Designing Whisker Sensors for Noisy Environments

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***Abstract*—Whiskers are a sensing method that could allow robots to obtain detailed tactile information about an environment with minimal damage risk. When a whisker contacts an object, it bends, transmitting mechanical signals to its base. Because whiskers are proximal sensors and do not depend on light, they succeed when vision-based sensors are most likely to fail. However, the benefits of whisker sensors are still limited to laboratory environments, partly because separating useful from noisy sensor signals is much harder in the unstructured world. Here we present two versions of whisker sensors that begin to address this challenge. The first sensor can remove airflow and inertial effects from contact signals. This sensor is also highly reconfigurable, making it an accessible testbed to investigate differing whisker array geometries. The second sensor can determine whether the whisker makes contact with a rigid versus a compliant surface. As tactile information from engineered whisker sensors becomes more informative and reliable, robotic platforms can make more informed choices about their interaction with the world.**

Tactile exploration of unstructured environments presents multiple challenges. Tactile sensors require a large dynamic range, as they must contact objects with varying forces and speeds. They must remain sensitive to small and robust to large contact forces while avoiding breakage and damage. Moreover, it is not just the sensor that risks breakage; damage to the environment is of equal concern—grasping, moving, and contacting objects all present opportunities for accidental damage. Finally, because tactile sensors are proximal, ensuring a 3D space is adequately covered is an additional challenge.

Whisker-based sensing represents an approach towards tactile sensing with the potential to meet these challenges. Mirroring their biological counterparts [7], engineered whisker sensors keep their transduction method at or below the whisker's base [2, 5, 6, 1, 8, 9]. This geometry allows sensing electronics to be separated from the regions of the sensor that directly interact with objects, an approach that has also sometimes been used for tactile skin sensors [1, 10, 11]. The separation protects the electronics and allows the interactive portion of the sensor to be soft and compliant, minimizing damage to both sensor and environment. More specifically, many engineered whiskers are designed to bend during contact [2, 8]. The compliance allows whisking to occur at high speeds with minimal concern that unpredicted contact will exert large forces on the environment or the sensor. Engineered whisker sensors may also provide a safe and efficient means to map unknown 3D spaces. The whiskers' extended lengths can speed up the process of locating contact versus noncontact points in a 3D environment. This extended coverage is enhanced further when the whiskers are rotated, or "whisked," through space.

In laboratory environments, whisker sensors can gather high-density shape information [6, 9], map 3D spaces [2, 8], and classify objects [5]. However, achieving these feats in unstructured environments with multiple objects, non-contact stimulus sources, and moving/compliant objects is still challenging. The present work describes two whisker sensors designs that begin overcoming these challenges. The first sensor, WhiskSight [4], uses magnets to attach six rigid whiskers to create an easily-reconfigurable testing platform, ideal for investigating how whisker placement affects the information acquired (Fig. 1A). We show that this sensor can detect signals caused by airflow and by self-motion (inertia). These signals sometimes confound contact sensing of external objects, but since WhiskSight can detect them, they can be removed. The second design combines a tapered, flexible whisker with a spring suspension system. Because the whisker is both tapered and flexible (Fig 2A), we can differentiate between whisker contact with a compliant and a non-compliant surface.

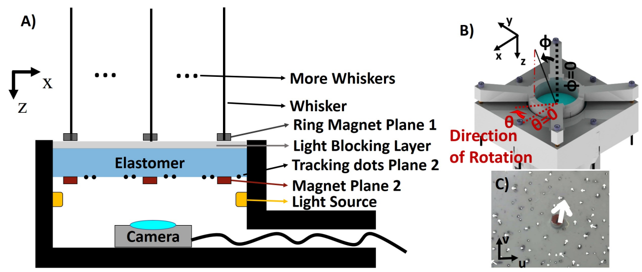

Fig. 1. A diagram of the WhiskSight sensor. Whiskers (rigid carbon fiber rods) are attached to an elastomer membrane suspended above a camera. The attachment uses disc magnets above and below the elastomer membrane for attachment, so the whiskers are easy to reconfigure. B) The camera captures the motion of the bottom of the magnet and uses it to calculate the whiskers' magnitude and direction of rotation, ϕ and θ in spherical coordinates. The whiskers are rigid so there is no bending, only rotation C) During rotation, only the bottom of the magnet moves. The arrows show motion of a tracked point in the camera image at 10x scale. This figure is reproduced from [4]

The rat whisker array consists of rows and columns of 30 whiskers with different lengths, curvatures, and thicknesses [7]. Whisking motions allow rats to detect, locate, and identify objects even in total darkness. However, few if any studies have quantified the relative effectiveness of different configurations of heterogeneous whiskers in an array for robotic applications. Although testing many different whisker arrangements may provide insight, rearranging the sensors can be time consuming and annoying, as both power and signal wires must be managed. Rearrangement of robotic whiskers typically increases the likelihood that the system will break.

By combining the camera transduction method shown in other sensors [11, 10, 6] with magnetically detachable whiskers, the WhiskSight sensor facilitates studies into the effect of array shapes on information gain [4]. The camera images from beneath the whisker array, and each of the whiskers

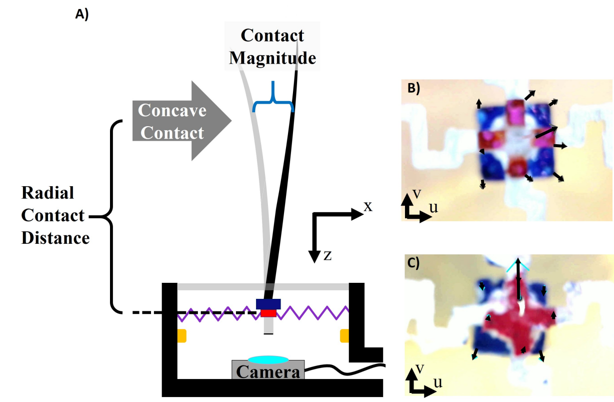

Fig. 2. A schematic of the compliant whisker sensor: A) A 3-d contact point on a whisker has three components: contact direction, contact magnitude, and the radial distance of contact. When laser cut springs suspend a compliant whisker, contact forces cause both rotation and translation at the whisker's base. By tracking nine points on the suspension system, we can determine the rotation and z-translation of the whisker base. B) Pure z-translation (axial force) brings the nine tracked points closer to the camera, increasing their apparent size. C) Pure rotation most strongly affects the black tracked dot in the image center. The arrows represent 10x the motion of the point in pixels.

is marked red to permit easy identification and tracking. Researchers can change the array shape, and a segmentation algorithm automatically determines the new shape (Fig 1C). Once the array shape is determined, the magnets' rotation and elastomer's motion are tracked using python's OpenCV package. This method yields rotation magnitudes accurate to 0.5° and rotation direction direction accurate to 6.5° (Fig 1B). Finally, each whisker's response to contact is distinct from its response to airflow or inertial stimuli, allowing signals from contact and non-contact stimuli to be differentiated.

The second version of the whisker sensor switches the elastomer suspension of WhiskSight for a spring suspension with a signal maximizing design. This enables the ability to detect downward deflections caused by axial forces and determine the point of contact along the whisker length (Fig 2A). In this design, four (red) points above the spring and five (4 blue, 1 black) points below the spring are tracked (arrows, Fig 2B,C). Unsurprisingly, when sensors can localize the contact point along the whiskers' length, the efficiency of 3-d spatial mappings increases [2]. Many radial distance determination methods rely on measuring the bending moments' change rates (Fig 2A). A typical "success" metric involves determining the radial contact distance to within 10 % of the whisker's total length [2, 5, 8, 9]. However, methods that rely on measuring rates of change of mechanical signals cannot work with compliant objects because both the whisker and the object will simultaneously deform. Previous work has suggested that 3D contact determination can be achieved with combinations of the axial force (z-deflection) and the bending moments, leaving rates of change of mechanical signals to determine compliance [3]. We verify this hypothesis using rates of change to distinguish between compliant and rigid surfaces. This metric allows a future robotic implementation to sense quickly in predictable environments while slowing down when the sensed signals are more ambiguous.

The two sensors represent engineered whiskers that can overcome some of the challenges from uncertain environments: information gain, robustness and opportunities for error. With continued improvements in engineered whisker sensors, the robots that employ these sensors can make informed decisions about their interactions with their environment.

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