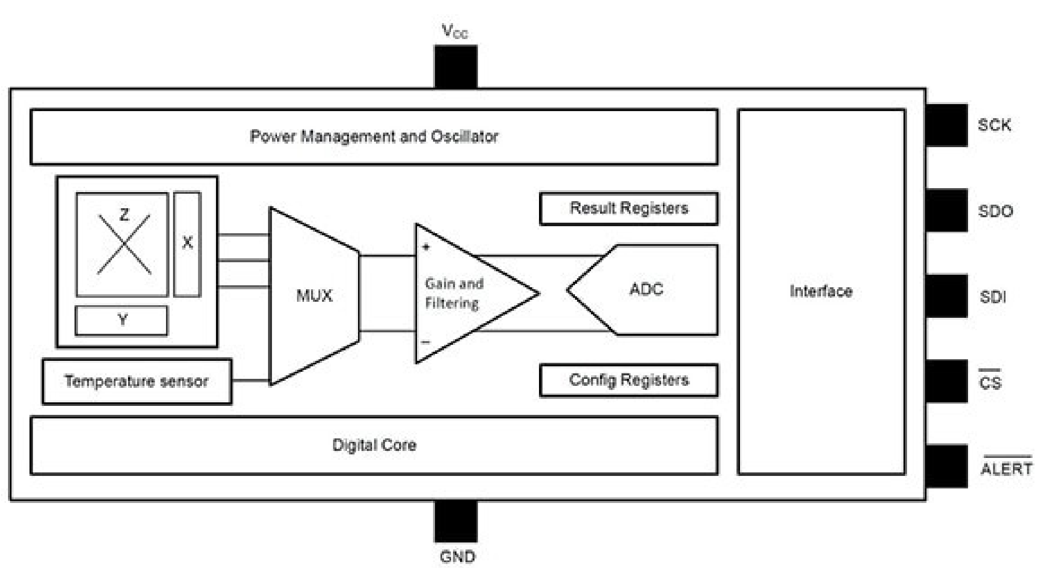

Figure 5: Except for an SPI interface (shown above) on the TMAG5170 models and an I²C interface on the TMAG5273 models, the internal functional blocks are the same for both families of 3D Hall effect sensor ICs. Image source: Texas Instruments

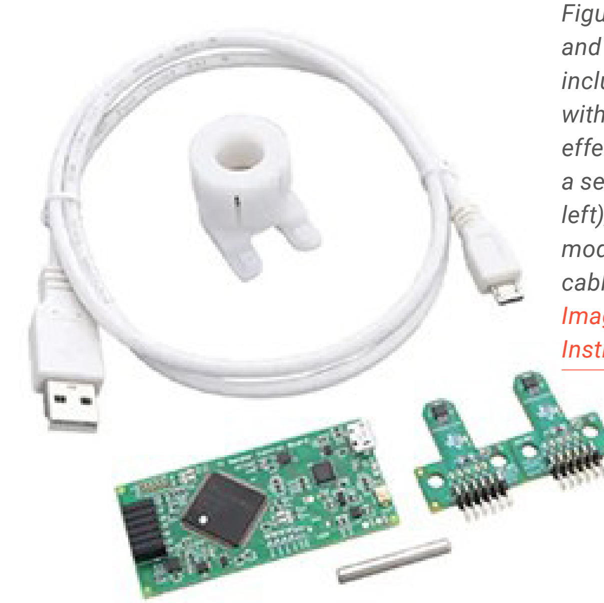

Figure 6: The TMAG5170EVM and the TMAG5273EVM both include a snap-apart board with two different 3D Hall effect sensor ICs (lower right), a sensor control board (lower left), 3D printed rotate and push module (center), and a USB cable to provide power. Image source: Texas Instruments

Using the 3D Hall sensors

There are a few implementation considerations designers need to be aware of when using these 3D Hall effect position sensors:

- The SPI readout of the result register in the TMAG5170, or the I²C readout in the TMAG5273, needs to be synchronized with the conversion update time to ensure the correct data is read. The ALERT signal on the TMAG5170, or the INT signal on the TMAG5273, can be used to notify the controller when a conversion is complete and the data is ready
- A low-inductance decoupling capacitor must be placed close to the sensor pin. A ceramic capacitor with a value of at least 0.01 microfarads (µF) is recommended
- These Hall effect sensors can be embedded within enclosures made from nonferrous materials such as plastic or aluminum with the sensing magnets on the outside. Sensors and magnets can also be placed on opposite sides of a pc board

Conclusion

With the growth of 3D motion and control, designers need to get accurate measurements in real-time, while keeping costs to a minimum through simplified design, while also minimizing power consumption. As shown, the TMAG5170 and TMAG5273 integrated 3D Hall effect sensors address these issues, offering the flexibility of fast sample rates and low latency for accurate real-time control, or slow sample rates to minimize power consumption in battery-powered devices. High accuracy is ensured with the integrated gain and offset correction algorithms, combined with independent temperature correction for the magnet and sensor.

Suggested reading

1. The Fundamentals of Proximity Sensors: Their Selection and Use in Industrial Automation
2. Why and How to Use the Serial Peripheral Interface to Simplify Connections Between Multiple Devices

Figure 7: Illustration of the 3D printed rotate and push module mounted on top of the EVM. Image source: Texas Instruments