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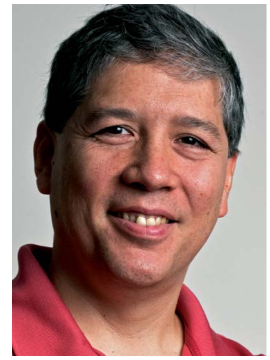
Looking Ahead to the Next Decade of TACTILE SENSING

INTRODUCTION



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WHEN YOU PUSH A BUTTON, you want something to happen. These days, the button is often implemented via tactile sensing, and a lot of technologies are dedicated to providing reliable and robust user interaction.

The tactile sensor industry is transforming due to new manufacturing breakthroughs. Advanced sensor technologies have been moving from the lab to commercial implementation, allowing for their incorporation into more everyday products. That's especially true when it comes to thin-film flexible pressure sensors.

This eBook examines how sensor innovation combined with manufacturing advances are improving the quality of tactile-based feedback systems.

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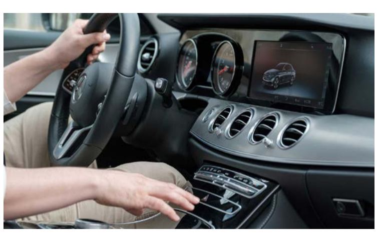

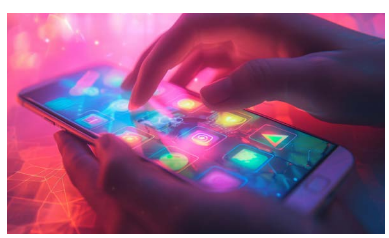

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CHAPTER 1:

The Next Decade of Tactile Sensing: Evolution and Trajectory of Tactile Sensing

JOHN JUTILA, CEO, *Tekscan*

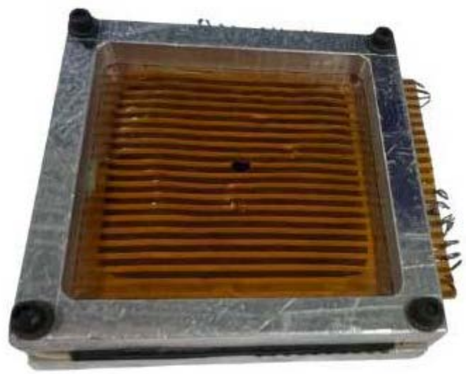
Discover how manufacturing breakthroughs, rising demand, new applications, and strategic partnerships are set to revolutionize the future of tactile sensors.

For over three decades, Tekscan, a pioneer in the realm of tactile sensing, has been at the forefront of market innovation and application mastery. Originating from a groundbreaking thin-film flexible pressure-sensor prototype developed by MIT engineers (**see figure**), Tekscan has since developed an extensive understanding of market dynamics and application requirements.

This expertise highlights an impending convergence of factors — a "perfect storm" — where sensor innovation combined with manufacturing advances meet an escalating demand driven by essential market needs.

Looking forward, the tactile sensor industry is on the brink of a significant transformation, propelled by manufacturing breakthroughs and the increasing incorporation of these technologies into everyday products. As we continue to push the boundaries of what's possible, the gap between innovative research and commercial success is expected to close, ushering in a new era of sensor technology that's more sensitive, adaptive, and integrated than ever before.

Since its inception, the tactile sensing market has been evolving steadily. As with any evolution, the journey has been characterized by



These are the original pressure-mapping tactile sensor prototypes developed in 1983 by a team including Tekscan founder and CTO Rob Podoloff, then an engineering student at the Massachusetts Institute Technology AI Lab. (Photo courtesy of Rob Podoloff)

punctuated equilibrium with step changes in the market. It's led to a rapid growth in new application pathways, which then mature and stabilize until the next disruption occurs.

Evolutionary disruptions along the way have included advances in conductive and resistive inks, improved FPGA modules enabling real-time programmable logic, and open-source software leading to rapid development of data analytics and user interfaces, among others.

The relative stability in commercial application growth over the past decade, excluding the effects of the global pandemic, is poised for change. The tactile sensing market is about to witness a convergence of technical and market forces that will disrupt and accelerate the industry over the next 10 years. This is due to several factors:

- **Innovation:** The tactile sensor innovation engine has been running hot for the past decade in the race to support emerging growth market applications, including touchscreens, gaming controls, robotics, medical wearables, and other markets.
- **Manufacturing advances:** The ability to manufacture more complex printed flexible electronics designs, as well as more efficient scale for standardized designs, will be leveraged with new production investments to drive growth.
- **Increased market adoption:** As the industry continues to scale up and commercialize tactile sensing technologies, improved availability combined with reduced manufacturing costs will drive market adoption levels at a faster pace.

All of these trends have the potential to feed on each other, resulting in a power curve effect that accelerates growth dramatically over the coming decade.

Market Adoption of Tactile Sensing

Tactile sensors, generally defined as measuring some aspect of "touch," are often compared with the abilities of human skin. Currently, mainstream applications are limited mainly to sensing force and pressure over a surface area. Experimental niche technologies exist to sense other surface or contact characteristics like temperature, surface slippage, roughness, and other factors.

Tactile sensors have proven their functionality and are already operating in a very broad spectrum of applications. Tekscan alone has penetrated thousands of uses for research, applications, systems solutions based on tactile sensing, or embedded sensors in various devices. Combined with emerging entrants into the market, the breadth of adoption growth is astounding.

The market for tactile sensors is now generally estimated at over $30 billion annually. The largest market area for tactile touch sensing is, of course, in touchscreen displays and controllers, which are embedded into a wide variety of consumer, medical, military, and industrial products representing over 80% of tactile applications.

While touchscreen technology is relatively mature, advances in materials and manufacturing continue to evolve. To make screens more '"tactile," developers are seeking to measure touch pressure or pressure distribution, in addition to position, leading to new innovations. The market for printed flexible sensors is widely estimated at over $3 billion per year, with tactile sensors representing a portion of the total.

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CHAPTER 2:

The Next Decade of Tactile Sensing: Apps Driving the Future of Tactile Sensors

JOHN JUTILA, CEO, *Tekscan*

Industry markets from medical to transportation push tactile sensing to its limits.

MANY MARKETS, from medical to transportation, take advantage of tactile sensors. This article looks at how these industries apply them.

Medical Applications for Tactile Sensing: From Clinical Settings to Portable, Wearable Devices

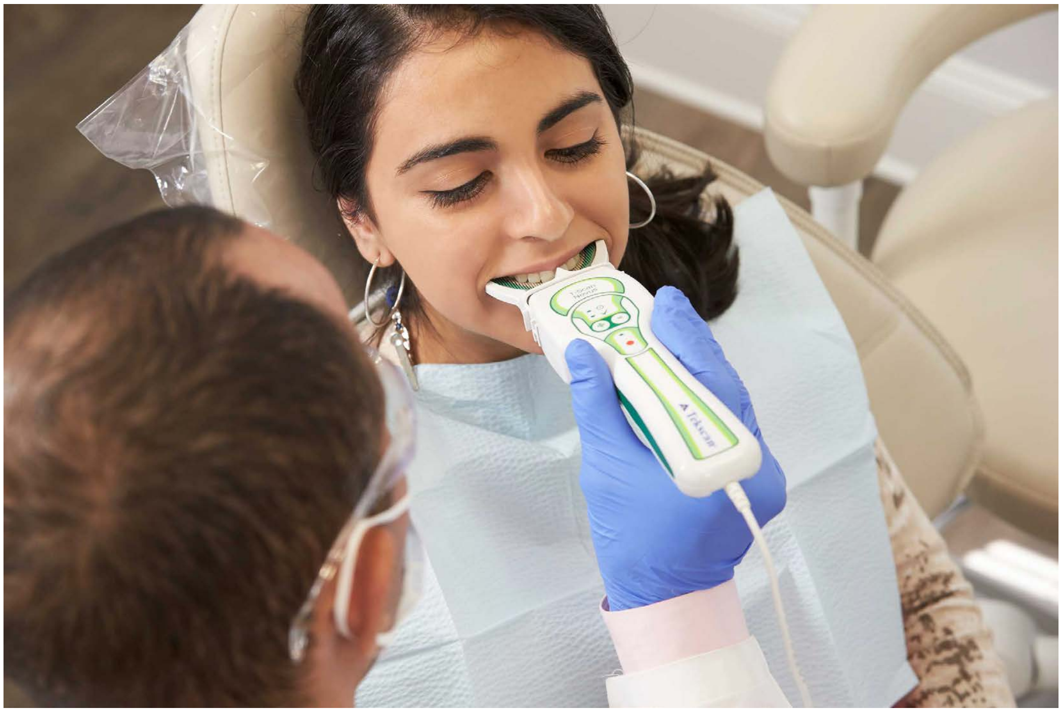
Tactile sensors abound in the medical arena, from clinical settings where physical therapists are using them as part of a system to assess patients' foot pressure and gait, to manufacturers embedding tactile sensors into custom insoles aimed at improving foot function.

Researchers at universities are utilizing the technology to characterize skeletal motion and dynamics, while manufacturers investigate the feasibility of embedding it into smart seats and beds that sense pressure and movement. **Figure 1** illustrates tactile sensors embedded into an occlusal analysis system used in dental offices worldwide to help assess patient bite force.

Medical device manufacturers have embedded tactile sensors into devices as part of drug delivery systems. Smart textiles are becoming more popular for sports applications as well, to measure foot placement dynamics, bicycle seating uniformity, handle grip pressure, breathing rate, and even saddle-to-horse pressure distribution.

Transportation: Widespread Adoption plus Niche and Emerging Applications for Tactile Sensing

Market adoption of tactile sensors in the automotive industry has always been significant, and demand is growing with the emphasis on electric vehicles and the new design considerations they bring. Tactile sensors are embedded into automobile seats to sense



1. The T-Scan system uses tactile sensors to help dentists analyze patient bite contact pressure. (Photo courtesy of Tekscan)

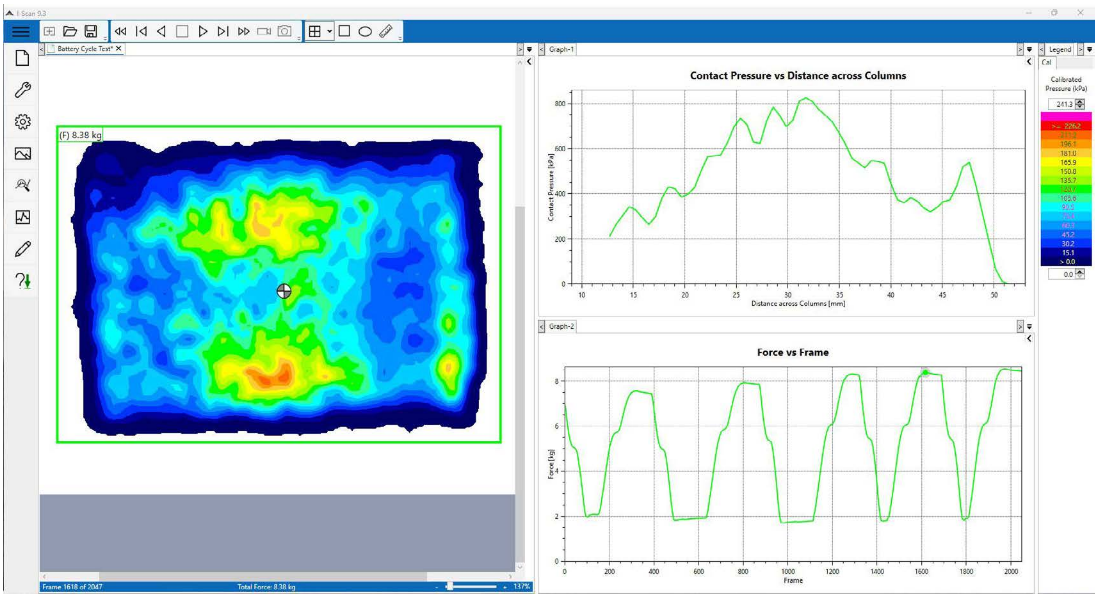
passenger presence and weight, in instrument touchscreens, and other controls.

Tactile sensors are used in safety tests to measure seatbelt pressure distribution, seating dynamics during vehicle acceleration and deceleration, steering wheel grip pressure, and in sensor-instrumented crash dummies. Automotive engineers also rely on tactile sensors to measure sealing pressure of doors **(Fig. 2)** and engine blocks, brake pad contact, and even tire tread dynamics. These represent just a few of many applications for tactile sensing in automotive research and design.

2. Tactile sensors enable automotive engineers to verify proper and even door seal pressure. (Photo courtesy of Tekscan)

Similar applications also can be found in other forms of transportation, including marine and aerospace environments. Many unique applications have been applied in those environments, too, such as measurement of ice pressure against boat hulls for ice breakers, understanding the distribution of pressure against the body in pressurized space suits, or sensing forces against seats during high G force acceleration in jet aircraft.

Understanding pressure distribution in lithium batteries during charge and discharge cycles is important for safety and performance in everything from mobile phones to electric vehicles. New advances in lithium battery technology are critically linked to mechanical heat and pressure dynamics, which require tactile measurements during design as well as manufacturing **(Fig. 3)**.



3. Tekscan pressure-mapping technology combines tactile sensors, electronics, and software to measure swelling of lithium-ion batteries over time. (Photo courtesy of Tekscan)

Tactile Sensing in Industry and Research

In industrial markets, tactile sensors are embedded into industrial machinery to measure contact pressure distribution for a variety of feedback control applications. Pressure distribution is also important for maintenance and quality control to measure a range of factors.

These include proper heatsink contact, gasket and seal effectiveness, industrial brake contact surface distribution, nip roller alignment **(Fig. 4)**, contact uniformity across surfaces for wafer polishing, and to dynamically measure pressure changes on surfaces of batteries and other products over time.

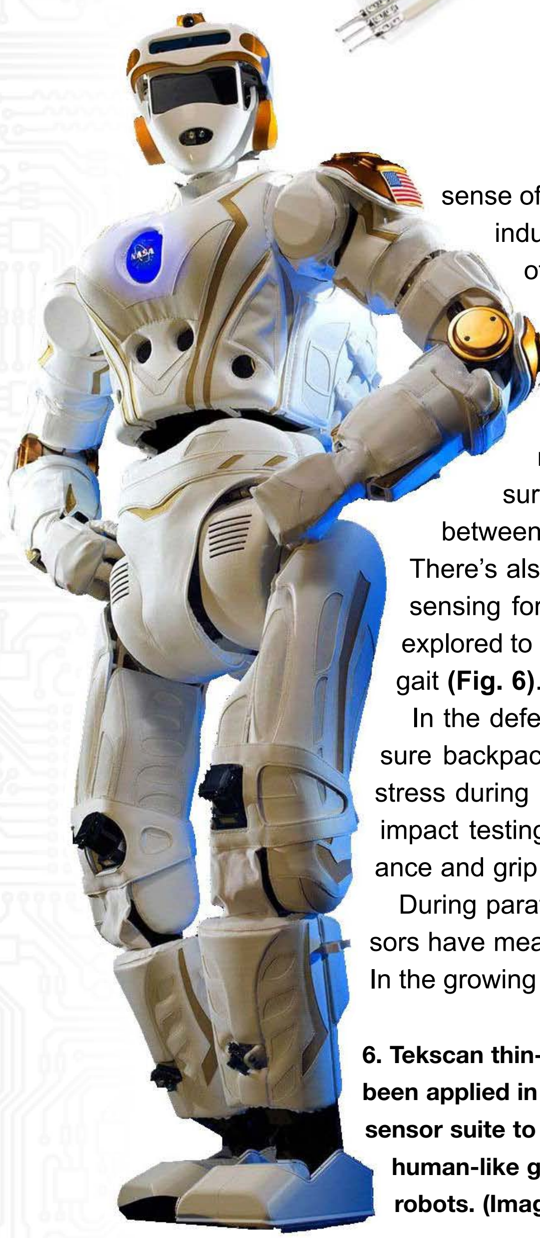
4. Thin-film tactile sensors fit between industrial rollers to verify alignment (Photo courtesy of Tekscan)

In consumer markets, tactile sensing is most common in touchscreen devices, but it can also be found in a variety of other applications. Tactile sensors that measure surface pressure have been embedded into power tools, gaming controllers, lock mechanisms, and consumer foot measurement for custom engineered shoes and boots **(Fig. 5)**.

Tactile sensing is widely used in product research to measure such things as virtual-reality (VR) goggle face contact pressure, proper mating and sealing of smartphone cases for design or quality control, or to analyze golf swing balance and hand-grip pressure to enhance skills.

In robotics, tactile sensors provide the

5. Small embedded tactile sensors can be designed into OEM devices. (Photo courtesy of Tekscan)



sense of touch so vital to appropriate handling of objects, such as in industrial manufacturing applications where improper handling of components during assembly can be costly. Hence, usage in robotics and drones is increasing mainly to measure and control grip forces for robotic hands or grippers, or drone package pickup and carriage.

Other tactile measurements are being explored in robotics, including sensing of slippage during grip, and surface "roughness" and "squishiness," useful for distinguishing between different types of vegetables or ripeness, for example. There's also growing interest in foot and gait pressure and movement sensing for autonomous "walking" robots. Tactile sensors have been explored to help the robot exhibit better balance and a more human-like gait **(Fig. 6)**.

In the defense markets, tactile sensors have been employed to measure backpack-carrying load and stress as well as foot insole and gait stress during infantry operations, applied to body armor and helmets for impact testing, and test ejection seat force distribution to measure balance and grip for firearm research and training **(Fig. 7)**.

During paratrooper and fast rope insertion or medical evacuation, sensors have measured body contact pressure for harnesses and stretchers. In the growing field of "Soldier Systems," tactile sensors are used in smart textiles for real-time monitoring of breathing rates and gait analysis to sense vital signs for impairment due to potential injury.

6. Tekscan thin-film sensors have been applied in a proprioceptive sensor suite to afford a more human-like gait to humanoid robots. (Image courtesy of NASA)

Finally, R&D has always been a strong adopter for new sensing tech-

7. Tekscan and SEMI are collaborating to develop flexible, stretchable sensors to measure hand grip for tactical training. (Photo courtesy of SEMI and Tekscan)

nologies by corporate, government, and university labs for conducting research involving tactile measurements or embedding into new emerging applications. In this arena, tactile sensing has deployed in many thousands of applications.

Sensors and electronics can be modified or customized for a large variety of research applications to measure tactile characteristics in static contact environments or real-time, and be integrated with laboratory systems such as LabVIEW or MATLAB for analysis and integration with other data. In the case of pressure mapping, these thin-film flexible sensors enable researchers to visualize contact pressure across a surface area dynamically — a trait that would otherwise be unobservable.

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credit: Thieme

CHAPTER 3:

The Next Decade of Tactile Sensing: Innovation, Manufacturing, and Roadmap

JOHN JUTILA, CEO, *Tekscan*

Advances in manufacturing are opening the door to a plethora of tactile-sensing innovations.

Research using tactile sensors can be used for other purposes. The past decade has seen an abundance of innovation and investigation into novel tactile measurement methods and designs. Despite this continuous research and exploration, most of these new techniques have yet to be commercialized.

Well-established sensor technologies like strain gauges and piezoresistive, piezoelectric, and capacitive sensing have been dominant and are relatively mature. Robust innovation in new sensor designs has taken place without parallel growth in related new product commercialization.

This extensive and ever-growing archive of potential tactile sensor innovations includes everything from new materials incorporating nanotube or graphene structures to esoteric "e-skin" methods that mimic the sensing capabilities of human skin. They also extend to such concepts as percolation mechanisms, quantum tunneling, microfluidic sensing, optical Bragg grating, origami structures, magnetic Hall effects, micro-structures, and resistive tomography.

Innovation and Commercial Adoption of Tactile Sensors

Mainstream tactile sensor research has generally been driven by high-profile applications for robotics, drones, gaming controls, VR, smart textiles, and touch displays. It's resulted in a large pool of new R&D concepts and prototypes that haven't yet achieved commercial adoption. This growing pool of innovation will spill over into commercial applications in the next decade due to several factors.

First, some of the emerging high-profile applications that funded their development will reach widespread adoption, creating growing demand for embedded tactile-sensing features. Second, even though many tactile-sensing technologies were developed to solve specific problems, other uses will be discovered that may prompt new demand and drive commercialization.

For example, the original Tekscan piezoresistive pressure-mapping sensor was developed to enable high-resolution dental bite pressure analysis for occlusal evaluation. Once commercialized, a plethora of new applications have emerged over several decades for this same fundamental piezoresistive sensor technology, driving much higher demand.

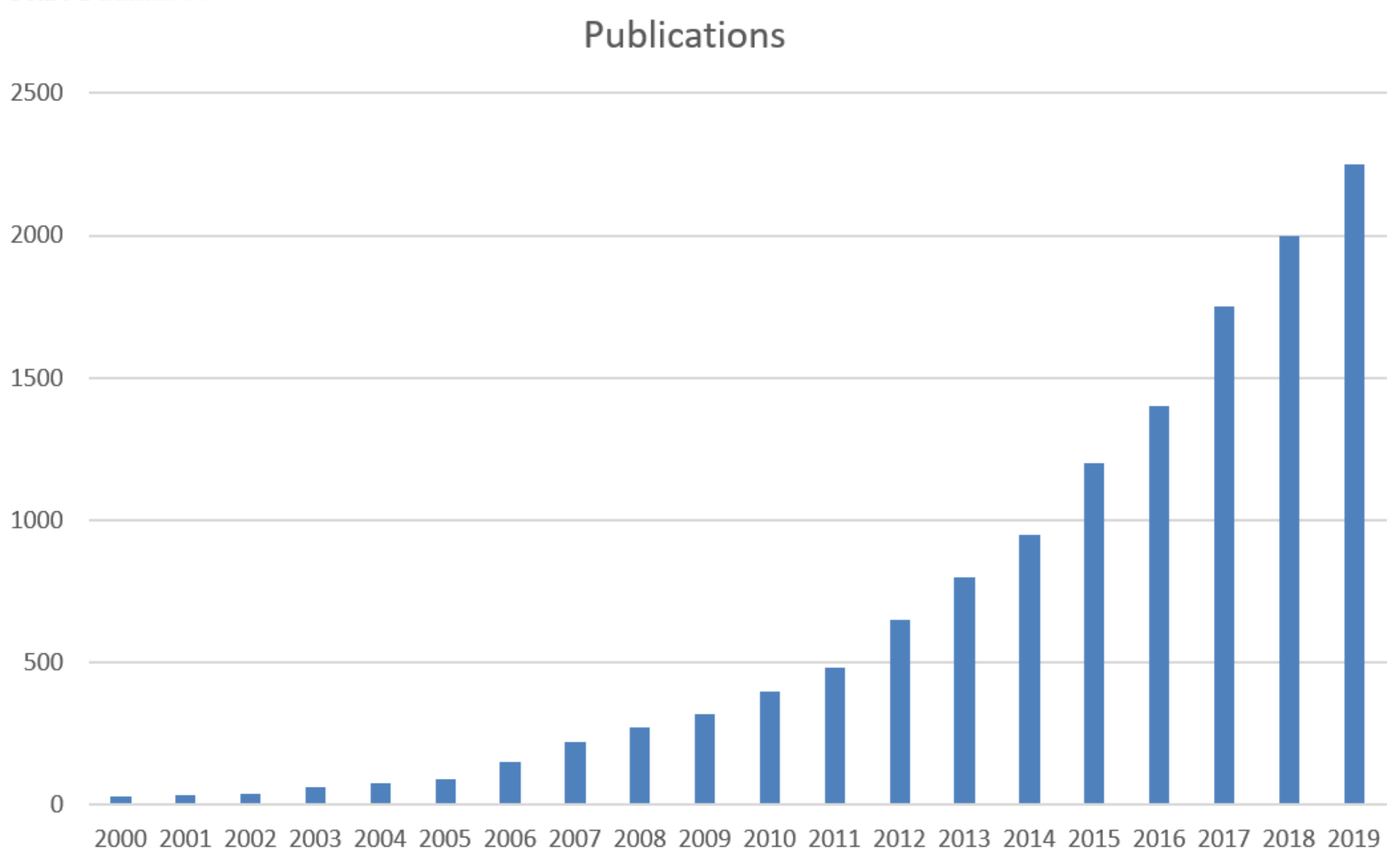
Finally, the ability to manufacture and produce new tactile sensor innovations at scale can be challenging, especially for complex or esoteric designs. Recent manufacturing innovations are adding promising new methods to the production toolbox that will enable more designs to transition from "Lab to Fab" than ever before, even for low-volume production.

Manufacturing Methods for Printed Flexible Electronics

Viable scale manufacturing techniques for printed flexible electronics will continue to evolve and ultimately enable economical sensor manufacturing in higher volumes. The printed flexible electronics market is now estimated at over $10 billion per year, producing products such as flexible sensors, ultra-thin RF antennae, smart textiles, and thin flexible heating strips.

Over the past few decades, a variety of new methods have enabled reliable manufacturing of thin-film flexible electronics, the preferred format for tactile sensors. Printed flexible electronics allow tactile sensing to conform to a variety of surfaces, such as robot grip fingers, shoe insoles, football helmets, and so on, creating wide applicability in the market.

1. This chart illustrates the number of research publications per year obtained for the term "Flexible Electronics" on Web of Science. (Chart provided by Frontiers in Electronics, 2020)



2. Presses like the Thieme 3000 enable automated flatbed screen printing on individual sheets for a variety of industrial and electronic applications. (Photo courtesy of Thieme)

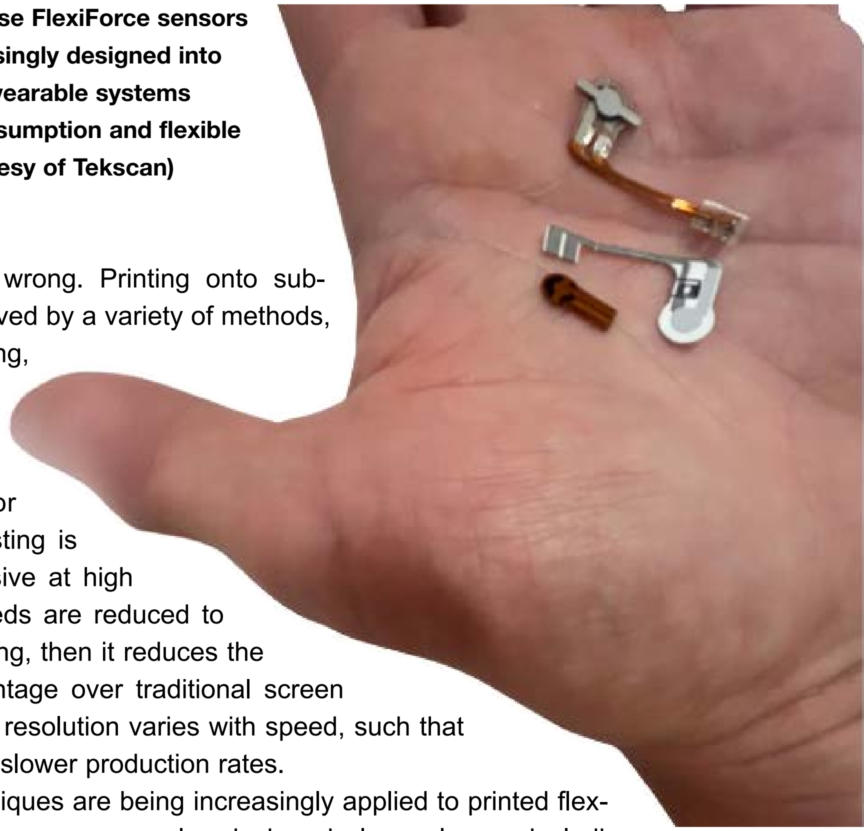
Tactile sensor formats that are bulky or inflexible have a much more limited application footprint and will be adopted for a much narrower set of applications, limiting their demand growth volume (**Fig. 1**).

Initially, screen printing borrowed from the publishing markets allowed for flexible job-shop production of printed flexible sensors on individual substrate sheets. This process remains a staple today, supported by modern flatbed screen presses such as the Thieme 3000, which offers improvements in automated sheet feeding, cleaning, alignment, inspection, and conveying to dryers (**Fig. 2**).

Adoption of rotary screen methods can increase production throughput at the expense of print resolution. And thanks to direct-to-screen printing advances, rapid changeover from one type of sensor to another can reduce setup times by enabling on-the-fly creation of screen emulsion masks.

More recently, high-speed roll-to-roll machinery (**Fig. 3**) has migrated from publishing to printed electronics markets. However, it currently remains limited to sensors with minimal print-to-print variation, while end-of-roll batch testing (often in kilometer lengths) can create challenges in assuring overall yields

3. High-speed roll-to-roll printing lines are used to manufacture flexible electronics at scale, though they can be limited by inspection difficulties and print variability. (Photo courtesy of VTT Technical Research Centre of Finland)



4. Micro sensors like these FlexiForce sensors from Tekscan are increasingly designed into compact products and wearable systems requiring low power consumption and flexible integration. (Photo courtesy of Tekscan)

when something goes wrong. Printing onto substrate rolls can be achieved by a variety of methods, including slot die coating, flexographic, gravure, ink jet, rotary screen, or other methods.

In-line electrical or visual image quality testing is challenging and expensive at high roll speeds, and if speeds are reduced to enable such in-line testing, then it reduces the volume efficiency advantage over traditional screen printing. Moreover, print resolution varies with speed, such that finer resolution requires slower production rates.

Additive printing techniques are being increasingly applied to printed flexible electronics to achieve more complex designs in low volumes, including 3D, aerosol jet, or impulse printing. With additive printing, complex layers of various substrates, conductive inks, and various sensing materials becomes possible.

While flexible electronics printing is the core process for thin-film sensor manufacturing, secondary operations continue to remain problematic for achieving high-throughput scale, including lamination, die cutting, pinning or connectorization, packaging, and testing. Continued investments in automation, e.g., automated pinning, digital rotor die cutting, robotic assembly and test, CCD image analysis, in-line flying probe testing, and other innovations, will help achieve higher efficiencies and scale.

Companies such as Tekscan are partnering with an ever-growing range of equipment suppliers and printed electronics contract manufacturers to mix and match new designs with appropriate production methods and volumes for various sensor designs.

The advancement of manufacturing techniques enables production of a broader variety of sensor designs, serving a larger market footprint over time. It also facilitates high-volume and low-cost consistent production of specific types of sensors, favorable for large-scale embedded applications.

Innovation in High-Volume Manufacturing

Strain gauge, resistive, piezoresistive, and capacitive thin-film sensor currently dominate the high-volume market landscape due to design and production simplicity and cost (**Fig. 4**). Sensor performance trends observed include:

- The need for both smaller and larger sensor surface areas.
- Higher and lower sensing resolutions (the latter seeking to reduce costs at the expense of resolution)

- Simplified signal processing or electronics to reduce costs and power.
- Wider operating environments (temperature, humidity, harsh environments, etc.).

Innovative manufacturing methods will enable new, and more complex, technologies to find their initial foothold in market applications with potential further growth. For example, multimodal sensors, which can measure pressure and temperature simultaneously, are in demand for industrial and energy applications, while "micro-sensors" are increasingly designed into consumer or medical electronics applications.

There's a growing market for flexible and stretchable sensing materials that can be integrated into smart textiles and conform to irregular or dynamic surfaces such as vehicle seating. Design and manufacturing of flexible and stretchable sensors are challenging due to dynamic changes in conductive or resistive inks, which may cause hysteresis, drift, or other performance issues over time. Moreover, wearable sensors require low power consumption, favoring certain technologies like piezoresistive sensing.

Embedding Sensors in Product Design

The growing ubiquity of tactile sensing for embedded applications is driving further improvements in integration, connectivity, and application intelligence. Large-scale sensor deployment requires standardization and ease of integration using simplified electrical signal processing to reduce costs, as well as the availability of modular firmware and software toolsets for varied applications.

In the case of mapping sensors (such as pressure- or temperature-mapping profiles), open-source tools are now readily available for image interpretation borrowed from visual and infrared camera image analysis routines.

Pressure and Force Sensor Integration: Considerations and Best Practices

When it comes to successful integration of tactile sensors into commercial devices, one of the most critical factors is how well the sensor is embedded into the larger system — electrically and mechanically. Engineers must evaluate not only signal accuracy and range, but also power constraints, circuit complexity, environmental durability, and the ease of calibration and production scaling.

One example of this system-level thinking is the approach Tekscan recommends to engineers integrating its FlexiForce tactile force sensors. These resistive sensors are widely adopted for embedded force measurement in medical, industrial, and consumer applications.

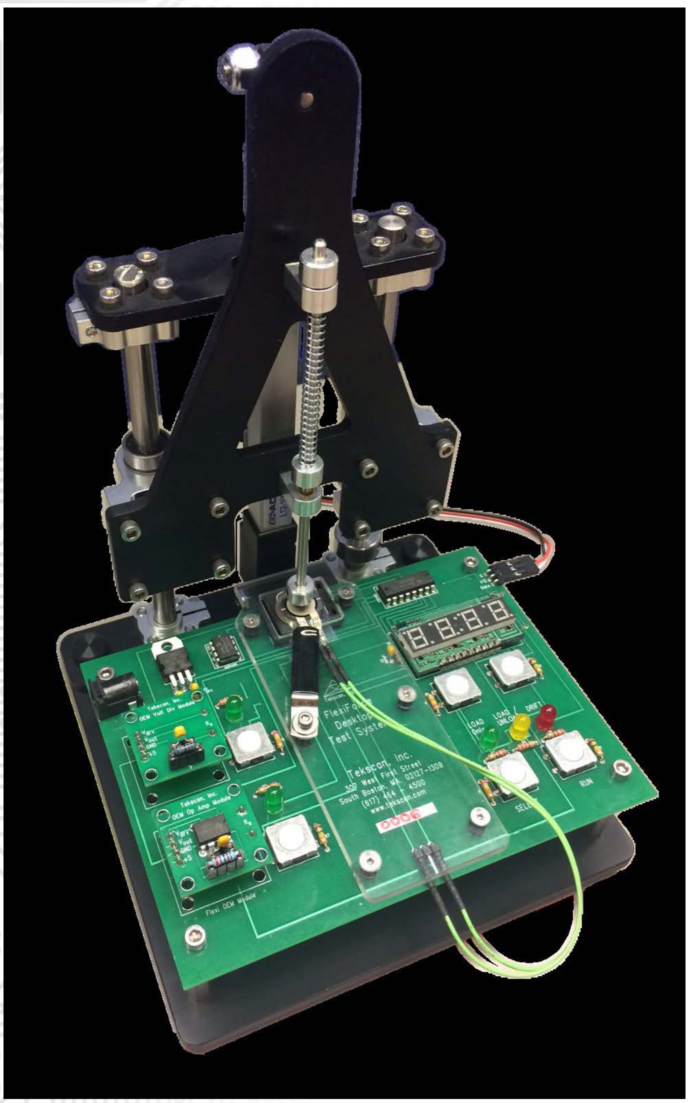
Achieving consistent and reliable results with any tactile sensor depends heavily on proper electrical and mechanical integration. Each technology has its own nuances, and the sensor manufacturer should be able to advise on a structured approach to help save time and costs in integration.

The initial phase involves sensor characterization, when engineers establish how the sensor performs under controlled force inputs. One way to do this is by using a desktop loading fixture with a known load cell reference (**Fig. 5**). This step allows the team to evaluate signal stability, hysteresis, linearity, and repeatability. Circuit selection begins here as well, often starting with a simple voltage divider. While not linear at high loads, this circuit provides a quick, low-cost starting point.

At times, designers who are trying to leverage sensor performance will utilize more advanced circuits to achieve linearity over a greater dynamic range. Though they improve performance, op-amp circuits can introduce a tradeoff: additional cost and complexity to system electronics (**Fig. 6**).

For instance, inverting op-amp configurations provide excellent linearity through zero and perform well across wide force ranges, while non-inverting op-amps offer strong linearity through an offset, suitable for more moderate ranges. All three circuits support sensitivity tuning through resistor or potentiometer adjustments, and engineers are encouraged to keep reference voltages between 0.25 and 0.75 V to optimize resolution and minimize power.

Once basic functionality is confirmed, the process moves into proof-of-concept prototyping. Here, the sensor is embedded into the intended mechanical environment — be it a housing, seat, or device interface. Engineers evaluate whether the circuit performs consistently when real-world interface materials and form factors are introduced. This stage is critical, as mechanical design (load concentration, puck materials, and even adhesive selection) can significantly influence electrical output.

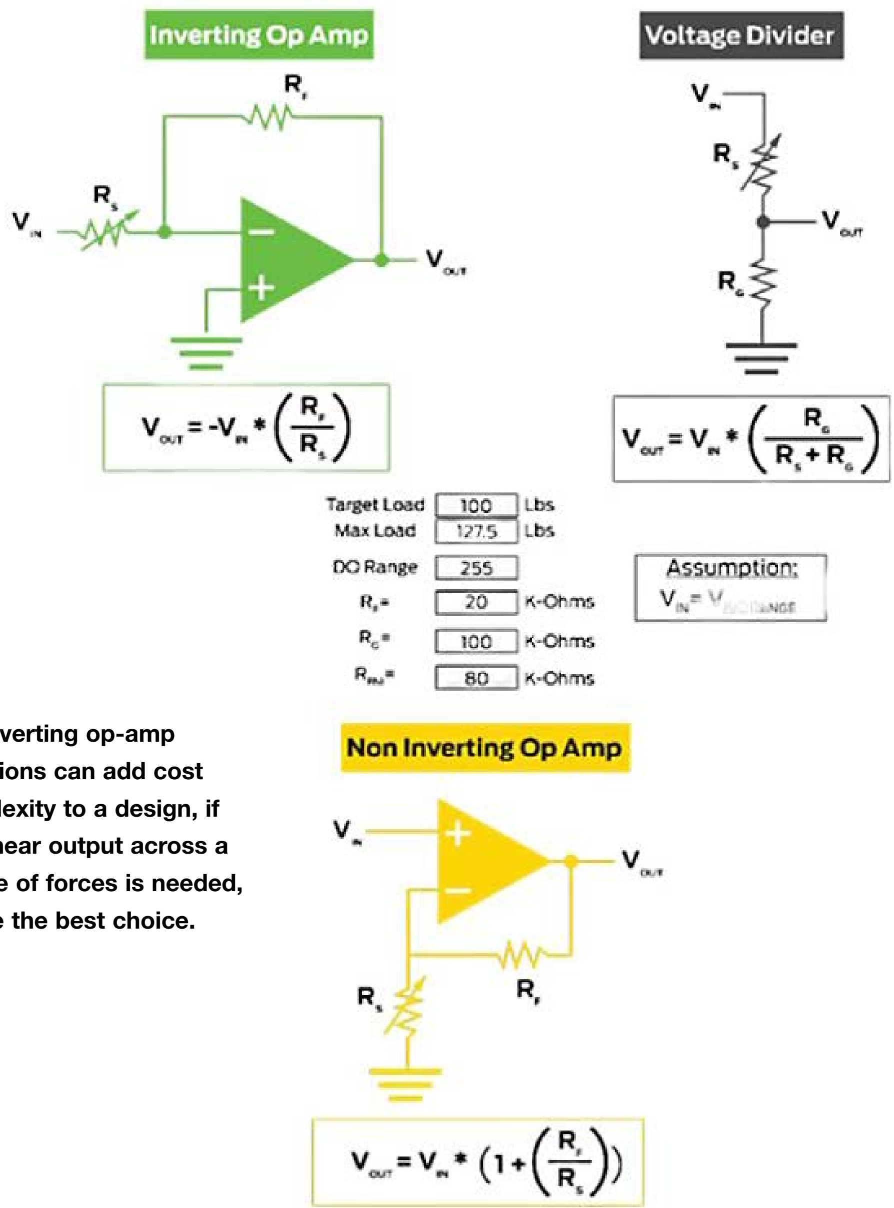


5. Using a desktop loading fixture with a known load cell reference is one way to establish how a tactile sensor will perform under controlled force inputs. (Photo courtesy of Tekscan)

From there, design teams typically develop a more advanced prototype, complete with calibration routines. Tekscan, for example, offers a [Prototyping Kit](#) to help streamline this phase, allowing teams to apply known force levels and build a two- or three-point calibration curve. A common best practice is to load the sensor to 120% of its maximum expected force several times before calibration. This "conditioning" process helps stabilize sensor behavior. Sensitivity is typically set so that 100% of applied force produces about 90% of full-scale output, leaving room in the signal range to accommodate unexpected increases in force.

Following calibration, the next phase involves application and field testing to validate performance in real-world conditions. In one deployment involving infusion pump prototypes, the engineering team discovered that inconsistencies in sensor output were caused not by the sensor or circuit, but by a humidity-sensitive adhesive that interfered with load transmission. This example underscores the critical connection between mechanical and electrical design — and the need for thorough, system-level validation during integration.

After application and field testing is complete, it's time to finalize the embedded design for production. At this point, teams are locking in resistor values, documenting calibration procedures, and ensuring consistent electrical output across



6. While inverting op-amp configurations can add cost and complexity to a design, if a highly linear output across a wide range of forces is needed, it might be the best choice.

units. This step ensures long-term repeatability and smooth transition into production scaling.

Such a structured integration process reflects best practices in integrating tactile sensors and emphasizes a critical point: While sensor selection is important, the integration and validation workflow is just as critical. Reliable performance depends not only on sensor specifications, but on careful attention to system-level design, electrical and mechanical integration, thorough testing, and proper calibration.

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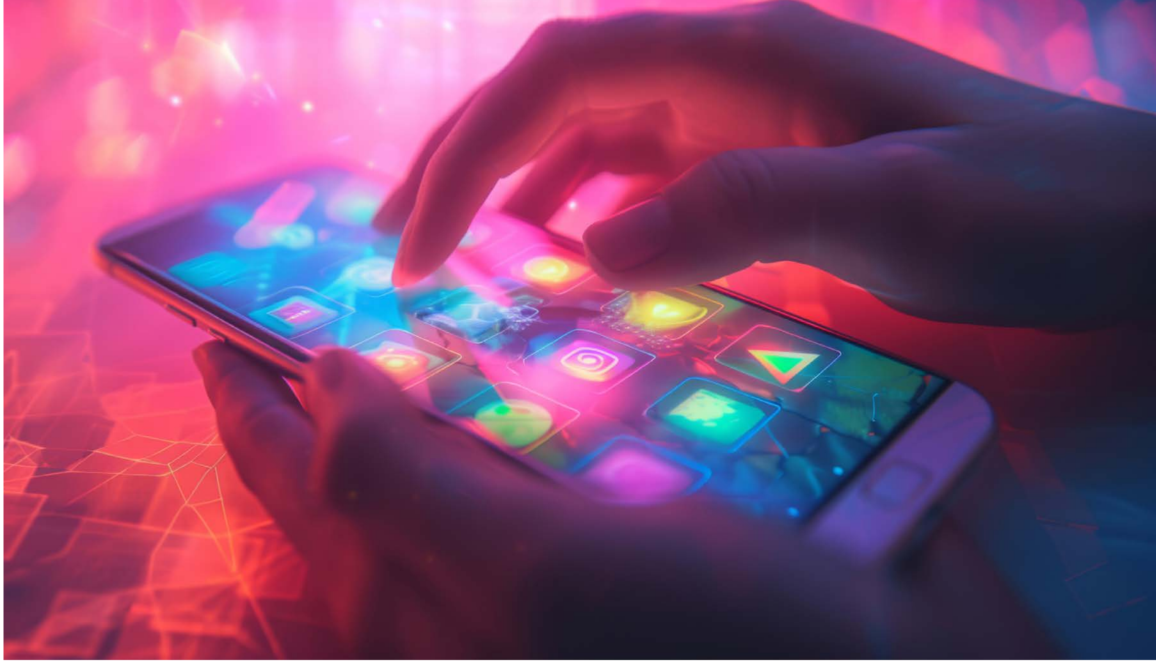

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CHAPTER 4:

The Next Decade of Tactile Sensing: Sensor Connectivity and Analytics

JOHN JUTILA, CEO, *Tekscan*

Sensor connectivity is an often-overlooked factor that can make or break performance.

Sensor connectors tend to get overlooked and become an afterthought in system designs, but they can have critical impact on application performance. Connectors add resistance to measurement circuitry, and any variation in the connector electrical performance will introduce variability in sensor measurement accuracy.

Variation may occur in manufacturing tolerances or how connectors are placed and secured from device to device, causing different sensor outputs between devices. These component variations can be corrected during sensor calibration as part of manufacturing test and quality control to adjust sensor outputs via component or software compensation.

Furthermore, variation may crop up over time due to connector flexing, vibrations, or thermal stress, especially in "high flex" environments such as smart textiles. These expected component tolerances must be well understood and either accepted in their contribution to overall output variations or tightly controlled to mitigate their impact where performance is compromised. Many product designers underestimate the impact of proper sensor connector engineering only to regret it later when field issues occur.

Connector Types

Traditional ZIF, tab, and pin connectors using mechanical compression onto conductive traces and substrates are common to interconnect sensor conductors with board electronics. Due to the high-mix, low-volume nature of many printed flexible sensor applications, such connectors are often manually attached to sensor substrates and conductors, introducing potential human error variation. However, these can usually be corrected during calibration.

High-volume applications may justify expensive automated connector machinery investments and custom fixtures to reduce per unit cost as well as assure repeatability. For applications requiring periodic sensor replacement due to wear or other reasons, pogo pin connectors provide a fairly reliable and repeatable connection. However, they need enough space to accommodate them.

As an alternative to mechanical connectors, some designers are employing z-axis conductive tapes or adhesives or conductive epoxies to bond conductive traces to other circuit elements on electronics boards. These adhesives, when cured properly, provide reliable electrical bonding in low mechanical stress environments and may simplify and thus reduce connector costs. This approach is also becoming more common in wearable consumer devices, where space restrictions and miniaturization prohibit the use of mechanical connectors.

Application of Sensors

When utilizing printed sensors in applications, many benefit from the customization and flexibility of the form factor. With these benefits come nuances to the sensing technology, which can be managed if they're understood and characterized.

For continuous sensing use over time, periodic calibration may be required to ensure sensor output levels remain representative of expected measurement values. In applications where differential values are important, such as quadrant pressure differences to measure toggle orientation and force, calibration is less of a concern as all sensor elements will typically age similarly.

For applications in which absolute values are critical, such as measurement of a liquid storage tank's ground contact plate pressure over time to estimate changes in liquid levels, then sensor drift may be problematic and require periodic recalibration. Software-based calibration can be adequate when sensor drift is relatively predictable over time and estimated using compensation tables based on age.

In more dynamic situations where sensors may experience more volatile environmental conditions, then a reference sensor may be used to establish a reference measurement whose output is used to automatically recalibrate the main sensor or sensor array. For example, a low-drift force plate sensor may be used to recalibrate an entire foot mat pressure-mapping array each time the consumer stands on a floor measurement kiosk mat.

It's important for the designer to understand the causes and nature of drift in their sensor design. For instance, a constant static force load on a thin-film force sensor may induce significantly more drift than a fluctuating load.

Connected Sensors: Fueling IoT and Predictive Analytics

Sensor signals streamed from large numbers of local or remote locations require data connectivity through Wi-Fi, Bluetooth, or other networking methods to enable Internet of Things applications.

For thin route networks where communication data rates are limited, recent advances in edge computing can process and interpret sensor image data locally using embedded computing. Therefore, only small bits of data need to be sent remotely to trigger action, such as a warning flag that elevator brakes will require maintenance service within six months.

The rise of "sensors everywhere" is a precursor to accumulating large quantities of sensor profiles needed for effective machine learning. As tactile sensors become more standardized and widely embedded, opportunities to collect and mine sensor I/O data in bulk will generate new machine-learning model insights that further enhance sensor utility.

For example, insole pressure sensors that map pressure profiles while walking can now be streamed in real-time or in batches to cloud collectors via Wi-Fi- or Bluetooth-enabled smartphone apps (**see figure**).

When merged and mined with periodic clinical data, these profiles can reveal new insights for physical therapy monitoring of emerging health issues, such as precursors for growing loss of balance due to Alzheimer's, or improper gait requiring insole replacement.

F-Scan GO enables live streaming of foot insole pressure data. (Credit: Tekscan)

Looking Ahead: The Future of Tactile Sensing

The coming decade is set to mark a pivotal era for tactile-sensing technologies, characterized by a dual thrust of innovation and practical application. On one hand, we'll see a diverse array of emerging technologies being harnessed to unlock new capabilities, signaling an era of experimentation and discovery. On the other, there will be a strategic focus on refining a selection of cost-effective sensor technologies that promise to become the backbone of mainstream and niche markets alike.

Such convergence is expected to foster a rich ecosystem of sensor-based applications, supported by advances in printed flexible electronics and additive manufacturing. This will make it feasible to produce even the most sophisticated sensors in small volumes without compromising on cost.

In anticipation of these transformative shifts, businesses must double down on their commitment to the future. Industry leaders should aim not only to pioneer the development of novel sensor designs and manufacturing techniques, but also forge strong partnerships across the technological, market, and application spectrums.

Companies like Tekscan, for example, are preparing for this next step-change in the market: There's investment in research and engineering to evaluate and incubate new sensor designs and manufacturing technologies while continuing to develop mainstream applications in collaboration with a wide variety of technology, market, and application partners through the Tekscan TactileLab.

These collaborative endeavors are crucial, as they lay the groundwork for integrating tactile-sensing technologies into a broader range of applications, ensuring that the next wave of innovations will not only be groundbreaking, but also widely accessible and applicable.

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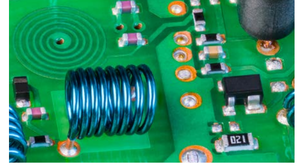


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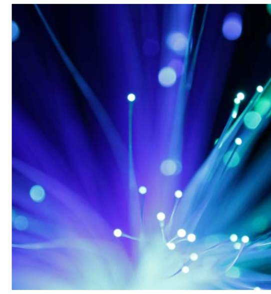

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