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Why copper-electrode
NTC thermistors
deliver more reliable
temperature sensing

Enabling autonomous
mobility in robots

A cost-effective
approach to random bin
picking

Enhance autonomous
robot localization
precision with advanced
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Editor's note

Welcome to the DigiKey eMagazine Volume 38 – Robotics.

The field of robotics is moving quickly from the factory floor into almost every part of our lives. From industrial and collaborative robots to autonomous mobile machines, today's robots are becoming smarter, faster, and more capable. This edition will take a closer look at some of the technologies and the companies helping to advance them.

We begin with Toshiba's Power Semiconductors, which play an important role in delivering efficient and reliable power for robotic systems. NXP's MCX N Series high-performance, dual-core Arm Cortex-M33 microcontrollers bring the processing power and flexibility needed for increasingly sophisticated embedded applications.

Precision is another key part of successful robotics. Same Sky's AMT encoders provide accurate motion feedback, while Murata's NCU15 and NCU18 NTC thermistors offer dependable temperature sensing for monitoring and protecting robotic electronics.

We also take a look at the technologies behind autonomous operation. Analog Devices' "Enabling Autonomous Mobility in Robots" explores how advanced sensing and processing can help robots understand their surroundings and navigate more effectively.

Rounding out the issue are two supporting articles focused on practical robotics challenges. "A Cost-Effective Approach to Random Bin Picking" looks at ways to make robotic picking applications more accessible and efficient, while "Enhanced Autonomous Robot Localization Precision with Advanced IMUs and Sensor Fusion" explores how improved inertial sensing and sensor fusion can help robots better determine their position and movement.

Taken together, these articles highlight the many pieces that have to work seamlessly to make modern robotics possible – from power and processing to sensing, motion control and autonomous navigation.

We hope you enjoy this issue and find plenty of useful ideas and insights as you explore the technologies shaping the future of robotics.

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Efficient robot motion with Toshiba's motor drivers, MOSFETs, and isolation

TOSHIBA



In a robot joint, there is no room for a fan, so the heat the drive stage generates has to escape through the housing. Keeping losses low requires a driver that appropriately shapes the current waveform and MOSFETs that carry it efficiently. The high-voltage power stage also requires isolation from the control electronics to preserve signal integrity and protect the operator. [Toshiba](#) supplies all three (drivers, MOSFETs and isolation) and provides a reference design showing how they all work together.

Drivers for brushed, brushless, and stepper motors

A suitable driver depends upon the motor type. Fortunately, Toshiba's brushed DC portfolio offers more than 90 ICs. For a straightforward brushed DC motor joint, the [TB67H453FNG](#) (Figure 1) is a practical starting point. It is a PWM-chopper H-bridge driver operating from 4.5 to 44 V at up to 3.5 A. Its integrated output MOSFETs have a typical on-state resistance of 0.3 Ω on both the high and low sides. The device draws 1 μ A in standby mode and comes in an HTSSOP 16-pin package, and its built-in current monitoring makes it well suited to cleaning robots and other small household platforms. A lower-voltage variant, the [TC78H653FTG](#) covers 1.8 to 7.5 V for battery-powered devices.

When a joint uses a brushless DC

motor instead, the driver must add commutation logic rather than relying on a simple bridge configuration. The [TC78B009FTG](#) handles this as a sensorless pre-driver controlling six external MOSFETs, offering rectangular wave commutation at 120, 135, 142.5 or 150 degrees, with closed-loop speed control stored in onboard non-volatile memory. The [TC78B027FTG](#) takes a different approach, utilizing a single Hall sensor with sine-wave output and Intelligent Phase Control, which automatically aligns the driving voltage and current phases to improve efficiency. These pre-drivers operate closed-loop, though neither performs full field-oriented control (FOC).

For joints that require torque control across their full speed range, closed-loop commutation is not enough and FOC becomes necessary. Toshiba's industrial platform for FOC is the [TXZ+M4K microcontroller](#), an [Arm Cortex-M4F](#) running at 160 MHz, whose hardware Advanced Vector Engine Plus executes the Clarke and Park transforms and the PI loop deterministically rather than consuming CPU cycles. Toshiba has also begun sampling the SmartMCD [TB9M030FG](#), which integrates an Arm Cortex-M0 core, gate driver, and vector engine for sensorless FOC from zero speed.

Not every robot joint needs continuous rotation. In applications where a joint holds its position

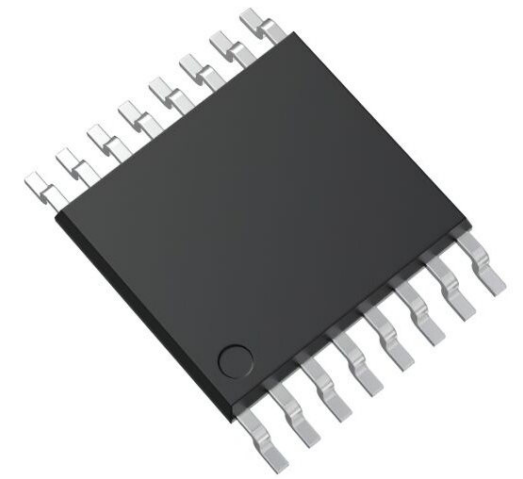


Figure 1. The TB67H453FNG brushed DC motor driver.

Image source: Toshiba

rather than turning continuously, stepper motor control applies. The [TB67S128FTG](#) operates to 50 V and 5 A with combined on-resistance around 0.25 Ω , supporting full step through 1/128 micro-stepping natively and extending to 1/1024 through its serial interface.

Advanced micro-stepping and load-adaptive current

The 1/128 step divisions set the step count, but do not guarantee smooth motion on their own because micro-stepping resolution alone is not enough. The current waveform also has to hold its sinusoidal shape across each step, and the drive current has to match the actual load.

The TB67S128FTG (Figure 2) handles both requirements and

reduces the external component count in the process. Its Active Gain Control detects the induced voltage during operation to infer the load and then adjust the drive current accordingly, lowering heat and power draw compared with running at a fixed conservative current. Advanced Dynamic Mixed Decay manages current decay across each step, while the Advanced Current Detection System eliminates the external sense resistors.

Building on these capabilities, the [TB67S579FTG](#) offers Advanced Micro-stepping Technology, combining second-generation Active Gain Control with an Automatic Wave Generation System that produces micro-stepping from a single clock input, and Continuous Micro-stepping that generates a smooth sinusoidal current waveform to reduce vibration and audible noise at low speed. Noise is not the only consequence of a distorted

waveform; the same distortion appears as torque ripple in a joint. Holding the waveform smooth therefore resolves both issues, allowing a service robot moving a payload through an occupied corridor to run quieter and hold its motion more steadily.

MOSFETs and the conduction vs. switching trade-off

Between the driver and the motor are six MOSFETs, and their characteristics determine how much of the input power reaches the windings versus how much is lost as heat. The MOSFETs in a motor bridge dissipate power in two ways: Conduction loss scales with on-resistance and the square of the phase current, dominating at high torque and low speed, while switching loss scales with gate and output charge and with switching frequency, dominating at high speed and light load. A

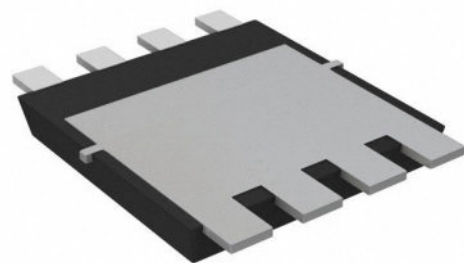


Figure 3. The TPW3R70APL N-channel MOSFET. Image source: Toshiba

robot joint moves through high-torque acceleration and high-speed cruising within a single trajectory, so optimizing for one loss mechanism at the expense of the other results in a joint running hotter than necessary across half its operating range.

The two loss mechanisms also conflict in silicon. Lowering RDS(on) generally means a larger die which carries more gate charge, raising switching and drive loss. However, Toshiba created a compromise using the product of on-resistance and gate charge, where a lower figure indicates a device improves both rather than trading one for the other. Its low-voltage trench generations, U-MOS IX-H through U-MOS11-H, target that balance, and the high-voltage DT MOS super-junction families do the same at mains-connected voltages.

As an example, the [TPW3R70APL](#) (Figure 3) is rated at 100 V and 150

A in a DSOP Advance package, specifying 3.1 mΩ typical on-resistance at a VGS of 10 V, 21 nC switching charge, 74 nC output charge, and 0.88 °C/W channel-to-case thermal resistance. The low milliohms keep conduction loss down through the high-torque portion of a move, while the modest charge figures keep the switching loss down through the high-speed portion.

Isolation between control and power domains

The switching stage is the noisiest and highest-voltage part of the circuitry. As it shares a housing with the control electronics and communication interfaces, isolation is required to separate these two voltage domains, block ground loops and keep switching transients from reaching the control side.

Toshiba's gate driver photocouplers, e.g., the [TLP5791H](#), [TLP5794H](#), and [TLP5795H](#) are designed to carry the switching signal across the isolation boundary, covering the 1 A to 6 A drive class with common-mode transient immunity up to 40 kV/μs, preventing false switching when the inverter's dV/dt couples back across the barrier. Building on that base, the TLP5222 adds overcurrent detection with isolated fault feedback and an active Miller clamp, while the [TLP5814H](#) targets SiC devices.

Between the driver and the motor are six MOSFETs, and their characteristics determine how much of the input power reaches the windings versus how much is lost as heat.

Current sensing crosses the isolation boundary in the opposite direction, since phase current has to be measured on the high-voltage side and reported to a controller on the low-voltage side. The [TLP7820](#) and [TLP7920](#) optically coupled isolation amplifiers handle this using a delta-sigma converter, specifying 0.02% typical linearity, 20 kV/μs common-mode transient immunity, and 5,000 Vrms minimum isolation. Typical applications include inverters, servo amplifiers, robots and power supplies.

Toshiba's servo drive reference model

After choosing the right driver, MOSFETs, and isolation, it is imperative to understand how they work as a system. Toshiba demonstrates this integration with its [Servo Drive Reference Model](#), designed for robots, cobots, SCARA arms and automated guided vehicles. The design pairs the M4K microcontroller with its hardware FOC engine, PMD timers and 32-bit encoder input, with a low-voltage power board built on six TPW3R70APL MOSFETs, capable

of driving 48 V BLDC motors with up to 200 W.

The design isolates the USB-to-UART link and uses a photorelay to switch the motor brake from the low-voltage side, while separate feedback boards accept differential encoders and resolvers. Toshiba demonstrated the model on a modified AR3 robot arm fitted with 24 V BLDC motors, well within the board's 48 V capability, driving 1:50 or 1:64 gearboxes. On that platform, it achieved positioning accuracy of 0.2 to 0.3 degrees per axis and acceleration of 300 rad/s².

Conclusion

Sourcing your drivers, MOSFETs and isolation from a single supplier removes the guesswork of matching devices across vendors. Toshiba's reference design takes that further by providing a documented starting point, with the hardware arrangement and its measured performance already published.

For more information on Toshiba's motor drivers, MOSFETs, and isolation devices, please visit [Toshiba's power solutions page on DigiKey](#).

Figure 2. The TB67S128FTG stepper motor driver. Image source: Toshiba

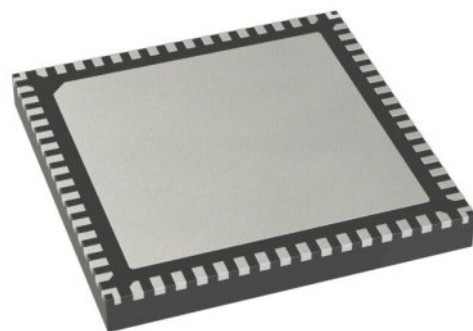




Figure 1: A mobile robot making a delivery
Image source: Adobe Stock

Bringing intelligence to the Edge with NXP's MCX N microcontrollers for mobile robotics



Mobile robots (Figure 1) handle several demanding tasks at once, running motors precisely, sensing their surroundings, making decisions locally without waiting on the cloud, and holding all of it within a strict power and thermal budget. Meeting those requirements with separate devices for control, sensing and machine learning adds cost, board area and latency at every interface between them. [NXP Semiconductors](#) consolidates these functions in its [MCX N series](#) microcontrollers, which combine dual-core processing, dedicated machine learning acceleration and hardware security in a single device built for the intelligent edge.

Dual-core Cortex-M33 performance

The MCX N series features two Arm Cortex-M33 cores running up to 150 MHz, each with TrustZone, a memory protection unit, a floating-point unit, and DSP extensions. The dual-core architecture lets you keep a deterministic real-time control

task on one core, while application and communication workloads run on the other. For example, a motor loop holding a fixed update interval will not be disturbed by network traffic or sensor processing competing for the same core. TrustZone adds another division, partitioning secure and non-secure code so that safety-critical firmware remains isolated from the application code running on the same silicon.

Backing the cores is up to 2 MB of dual-bank flash and up to 512 KB of SRAM, of which 416 KB is protected by error-correcting code that detects and corrects bit errors before they propagate into a control decision. The dual-bank flash matters most once a robot is deployed, since it lets the device write a firmware update into one bank while continuing to execute from the other. This means that an OTA update never takes the device offline or leaves it in an unrecoverable state if the transfer is interrupted.

On-device machine learning with the eIQ Neutron NPU

The feature that most distinguishes the MCX N is its integrated neural processing unit. Specific members of the family (Figure 2), including the MCX N54x and MCX N94x, carry NXP's eIQ Neutron NPU, a dedicated machine learning accelerator, while the MCX N23x excludes it for designs that do not require on-chip inference.

NXP rates the NPU at up to 42 times faster ML inference than the Arm cores alone, at lower energy and with smaller model sizes, while the PowerQuad DSP accelerator speeds up signal-processing tasks such as voice processing by roughly 8 times. For mobile robots, this headroom keeps object classification, anomaly detection, keyword spotting, and predictive maintenance running locally, next to the sensors. Low latency and independence from a network connection are critical. Running inference on the NPU rather than the cores also frees

MCX N Series Products

Family	Flash	SRAM	CoolFlux DSP	USB HS	DAC	Op Amp	Flewx-comm	CAN-FD	Packages
N94x	2 MB	416 KB w ECC		For N947	2x 12b + 1x 14b	3	10	2	VFBGA184, 9x9mm and HLQFP100, 14x14mm
N54x	2 MB	512 KB	-		1x 12b	-	10	1	VFBGA184, 9x9mm and HLQFP100, 14x14mm

Figure 2: The MCX N Series products. Image source: NXP

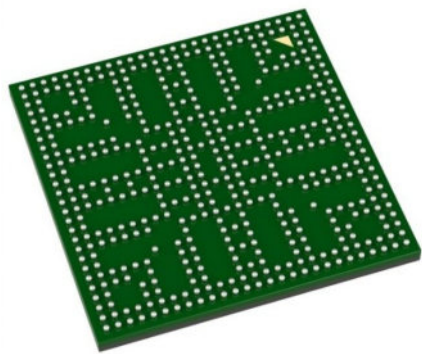


Figure 3: The i.MX 8M Nano quad-core applications processor
Image source: NXP

up the Cortex-M33 pair for control and communication tasks, making concurrent sensing and motion practical on the same device.

From trained model to working firmware with eIQ

Hardware alone does not deploy a model, so NXP pairs the NPU with its eIQ machine learning software environment. Within the [MCUXpresso SDK](#), the eIQ Toolkit offers a Neutron Converter Tool that accurately maps quantized TensorFlow Lite models onto the NPU, TensorFlow Lite for Microcontrollers to run inference, and utilities such as the eIQ Time Series Studio for models built on sensor data. Quantization is crucial at this step, because reducing a model to integer arithmetic brings its memory footprint and compute demand within reach of a microcontroller, and the toolchain performs that conversion rather than leaving it to hand-tuning. This means that you get a defined path

from a trained model to working firmware, without building a custom deployment flow.

Precise motor control for mobile robotics

Alongside inference, the MCX N handles the motor control that keeps a robot moving, with the MCX N94x carrying the peripherals for it. The MCX N94x includes two enhanced FlexPWM modules, two quadrature decoders for position and speed feedback, and an event generator that offloads time-critical logic from the cores. Supporting these are additional timers and an analog front end of high-speed ADCs, multiple DACs, on-chip op-amps, analog comparators, and a SINC filter.

Field-oriented control depends on sampling phase currents at the correct instant within the PWM cycle. The FlexPWM modules synchronize directly with the ADCs to ensure the timing is repeatable, while quadrature decoders track rotor position without consuming core cycles. The on-chip op-amps

and comparators handle current-sense amplification and overcurrent detection that would otherwise require external components, reducing both component count and the board area a robot's drive stage occupies. Having two independent FlexPWM modules allows a single device to drive two motors, which suits differential drive arrangements in mobile platforms.

Connectivity and integrated security

A robot must communicate with its sensors, its actuators and often a host controller or network, and the MCX N carries the required interfaces. It supports configurable serial channels through FlexComm, dual CAN FD for in-machine communication, I3C for sensor aggregation, 10/100 Ethernet, and both full-speed and high-speed USB.

On the security side, the MCX N integrates the EdgeLock secure enclave with hardware-based key management, a true random

number generator, cryptographic acceleration and secure boot anchored to an immutable root of trust that verifies firmware authenticity at every startup. PRINCE encrypts external flash on the fly, and together with tamper detection and the dual-bank flash and ECC memory noted earlier, the device protects both its code and its data without a separate secure element. For robots working in shared spaces and communicating over networks, building this protection in from the start avoids the cost of retrofitting security once the architecture is settled.

Scaling across the NXP portfolio

The MCX N is the high-performance member of a broader family, so being familiar with the rest of the lineup will help matching a device to an application. The MCX C series sits at the entry point with a Cortex-M0+ at 48 MHz and up to

256 KB of flash, making it ideal for budget-sensitive designs, while the MCX A steps up to a Cortex-M33 at up to 96 MHz with a motor control subsystem and broader analog integration.

The MCX N series offers the dual-core performance and NPU described here, and the MCX W series adds wireless connectivity for Matter, Thread, Zigbee, and Bluetooth LE, running a 96 MHz Cortex-M33 alongside an independent radio subsystem that keeps connectivity functions off the main core. Because all four series use the same MCUXpresso tools and SDK, you can switch between them without restarting development.

For applications that require more processing than a microcontroller can provide, NXP offers crossover and applications processors. Its [i.MX RT series](#) delivers high-frequency Arm Cortex-M7 performance with microcontroller-

style usability, while the [i.MX 8M Nano](#) (Figure 3) combines quad-core Arm Cortex-A53 cores at up to 1.5 GHz with a Cortex-M7 at up to 750 MHz for Linux-class workloads.

Conclusion

Engineers building mobile robots and other intelligent edge systems can use NXP's MCX N series to bring control, machine learning, and security into one device, reducing the interfaces they have to design around and shortening the path from prototype to product. Evaluation runs on the MCUXpresso ecosystem, with low-cost [FRDM-MCXN236](#) and [FRDM-MCXN947](#) boards for early software work, and the fuller [MCX-N5xx](#) and [MCX-N9xx](#) EVKs are available when you need the complete peripheral set in front of you.

To explore the full range of MCX N series microcontrollers, please visit NXP's product highlight page on [DigiKey](#).

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Position feedback without trade-offs using Same Sky's capacitive encoders

same sky

Encoders rarely fail completely; instead, they degrade gradually, which closed-loop controllers cannot detect. The servo loop accepts miscounted edges and drifting position data as accurate and acts on them with full confidence, driving the axis to the wrong place but reporting a correct arrival. This is why the choice of encoder sensing technology matters more than the headline resolution figure, as two of the three technologies commonly used today degrade in this way. Optical encoders resolve fine increments but depend on an unobstructed light path, which dust, grease and condensation progressively obscure. While magnetic encoders survive such contaminants, they sit inside the stray magnetic fields generated by the motors they monitor.

Same Sky's (formerly CUI Devices) AMT series encoders work using capacitive sensing, which is not susceptible to contaminants, and is as rugged as magnetic sensing with higher accuracy and resolution. Unlike the other two options, this technology supports field-programmable resolution.

How capacitive sensing works

An AMT encoder has three parts: a stationary transmitter, a rotor carrying a sinusoidal metal pattern and a stationary receiver. The transmitter emits a high-frequency

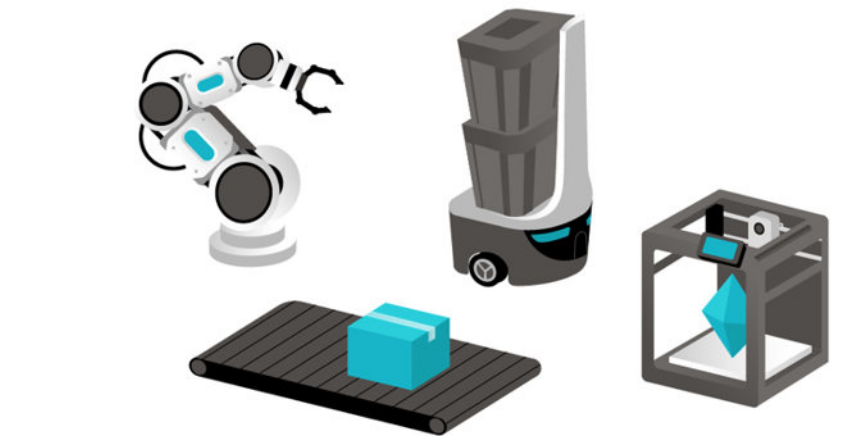


Figure 1: Encoders can be used in a wide variety of industrial applications to provide precision movement and essential feedback *Image source: Same Sky*

AC field, and as the rotor turns, its metal pattern varies the capacitive reactance between the transmitter and the receiver, modulating the field in step with the shaft position. A proprietary ASIC in the receiver demodulates the signal and converts it into output pulses that are compatible with the same circuitry that an optical encoder utilizes.

There are two main advantages with this architecture. First, nothing in the signal path depends on an optical window, so contamination that can blind a photodetector has no equivalent effect, and the design tolerates submersion in non-conductive fluids, such as gear oil. Second, position is derived from an electric field rather than a magnetic one, so mounting the encoder directly on a motor does not compromise its readings.

Note that the fluid tolerance is a property of the sensing method, not a sealing specification. AMT

encoders carry no formal IP rating, so wet or wash-down environments must be verified against your specific mounting.

Resolution you can change after the design is fixed

The typical design process requires committing to an encoder resolution before characterizing the control loop that relies on it. Capacitive sensing removes this commitment because its resolution depends on how the ASIC interprets the modulated field data, rather than on a fixed value.

The AMT incremental kits make the resolution user-adjustable across 16 to 22 selectable values depending on the series, from 48 PPR up to 4,096 PPR on the AMT11 and AMT13 and 5,120 PPR on the AMT10E. The AMT10 is set with a DIP switch, while the AMT11, AMT13 and other series are software-configurable.

we get technical

The ability to change the resolution after mounting the encoder gives you greater flexibility during development. You can run the prototype at a coarse resolution while mechanical revisions are still underway, then increase the resolution once the control loop bandwidth is established and the actual feedback requirements are known. To support this workflow, Same Sky offers both configurable and preconfigured encoders. The configurable “-V” kits offer multiple sleeve bores, mounting orientations and interface options, allowing a single AMT10-V to support up to 288 configurations from a single part number. Once the orientation, resolution and bore diameter have been finalized, preconfigured models provide a fixed part number for production.

Whichever encoder format is selected, it can be configured using Same Sky's [AMT Viewpoint GUI](#). This free Windows application connects to the encoder through an [AMT-PGRM module](#) and sets the resolution, direction, pole count and zero position. It also plots the output waveforms, allowing for quick data analysis.

Choosing between incremental, absolute and commutation feedback

Once the resolution has been determined, the next criterion is the type of feedback required. The main consideration is whether

the control system needs to know the shaft position the instant power is applied or whether it can find a reference position through a homing sequence. Which AMT family is the best fit for an application will depend upon this requirement. Figure 1 illustrates several industrial applications that rely on encoder feedback for precision movement and position control.

Incremental encoders provide relative position information rather than angular position, making them well suited to systems that can execute a homing routine to find a known reference point. Because position is derived by counting quadrature pulses, the controller can track motion without the overhead of polling a serial bus.

Examples of incremental encoders are the AMT10 and AMT10E series (Figure 2) that come in a 28 mm body, running 48 to 2,048 PPR and up to 5,120 PPR respectively, with A/B quadrature outputs and an index pulse in single-ended or differential line driver output. For smaller motors, the AMT12 series comes in a 22 mm body for use with 1 to 6 mm shafts, small enough to mount on a NEMA 08 frame.

Homing is not always a practical option, especially in systems that must know their position immediately after power-up. In these applications, an absolute encoder eliminates startup

uncertainty by reporting a shaft's exact position as soon as power is applied. Same Sky offers 12-bit and 14-bit resolution options, providing 4,096 or 16,384 distinct positions per revolution, respectively. For axes that can rotate many times between limits, such as geared drives, rotary tables, or lead-screw actuators, multi-turn versions track the total number of revolutions in addition to angular position. With a multi-turn count range of -8,192 to +8,191 revolutions, the encoder retains position information across power cycles, allowing the system to resume operation without a homing sequence.

Once absolute feedback has been selected, the next consideration is the communication interface based on factors such as cable length, electrical noise, and the number of encodes in the system. For short, point-to-point connections between the encoder and a controller, the AMT20 and AMT22 use Serial Peripheral Interface (SPI), a simple and efficient protocol suitable for direct communication. Applications requiring longer cable runs or operation in electrically noisy environments are better served by the AMT21 and AMT24, which use the differential RS-485 interface. In addition, RS-485 allows up to 64 encoders to share a single bus. For systems that require a Synchronous Serial Interface (SSI), the AMT23 provides a single-ended SSI output option.

While incremental and absolute

encoders are selected primarily based on how position information is acquired and communicated, some applications require an additional type of feedback. Brushless DC (BLDC) motors, for example, need commutation information in conjunction with shaft position so the controller can energize the correct motor phases. For these applications, the AMT31 and AMT33 provide both functions, generating U, V, and W commutation signals together with incremental A, B, and Z outputs, and supporting 2 to 20 poles. Aligning a commutation encoder to a motor's electrical phase normally involves measuring back-EMF on an oscilloscope, but Same Sky's AMT One Touch Zero™ Alignment Tool, the [AMT-OTZ-1](#), replaces that with a button press, which saves about 20 minutes per motor build.

Why supply current matters on battery power

It is usually possible to ignore encoder supply current on mains-connected equipment, but on battery-powered platforms it becomes a more significant design consideration. Encoders draw current continuously whenever they are energized, including periods when a motor remains stationary. Because encoder technologies differ substantially in their operating current requirements, the choice of sensing technology can have a measurable impact on overall system power consumption

and battery life.

Same Sky's AMT series capacitive encoders are designed with low power consumption in mind. The AMT10 and AMT10E models draw just 6 mA at 5 V, while their remaining incremental, absolute, and commutation encoder families draw only 16 mA. In Same Sky's four-axis comparison, four AMT10 encoders consumed a total of 0.12 W, while four optical encoders drawing 85 mA each consumed approximately 1.7 W, and four magnetic encoders operating at 160 mA each consumed about 3.2 W.

One and a half to three watts may appear small when compared with motor power, but encoder power draw is continuous and accumulates over the entire operating cycle. In battery-powered equipment, reducing this constant load can help extend operating time, improve energy efficiency and ease battery-capacity requirements.

Mounting and retrofit considerations

Every option above must attach to a motor shaft. AMT kits accommodate shafts from 1 mm to 15.875 mm (5/8 in.), typically through nine sleeve bore options per kit, with a locking hub that reduces mounting and alignment time to seconds. This flexibility is especially valuable in retrofit applications, where a



Figure 2. The AMT10 and AMT10E incremental encoders

Image source: Same Sky

machine already in service gains encoder feedback or transitions to capacitive sensing without requiring changes to the motor mount or surrounding structure, as the kit adapts to the existing shaft.

Conclusion

Same Sky's AMT capacitive encoders combine contamination tolerance, magnetic immunity, field-programmable resolution and low power consumption in a flexible platform. With incremental, absolute and commutation options, the AMT series gives designers a practical way to match position feedback to the needs of robotics, mobile equipment and industrial automation.

For more information on Same Sky's AMT series encoders, please visit the [AMT series product highlight on DigiKey](#).

Why copper-electrode NTC thermistors deliver more reliable temperature sensing



Temperature sensing is a critical requirement in nearly every electronic system today, from the battery pack in an electric vehicle to the compute board in a data center. Negative temperature coefficient (NTC) thermistors have long been the workhorse for this job because they are small, inexpensive, and highly responsive. However, these devices carry a reliability weakness in the external electrode. [Murata](#) addresses the problem with its [NCU15](#) and [NCU18](#) NTC thermistors which replace the silver outer electrode with a copper structure engineered to prevent chemical migration and withstand wide-ranging thermal and humidity conditions.

NCU15 and NCU18 thermistors: A copper-based solution

To understand why this design matters, it helps to look at what goes wrong with silver. When a component built with a silver-bearing external electrode operates under an applied voltage in a humid environment, the silver at the positive electrode can oxidize and ionize. Those silver ions then travel through the thin film of surface

moisture toward the negative electrode where they are reduced back into metallic silver and gradually morph into conductive filaments known as dendrites. Over time, these filaments can bridge the gap between electrodes, creating leakage paths or outright short circuits. Because the electrochemical migration process is typically slow and humidity-driven, a design can pass bench tests, only to fail months later in the field.

Murata's NCU15 and NCU18 thermistors use a copper base finished with nickel and tin plating, without any silver in the external electrode. The nickel layer serves as a diffusion barrier while the tin layer preserves solderability, so the thermistor gains migration resistance while still soldering and mounting like any standard chip component on a production line.

Murata targets automotive and other high-reliability systems with its thermistors, given that long service life under thermal and humidity stress is critical.

Note that Murata still advises against continuous use of its thermistors in condensing or corrosive-gas atmospheres. The copper electrode should be understood as removing the main electrochemical migration failure mode rather than making

the device immune to every environmental stressor.

Package options and temperature range

NCU15 and NCU18 thermistors are offered in compact chip formats, with the NCU15 in the 0402 EIA case size (1005 metric) and the NCU18 in the 0603 EIA case size (1608 metric) (Figure 1). Their small thermal mass is reflected in a dissipation constant of ~1.0 mW per degree Celsius which supports the thermal responsiveness required when a sensor needs to track rapid temperature changes without lagging behind the measured event.

The thermistors cover an operating temperature range of -40 to +125°C, with automotive-grade models extending up to +150°C for under-hood and high-temperature environments. The NCU family is UL and cUL recognized, while the automotive family is AEC-Q200 qualified.

Resistance, tolerance and design flexibility

Murata's thermistors offer design flexibility in a wide range of applications. They are offered in a spread of nominal resistance

values at 25°C, including the common 10 kΩ, 47 kΩ, and 100 kΩ options along with higher resistances on the NCU18, each with its corresponding B-constant.

Tolerance options run from a tight ±1% for precision sensing down to more economical ±3% and ±5% grades, with a B-constant specified to ±1% on the common resistance values. This combination allows matching a specific part to your accuracy budget rather than having to over-specify. Around room temperature, the resistance of a 10 kΩ, 3380 K device changes by roughly 4% per degree, ensuring fine temperature resolution for most applications. Choosing copper over silver also carries a supply chain benefit by reducing dependence on silver, which supports a more cost-effective electrode construction without compromising sensing performance.

Key applications

Automotive electronics face some of the harshest conditions for temperature sensors. Under the hood, systems typically cycle between sub-zero cold starts and sustained high temperatures near the engine or power electronics, while EV battery packs and inverters add regular humidity exposure on top of thermal stress.

Automotive-grade NCU thermistors offer a +150°C rating to handle the upper end of the temperature

range, and their AEC-Q200 qualification confirms that they have been tested against accelerated stress, including temperature cycling, humidity, and sustained high-temperature storage. The migration resistance is a key characteristic in always-on equipment, such as computing servers and factory automation systems, where sustained DC bias under continuous load is typical.

For portable designs, compact 0402 and 0603 packages and low thermal mass are key advantages. In drones, NCU thermistors monitor motor windings, electronic speed controllers, and battery cells, quickly detecting temperature increases caused by high current loads. Their short thermal time constant provides early warning of overheating, allowing the flight controller to reduce power before thermal runaway can occur.

AR/VR headsets and wearables use these compact sensors to monitor SoC, display driver, and battery temperatures, helping protect the electronics while keeping surfaces that contact a user's face or wrist within safe limits. Distributed IoT nodes can utilize them placed next to power management or RF sections to detect thermal faults in enclosures that typically have little to no active cooling. In health and wellness wearables, the ±1 percent

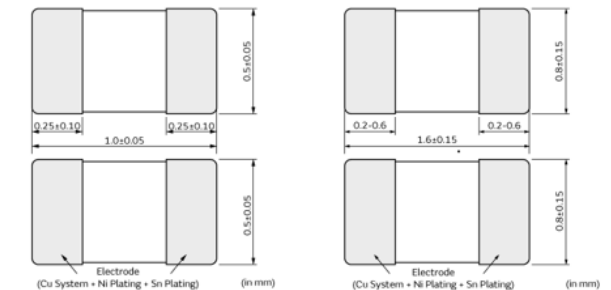


Figure 1: Dimensions for the NCU15 (left) and NCU18 (right) NTC thermistors
Image source: [Murata](#)

tolerance of the NCU15 and NCU18 series supports accuracy to within roughly a tenth of a degree around 37°C, ensuring highly accurate body temperature readings.

Conclusion

By replacing the traditional silver external electrode with a copper, nickel, and tin structure, Murata's NCU15 and NCU18 thermistors address one of the most common long-term reliability concerns in temperature sensing: electrochemical migration. Combined with compact package options, wide operating temperature ranges, tight tolerances, and qualifications for demanding automotive and industrial environments, these thermistors provide a durable and accurate solution for dependable temperature monitoring.

Explore the entire range of NTC thermistor options on [DigiKey](#) to compare resistance values, tolerances, and case sizes to meet your specific application.

Video spotlight



i7500 Industrial Label Printer

The i7500 is a 3" open-core printer with built-in Brady LabelSense Technology. Designed for high volume, zero waste printing. No calibration or trial and error so you always print on the first label. Change materials in 40 seconds with faster ribbon removal and intuitive loading.

[Learn more](#)

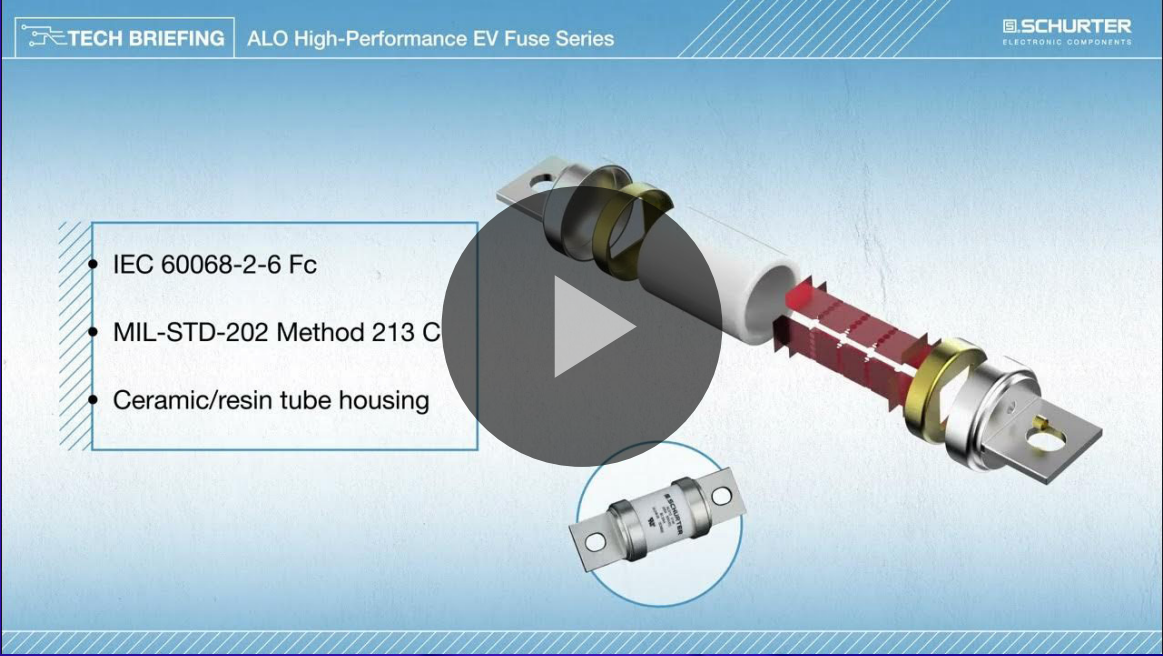


RX14T 48 MHz entry-level 32-bit MCU

The RX14T is an entry-level motor control microcontroller (MCU) featuring a 48MHz RXv2 core that delivers an excellent balance of performance, functionality, and cost. Designed for home appliances and industrial equipment, the RX14T provides robust 5 V operation with outstanding noise immunity, making it highly reliable in electrically noisy environments.

[Learn more](#)

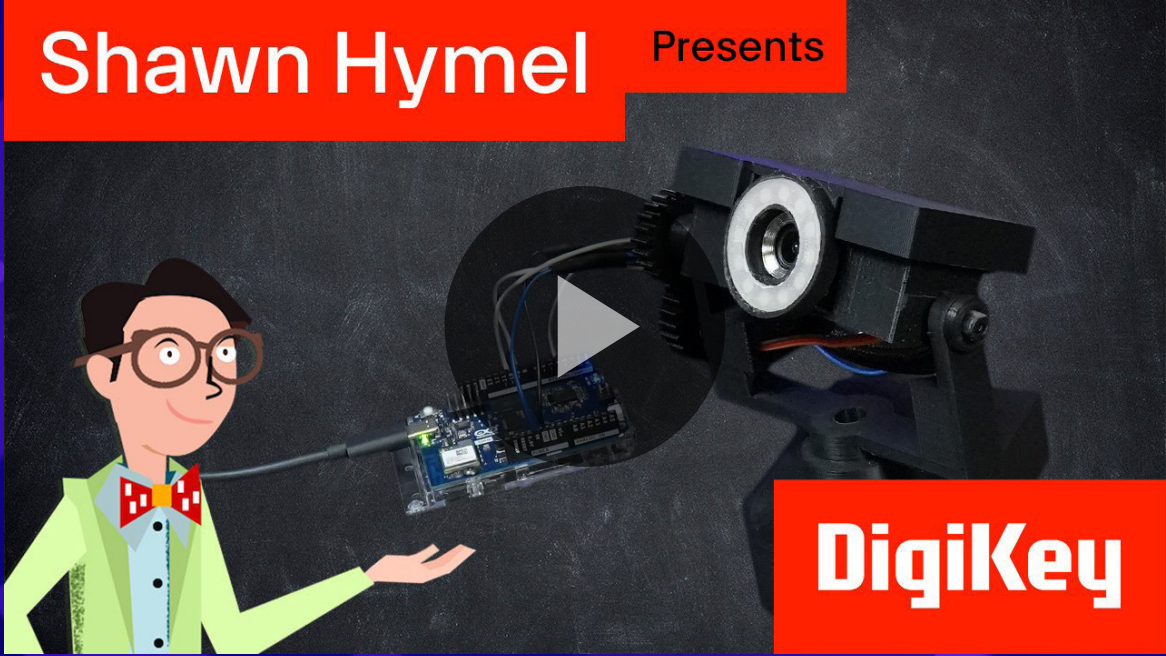
Video spotlight



ALO High Performance Fuse

SCHURTER's ALO High Performance Fuse delivers reliable high-voltage protection for EV applications up to 1,000 VDC and 900 A. With a 50 kA breaking capacity, multiple mounting options, and rugged ceramic or resin housings, the ALO series offers the flexibility, safety, and performance needed for today's electric vehicle power systems.

[Learn more](#)



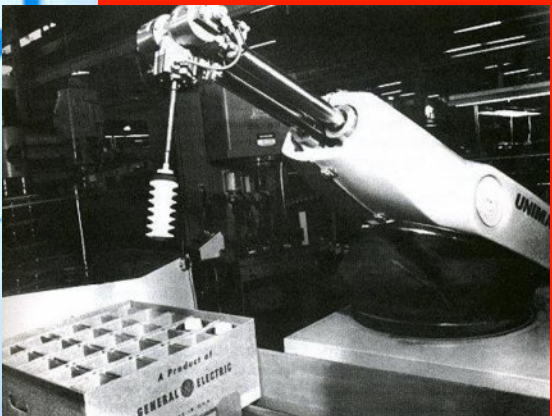
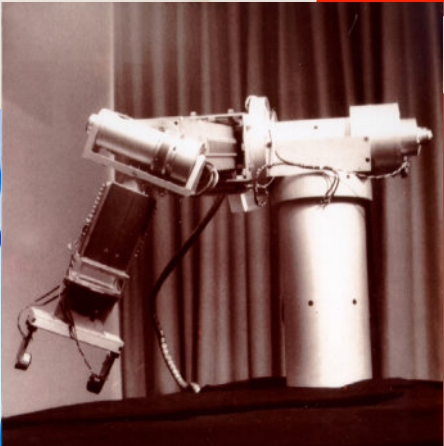
Face expression recognition robot with Arduino UNO Q

The Arduino UNO Q is a unique hybrid board that blends a Qualcomm QRB2210 application processor with an STM32U585 microcontroller, making it ideal for projects that need both AI/ML inference and real-time control. Unlike typical single-board computers, the UNO Q shines in headless edge-AI applications (e.g. computer vision, local web servers, ONNX/TensorFlow Lite inference, and USB-camera processing) while the MCU handles the precise timing required for servos, LEDs, and sensors. That combination makes it a powerful platform for robotics, mechatronics, smart cameras, and interactive art.

[Learn more](#)

A robot for industry: The robot arm, George Devol, and Vic Scheinman

Written by David Ray, Cyber City Circuits



“What would a robot arm have to become before a computer could truly control it?”

The machine beside the furnace

In 1961, workers at a General Motors plant in Trenton, New Jersey, found themselves sharing the factory floor with a new kind of machine. A robot. Installed beside a hot die-casting operation, it reached toward the press, handled newly formed parts, and moved them away, allowing its human coworkers to avoid the heat, fumes, and danger. The job was repetitive, unpleasant, and potentially deadly. It was also exactly the sort of work its designers believed a machine should perform.

The machine was called Unimate. It did not have a head or legs, just one arm. The Unimate was not intelligent. Fitted with the proper tool, Unimate could be taught where to move, what to pick up, and where to place it. Hydraulic actuators and pistons supplied the muscle. A position-control system kept track of the arm’s movements, while a built-in memory stored the sequence of instructions needed to complete the job. Once the sequence had been recorded, the machine could perform it repeatedly without becoming tired, distracted, or reluctant to reach into the press without gloves.

Its most important feature was memory. Conventional automation could perform repetitive work, but its motions were generally built into the machine itself. Changing the job might require new cams,

mechanical linkages, belts, relays, switches, or an entirely different piece of equipment. Unimate separated the machine’s instructions from part of its mechanism. Its behavior could be quickly changed without rebuilding the entire arm.

This made Unimate enormously important. It could repeat a stored sequence as many times as the user wanted, but it had to be taught manually. The Unimate could not accept a keyboard command or calculate the motions required to carry it out. It really just had the memory of the positions it was in when it was programmed. The Unimate had demonstrated that a programmable arm could perform useful industrial work.

George Devol

George Charles Devol Jr. was born in Louisville, Kentucky, in 1912. Although he never earned an engineering degree, he began experimenting with electricity and machinery while a young man in school, where he helped operate the school’s electric generating plant. Devol was

less interested in studying an established field than in building something that did not yet exist.

In 1932, during the Great Depression, Devol formed the United Cinephone Corporation. Talking pictures (sometimes called ‘talkies,’ but today the children call them ‘movies’) were still relatively new, and Devol hoped to improve the method for recording sound directly onto film. Competing against companies such as RCA and Western Electric proved difficult, but the work introduced him to photocells, vacuum tubes, amplifiers, and the problem of converting recorded information into a controlled output.



Figure 1: Brochure catalog cover for United Cinephone Corporation

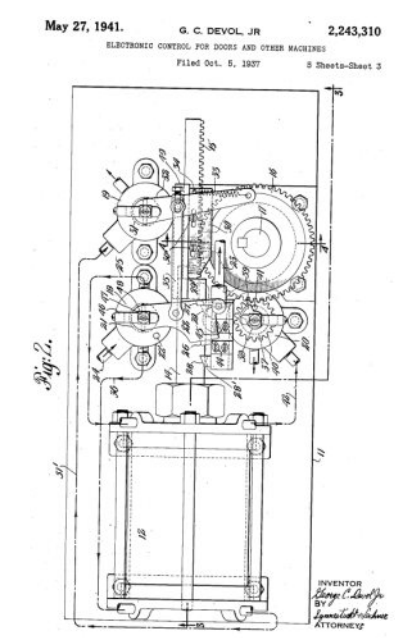


Figure 2: Electronic control For doors and other machines

The Phantom Doorman

When the sound-film business failed to develop as he hoped, Devol gave it up. What else could he do with all those photocells and vacuum tubes? One answer was coming up with an automatic door.

While Devol isn't responsible for the "first automatic door," he developed an electronic control that combined light sensing with motor operation. As a person approached the door, they would break a photoelectric beam, the control circuit responded, and the mechanism opened the door. One key part of his patent was that there was a capacitor bank that would keep the door open for a time in case anyone was near the door, so it wouldn't hurt anyone as it closed. His patent was broad enough to



Fig 3: Magazine advertisement for Devol's automatic door, sold by Yale and Towne Mfg. as 'The Phantom Doorman.'

describe similar controls for locks, valves, conveyors, presses, and other machinery, but the door made the idea immediately profitable. United Cinephone licensed this technology to Yale & Towne, which sold it as the "Phantom Doorman."

Sperry Gyroscope and the Speedy Weenie

During World War II, Devol worked at Sperry Gyroscope on radar equipment and microwave test systems. After the war, his projects ranged across printing, packaging, identification (like bar codes), and digital magnetic recording. While at Sperry, Devol learned a lot about microwaves, and he helped develop the "Speedy Weeny," a vending machine that used microwave energy to cook



Figure 4: Believe it or not, the Speedy-Weenie was short-lived

and dispense hot dogs. Machines were reportedly installed at several locations, including Grand Central Terminal.

Programmed Article Transfer

By the early 1950s, Devol had accumulated most of the pieces required for something far more consequential than hot dogs. He had figured out a neat trick. Photocells can detect information. Codes can identify objects. Magnetic media can store instructions. Automatic machinery can now work. The next step was to combine them into a machine that could respond to an event while also remembering an entire sequence of movements to different positions.



Figure 5: George Devol and Wife in Mid-1940s, likely while working at Sperry Gyroscope or while trying to hustle Speedy Weenies

Factories were already filled with automatic machinery. Cams, switches, relays, conveyors, and transfer mechanisms could perform the same operation thousands of times with remarkable speed and reliability. The problem came when something about the process or the product changed. A machine designed to move one part through a single sequence of operations might require new cams, switches, tooling, or an entirely new transfer mechanism before it could be changed for a new operation.

Devol figured that instead of building each sequence of movements physically 'hard-coded' into the machinery, why not build a more general-purpose machine and store the movements as instructions?

On December 10, 1954, Devol

filed a patent application for what he called "Programmed Article Transfer." The patent, issued in 1961 as U.S. Patent 2,988,237, described a powered transfer head capable of lifting, rotating, extending, gripping, and releasing an object.

The machine could be guided slowly through an operation while its movements were recorded onto a magnetic drum. During automatic operation, the controller read the stored commands and compared the arm's actual position. The mechanism continued moving until the two matched, then advanced to the next instruction. The stored sequence could be erased and replaced when the machine was assigned a new job.

Devol had separated the work from as much of the machine's

fixed construction as the available technology allowed. Devol gave robots a memory. Unimate remembered a sequence of positions and control functions and repeated them. That limited flexibility was still enough to make one type of machine useful for many different jobs, including material handling, welding, spraying, and other repetitive work.

A patent alone is never enough to start printing money. Turning the concepts and diagrams into an industrial machine would require years of work. Devol had described the machine, but he still needed someone capable of building a company around it.

According to lore, Devol met Joseph Engelberger at a cocktail party in 1956. Their conversation

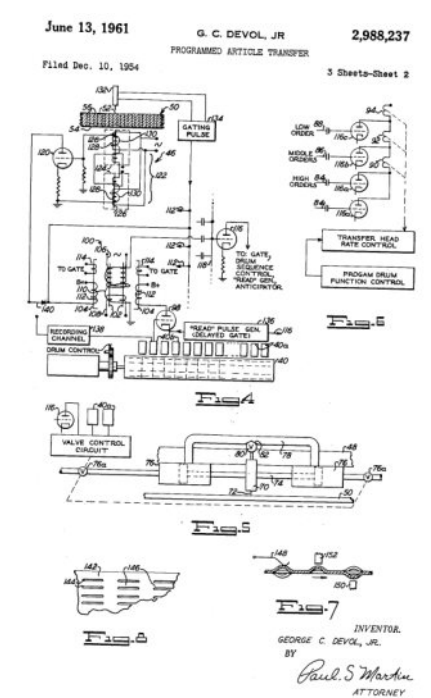


Figure 6: Programmed Article Transfer



Figure 7: Recreation of the historic moment that Devol and Engelberger met at a cocktail party

drifted toward science fiction, Isaac Asimov, and then to Devol’s programmed transfer machine. Engelberger recognized it for what it was. A robot.

Devol brought the concept, the patent, and years of experience with sensors, controls, and magnetic recording. Engelberger brought engineering management, financing, organization, salesmanship, and an unreasonable amount of persistence. Together, they began turning ‘Programmed Article Transfer’ into ‘Unimate.’

Fig 9: A later Unimate machine

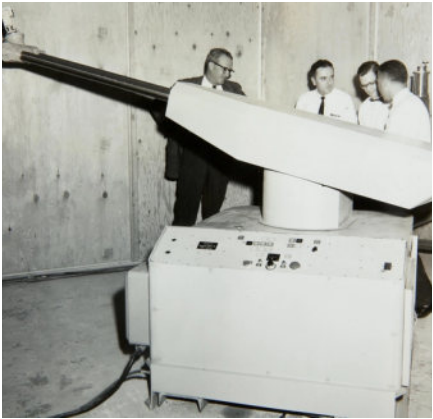
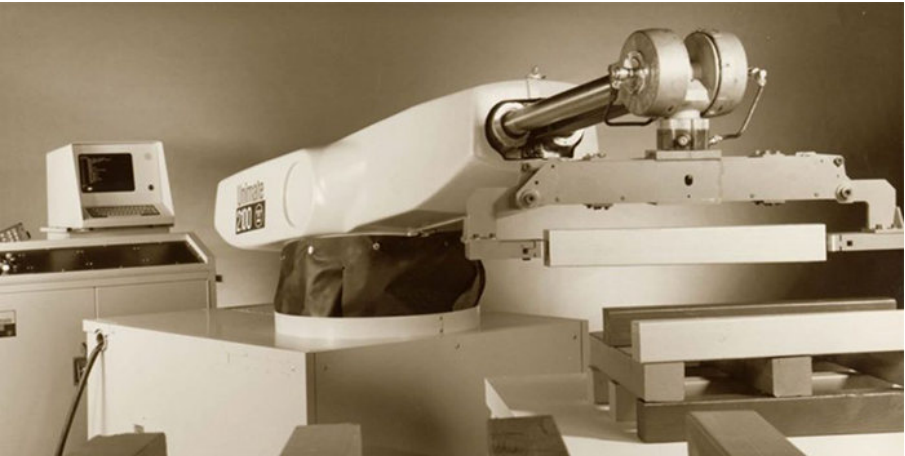


Figure 8: Devol and co with a Unimate machine

The Invasion of the Unimate in Trenton, New Jersey

After they settled on a prototype, there was the difficult matter of convincing someone to buy one. According to Engelberger’s later recollection, he approached forty-six companies searching for anyone willing to place a robot on its factory floor. The hesitation was understandable. Unimation was proposing an expensive, unfamiliar machine controlled by hydraulics, relays, and fancy magnetic memory. If it failed, it could stop an entire production line

dead. If it succeeded, no one yet knew how long it would continue succeeding in the heat, dirt, and abuse of a factory. It is easy to imagine the two men being laughed out of at least one or two meetings. Eventually, General Motors was willing to give it a try.

In 1961, the first production Unimate was installed at the General Motors plant outside Trenton, New Jersey. The robot was assigned to unload a die-casting press. It performed a dangerous and repetitive task. Reach for a die press, grip the red-hot casting, and place the part where it belongs. The environment was hot, dirty, and dangerous, but the task itself didn’t change from one cycle to the next. This was exactly the problem Unimate had been designed to solve.

Its arrival also created two opposing fears. Factory managers worried that the robot would not be dependable enough. Workers were worried that the Unimate would be more dependable than the workers themselves were.

To management, an unreliable robot was an expensive piece of machinery that could disrupt production. So, at first, instead of selling the machines, they were renting them. Literally charging by the hour, costing as much as four men and often out-performing all four.

In 1966, they brought a Unimate onto The Tonight Show starring

Fig 10: Engelberger took the Unimate on Johnny Carson, where it putted a golf ball, conducted a band, and poured a beer



Johnny Carson. The arm sank a golf ball, poured a beer, and conducted the studio band. Engelberger told Carson that a company could rent one starting at \$6 an hour.

At the same time, inside several university laboratories around the country, researchers were beginning to pursue a different kind of arm. They did not want merely to record positions and play them back. They wanted a computer to control and calculate the movements.

Fig 11: Unimate 1967 Pouring Coffee

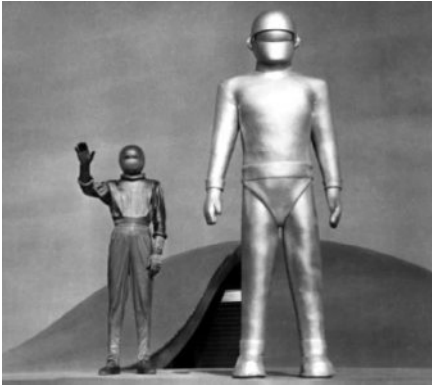


Victor Scheinman

Victor David Scheinman was born in Augusta, Georgia, in 1942, where his father was stationed with the United States Army. After the war, the family moved to Brooklyn, New York.

Scheinman’s earliest experience with robots frightened him. Gort from the 1951 sci-fi film “The Day the Earth Stood Still” haunted his dreams. In response, his father encouraged him to build his own version of Gort using wood

Fig 12: Gort from the film “The Day the Earth Stood Still”



and silver paint. He attached a movable visor operated by a string. Although it wasn’t a complex robot, creating it changed how he viewed machines.

By his teenage years, Scheinman had assembled a workshop of his own. He earned his amateur radio license at thirteen. He worked on many projects, including an electronic banjo and an amateur lie detector. While a sixteen-year-old high school senior, Scheinman attempted something considerably more ambitious. He called it EMVI, the Electro-Mechanical Voice Inscriber.

The idea was to build a typewriter that responded to the human voice.

There is a short film reel from the 1958 New York Science Fair (see suggested reading) that follows Scheinman from his science classroom to his home workshop. He brought theories and problems to his science teacher, then returned to the workbench to turn them into hardware. A person spoke a sound or letter into a microphone. The machine examined the resulting signal, attempted to distinguish it from the other sounds the machine had been prepared to recognize, and activated an electromagnet connected to the appropriate typewriter key. The key moved, struck the paper, and printed the letter.

EMVI could not listen to ordinary conversation and transcribe

whatever it heard. The machine appears to have distinguished only a limited collection of carefully spoken sounds or letters, like ‘A’ and ‘P.’ Whatever its precise limits, it was an extraordinary project for a high-school student in the 1950s.

Scheinman at MIT

EMVI earned attention at a New York City science fair and helped carry Scheinman to the school he had wanted to attend since the fifth grade. In 1959, at sixteen years old, he entered the Massachusetts Institute of Technology.

Scheinman did not arrive at MIT intending to become a roboticist. He studied aeronautics and astronautics and expected his future to involve aircraft, rockets, or spacecraft. Even there, however, his projects continued to combine sensing, electronics, control, and physical movement.

As president of MIT’s model-airplane club, he experimented with radio-controlled aircraft and other methods of controlling models. During the winter, the group experimented indoors by directing the models using a spotlight and photocells mounted aboard the aircraft.

His undergraduate research involved hydrofoils, for which he built an ultrasonic sensor intended to measure wave height and help maintain the foil at a controlled

depth beneath the water.

Boeing

Scheinman graduated from MIT in 1963 and spent several months at Boeing. The assignment was unusually broad. He was allowed to move among advanced engineering groups and worked on projects involving a lunar-gravity simulator, ballistic-missile systems, submarines, and rockets. He also learned to program analog computers, building calculations from interconnected resistors, capacitors, and other circuit elements.

Boeing showed him the scale of the modern aerospace industry. Aircraft, missiles, and spacecraft required hundreds or thousands of

people, each responsible for some small portion of a machine too large for any one person to design and build alone. He would later describe the individual aerospace engineer as one small tooth inside an enormous set of industrial gears. It wasn’t for him.

Stanford University

After a short stint at Boeing, Scheinman entered Stanford University. He initially joined Stanford’s aeronautics and astronautics program, but he found he had already studied the material at MIT and transferred into mechanical engineering. Scheinman accepted a research assistant position at the Stanford Artificial Intelligence Laboratory

Fig 13: Photo of John McCarthy with a camera and two robot arms in the background.

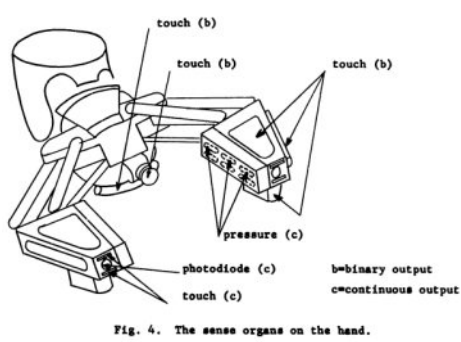
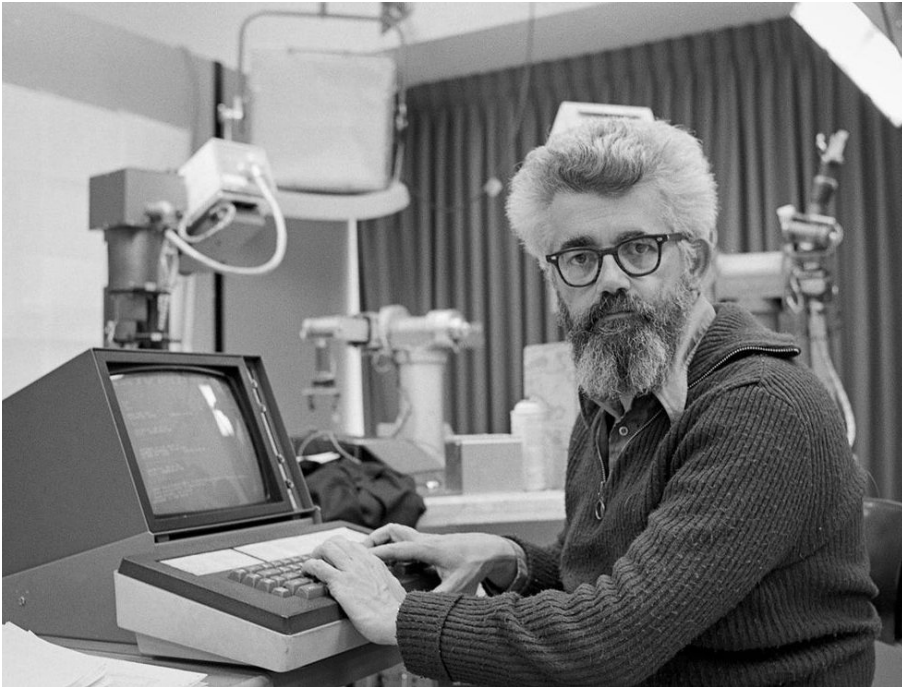


Figure 14: Drawing of MH-1 showing the various sensors Ernst used

(SAIL), where they were trying to tie a computer to a robot arm.

Retro Electro fun fact: SAIL was established several years earlier by John McCarthy and Les Earnest. Both would have worked hand in hand with Scheinman in his work. McCarthy is known for many contributions, including coining the term “Artificial Intelligence” in a 1955/1956 research proposal at Dartmouth College. You can read that story in the Retro Electro article “Programming a Calculator to Form Concepts: Part One.”

The idea of connecting a mechanical arm to a computer was not entirely new. At MIT, while Scheinman was an undergraduate, Heinrich Ernst’s MH-1 had already demonstrated that a computer-controlled tool could use sensory information. Connected to MIT’s TX-0 computer, the MH-1 searched a table for blocks, picked them up, and placed them inside a

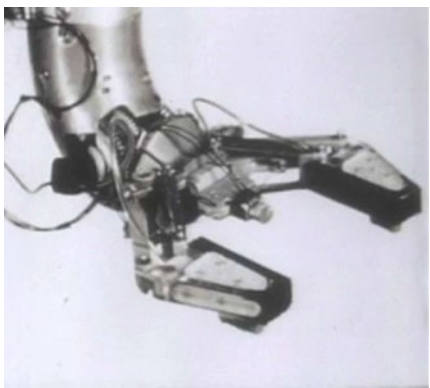


Figure 15: Photo of the finished MH-1

box. Tactile sensors enabled the computer to respond when the machine encountered something.

Scheinman did not work on the MH-1, but he certainly would have met some of the graduate teaching assistants who were there at the time, like Ernst, and at Stanford he encountered many of the same problems.

The laboratory had acquired the “Rancho Arm,” an electrically powered prosthetic arm originally developed to assist people with disabilities. It had been designed around the movements of a human arm and controlled through a set of switches. Stanford researchers connected it to a computer, but it was hard to work with, its positioning was poor, and its parts were not intended for the wear of repetitive laboratory experiments.

The laboratory’s hydraulic arm exchanged uncertainty for force. It was very fast and powerful enough to shake the whole building. It leaked oil and required continuous real-time control. There are stories of oil-coated footprints dotting

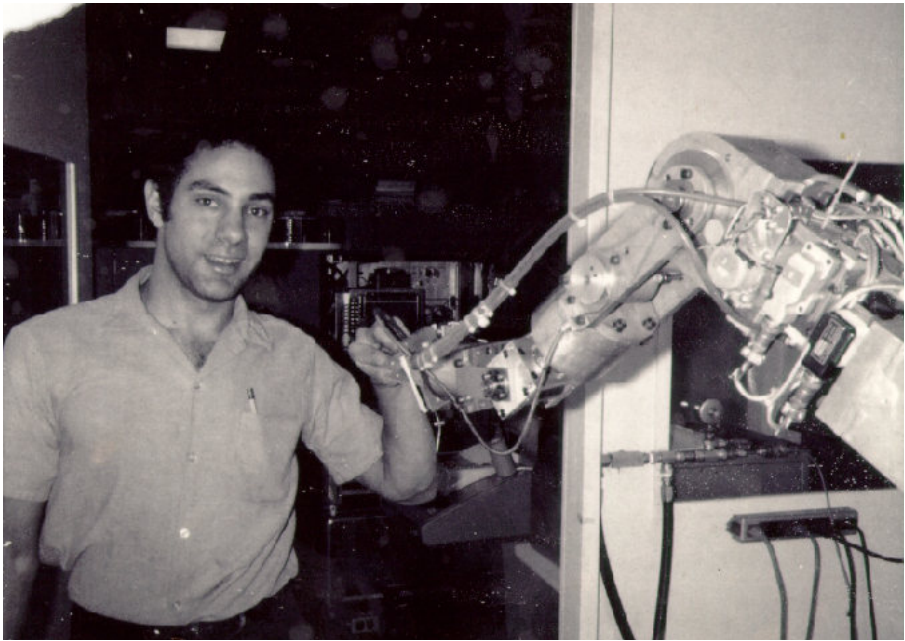


Fig 16: One of the earliest arms Stanford tried was the Rancho Arm, but it was too imprecise to be useful

the halls of SAIL from this time. Stanford’s time-shared computer had to be placed into a dedicated operating mode whenever the arm moved, locking every other user out. In interviews, it sounds like they only had five or ten minutes at a time, around two in the morning, to run their experiments, and if the computer controlling the arm stopped at any point, the arm would drop dead and collapse, worsening the oil problem.

Retro Electro fun fact: Time-share computer systems were becoming common in large universities at this time. One of the earliest successful attempts at time-share computing was Project GENIE at UC Berkeley. You can learn more about that, the BCC-500, and how it led to the very first wireless ARPANET node in Hawaii in the Retro Electro article “The ALOHA System: Task II”

Fig 17: Scheinman and the Stanford Hydraulic Arm



The computer was the limitation

A human operator had years of muscle memory moving to an awkward joint arrangement without calculating the angle of each bone and muscle involved. A robot arm couldn't do that. Before the arm moved, the computer needed to translate a desired 3D position into specific joint positions.

Instead of asking how a computer might control an 'off-the-shelf' arm, Scheinman asked what kind of arm a computer would want to control. If the math was too complicated, the calculations consumed time that the researchers didn't have. He wanted to start with the computer and design an arm to match its capabilities. The arm's physical form factor was designed to simplify the mathematics.

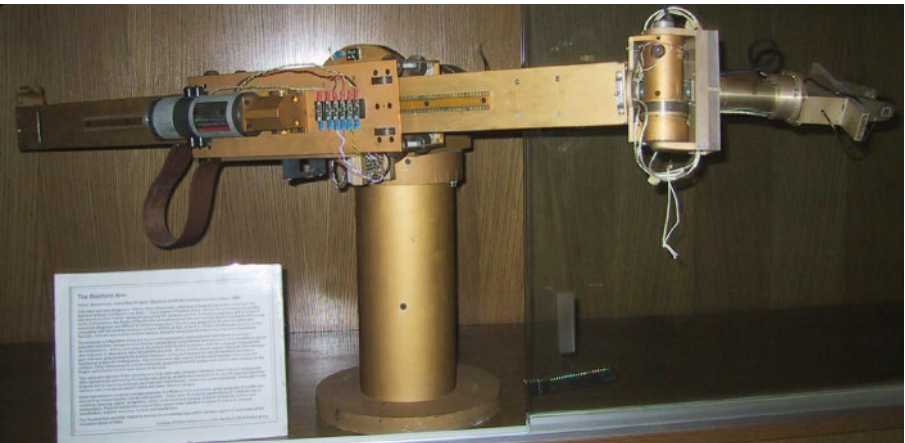


Figure 18: The original Stanford Arm on display at Stanford

Often, when the time-sharing computer was locked out for specific programs or experiments, the researchers would call it 'Spacewar!' mode, after the first video game designed at MIT in 1962. It was so calculation-intensive that while anyone was playing the game, the entire time-share system had to lock everyone else out.

The 1969 Stanford Arm

Scheinman completed the Stanford Arm design as his engineering thesis in 1969. The Stanford Arm has often been described as the first successful electrically powered, computer-controlled robot arm. The arm had six degrees of freedom, five rotary joints and one 'prismatic' joint. Instead of bending a humanlike shoulder and elbow, part of the arm extended and retracted along a sliding rail. Its nonhuman form helped separate parts of the positioning problem and simplified the calculations needed to determine where each joint should move.

Electromechanical brakes solved another problem created by Stanford's time-shared computer. While the arm was moving, the computer could temporarily devote itself to the servo calculations needed to control the joints. Once the arm reached its position, the brakes locked the mechanism in place. The computer could then calculate the next trajectory or return its attention to another user

without allowing the arm to sag or collapse.

Unimate looked nonhuman because that shape suited work beside a die-casting press or other machines. The Stanford Arm looked nonhuman because that shape suited the computer.

The system used calculated trajectories to move between locations, vision to reduce positional uncertainty, and contact information to complete and inspect the physical assembly. The Stanford Arm was a successful prototype, but producing another required drawings, machining, custom electronics, computer interfaces, control programs, and researchers capable of making the entire arrangement work. Another university could not simply order one, place it on a table, and begin experimenting.

The MIT Arm

In the early 1970s, Marvin Minsky of MIT's AI Lab asked Scheinman to

Fig 19: Stanford Arm Product Listing

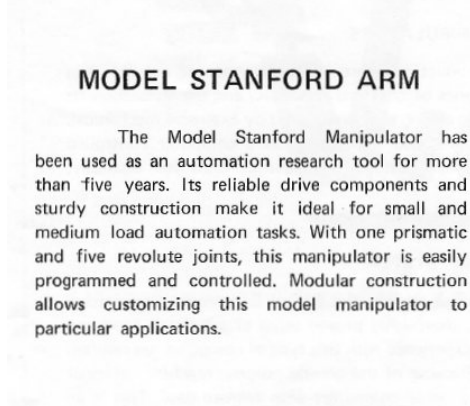
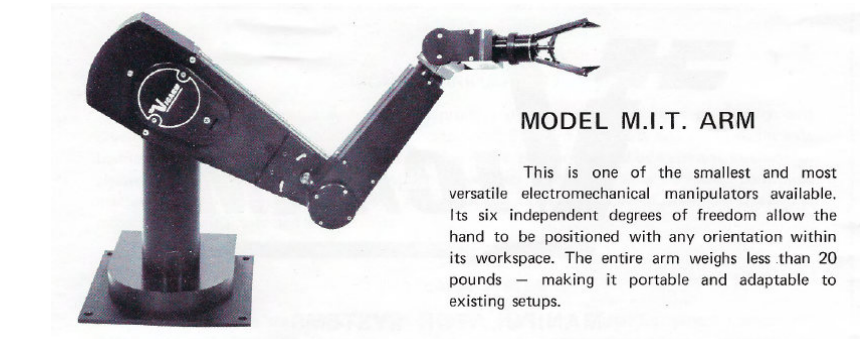


Fig 20: MIT Arm Product Listing



design an arm for the MIT Artificial Intelligence Laboratory. Stanford temporarily loaned Scheinman to MIT, where he spent several months designing the complete machine.

The new MIT Arm abandoned the Stanford Arm's sliding 'prismatic' joint in favor of six rotary joints. Each joint contained a direct-current torque motor, position feedback, and a brake.

The MIT Arm also exposed a new problem. MIT wanted Scheinman to build the machine, but Stanford was a school, not a robot manufacturer. Producing additional arms required outside machinists, dedicated



electronics, and a place where the parts could be assembled and tested. Scheinman therefore purchased a small machine shop in Mountain View and founded Vicarm in 1973. Early customers included General Motors, the National Bureau of Standards, AT&T, the Naval Research Laboratory, and several universities.

Vicarm Inc.

Vicarm initially sold what those customers could not easily build for themselves, a robot arm. Scheinman remembered pricing one of the earliest MIT-style arms at approximately \$4,000. That figure did not account for the actual cost of building and supporting the machine. In 1975, he hired Stanford graduate Brian Carlisle to help manufacture, test, and deliver the arms. Bruce Shimano, who was completing his doctorate at Stanford, worked on control and software in the evenings.

The price soon climbed toward \$15,000. Scheinman was discovering where the robot actually ended. The motors

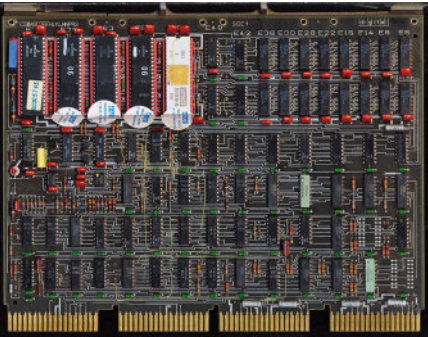


Figure 21: A DEC M7264 LSI-11 processor board, representative of the computer family used by Vicarm and in early PUMA controllers

needed servo electronics. The servo system needed a computer interface. The computer needed capable software. The operator needed commands for describing a path, controlling the gripper, and combining movements into a useful task. Each layer exposed the need for another.

Digital Equipment Corporation (DEC) helped make it small enough to sell. Its LSI-11 condensed the architecture of the much larger PDP-11 ‘minicomputer’ onto a small collection of circuit boards. Vicarm could now place much of the computer inside a controller’s enclosure rather than requiring access to a room-sized university computer.

Even the LSI-11 could not calculate trajectories and operate every joint servo quickly enough on its own. Vicarm distributed the work. Small MOS Technology 6502 processors handled the real-time control of the individual joints and end effector, while the LSI-11 calculated trajectories, solved the arm’s

geometry, and coordinated the complete motion.

Retro Electro fun fact: The MOS 6502 came out at just the right time and revolutionized the way digital systems could be designed and built. The whole design was the brainchild of Chuck Peddle, who later designed the Commodore PET and many other products. You can read his story in the Retro Electro article [“The Birth of the Microprocessor and Chuck Peddle.”](#)

Bruce Shimano’s work began as a small test program for a General Motors research group. GM’s engineers wanted to demonstrate immediately that the newly delivered machine could move. Otherwise, management would see an expensive arm sitting motionless on a table while the researchers spent months developing the control system.

The test program grew. It became a way to command positions, coordinate joints, and describe motion sequences. Scheinman named this new programming language VAL (short for Victor’s

He did not have a booth, but he did have a robot. The complete Vicarm system was compact enough to travel with him aboard an airplane.



Figure 22: Joseph Engelberger

Assembly Language), modeled after the robot-programming language being developed at Stanford.

With the arm, controller, and VAL, Vicarm moved closer to selling a complete robot. A customer no longer had to invent every layer between the computer and the gripper before moving the arm. This is what really made Vicarm quickly successful, creating a packaged, ready-made product.

A robot outside the trade show

The difference became visible at a 1975 robot show in Chicago. He

did not have a booth, but he did have a robot. The complete Vicarm system was compact enough to travel with him aboard an airplane. The arm weighed approximately fifteen pounds. The controller and supporting equipment added another twenty-five. Compared with the hydraulic machines already associated with industrial robotics, it looked less like factory equipment and more like laboratory apparatus.

The show’s organizers reportedly reached a similar conclusion. They dismissed the little arm as a toy and refused to let Scheinman demonstrate it on the exhibition floor. So he carried it outside.

On the front steps, Scheinman found an electrical outlet, ran an extension cord to the controller, and started the robot. The small electric arm moved under computer control while the already established robot manufacturers displayed their much larger machines inside. The contrast was difficult to miss.

Retro Electro fun fact: Bill Lear and Paul Galvin pulled the same stunt out in front of the Radio Manufacturers’ Association Conference when they didn’t want to pay for a booth to demonstrate the new Motorola Car Radio. You can read that story in the Retro Electro article [“The First Car Radio: Motorola’s Sound in Motion.”](#)

The industrial robots inside were large, powerful, and credible. They had been built for foundries, machine loading, material handling, and spot welding. Many moved through sequences of taught points, repeating motions previously stored in mechanical, magnetic, or analog control systems. Inside the hall stood the robot industry as it already existed. Outside, running from an extension cord, was something else.

The machine outside could do something different. Its controller calculated coordinated motion in real time. Instead of merely advancing from one recorded joint position to the next, the arm could follow a programmed path through space. VAL gave the operator a language for describing what the robot should do. Researchers, programmers, and younger engineers began gathering around it. The little arm attracted attention precisely because it did not resemble the established industrial machines.

Joseph Engelberger of Unimation invited Scheinman to bring the robot into his booth and gave him space to demonstrate it on a table. Other exhibitors reportedly objected, but Vicarm had entered the show. This wasn’t Scheinman’s first meeting with Engelberger. Years earlier, George Devol had supported Scheinman through a Stanford fellowship, allowing him to travel with Devol and Engelberger and study early robot installations.

Scheinman had also carried a Vicarm to Unimation’s headquarters in Connecticut and demonstrated its calculated straight-line motion on Engelberger’s desk.

Engelberger could see that the compact machine was more than a toy. Its small size was evidence of what electric actuation, digital control, and a programming language could make possible. Scheinman could see what Unimation possessed that Vicarm did not. Unimation had already established manufacturing, industrial customers, field service, and the credibility needed to sell machines to factories.

General Motors and the 1977 Unimation purchase

General Motors provided the pressure that finally brought the two companies together. GM researchers had purchased Scheinman’s arms and recognized their potential for assembly work. The company wanted a larger machine that could operate within approximately the same workspace as a human worker. It needed to handle components on an assembly line rather than small objects on a laboratory table.

Vicarm could design such a robot, but GM questioned whether Vicarm could manufacture, deliver, and support it in the quantities an automobile company might require. Scheinman had built a dozen arms, mostly for research laboratories.

That was very different from supplying a production system to General Motors.

In 1976, GM issued a request for what it called the “Programmable Universal Machine for Assembly,” the PUMA. Vicarm possessed much of the needed technology but lacked the resources to compete against competitors like Bendix, Honeywell, and Unimation.

In the winter of 1976, on his birthday, Brian Carlisle braved the Michigan snow to give the demonstration to GM that they had been working on. He met with GM researchers, Mitchell Ward and Lothar Rossel, at the GM Tech Center. The demonstration went well and made General Motors want the Vicarm. The thing that truly separated it from the competition was that it had six different movement points, while many others had six or even more, but the Vicarm could control all six at the same time. Other machines would move only one joint at a time, never all joints at once. The team at General Motors had to have it.

GM sent two engineers to Vicarm and stayed with them for a while to help with things like ‘design for manufacturing.’ In an interview, Carlisle expresses that it was also to see how well the team worked together. To gauge their abilities. When asked what he thinks many people get wrong about this story, he says that GM took a larger risk with Vicarm than they get credit for.



Figure 23: Part of the founding PUMA team. Left to Right: Joseph Engelberger, Brian Carlisle, Bruce Shimano, Vic Scheinman

They took a big gamble on a bunch of ‘West Coast guys.’

GM’s concern was not whether Scheinman could make the machine work. It was whether his small company could still be there when the machine needed another unit, a replacement part, or a service technician. After considering that they couldn’t manage a large GM contract on their own, the team of Scheinman, Carlisle, and Shimano went to Engelberger to work together. Unimation was already making \$25-\$30M in annual sales, but it was almost entirely with hydraulic-based machines. Vicarm’s machines would do more than complement their existing catalog, and in 1977, Unimation purchased Vicarm. The Mountain View operation became Unimation’s West Coast division, with Scheinman serving as its general manager. Carlisle continued working on mechanisms, electronics, and production, while

Shimano became central to the software and control system.

At first, little changed beyond the name on the door. The group soon moved into a larger facility and began developing the human-scale assembly robot that GM requested. Prototypes were built in California, while Unimation’s established facilities in Connecticut prepared to manufacture the machines in volume. By selling to Unimation, Vicarm gained the industrial infrastructure it had been missing. Unimation gained a compact electric arm the market was demanding.

The PUMA system

A human-sized industrial requirement

General Motors used the name ‘Programmable Universal Machine for Assembly’ for a proposed manufacturing system combining robots, part feeders, fixed

Scheinman estimated that several thousand PUMA robots were eventually manufactured. A generation of engineers learned manipulation, trajectory planning, feedback control, machine vision, and robot programming on a PUMA arm.

machinery, transfer equipment, and human workers. The goal was to automate relatively low-volume assembly work without building a dedicated machine for every product.

Much of an automobile was assembled by people standing in stations along a conveyor. After the body had been welded together, many of the remaining components weighed approximately five pounds or less and were installed within the reach of a human arm. GM reasoned that a robot designed for those tasks should occupy approximately the same space as the worker it replaced.

Retro Electro fun fact: General Motors often would send out ‘Requests for Proposals’ like the PUMA requirements. The first PLC, the Modicon 084, started life as a set of GM requirements in 1967 that Dick Morley and his team at Bedford Associates took on. You can read that story in the Retro Electro article “The Automation Revolution: Modicon 084.”

Factories had already been arranged around people in stations. Conveyors moved parts through existing human-sized workstations. Feeders, fixtures, tools, and aisles had been positioned where workers could reach them. A robot that fit into the same space could be introduced without rebuilding the entire production line.

GM also saw the arrangement as a form of insurance. If a robot failed, the machine could be removed and a person placed at the station. The line could continue operating while the robot was repaired.

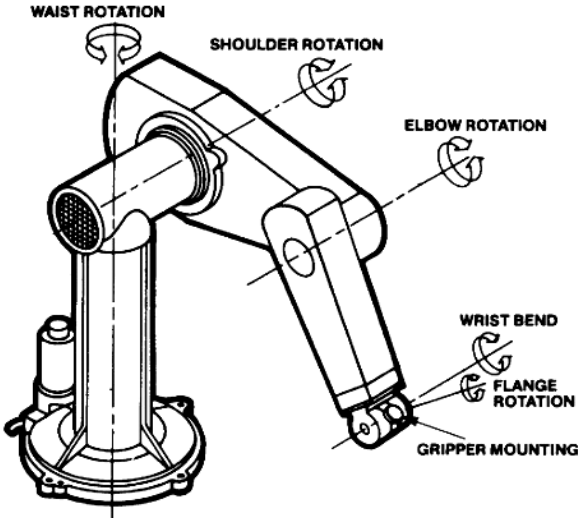
Scheinman later considered this part of the plan misguided. A

factory would need replacement workers waiting for a robot to fail, and each worker would need to know how to perform which job happened to require attention any given day. A spare robot could eventually provide a more practical substitute because its program could be changed for the required station.

The resulting PUMA carried the Stanford Arm, MIT Arm, and Vicarm lineage into a larger industrial machine. It was electrically powered and had six rotary joints. The ‘waist,’ shoulder, and elbow positioned the wrist in space, while three additional wrist axes oriented the tool. The arrangement gave the arm approximately the reach and flexibility needed for work performed by a person, but it did not attempt to reproduce human anatomy precisely.

The VAL programming language connected the machinery to the operator. Instead of programming

Figure 24: Drawing of the Puma 560 and its 6 different joints



the robot only as a collection of motor movements, the user could define positions, name locations, control the gripper, and combine movements into a sequence. The controller translated those instructions into joint trajectories. A location in the program described where the tool should be, while the control system determined how the joints needed to cooperate to place it there.

From prototype to factory product

Scheinman, Brian Carlisle, Bruce Shimano, and the small West Coast Unimation Team developed the first PUMA prototypes, controller, and software. Shimano recalled that approximately eighteen months passed between winning the GM project and delivering the first prototype. Another year

passed before production began, followed by several more years of refinement.

The prototypes could be assembled and repaired by the people who had designed them, but a commercial product had to be built repeatedly by people who had not. Manufacturing therefore shifted toward Unimation’s established operation in Danbury, Connecticut. Carlisle helped transfer the electrical designs, mechanisms, test procedures, and production knowledge from the West Coast group to the factory.

According to Shimano’s recollection, the Danbury operation was so firmly organized around large hydraulic machines that Carlisle initially found himself working inside one of their robot test bays. The facility did not have an oscilloscope ready for him, and

the company was only beginning to introduce computers into its own operations.

GM’s insistence on electric actuation forced a significant change inside Unimation. Some engineers remained convinced that hydraulics were the better industrial technology. Hydraulic machines could produce enormous forces efficiently, but their precision servo valves were expensive, their control was difficult, and leaks remained a constant problem.

Factory product and research standard

GM purchased a substantial number of the robots and placed them anywhere they could fit. Other manufacturers followed, and the PUMA family expanded into several sizes for assembly, handling, welding, etc.

The company intended to combine assembly robots, welding systems, machine vision, software, and application engineering into whole factory installations.

The machine also found a second life outside the factory. PUMA robots spread through universities and research laboratories because their behavior was well documented and VAL was easy enough to use. Scheinman and the Vicarm group had been unusually open about the software and the connections between the controller and arm. Researchers could attach sensors, replace portions of the control system, develop new programming languages, and compare new algorithms against a familiar machine.

The PUMA 560, in particular, became one of the most thoroughly

characterized robots in robotics research. The form factor and its math became the subject of textbooks and technical papers. That familiarity compounded. A laboratory selecting a PUMA gained access not only to a machine but also to the work already performed by other laboratories. Programs, mathematical models, control methods, and experimental results could be compared using a common mechanical platform.

Beyond PUMA

PUMA was not the end of the Vicarm group’s influence. In 1980, Scheinman co-founded Automatix

with Philippe Villers, founder of Computervision Inc. The company intended to combine assembly robots, welding systems, machine vision, software, and application engineering into whole factory installations.

Scheinman pushed that idea even further with RobotWorld. Instead of placing a human-sized arm inside a factory designed for people, RobotWorld scaled the entire workspace down to the parts being assembled. Integrated vision located imperfectly positioned parts while several robotic modules worked together inside the same compact coordinate system.

RobotWorld found customers at General Motors and Hewlett-Packard, and the technology was later transferred to Yaskawa for small-parts and laboratory automation. During this period, Scheinman received the Joseph F. Engelberger Robotics Award for Technology in 1986. In 1990, the American Society of Mechanical Engineers (ASME) presented him with its Leonardo da Vinci Award, recognizing an important advancement in machine design with RobotWorld.

Brian Carlisle and Bruce Shimano followed another path. After Westinghouse acquired Unimation, they left with much of its West Coast engineering group and formed Adept Technology in 1983. The team developed the AdeptOne, a direct-drive SCARA robot



Figure 25: Vic Scheinman at an Automatix trade show demonstration in 1985

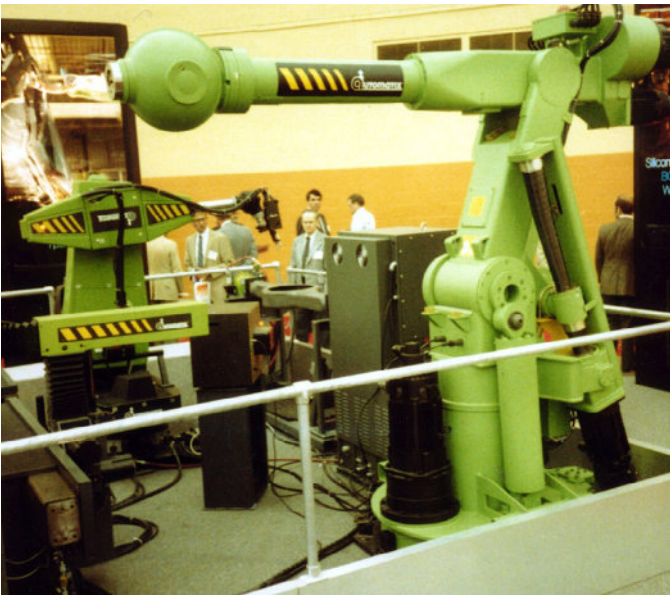


Figure 26: Automatix machine demonstration



Figure 27: Display of Adept Robots for various applications

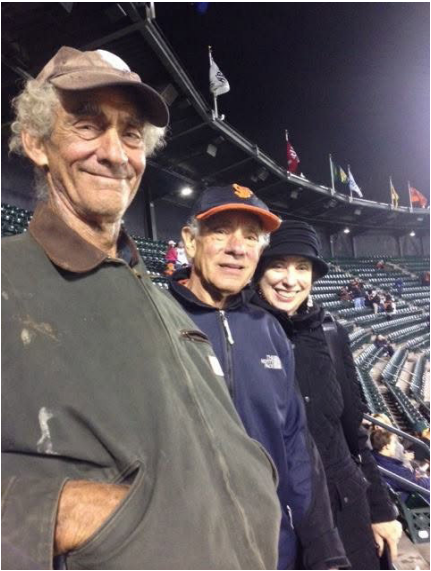


Figure 28: Last photo of Victor Scheinman taken Sept 16, 2016 at a Giants game

optimized for vertical assembly. Scheinman did not design Adept's later machines, but the company carried forward the lesson learned at Vicarm. Mechanics, electronics, software, control, manufacturing, and support had to be developed together and could not be relied upon separately.

The SLAC laser

The writer is going to sidebar here to tell a story.

The Stanford Linear Accelerator Center (SLAC) was built outside Stanford University in the early 1960s. It was a 4-km-long strip in the hills and the longest man-made structure in the world at the time. SLAC was completed in 1966. It was named Project "M," sometimes called Project Monster, and it was the largest and most expensive

public-facing scientific instrument ever built to that point.

In 1974, the team discovered a subatomic particle, and the lead researcher, Burton Richter, shared the 1976 Nobel Prize for the discovery. The next year, 1975, another researcher, Martin Perl discovered the tau lepton. For this, he shared the 1995 Nobel Prize in Physics. Since SLAC was doing so well that they were generating Nobel Laureates, they had a huge increase in funding, and with that came new equipment, like the world's first free-electron laser (FEL.)

In an interview, Brian Carlisle remembered Victor Scheinman as a frugal man. He would save money any which way he could, but he was a sucker for a good deal. In 1976, he found a once-in-a-lifetime deal. When SLAC had to get rid of the old laser to make room to build the FEL, they listed it for sale. For Sale by Owner: \$5,000 (almost \$30k today). This happened at just the same time he was selling Vicarm to Unimation.

He had the laser freighted to his home's garage in Palo Alto. It was not a small piece of laboratory equipment. Carlisle remembered it as roughly fifteen feet long, eight feet high, and six feet wide. Scheinman had no immediate use for the laser. He had purchased it because he wanted to take it apart and discover how it worked.

The legacy left

Scheinman estimated that several thousand PUMA robots were eventually manufactured. A generation of engineers learned manipulation, trajectory planning, feedback control, machine vision, and robot programming on a PUMA arm.

Unimate proved that an arm could perform useful work by remembering it. Victor Scheinman's machines showed that the arm itself had to be redesigned before it could become a practical extension of a computer. The companies that followed pushed the boundary outward again, until the robot included not only the mechanism but also its software, senses, tools, and workplace. The arm remained the part people could see. The larger invention was the system around it.

The writer is grateful for the opportunity to speak with Victor Scheinman's son, David Scheinman. He provided stories and added character to his father that the writer was able to thread into the story. The writer is thankful to Brian Carlisle, who built Vicarm and PUMA hand-in-hand with Vic Scheinman, and who gave his time to speak with the writer for this article. Thank you.

DigiKey has an assortment of robots and robotics accessories in stock in the catalog right now. Check it out the next time you find yourself in need of a new robot arm.

1912

George Charles Devol Jr. is born in Louisville, Kentucky.

Late 1930s

Devol develops a photoelectric automatic-door control. Yale & Towne licenses the technology and markets it as the Phantom Doorman.

1940s

Devol works on radar and microwave test equipment at Sperry Gyroscope. After the war, his experiments expand into identification systems, packaging machinery, magnetic recording, and the microwave-powered Speedy Weenie vending machine.

1956

Devol meets Joseph Engelberger at a cocktail party. Together, they begin transforming Devol's patent into a commercial industrial robot.

1959

Scheinman enters the Massachusetts Institute of Technology to study aeronautics and astronautics.

1961

Heinrich Ernst completes the MH-1 mechanical hand at MIT. Connected to the TX-0 computer, the machine uses sensory feedback to locate and manipulate blocks.

1963-1964

Scheinman enters Stanford University where he later joins the Stanford Artificial Intelligence Laboratory, where researchers are attempting to place a mechanical arm under computer control.

1966

Joseph Engelberger demonstrates the Unimate on The Tonight Show Starring Johnny Carson. The robot sinks a golf putt, pours a beer, and conducts the studio band.

1932

Devol establishes the United Cinephone Corporation to develop methods of recording sound directly onto motion-picture film.

1942

Victor David Scheinman is born in Augusta, Georgia.

December 10, 1954

Devol files his patent application for "Programmed Article Transfer," describing a general-purpose machine that records and repeats a sequence of movements.

1958

Sixteen-year-old Victor Scheinman demonstrates EMVI, the Electro-Mechanical Voice Inscriber, at a New York science fair. The machine attempts to recognize spoken sounds and operate the corresponding keys of a typewriter.

1961

Devol's Programmed Article Transfer patent is issued as U.S. Patent 2,988,237. That same year, the first production Unimate begins unloading a die-casting press at a General Motors plant near Trenton, New Jersey.

1963

Scheinman graduates from MIT and briefly works at Boeing on aerospace, military, and analog-computing projects.

Mid-1960s

Stanford experiments with the Rancho Arm and a powerful hydraulic manipulator. Both reveal the difficulty of controlling mechanisms not designed around the computer's capabilities.

1969

Scheinman completes the Stanford Arm design for his engineering thesis. Its electric motors, simplified geometry, brakes, and nonhuman structure are selected specifically to make computer control practical.

1973

Scheinman purchases a machine shop in Mountain View, California, and establishes Vicarm to manufacture robot arms for General Motors, the National Bureau of Standards, AT&T, the Naval Research Laboratory, and university researchers.

Mid-1970s

After being denied exhibition space at a Chicago robot show, Scheinman reportedly demonstrates his compact Vicarm system outside the building. Joseph Engelberger recognizes its potential and provides space on a foldout card table inside the Unimation booth.

1977

Unimation purchases Vicarm. Scheinman becomes general manager of Unimation's West Coast division, giving the former startup access to industrial manufacturing, sales, service, and production support.

Early 1970s

Marvin Minsky asks Scheinman to design a smaller arm for the MIT Artificial Intelligence Laboratory. The resulting MIT Arm uses six rotary joints with electric torque motors, position feedback, and brakes.

1975–1976

Brian Carlisle joins Vicarm to manufacture, test, and deliver its machines. Bruce Shimano develops control software that grows into VAL, while the LSI-11 and smaller microprocessors allow Vicarm to package the arm, controller, and programming system as a complete robot.

Late 1970s

The West Coast team develops the first PUMA prototypes, controller, and VAL software. Production moves to Unimation's Danbury operation, and the PUMA family eventually becomes both a factory product and a widely used robotics-research standard.

1980–1990

Scheinman co-founds Automatix and develops RobotWorld, while Brian Carlisle and Bruce Shimano form Adept Technology in 1983. Scheinman receives the Joseph F. Engelberger Robotics Award in 1986 and ASME's Leonardo da Vinci Award in 1990.

- Video: [“Unimate Robot TV Intro” on Robots in Film and Television](#)
- [“Busy Life For A Bright Machine”](#) by Steven Ungar for The Stanford Daily - January 27, 1971
- [“Victor Scheinman: My Man in the Smithsonian”](#) by Harvey Cohen
- [“Robots and Their Arms” The Stanford Arm](#) by Stanford University
- [“Stanford Hydraulic Arm”](#) images by Mark Richards for Computer History Museum
- [“MH-1, A Computer-Operated Mechanical Hand”](#) by Heinrich Ernst (1961)
- [“George Devol: A Life Devoted to Invention and Robots”](#) by Bob Malone for IEEE
- [“National Inventors Hall of Fame - George Devol: Industrial Robot”](#)
- [“Computer Timeline: George Devol”](#)
- Video: [“First Industrial Robot Ever Installed on an Assembly Line | Innovation Nation”](#) for the Henry Ford Museum
- Video: [“First Industrial Robot Ever Installed on an Assembly Line | Innovation Nation”](#) for the Henry Ford Museum
- Video: [“UNIMATE: The Pioneer of Industrial Robotics”](#)
- Video [“George Devol, the Unimate, and VICARM”](#) for History Channel
- Video: [“Inside an Original 1978 Ultimate PUMA Robot Arm and Compared with Later Unimation Versions”](#) by Ultimate Universe
- [“Five Little-Known Inventions From Deceased Robot Maker George C. Devol”](#) by Kelly for Gizmodo
- [“Robots Are a Few of My Favorite Things”](#) by Chris Garcia
- Video [“60 Years of Artificial Intelligence at Stanford”](#) by the Stanford University School of Engineering
- [“The Origin of Robot Arm Programming Languages”](#) by Rodney Brooks
- [“LSI-11 User Manual”](#) by DEC
- [“The Nobel Prize Press Release, Physics, 1976”](#)
- [“SLAC at 50: honouring the past and creating the future”](#) by the CernCourier
- [“SLAC’s Early History”](#) by SLAC National Accelerator Laboratory

Suggested reading

- [“History of Industrial Robots: From the First Installation Until Today”](#) compiled by the International Federation of Robotics
- Video: [“The Kid Who Invented A Robotic Arm Built A Voice Controlled Typewriter in 1958”](#)
- Video: [“Victor Scheinman JMC2009 Awards Talk”](#) at Stanford University
- [“Oral History of Victor Scheinman”](#) by the IEEE History Center on ETHW
- [Estate of George C. Devol](#)



Enabling autonomous mobility in robots



Industrial robotics is in the midst of its fourth wave of innovation and transformation – reshaping how goods are produced, moved, and managed. The first wave brought stationary, fixed-mounted robots focused on precision and repeatability. The second introduced mobility: first programmed, then increasingly autonomous. The third combined multi-axis robots with autonomous moving robots, creating mobile manipulators. Currently, the fourth, still emerging, brings fully autonomous robots with human-like features and capabilities. Each wave marks a fundamental leap – expanding what machines can do and signaling how deeply robotics will shape our world.

The era of fixed automation

Introduced in the mid-20th century,

mounted robotic arms transformed production lines by automating repetitive and high-precision tasks like welding and assembly. Guided by programmable logic controllers (PLCs) and often isolated behind safety cages, they excelled in speed, consistency, and efficiency. Although rigid and limited to preprogrammed motions, and despite being blind to the world (outside of their narrow focus), they laid the foundation for today's automation economy.

Breaking free: The shift to mobility

The second wave of robotics introduced mobility with self-driving robots. In the 1970s through 1980s, guided vehicles (GVs) followed fixed paths marked by tapes, wires, or strips – limiting flexibility. Modifications resulted in additional

costs and rigid routes, which made GV's prone to disruptions and restricted their scalability. Automated guided vehicles (AGVs) were the next step – they dropped the rails/tape and began to use sensors. AGVs still followed predefined routes, but with more flexibility and programmability.

The ascent of autonomous mobility

Autonomous mobile robots (AMRs) gave rise to a new chapter in the evolution of industrial automation, bridging the gap between static efficiency and dynamic adaptability to execute tasks without human intervention.

Enabled by advances in sensor technologies, AI, and computing, AMRs abandoned fixed tracks in favor of real-time perception and

Automation and robot market trends

1 million mobile robots to ship in 2030¹

The installed base of mobile robots is projected to surpass 4.2 million by the end of 2030, with nearly 1 million to be added in 2030 alone (excluding Amazon).¹

Labor shortage remains the most significant driver of demand for mobile robots.¹

A recent McKinsey survey of 65 top logistics and supply chain executives revealed that 70% plan to invest approximately \$100 million in automation over the next five years, prioritizing speed, process stability, and reduced labor dependency.²

Only 20% of warehouses in N. America have adopted any form of automation.³

80% of the warehouse automation market in N. America is still available with a projected automation compounded annual growth rate of 8.3% over the next few years.³



Industrial robotics is in the midst of its fourth wave of innovation and transformation

Image Source: Analog Devices Inc

ADI: accelerating AMR time-to-market & scalability with complete end-to-end solutions

Robotic market leaders rely on ADI's core technologies to enable high-volume manufacturing, efficiently scale production, and shorten time to market. ADI provides comprehensive end-to-end solutions and subsystems – not just standalone components – drawing on our expertise in hardware, software, and AI to deliver measurable improvements across key areas.

- **Reliable sensing:** ADI's portfolio of accurate [angle](#) and [depth sensing](#), combined with high-speed, low-latency connectivity, simplifies system design with industry-leading 3D ToF solutions, enabling the highest-resolution enhanced systems for industrial environments.
- **Efficient power and battery management:** ADI's power portfolio provides smaller and lighter solutions, reducing thermal issues in tight spaces. Its industry-leading battery management system (BMS) optimizes battery use, helping to extend operational hours, prevent damage without unnecessary downtime, and boost productivity.
- **Industrial communications:** wired and wireless connectivity: ADI provides both Ethernet and GMSL (Gigabit Multimedia Serial Link) – a high-speed serial interface that transmits uncompressed video, data, and power over a single lightweight cable, simplifying system architecture and reducing latency. Additionally, ADI offers one of the only wireless networks designed for harsh industrial environments and optimized for low power, resilience, and scalability.
- **Functional safety and certification:** ADI adds a layer of embedded software and AI to enhance functionality, speed certification, and help ensure worker safety.

adaptive navigation. In contrast to AGVs, AMRs have lower installation costs and provide greater flexibility. Leveraging technologies like reliable, low-latency Ethernet/GMSL connectivity, Depth Sensing/LIDAR (light detection and ranging), and SLAM (simultaneous localization and mapping), these robots can navigate complex and dynamic environments. Today, [Analog Devices, Inc. \(ADI\)](#) is working with Teradyne Robotics, a world leader in automation systems, to advance autonomous operations.

Autonomous robots don't just move – they think!

Unlike AGVs, AMRs are context-aware. They employ increased sensorization and more advanced processing, becoming more adaptable and human-like. This ability enables them to detect obstacles, reroute dynamically, and prioritize tasks based on operational needs, thereby enhancing their efficiency, versatility, performance, and reliability.

AMRs are transforming industries. They streamline warehouse operations such as restocking and order fulfillment without manual oversight, enable just-in-time production on factory floors, and safely transport supplies in hospitals while assisting with infectious patient care. In high-risk environments like chemical spills or wildfires, they go where

AMRs are transforming industries. They streamline warehouse operations such as restocking and order fulfillment without manual oversight, enable just-in-time production on factory floors, and safely transport supplies in hospitals while assisting with infectious patient care.

humans can't, gathering data and maintaining continuity.

AMRs excel in dynamic environments where traditional automation falls short. They're game changers in brownfield sites and operations that require frequent reconfiguration. Their ability to safely share spaces

alongside humans opens new possibilities across industries, from logistics and fulfillment centers to research labs.

The challenges

Despite the breakthroughs in the autonomous operation of

Automated guided vehicles (AGVs) dropped the rails/tape and began to use sensors

Image Source: Analog Devices Inc





Mobile manipulator working alongside human operators in Analog Devices Beaverton, Oregon chip fabrication facility *Image source: Analog Devices Inc*

mobile robots, significant hurdles remained. High-mix environments demanded advanced perception and reasoning, along with reliable sensors, AI, and data processing, while limitations in battery life, payload capacity, and interoperability hindered widespread deployment. Overcoming these challenges calls for bold new innovation and enhanced development in these fields.

- **Motion:** BLDC (brushless direct current) motor motion control, advanced navigation and localization hardware, software, and AI enable robots to maintain position and navigate through complex environments, with [angle sensors](#) (encoders)

and [inertial measurement units \(IMUs\)](#) accurately measuring acceleration, orientation, and angular velocity.

- **Perception:** [Time-of-flight \(ToF\)](#) cameras built for precise depth sensing, and audio sensors designed for detecting human voice, presence, and activity, enhance human-robot interaction and coordination.
- **Power:** Effective power and [battery management](#) are essential for continuous operation, minimal downtime, and reliable performance. Real-time energy monitoring ensures robots have sufficient power to complete tasks and return to a charging station. Management of energy flows between the

mobile base and the arms mounted on them.

ADI collaborates with robot manufacturers and industrial end-users to address the operational challenges of autonomous mobile robots. Direct engagement with end-users provides ADI with vital insights into current obstacles and emerging requirements, accelerating deployment, improving scalability, and reducing time-to-market for customers.

Mobile manipulators

Mobile manipulators (MoMas), the third wave of innovation, combine articulated robotic arms with autonomous mobile robots (AMRs), transforming mobile platforms from simple transport into adaptive, interactive automation. With six degrees of freedom, MoMas can precisely position and orient tools in three-dimensional space, enabling reliable manipulation of parts with varying locations, heights, and orientations. This flexibility reduces dependence on fixed tooling and tight tolerances, accelerates deployment, and enables scalable automation across changing layouts and product mixes – unlocking workflows that were previously impractical or uneconomical to automate.

Humanoid robots: they're here

We are now entering the fourth



We are now entering the fourth wave: autonomous humanoid robots *Image source: Analog Devices Inc*

wave: autonomous humanoid robots. These bipedal, wheeled, or multi-limbed machines operate in human environments, performing tasks that require dexterity and decision-making, marking a shift from specialized automation to general-purpose labor.

ADI collaborates with leading humanoid robot developers worldwide, providing advanced perceptual capabilities and developing embodied physical AI to enable humanoid robots to interact seamlessly with their human counterparts in automotive, industrial, and healthcare sectors. ADI's zero-power, multi-turn [ADMT4000](#) technology is a key enabler for next-generation humanoids, tracking multiple rotations without any electrical power. It's ideally suited for

humanoid robot actuators, eliminating the need for re-homing on power-on, following a power interrupt or battery swap.

The future is mobile and autonomous

The trajectory is clear: autonomy is now the norm, not the exception. AMRs have evolved from niche products to core components driving smart operations. With over 100,000 units sold each year, they are the fastest-growing segment of the industry. As we look to a future with more advanced humanoid robots, mobility and autonomy are not just the foundation of efficient industrial operations; they are the cornerstone of what comes next.

Explore Analog Devices' end-to-

end solutions for robotics on the [DigiKey website](#).

References:

¹ Ash Sharma. "Mobile Robot Forecast Downgraded as Macro-Economic Factors Continue to Bite." *Interact Analysis*, December 2024.

² McKinsey Global Industrial Robotics Survey, 65 senior leaders and executives in automotive; food and beverage; life sciences, healthcare, and pharmaceuticals; logistics and fulfillment; and retail and consumer goods sectors, August 2022.

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A cost-effective approach to random bin picking

By Keith Larson

As the industry moves to increasingly automated manufacturing lines, many complex tasks once reserved for human operators are now performed by machines. Among the most complex of these is random bin picking. That is, the ability to peer into a trayful of randomly arranged components, then identify and retrieve the one that matches the line's next task – and it may be halfway hidden under a stack of other components.

Applications for random bin picking range from machine loading to kitting and sorting, and the technology is widely used in the automotive, electronics, e-commerce, and medical device industries. While the task is relatively straightforward for a person, the robotic arm assigned to the job must leverage high-speed 3D machine vision, pattern recognition, and path-planning algorithms to succeed. More recently, machine learning approaches are also helping to refine the identification and successful retrieval of bin components.

Structured light versus laser scanning

While the use of laser light to methodically scan and map surfaces is well known, most modern random-bin-picking systems leverage “structured light” approaches that are faster,

safer, and more cost-effective than laser mapping. Beyond bin picking, structured-light scanning is widely employed in fields such as industrial design, quality control, augmented reality gaming, and medical imaging. Ambient lighting conditions and reflective component surfaces are potentially complicating factors.

Structured light involves rapidly projecting a series of patterns, such as stripes and grids (Figure 1), onto the bin's contents. From any angle other than the projector's, the patterns are distorted. These distortions reveal the three-dimensional complexity of the bin's contents and are captured in a series of still images, which is where the need for high-speed connectivity and high-power computing enters the picture.

FPGAs take on repetitive tasks

Most structured-light solutions are composed of two modules connected through Ethernet: a sensor module and a computing module. The sensor module is connected to a projector and initiates the projection of a series of structured light patterns into the bin. A camera that is positioned off-axis relative to the projector captures the resultant images. In the case of [Lattice Semiconductor's](#) structured-light solution, a series of 41 discrete images is generated, including

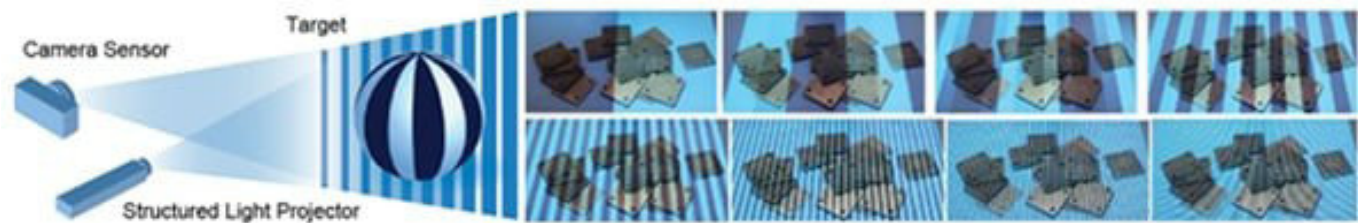


Figure 1: By capturing and analyzing the images created by light-and-dark patterns projected into a bin full of components, structured-light scanning reveals the identity, location, and orientation of the various parts within the bin

Image source: Lattice Semiconductor

positive, negative, horizontal, and vertical patterns. The sequence of images captured by the camera comes back to the sensor module over an MIPI Camera Serial Interface (CSI) link.

The sensor module also includes [field programmable gate array \(FPGA\) resources](#) that encode the series of 41 images into a single, 10-bit coded image, with the location of a common “corresponding pixel” from the generated images indicated. This coded image is then passed to the computing module over an Ethernet link. This encoding

significantly increases the speed of transmission to the computing module, as well as the responsiveness and performance of the overall system. For example, sending 41 raw images of 1920 x 1080-pixel resolution represents 680 MB of data traffic, whereas the single encoded image represents only 41 MB of data. This represents a 16-to-1 reduction in data volume, along with a corresponding increase in system performance.

[Additional FPGAs](#) in the sensor module can further offload computing module tasks by generating the pixel-by-pixel depth

map that effectively outlines individual objects in the bin and helps the computing module calculate an optimal pick-point target for the associated robot arm. This is a very repetitive task that can be done in parallel for each pixel. Alternatively, the user can use the same computing module resource but add extra capabilities. Similarly, the FPGA can perform all or part of machine-learning-based object detection and segmentation to further offload the computing module.

Hardware versus software

The reason a combination of FPGAs in the sensor module and CPUs/GPUs in the computing module works so well in this application lies in each platform’s complementary strengths. FPGAs excel at highly repetitive tasks, such as the sensor-specific processing and frame-level synchronization required to consolidate 41 images’ worth of information into a single

encoded image. It’s a task well-suited to a configurable hardware implementation. Meanwhile, the strength of the CPU/GPU lies in complex, high-level computations, such as for optimization and decision-making, which is most readily implemented in software (Figure 2).

In the case of the random-bin-picking application, the local FPGA encoding at the sensor module dramatically reduces the data that must be sent to the computing module, increasing the speed of pick execution. Meanwhile, the FPGA also reduces the calculation demands on the CPU/GPU housed in the computing module, allowing a lower-cost processor to be used.

The small form factor and the low power consumption of the FPGAs also mean that the sensor module can be housed in a relatively small plastic enclosure without the need for power dissipation accommodations, such as a fan or heatsink. The overall net effect is a lower bill of materials for the total solution.

Closing the loop

Once the encoded image is transferred from the sensor module to the computing module, the CPU/GPU uses triangulation to generate a depth image from the encoded image much like a topographical map of the bottom of the ocean. This depth image is then used for object detection (segmentation)

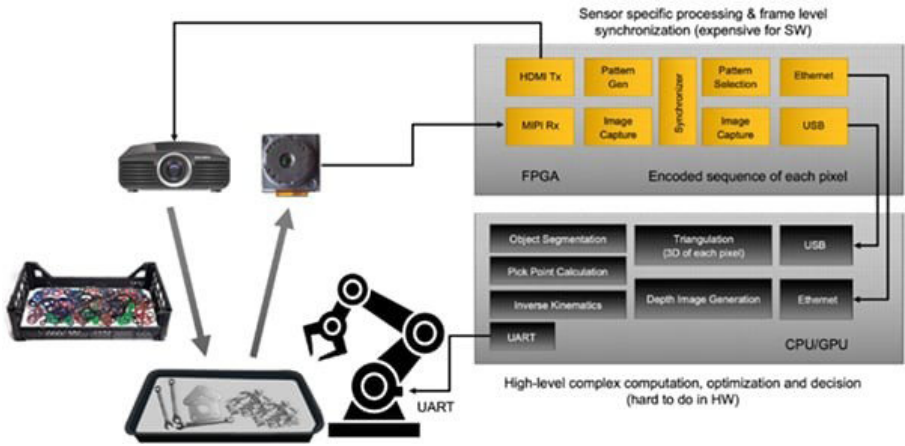


Figure 2: By appropriately dividing the computational workload between FPGA and CPU/GPU resources, the Lattice Semiconductor approach to random bin picking both optimizes system performance and reduces system costs from a bill-of-materials perspective Image source: Lattice Semiconductor

and subsequent pick-point calculations. While computer vision plays the main guiding role in object identification and the calculation of picking points, in more complex applications, CAD models are sometimes used to facilitate object detection via geometrical matching. More recently, machine learning-based approaches have been developed to handle more complicated scenarios; some leverage deep learning to improve performance based on the results of each progressive pick.

Finally, once the 3D rendering of the bin’s contents has been completed and an appropriate pick-point for retrieving the next component selected, instructions are communicated to the robot for

execution. Once the random pick is completed, the cycle starts again.

Conclusion

Structured light is both safer and higher performance than lasers when it comes to random bin picking applications. Further, a hybrid approach that leverages both FPGA and CPU/GPU resources performs best and is also most cost-effective from a bill-of-materials perspective. This is due both to the appropriate division of labor between the two semiconductor technologies and the relatively low power consumption of the FPGAs in the sensor module, which in turn eliminates the need for auxiliary cooling measures.

Enhance autonomous robot localization precision with advanced IMUs and sensor fusion

By Stephen Evanczuk

Inertial measurement units (IMUs) are fundamental to a broad range of mobile systems, including industrial robotics, humanoid robots, unmanned aerial vehicles (UAVs), and immersive mixed-reality systems, among others. Although the specific demands for these systems vary with each application, designers are consistently challenged to provide increasingly accurate, real-time orientation and motion data for the general class of application called autonomous mobile robots (AMRs).

This article briefly discusses the unique challenges of AMR localization. It then introduces advanced IMUs from [Analog Devices](#) and shows how they can be used to address these challenges in indoor, global positioning system (GPS)-denied environments, while drawing lessons from broader cross-domain use.

Why localization is a challenge for AMR developers

AMRs are central to the productivity of smart factories and warehouses where they help streamline material flow, reduce waste, and improve utilization. Ensuring their accurate localization within the facility is critical to success. In purpose-built facilities, AMR localization challenges can be mitigated through well-placed fiducials (reference markers) or optimized layouts, but most AMRs operate in legacy facilities. In such facilities, the combination of varying lighting, reflective surfaces, and complex geometry makes localization much harder.

Furthermore, the lack of consistent infrastructure, such as standardized aisle widths or predictable floor markings, means

that robots confront more complex navigation and mapping tasks.

The nature of the navigational environment results in two key operational challenges.¹

- First, the robot must perform efficient path planning to determine the most optimal route through its environment based on current conditions
- Second, it must execute precise localization, continuously updating its own position and orientation in real time as it moves

In GPS-denied indoor environments, these two objectives must be met entirely with on-board sensing capabilities and computational resources.

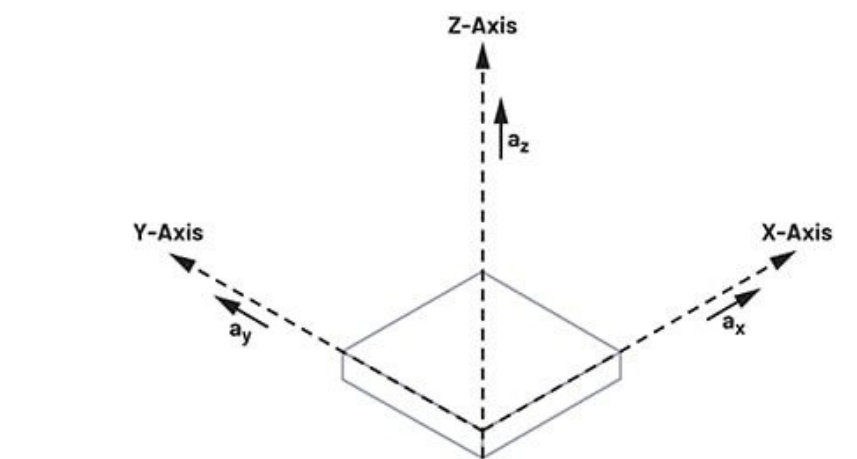


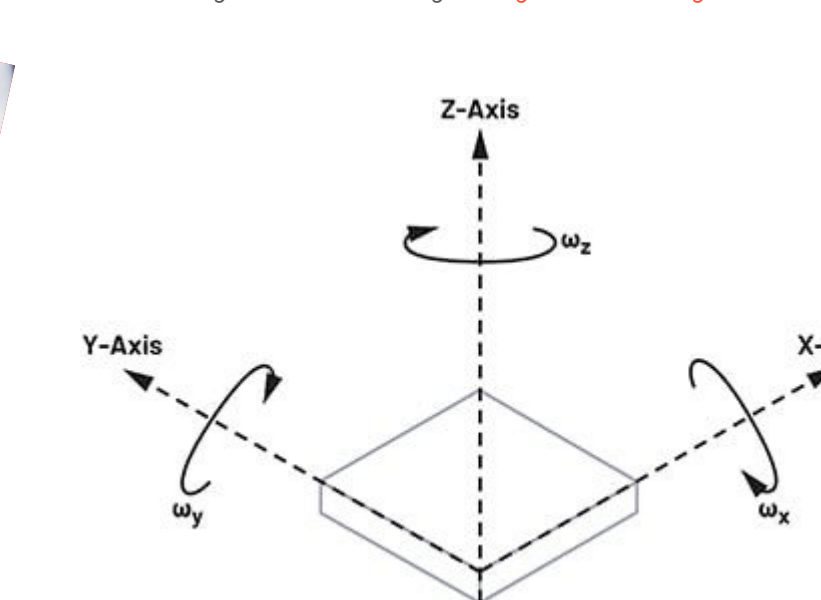
Figure 1: A triaxial accelerometer measures acceleration along the x, y, and z axes, providing both dynamic motion data and a static gravity reference

Image source: Analog Devices

To meet these challenges, AMRs use a mix of sensor modalities. Visual perception systems, including cameras, light detection and ranging (LiDAR), and radar, provide rich environmental data.

Odometry systems, such as wheel encoders and IMUs, track motion directly from the robot's movement. Each sensor type offers distinct advantages: Some excel at long-range detection, others at precise

Figure 2: A triaxial gyroscope measures angular velocity about each axis, enabling accurate tracking of orientation changes



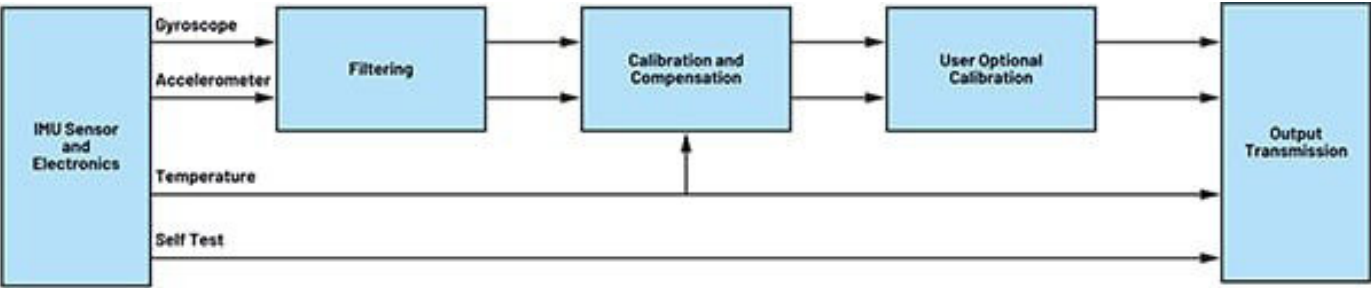


Figure 3: A functional block diagram of an advanced IMU shows an extensive sensor signal chain providing sensing, calibration, compensation, and filtering integrated into a single compact device *Image source: Analog Devices*

detection, but each also has limitations. By combining them intelligently, AMRs can achieve the redundancy and coverage needed to maintain accuracy in dynamic, unpredictable conditions.

What an IMU measures and why it matters

An IMU integrates microelectromechanical systems (MEMS) sensors to measure acceleration and angular velocity in three dimensions. A triaxial accelerometer measures motion along the x, y, and z axes relative to Earth’s gravity, capturing both static forces, such as tilt, and dynamic forces, such as acceleration during motion (Figure 1).

A triaxial gyroscope measures angular velocity (ω_x , ω_y , ω_z) about each axis (Figure 2), enabling the robot to track orientation changes.

At the core of both accelerometers and gyroscopes in modern IMUs, MEMS structures deflect or vibrate when subjected to acceleration or rotation, and the resulting

changes in capacitance or vibration frequency are converted into electrical signals. The advantage of MEMS-based IMUs is their combination of small size, low power consumption, and high measurement rates, making them practical for integration into mobile platforms.

Some IMUs also include additional

sensors that expand their capability. A high-performance magnetometer provides magnetic field measurements that aid orientation estimation in challenging environments, although magnetometers are more common in legacy IMUs. An integrated temperature sensor enables thermal compensation of

Figure 4: An AMR’s sensor stack typically combines vision sensors, an IMU, and wheel encoders to provide complementary information for localization *Image source: Analog Devices*

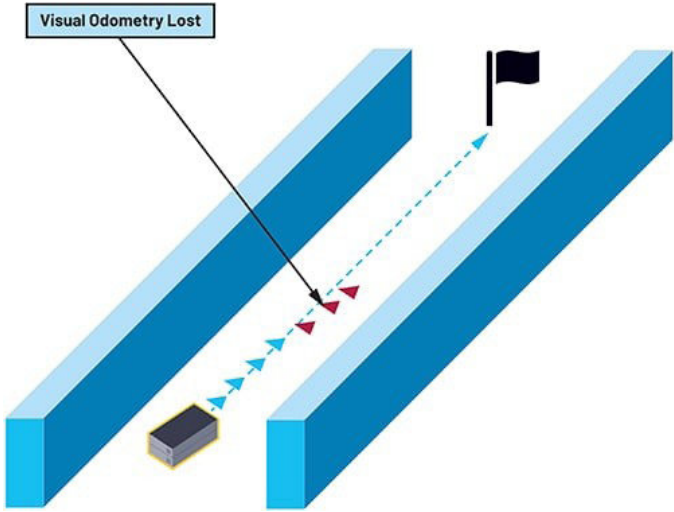
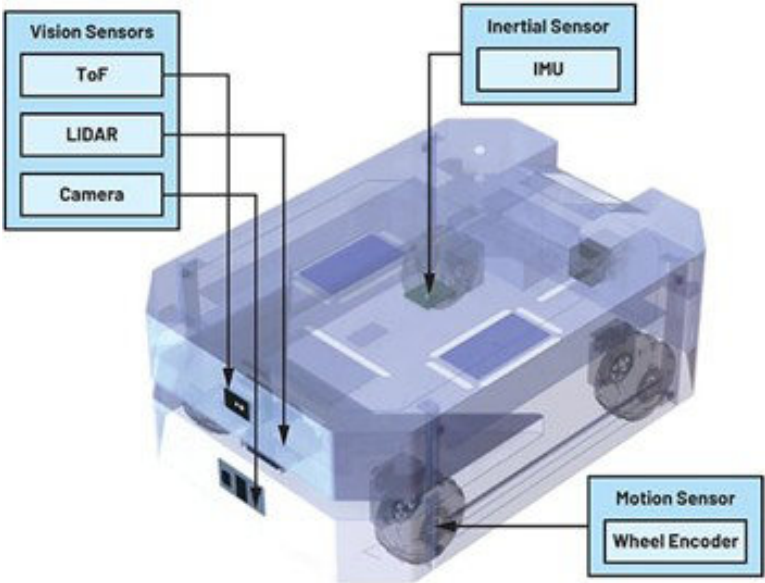


Figure 5: In a long, featureless corridor, robot visual odometry may fail quickly, causing the AMR to lose its position if heading and orientation information from an IMU are lacking *Image source: Analog Devices*

accelerometer and gyroscope data. A barometer may also be included to measure atmospheric pressure and estimate altitude.

Beyond their sensor array, advanced IMUs also integrate extensive data acquisition signal chains for analog-to-digital

conversion, preliminary finite impulse response filtering, and factory calibration to correct sensor biases and axis misalignment (Figure 3). These devices often allow rotation ($d\theta$) from the IMU’s internal coordinate frame to match the robot’s frame before output, reducing the computational load on

the main processor.

How IMUs strengthen localization when other sensors falter

Certain characteristics of different physical environments can impact the effectiveness of individual sensor modalities. To mitigate the limitations of different sensory systems, a typical AMR relies on a diverse sensor stack that can include vision sensors, time-of-flight (ToF) systems, LiDAR, radar, wheel encoders, and an IMU (Figure 4).

In a feature-sparse corridor, for example (Figure 5), the long stretch of walls lacks the distinctive elements needed for visual simultaneous localization and mapping (SLAM) algorithms to match frames to a stored map. Without unique visual cues, the robot’s pose estimate can drift quickly, causing an AMR to lose

Table 1: Shown is the impact of various environmental factors on sensor effectiveness *Table source: Analog Devices*

Sensor modality	Affected by poor lighting	Affected by dynamic movers	Affected by reflective surfaces	Reliant on rich scene geometry
Standard RGB camera	Yes	Yes	No	No
Time of flight	No	Yes	Yes	Yes
LiDAR	No	Yes	Yes	Yes
Radar	No	Yes	Yes	Yes
Wheel odometry	No	No	No	No
IMU	No	No	No	No

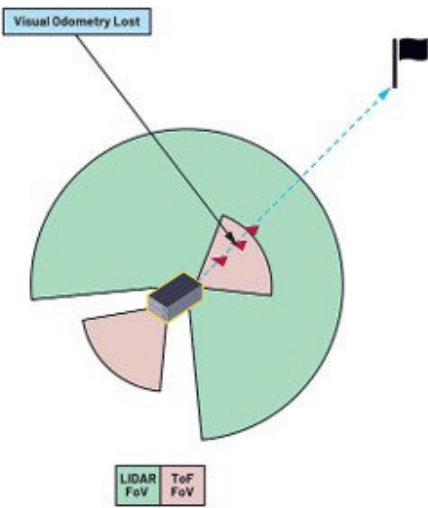


Figure 6: In a large open area, where sensor range limitations and lack of distinguishing visual features degrade visual sensing, IMU measurements and wheel odometry can sustain localization
Image source: Analog Devices

its position. In this scenario, the heading and orientation information provided by an IMU can sustain robot navigation despite the loss of visual odometry.

In large open spaces, such as a 50 m x 50 m warehouse, many visual features are beyond the effective range of LiDAR (Figure 6), which typically provides a maximum reach of 10 m to 15 m. Uniform layouts such as evenly spaced shelving or storage racks can confuse visual odometry because of the similar appearance of multiple different locations. In this scenario, the combination of IMU measurements and wheel encoder data allows the robot to maintain local pose estimates.

Sloped surfaces present another challenge (Figure 7). Standard two-dimensional LiDAR captures points in a flat plane; therefore, a slope can appear to be a vertical obstacle. This misinterpretation can disrupt navigation or cause the robot to avoid traversable paths. Here, IMU pitch and roll data can provide gradient information to mitigate this LiDAR misinterpretation, enabling SLAM algorithms to resolve the gradient and distinguish between traversable slopes and true obstacles.

Environmental factors also degrade localization performance of different sensor modalities (Table 1). Factors such as poor lighting, dynamic environments, reflective surfaces, and a need for rich scene geometry can impact most sensory modalities.

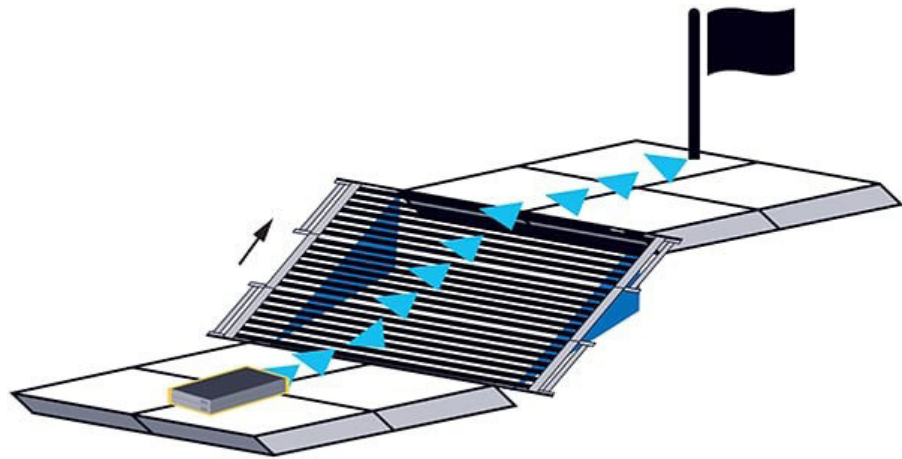


Figure 7: IMU pitch and roll readings can reveal the gradient of a slope, correcting 2D SLAM misinterpretations and enabling safe AMR navigation
Image source: Analog Devices

How IMUs' unique performance capabilities benefit AMRs

IMUs update at higher rates than perception sensors, enabling rapid response to dynamic changes in the environment. Unlike perception systems, which typically operate at 10 Hz to 30 Hz, IMUs can provide processed data at 200 Hz and raw data at up to 4 kHz. With its 10x faster update rate, an IMU can enable updated pose estimates during the longer intervals between perception measurements. This higher update rate ultimately leads to faster reaction times to sudden changes in motion and enhances system reliability in dynamic environments.

IMUs provide the foundation for AMR dead reckoning, where an AMR estimates its current position from a known starting position based on integration of IMU acceleration and angular

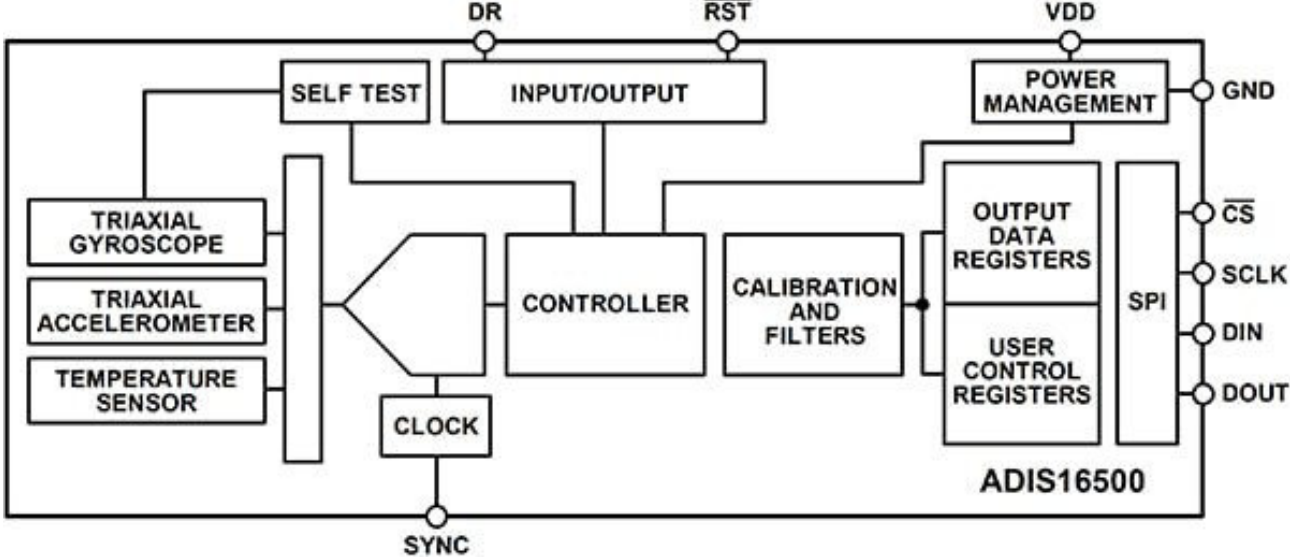


Figure 8: The ADIS16500AMLZ IMU integrates a gyroscope, accelerometer, temperature sensor, and a complete signal chain for data acquisition and signal conditioning
Image source: Analog Devices

measurements. By providing data needed to update position, orientation, and speed continually, IMUs enable precise pose estimation for reliable AMR navigation.

Compact size and light weight also favor IMU integration in AMRs. For example, the Analog Devices [ADIS16500AMLZ](#) IMU (Figure 8) comes in a BGA package measuring only 15 x 15 x 5 millimeters (mm), yet it integrates a gyroscope, accelerometer, temperature sensor, and a complete signal chain for data acquisition and signal conditioning. This level of integration allows it to deliver comprehensive motion data to the host processor while enabling its use in space-constrained mechanical layouts without compromising the robot's

maneuverability.

With its $\pm 2000^\circ$ per second ($^\circ/\text{s}$) gyroscope dynamic range, the ADIS16500AMLZ captures rapid turns without saturation, which is essential for AMRs navigating tight spaces or performing quick obstacle avoidance. The ± 392 m per second squared (m/s^2) accelerometer dynamic range captures both smooth movement and high-impact shocks. Its 8.1° per hour ($^\circ/\text{hr}$) gyroscope bias stability and 125 microns per second squared ($\mu\text{m}/\text{s}^2$) accelerometer bias stability reduce drift to enhance dead-reckoning accuracy between corrections.

Factory calibration provides built-in correction for sensitivity, bias, and axis alignment, while dynamic offset correction accounts

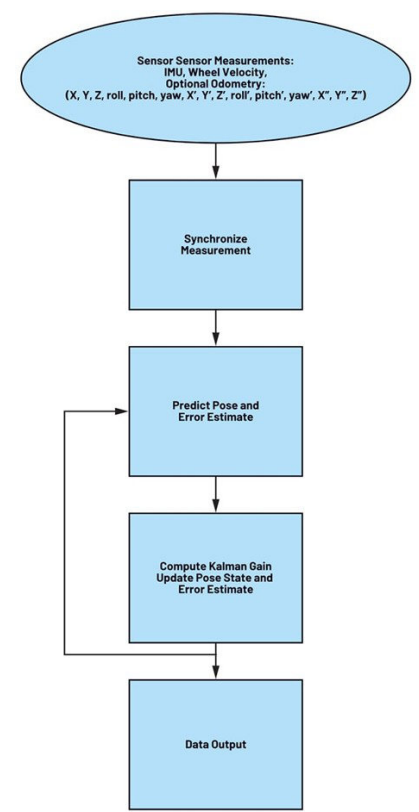
for temperature shifts, supply voltage changes, and magnetic interference, as well as noise reduction.² The IMU's mechanical shock tolerance of $19,600 \text{ m}/\text{s}^2$ and an operating range of -25 to 85°C enable deployment in demanding environments, while its low-noise, high-bandwidth ADCs ensure continued accurate data capture at the high update rates needed in responsive control systems.

IMUs in general are also relatively resistant to electromagnetic interference (EMI) and can operate in varied lighting and environmental conditions. As a result, these devices can serve in a broad array of applications.

Mitigating the performance limitations of IMUs

Despite their performance benefits, IMUs present some inherent limitations.³ Unfiltered noise can

Figure 9: A simplified EKF algorithm processes noisy sensor measurements over time to produce a corrected, continuous estimate of robot pose and motion *Image source: Analog Devices*

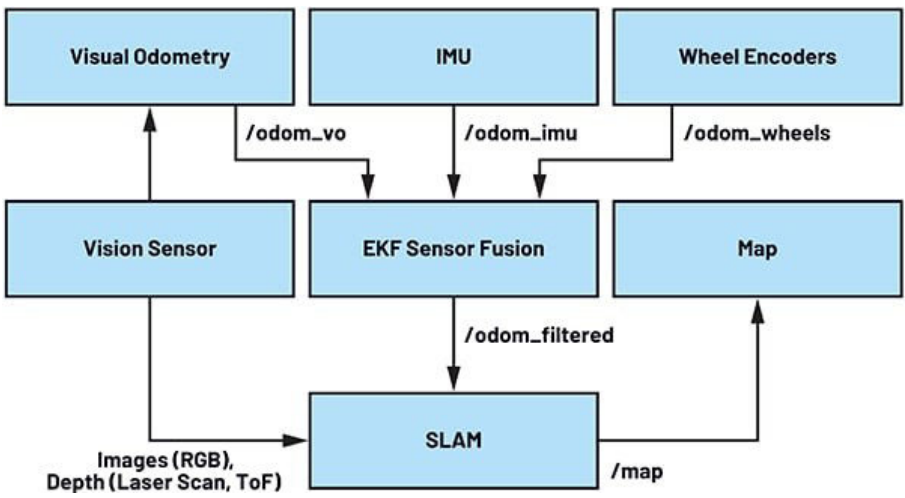


Sensor fusion can overcome IMU limitations by integrating IMU data with other sensor inputs to increase the quality and reliability of the data, improve estimation of unmeasured states, and increase coverage to enhance safety. State estimation techniques such as extended Kalman filtering (EKF) (Figure 9) can correct for noise, random walk, and bias instability during normal AMR operation. By measuring acceleration due to Earth’s gravity, pitch and roll gyroscope errors can be eliminated. Finally, bias drift can be tracked and corrected. In operation, EKF effectively enables estimation of past, present, and future states despite lack of complete knowledge about the nature of the modeled system.

EKF has gained widespread use because it can model system dynamics and measurement uncertainties, then update the state estimate when new data arrives. Measurements that may contain Gaussian white noise or other inaccuracies are observed over time and used for correction. The filter estimates the true value of measurements by synchronizing measurements between sensors, predicting pose and error estimates, and estimating and updating the uncertainty of the predicted value.

Sensor fusion algorithms are embedded in the Robot Operating System (ROS) open-source [robot_localization](#) package,⁴ which implements EKF-based fusion and utilizes the EKF algorithm at its core (Figure 10).

Figure 10: A typical ROS-based sensor fusion software architecture combines multiple sensor inputs through the robot_localization package to produce a robust, continuous pose estimate *Image source: Analog Devices*



affect IMU measurements, which reduces navigation accuracy. Bias in accelerometer and gyroscope sensors accumulates over time, leading to drift in orientation and motion estimates. Nonlinear sensor behavior distorts measurements, and thermoelectric events can lead to angle random walk (ARW) errors in gyroscopes and velocity random walk (VRW) errors in accelerometers that further degrade long-term performance. Unmitigated, these issues reduce localization reliability over time.

This ROS package enables the fusion of an unrestricted number of sensors and can accept a variety of input types, including IMU data, wheel velocity, and odometry. The fused output includes full 3D position and orientation, linear and angular velocities, and acceleration, which feed directly into navigation and SLAM algorithms. Using these inputs, robot_localization generates an estimated pose state expressed as a vector of actual and derived measurements:

Pose State = (X, Y, Z, roll, pitch, yaw, X', Y', Z', roll', pitch', yaw', X'', Y'', Z'')

Accelerate development of precise AMR locationing

The ADIS16500AMLZ IMU demonstrates how precision sensing and integrated processing can improve AMR localization performance. To help developers accelerate application development, Analog Devices provides the [ADIS16500/PCBZ](#) breakout board (Figure 11, left) and accompanying [EVAL-ADIS-FX3Z](#) evaluation system (Figure 11, right).

The breakout board comprises the IMU and a 16-pin header that mates to 2 mm ribbon cables to connect to the evaluation system. The evaluation system allows real-time sampling of the IMU at full sample rate and is powered via its USB port. All required software is downloadable from the [resource page](#).

Figure 11: The ADIS16500/PCBZ breakout board (left) and the EVAL-ADIS-FX3Z evaluation kit (right) enable the rapid development of applications based on the ADIS16500 IMU *Image source: Analog Devices*.



Conclusion

IMUs are essential for maintaining precise localization in AMRs, providing orientation estimates and motion tracking at high update rates even when other sensory modalities fail due to environmental conditions. By using sensor fusion to compensate for limitations across different sensor types, AMRs can perform precise navigation even in dynamic environments that normally confuse AMR localization. With the availability of highly integrated IMUs and associated breakout boards and evaluation systems, developers can quickly design AMRs able to achieve the accurate, reliable localization required for precise navigation.

References

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2. Randy Carver and Mark Looney, “[MEMS Accelerometer Calibration Optimizes Accuracy for Industrial Applications](#),” EE Times, October 2007.
3. Oliver J. Woodman, “[An Introduction to Inertial Navigation](#),” University of Cambridge, August 2007.
4. [robot_localization](#) Documentation, v2.6.12, Tom Moore, 2016.

This month in history

1815

November 2

George Boole is born

English mathematician George Boole was born in Lincoln, England. Boolean algebra became a mathematical foundation for switching circuits, digital logic, computer programming, and database search. His symbolic system allowed logical statements to be represented and manipulated mathematically as true-or-false values.



Boole's work later informed Claude Shannon's work, leading directly to the modern digital age.

1889

November 23

First coin-operated phonograph is installed

A coin-operated Edison phonograph was installed at the Palais Royale Saloon in San Francisco. The machine demonstrated a practical pay-per-play model for recorded sound and became an ancestor of the jukebox. Customers inserted a coin and listened through acoustic tubes, turning recorded music into an unattended public amusement business.



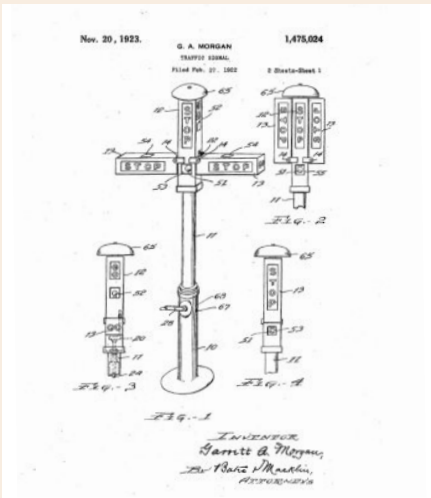
The Edison Phonograph Play.

1923

November 20

Garrett Morgan receives a traffic-signal patent

Garrett A. Morgan received U.S. Patent 1,475,024 for a traffic signal with an all-direction stop position. The design addressed hazardous transition periods at intersections and is an important part of traffic-control engineering history. Its intermediate stop phase separated crossing traffic from vehicles already in the intersection, anticipating the caution interval of modern signals.



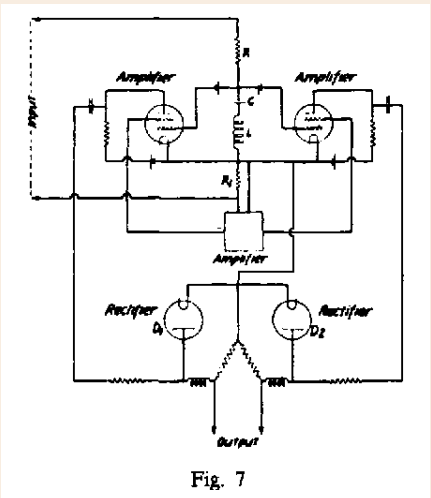
Patent 1,475,024: Traffic Signal.

1935

November 6

Edwin Armstrong presents frequency modulation

Edwin Howard Armstrong presented his wideband frequency-modulation system to the Institute of Radio Engineers in New York. FM reduced the effect of static and electrical noise, enabling higher-fidelity radio broadcasting and reliable two-way communication. Armstrong demonstrated that information carried by changes in frequency could remain intelligible even when amplitude noise disturbed the received signal.



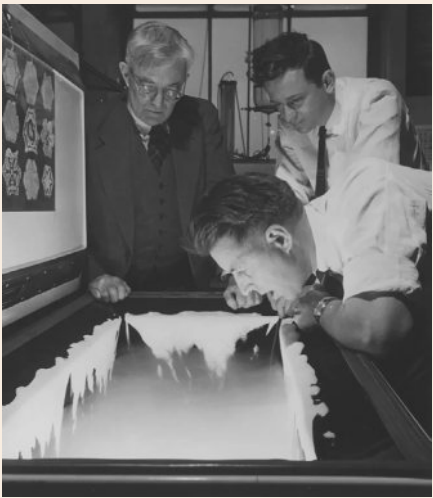
"A Method of Reducing Disturbances in Radio Signaling By a System of Frequency Modulation".

1946

November 13

Vincent Schaefer conducts a cloud-seeding experiment

Vincent Schaefer dropped dry ice into a supercooled cloud from an aircraft over Massachusetts. The experiment showed that artificial ice could alter cloud microphysics and launched sustained research into weather modification. Cloud seeding has remained scientifically and politically controversial since.



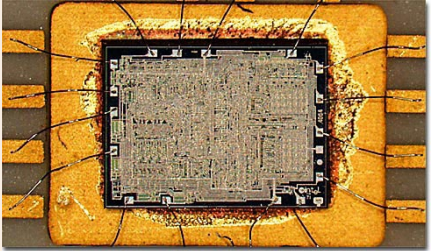
Schaefer and team experimenting with dried ice.

1971

November 15

Intel introduces the 4004 microprocessor

Intel publicly advertised the 4004, a general-purpose CPU on a single chip. The device demonstrated that programmable processing could be packaged as a commercial integrated circuit and reused across products. Designed for a Japanese calculator, the four-bit chip showed how one programmable processor could replace collections of purpose-built logic circuits.



The Intel 4004 was commissioned by Busicom calculators in 1969.



What does passion,
curiosity, and creativity
have in common?

Answer: **You**

Whatever you call yourself (Student, Maker, Tinkerer, Hobbyist, Tech-Wizard...) you embody the spirit of invention—and that spirit is what creates a better world for us all.

If you can dream it up, we'll help you build it at [digikey.com](https://www.digikey.com)

DigiKey

we get technical

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