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Applications and Challenges of Tactile Sensing Technology in Robotic Grasping

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Abstract. The ability to grasp is what turns a robot from a passive observer into something that can act on the world—and how intelligently it grasps hinges, above all, on how well it perceives. For a long time, robotic grasping leaned almost entirely on vision. That works until it doesn't: try looking through something transparent, catching reflections off a polished surface, or making sense of an object that barely has any visible texture, and the limits of a camera become painfully clear. These persistent blind spots have pushed researchers to go beyond vision alone. This paper traces the emerging landscape of tactile-based grasping. It looks at how tactile sensors are being built and refined today, where they are already proving useful, and what breakthroughs—and roadblocks—have surfaced in real applications. With that foundation in place, the discussion then turns to the deeper challenges the field still faces. Finally, this paper peers a little further ahead, toward a new generation of tactile perception systems shaped by hardware–software co-design and by the broader push toward embodied intelligence. The aim is to map out the terrain clearly enough that others working on multimodal robotic grasping can find both orientation and inspiration.

Keywords: Robotic grasping, tactile sensing, robotic manipulation, multimodal perception, visual-tactile fusion.

1. Introduction

As factories become increasingly intelligent, robots are shifting from rigid, preprogrammed motions toward adaptive behavior. One task epitomizes this transition: grasping — the most fundamental physical engagement a robot can have with an object. The quality of a grasp largely dictates whether a robot can handle the messiness of real-world jobs: sorting parcels in a warehouse, tidying a kitchen, or assisting in a surgery. Underpinning every intelligent grasp is the perception system. It's the part that senses what the object is, how it's shaped, and what's happening at the moment of contact.

Vision-based grasping has come a long way. But vision has its blind spots. Transparent or shiny surfaces throw off depth readings. A sudden change in lighting can wash out the features the model relies on. If one object sits behind another, the camera simply doesn't see it. And perhaps most critically, a camera can't tell the robot what happens after the fingers close—how much force is being applied, or whether the surface is slippery or rough.

Touch is becoming the next frontier for robotic grasping. In labs and companies alike, researchers are chasing the same goal from strikingly different directions. One group might be mixing materials, trying to cook up a sensor that's ultra-sensitive yet tough enough to handle a wide range of pressure [1]. A team down the hall is slicing the act of grasping into three moments—approach, contact, manipulation—and asking what the sense of touch must deliver at each step [2]. Elsewhere, the building blocks are taking shape: flexible electronic skins that can be wrapped around a gripper, and algorithms that fuse data from multiple modalities. These researches aren't just about making sensors. It's about giving robots the physical awareness they need to finally grasp anything, smoothly and with just the right amount of force.

Building on the progress so far, this work digs into a focused question: how can tactile sensing be woven into the grasp pipelines that is difficult to rely on vision? The paper explores the core tactile techniques, the ways they've been applied, the stubborn roadblocks, and the strategies that might finally push things forward. The final goal is to help achieve a deep integration of touch sensation and robots, enabling precise and reliable grasping.

2. Core technology system of tactile sensing technology

At its heart, robotic grasping isn't just about making contact—it's about holding something securely without crushing or deforming it. That's where a sense of touch changes the game. The moment a fingertip starts to slip, the grip tightens, immediately and automatically. If the pressure across the fingers feels uneven, the hand subtly shifts its posture to even things out. This tight loop of feel-think-act becomes critical exactly when vision falls short—inside a cluttered bin, under poor lighting, or when the object itself is transparent.

To build this kind of responsiveness, researchers have long relied on a toolkit of resistive, piezoelectric, and capacitive sensing principles. But making a sensor that works in the real world means pushing beyond textbook designs. One major push is to borrow tricks from biology: embedding functional layers that mimic human skin to reject noise and sense multiple things at once—pressure, texture, maybe even temperature—all from a single surface. The goal is a tactile system that doesn't just send data, but actually helps the robot react in a fluid, coordinated way.

2.1. Capacitive tactile sensing technology

Among the various implementations of tactile sensors, the capacitive sensing structure, owing to its simple architecture and high sensitivity, is widely employed in the measurement of small pressures. Capacitive tactile sensors operate by transducing an applied force into a change in capacitance, typically achieved through a reduction in the distance between two parallel plates. This capacitance variation is subsequently converted into a measurable electrical quantity, such as the period of a timing signal or a DC voltage level, via a dedicated readout circuit. Since the sensor does not measure force directly, the output constitutes an indirect measurement; nevertheless, after appropriate calibration it can provide a stable and repeatable estimate of the applied force.

Measuring tiny forces demands micro-scale capacitive sensors. Gu et al. built a 3D flexible capacitive sensor with micro-cone structures on a robotic fingertip, feeding back delicate grasp forces [3]. Yin's team used a PDMS-based capacitive design to separate normal from tangential forces, adding a copper shield over the convex PDMS surface to cut electromagnetic interference [4]. For the persistent problem of nonlinear output, Shi et al. chased it with a micro-structured composite dielectric layer, achieving wide range, high sensitivity, and good linearity [5].

Packing in too many sensing units creates its own bottlenecks: wiring complexity, cost, and reliability all suffer. Chao Tang et al. took a different route—a non-array soft sensor using differential electrode placement, with just two triangular electrodes and one rectangular one. It trims the wiring problem while keeping useful sensitivity [6].

Capacitive tactile sensors bring a few persistent challenges in grasping applications. Wiring alone can be troublesome. More fundamentally, the dielectric layers inside these sensors tend to drift with changes in humidity, or when traces of other dielectric materials contaminate the surface from the environment. The relationship between capacitance and force is also rarely a simple straight line, which introduces errors exactly where high precision is needed. On top of that, the sensor's own electric field is easily distorted by external electromagnetic noise. Bring a metallic object close, and its own field can bleed into the sensor's, throwing measurements off. The takeaway is that deploying capacitive sensors for grasping isn't just about the gripper. It means taking a hard look at the environment around the target and the material of the target itself.

2.2. Piezoelectric tactile sensing technology

Piezoelectric sensors work differently from capacitive ones. They rely on the direct piezoelectric effect. An external force is put on the sensor. The piezoelectric material then creates a charge signal. That signal is proportional to the force. By measuring the amount of charge, the force magnitude can be found.

Due to the leakage of charge generated by piezoelectric materials through the circuit, they are sensitive only to time-varying forces. Consequently, in practical gripping tasks, they can be employed in scenarios where dynamic forces are of interest, such as slip detection. Diao et al. proposed a force and slip detection sensor (FSS) based on a triboelectric-piezoelectric coupled nanogenerator, which successfully performed precise gripping tasks using electrical signals enhanced by the piezoelectric effect [7]. Luo developed a self-powered piezoelectric sensor made of thermoplastic polyurethane (PU) nanofibers, which estimates the mass of grasped objects based on the output from sensor arrays attached to the fingertips of a robotic hand [8].

Piezoelectric sensors build their reputation on a clean physical principle—the piezoelectric effect—that translates mechanical stress directly into electrical charge. The benefit is a sensing element that can capture the fastest vibrations, respond almost instantly, and remain remarkably consistent when measuring high-frequency dynamic forces. But the same principle comes with blind spots. Static or slowly changing forces produce no sustained output, making them nearly invisible to the sensor.

Temperature drift is a stubborn problem. Outside the lab, compensation circuits become necessary. The raw signal is so weak that a charge amplifier is usually needed to lift it above the noise.

These factors complicate the choice of a piezoelectric tactile sensor. The decision hinges on the grasping task demands, and just as much on the small errors from every added circuit.

2.3. Piezoresistive tactile sensing technology

Piezoresistive tactile sensors are the workhorses here. Their principle: pressure changes a material's conductivity. Measuring that shift directly gives the applied force.

Sensors are frequently arranged into arrays to better conform to irregular surfaces and enhance overall sensing accuracy. Due to their low cost and intrinsic stretchability, piezoresistive sensors are commonly employed as flexible arrays in tactile applications. M et al. designed and fabricated a soft robotic finger that integrates a flexible piezoresistive sensor via multi-material fused deposition modeling (FDM) 3D printing; by comparing bending responses under identical input pressure, they assessed its contact detection capability [9].

In the context of flexible objects, Tian et al. introduced a multi-touch piezoresistive sensing approach coupled with finite element modeling. In their setup, sensors embedded within the soft body capture resistance variations across multiple segments along the entire sensor length, making it possible to estimate both the shape and the applied force [10]. Addressing the demand for low-cost solutions, Chen developed a piezoresistive pressure sensor based on a (graphene-MWCNT)/urethane sponge composite. The composite was prepared through a straightforward polymerization and dip-dry process, yielding a device that combines low manufacturing cost with high sensitivity [11].

Piezoresistive sensors work on a simple principle: pressure deforms an elastic material, changing its resistance. They measure a wide range of static forces with stable performance. Simple fabrication and inherent durability have made them a common choice in tactile sensing.

But the pressure–resistance curve isn't strictly linear. That always introduces some error. Under constant load, the resistance value can drift over time, silently hurting accuracy in long-duration grasping. And in large arrays, these sensors draw significant power, pushing up the requirements for on-site energy supply.

3. The development of the field of tactile perception

3.1. Multiple sensory combinations

Multimodal tactile fusion is advancing not because of a trend, but out of necessity. Individual sensing technology can hard capture the full texture, compliance, and thermal profile that a hand encounters. In the unpredictability of real-world grasping—far messier than any lab setup—relying on a single modality almost always leaves critical detail on the table.

In practical scenarios, it is often necessary to integrate multiple tactile information for perception, so as to more accurately construct the properties of the object.

Based on this concept, Zhang et al. designed a composite sensor to adapt to the complex environment. This sensor incorporated both a piezoresistive sensor for detecting pressure signals and a capacitive sensor for detecting proximity signals. Considering the movement issues of the robotic hand, they also used flexible materials to manufacture the composite sensor. The technology for accurately quantifying tactile perception to distinguish hardness and texture has always been a challenge [12]. Qiu et al. develop a sensor for a robot arm. Their approach uses a piezoelectric layer to generate a coarse initial estimate of softness, while a piezoresistive layer captures the static contact profile; in tests, the sensor distinguished eight distinct material samples [13].

Bringing multimodal tactile sensing out of the lab means tailoring the array to the task at hand—the required spatial resolution, how fast or hard things make contact, whether temperature or vibration matters. For a dexterous hand trying to handle small objects, that adds up to a tough ask: high resolution packed into a tiny form factor. Those two already fight each other. Layering on more sensing principles only makes fabrication harder.

Then there's the crosstalk. Run multiple sensing mechanisms together. Untangling those mixed signals takes either a carefully built physical model or a decoupling algorithm of their own. Either way, it adds yet another hurdle to getting reliable, accurate recognition.

3.2. Neural network combined with tactile sensing

When a sensor's sensitivity and stability hit their practical limits, people often turn to neural networks to squeeze out a bit more precision. Natural touch is inherently multimodal and highly nonlinear—hard to capture with handcoded rules. That's where neural networks shine: they learn the messy inputoutput mappings directly from data, offering perception that's more adaptive and contextaware.

Take Zhao et al. as an example. Inspired by how humans feel their way in the dark, they built a shallow recognition network for a robotic fingertip. They started with neighborhood component analysis to cut the feature set down to just nine informative inputs, then hit 99.72% accuracy—all while keeping the computation light [14].

When a fragile object is included in the object being grasped, it is necessary to pay attention not only to the accuracy of the grasp but also to the protection of the object itself. Qiu et al. approached this case by mimicking the nondestructive way humans gauge softness: an electronic skin on a robot hand feeds piezoelectric readings into an improved machine learning classifier for a preliminary softness estimate, and strain feedback then guides the hand toward a safer contact force [15]. Zhou et al. tackled a similarly delicate scenario—robotic harvesting among branches—by embedding sensing arrays into fin-ray fingers and pairing them with a custom perception algorithm. This system brought the damage rate down successfully [16].

The role of neural networks goes beyond perception and lies in their powerful data processing capabilities. For example, in the context of signal processing, a suitable network can tease apart a single signal from mixed data.

Besides, training on large scale datasets remains a huge time consuming. A common solution is to train smaller and specific datasets to economy resources. However, this might result in its poor versatility and difficulty in being deployed on a large scale in unstructured environments.

3.3. Tactile-visual senser

During the grasping task, the object may suddenly tilt and fall. At this point, it is difficult to make timely adjustments merely relying on tactile sensation. However, as a further development of neural networks in the field of tactile perception - the visual-tactile fusion technology can to some extent prevent such incidents from occurring.

Mi et al. drew on the way humans feel through contact and built a vision-based tactile sensor rooted in contact mechanics. By incorporating the physics of Hertzian and planar contacts directly into the fitting framework, they managed to achieve high sensitivity while steering clear of data-intensive learning [17]. A different route was taken by Wang et al., who fused visual and tactile signals within a deep reinforcement learning setup—specifically, a deep deterministic policy gradient (DDPG) framework for five-fingered anthropomorphic hands—demonstrating that the approach can handle diverse grasps in unstructured settings [18].

Although capturing transparent objects is a problem for machine vision, it is inevitable in actual grasping tasks. Weibel et al. introduced a gradient-descent method for detecting the pose of transparent objects. The idea is to let vision trace the object's outline and then refine the in-hand pose estimate with tactile feedback. Doing so avoids depth maps and photorealistic rendering entirely, and the method remains robust across changing environments [19].

Integrating visual and tactile senses enables a more comprehensive acquisition of object information, pushing sensor technology further towards intelligent perception systems. However, the main challenges still lie in aligning the temporal and spatial aspects of the perception signals, as well as the high cost of training neural networks, which restrict its large-scale application.

4. Future outlook and core challenges

4.1. Future outlook

Tactile sensing is moving past measuring just one thing at a time. The shift is toward tightly integrated systems that fuse multiple senses and interpret what's happening on the fly. A few clear directions are taking shape.

Handling irregular objects demands sensors that can bend and stretch. The push is toward large-scale, highly integrated flexible arrays—electronic skins—built on high-performance ionic gels. These are becoming a central research focus.

Sensing is shifting from single-mode contact to multimodal decoupling. Temperature, texture, stiffness, slip direction—fusing these dimensions lets the robot build a fuller shape picture of the object in its grip. Paired with the right neural architectures, this richer input supports smarter grasp decisions.

On the application front, the most efficient path is to learn from biology. Human skin is the result of long evolutionary tuning: a structure–function blueprint that solves perception with minimal computation and energy cost. Adopting that coupled design offers artificial systems a way around brute-force complexity.

It is foreseeable that, with the synergistic advancement of research and development in materials, manufacturing processes, algorithms, and system architectures, tactile sensing technology will gradually approach and even surpass the perceptual performance of human skin, becoming a key technology that endows robots with comprehensive external perception capabilities.

4.2. Core challenges facing tactile sensing technology

Tactile technology is caught in a tangle that runs from raw materials all the way to system design. The goal is deceptively simple: machines that feel like human skin, robust enough for the real world, yet cheap and easy to scale. Pulling that off is brutally hard.

Sensitivity and wide range rarely coexist. Cram sensors close for high resolution, and signals start bleeding into each other. Wiring a dense, large-area array becomes a wiring problem. Many lab-made materials aren't ready for the factory floor. Their long-term endurance in messy environments remains a big unknown.

On the algorithm side, the data deluge is genuine. Multiple forces and environmental factors combine into a single messy signal, obscuring the quantity of actual interest. Annotating tactile data is far harder than labeling images, leaving AI models starved for clean training data. Durability under repeated shock and wear is a constant worry. Inside dense arrays, crosstalk is a given; from outside, temperature swings, humidity, and electromagnetic noise keep eating away at signal quality.

None of this has stopped touch technology from moving out of the lab. Persistent real-world demand keeps pulling it forward. The future points toward finer resolution, richer modalities, self-powered operation, and deeper intelligence. The ultimate prize: machines that don't just replicate human touch, but outpace it.

5. Conclusion

To date, touch sensing has moved from a niche research interest to a practical tool in robotic grasping. It gives robots a direct way to feel forces, sense contact interactions, and begin to handle the unpredictable conditions of the real world. This paper surveys what the last five years have brought. It maps out the working principles of major tactile sensor types, and places their applications side by side in real grasping tasks. It then unpacks the persistent difficulties facing current methods, and walks through perception approaches stage by stage to highlight where they succeed and where they fall short. The final outlook scans forward: as sensors get smarter and perception algorithms more deeply embedded, touch may finally become the steady backbone of grasping in unstructured environments—not just a hoped-for improvement.

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