Object Surface Exploration using Low-Cost Rolling Robotic Fingertips

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Abstract—Tactile sensors are numerous and varied, and the data they provide has proven advantages in industrial and consumer products. Despite this fact, these sensors are not used to their full potential. This illustrates the need for low-cost, versatile tactile sensors. In this paper we introduce novel robotic fingertips that use low-cost components coupled with mechanical ingenuity in order to attain important and high-quality tactile data. Our robotic fingertips contain a rolling mechanism, and can sense the force applied to an object, the normal direction of the contact point, as well as parallel movement along the object’s surface. We show three main uses for this fingertip. Firstly, we demonstrate how the fingertips can be used for the detection of soft or lightweight objects by applying extremely small forces to them. Secondly, we present a method of full-perimeter definition (location and normal direction) of rigid objects by tracing. Lastly, we explain how our sensors can be used to detect stiffness and stiffness anomalies in soft objects, such as organic tissue.

I. INTRODUCTION

The exploration of objects is naturally associated with touch. When we do not trust our eyes, we use our fingers to obtain the truth of the physical world. One cannot hope to find a small bump on an otherwise smooth object with the use of sight alone, therefore it is only natural to run our fingers across its surface, detecting the smallest of deformations with our sensitive fingertips. Similarly, tactile sensing is used in machines when vision is unavailable or insufficiently accurate [1], [2]. Tactile sensors can be used to explore many aspects of an object, including its shape [3], [4], [5], stiffness [6], [7], texture [8], [9], and other properties. Despite the many uses for tactile sensors, they have not been strongly integrated with industrial and home robotics, and are not used in many applications that could benefit from them. Tiwana, Redmond and Lovell [1] suggest that some of the main reasons tactile sensors have not been widely integrated in industrial and consumer products are their cost effectiveness, repeatability and reliability. These issues are pointed out by many reviews of tactile sensors [10], [11], [12], and many new tactile sensors focus on these issues as priorities. Many new tactile sensors incorporate optics [13], [14], [15], piezoelectric components [16] and other technologies [17] in order to grant new capabilities while maintaining low costs. Low cost sensors not only encourage new applications for haptics, but they also allow the construction of an array of sensors, which may provide additional information in less time. Some research has been done on sliding tactile sensors [18], [19], where the tactile sensor is deliberately slid along an object’s surface in order to learn about its properties. These sensors use advanced piezoelectric components to sense fabric texture.

In this paper we introduce the design and application of a novel robotic fingertip that provides a very low-cost solution to haptic sensing problems. In order to gain more data from a single contact, we introduce mechanical mechanism in the fingertip that senses the orientation of the surface it touches. Furthermore, the fingertip’s design allows us to run it across a surface using a rolling contact point, continuously gaining data along the fingertip’s path without applying significant tangential force, as opposed to all previously mentioned tactile sensors. We discuss several uses of our fingertips, including the detection of soft or lightweight object perimeters, stationary object perimeter exploration, and surface stiffness sensing.

This paper is structured as follows: in Section II we review the design of the robotic fingertips, and explain how they are able to sense surface orientation, force, and path distance with simple, low cost sensors. In Section III we discuss the use of the data sensed by the fingertips to detect objects, and estimate object shape or stiffness. We then conclude the paper in Section IV.

II. ROBOTIC FINGERTIPS

In this section we describe the robotic fingertips designed to provide important haptic data using low-cost elements. The robotic fingertip is depicted in Figures 1 and 2.

A. Design Overview

Our robotic fingertip is, at its core, comprised of a rolling element that is mounted at a small offset from the center of a second rolling mechanism. This design is similar in concept to a shopping cart wheel that is free to roll, but changes its orientation when the cart is pushed in a different direction. In our fingertip, a silicone-coated cylinder is the rolling element that comes into contact with an object. This cylinder, or “roller” is free to turn about its axis, and does so when any tangential force is applied to it. The roller itself is mounted on a “swivel mechanism” at an offset. This means that any tangential force applied to the roller causes it to turn about its axis, and does not transfer to the swivel mechanism. Normal force applied to the roller does not cause it to turn, as the normal force vector passes through the center of rotation.
and creates no torque. However, since the roller is at an offset from the center of rotation of the swivel mechanism, normal forces applied to the roller do create a torque about the swivel mechanism, unless the offset direction and normal force are collinear. This means that when a force is applied to the roller, the swivel mechanism turns so that it is perpendicular to the force (see Fig. 3). When the roller comes in contact with an object, the swivel mechanism rotates so that it is normal to the object’s surface at the point of contact. Any tangential force is translated to rotation of the roller. In this way, by touching the surface of an object we can know its surface normal at the contact point using a simple mechanical device.

The swivel mechanism that supports the roller is now placed on a linear rail with a spring, so that the entire mechanism (swivel mechanism and roller) can move along a linear path, as a linear function of force in the direction parallel to the rail. This means that if a force is applied to the roller, the force component parallel to the linear rail will cause the entire mechanism to displace, regardless of surface contact orientation. This mechanism is can be seen in Fig. 2.

The combination of the roller, swivel mechanism and linear rail is the basic concept of the robotic finger, which is depicted in Figures 1 and 2. The roller is the only element that is intended to come in contact with an object, while the linear rail is attached to a robotic arm, hand, or any other apparatus.

B. Sensors

We use two potentiometers and one optical encoder to gain important data from the robotic finger. Specifically, we use these low cost sensors to learn the direction and magnitude of a force vector applied to the roller, as well as the distance the roller has traveled along an object’s surface.

Firstly, we mounted a potentiometer (Bourns 3382G-1-103G) between the linear rail and the swivel mechanism. The potentiometer we used is small, low-cost and has a very low torque resistance (30 gf-cm max.). In this configuration, the potentiometer measures the angle of the swivel mechanism, which is analogous to the surface normal when the roller contacts an object.

Secondly, we attach an identical potentiometer to the linear rail, using a rack and pinion setup. This potentiometer measures the linear distance the entire mechanism has traveled. Knowing the spring stiffness, we can deduce the force component in the direction of the linear rail. The combination of these two potentiometer readings provides us with the full two dimensional force vector between the roller and the object.

Lastly, we use an incremental optical encoder (HEDS 9100 with a 512 step disk) to measure the rotation of the roller in respect to the swivel mechanism. While the robotic fingertip
is run along an object’s edge, the rotation of the roller can be counted to determine the distance traveled by the finger. Another important aspect of the roller rotation measurement is the evidence of contact. An extremely small tangential force is required to rotate the roller, therefore a light brush against an object can be detected using the roller rotation data. The force that turns the roller is given by Coulomb’s friction model:

\[ F_t > \mu \cdot F_n \]  

(1)

where \( F_t \) is the tangential force, \( \mu \) is the friction coefficient between the roller and the object it contacts, and \( F_n \) is the normal force between the roller and the object it contacts. In order to turn the roller, some minimal torque \( T_{\text{min}} \) is required to overcome the static friction \( T_{f,s} \) and induce a turn:

\[ T_{\text{min}} > T_{f,s} \]  

(2)

\( T_{\text{min}} \) can be determined experimentally. We define the torque on the roller by:

\[ T = r \cdot F_t = r \mu F_n \]  

(3)

where \( r \) is the radius of the roller. We can then rewrite the previous equations to find the minimal normal force:

\[ F_{n,\text{min}} = \frac{T_{f,s}}{\mu r} \]  

(4)

We wish to minimize the minimal normal force required to turn the roller \( F_{n,\text{min}} \). To do this, we attempt to improve all of the affecting parameters. We use a silicone coated roller in order to increase the typical value of \( \mu \). We use ball bearings to reduce the rotational friction, and therefore reduce \( T_{f,s} \). The last parameter \( r \) is more complicated. While it is easy to increase the radius of the roller, and therefore reduce the minimal required normal force, the finger should be kept as compact as possible in order to better explore concave objects. Therefore, we use a relatively small radius of \( r = 12.5 \text{mm} \). While the minimal force required depends on the object (by changing the friction coefficient \( \mu \)), our tests on steel found that the minimal force to turn the roller was extremely small, less than our measuring devices could detect (< 0.01 N). The distance resolution of the roller is given by:

\[ \Delta = \frac{2\pi r}{512} = 0.153 \text{ mm} \]  

(5)

All three sensors are connected to an Arduino microcontroller, which is mounted on the finger. LED lights are also connected to the microcontroller for visual feedback of the fingertip state (rolling, force magnitude etc.). The microcontroller is connected to a computer via USB cable.

III. UTILIZING DATA FROM FINGERTIP SENSORS

In this section we detail the main uses for the robotic fingertips as tactile sensors. Furthermore, we detail the methods for attaining important tactile information using the robotic fingertip and its sensors.

A. Soft or Lightweight Object Perimeter Exploration

Rigid, heavy objects can withstand an external force without moving. Conversely, lightweight objects are more prone to move when a force is applied to them, and soft objects such as organic tissue are likely to deform at the area where a force is applied. These limitations prevent us from applying significant forces to the object for tactile sensing. Instead, we use a method that is designed to apply minimal force to detect the perimeter of an object by use of lateral rolling. This method mimics a natural approach to “hesitant” tactile edge detection, where a person would slowly move their fingertips indirectly toward an object, until they brush them across it with little force.

In this method, the fingertip moves toward the assumed direction of the object, however as opposed to a direct approach, the fingertip path is not done in a straight line. The object is approached in an oscillatory movement that is mostly lateral to the object (assuming the direct approach is approximately normal to the object). This movement can be done in many ways, such as a “lowering pendulum” type of movement, or a “zigzag” pattern. These path examples are shown in Fig. 4. The selection of the progression path is heuristic, and further research is planned to select the best type of path. In experiments we used the “lowering pendulum” type path, given by:

\[
\begin{align*}
    x(t) &= x_0 + R \cdot \sin(A \cdot \cos(\omega t + \phi)) \\
    y(t) &= y_0 + R \cdot \cos(A \cdot \sin(\omega t + \phi)) - B \cdot t
\end{align*}
\]  

(6)

where \((x_0, y_0)\) is the starting location, \(R\) is the radius of the circular motion, \(A\) is the arc length (\(A = 2\pi\) is a full circle, a typical value is \(A \approx \pi/4\)), \(\omega\) is the frequency, \(\phi\) is the phase shift, \(B\) is the rate of lowering and \(t\) is the time variable. Similarly, we can define the “zigzag” function as:

\[
\begin{align*}
    x(t) &= x_0 + W \cdot \cos(\pi \omega t / w) / \pi \\
    y(t) &= y_0 - B \cdot t
\end{align*}
\]  

(7)

where \(W\) is the width of the pattern, and the remainder of the variables are similar to equation 6.

The goal of these motions is to contact the object with a force that is mostly tangential, with as little normal force (due to vertical velocity at the moment of impact) as possible. Normal force can be sensed by the fingertip via the linear rail and spring, however the minimal force required is non-negligible (\(\approx 0.5\) N), and therefore we do not attempt to detect the surface in this way. Instead, we use the fact that an extremely small tangential force on the roller causes it to turn, which can be sensed by the encoder. This means that when the fingertip lightly brushes against an object, it can detect its existence and location. This method can be used iteratively to increase the accuracy of the perimeter detection. Once the perimeter is detected, the fingertip can retreat slightly, and repeat the approach with a slower, more compact approach (alternate values of \(R, A, \omega, \phi, B\) in the path function). In this way, the accuracy of perimeter detection is increased. This is termed refinement, and in
Fig. 4. “Lowering pendulum” (left) and “zigzag” (right) paths to approach an object for low-impact perimeter detection.

It should be noted that this method cannot be used directly to trace the object’s perimeter, but rather gives a single point on said perimeter. In order to define the object, this method may be repeated at different points in order to approximate the shape of the object.

Several experiments were conducted using a robotic arm (Robotis Manipulator-H) with the robotic finger attached to its end effector. The finger was moved in a lowering pendulum path towards different types of object, both rigid and soft, using different path parameters and settings. Such an experiment is depicted in Fig. 5. The robotic finger was capable of detecting soft and rigid objects by application of extremely small forces ($< 0.01 \text{ N}$). As an example, we attempted to detect a soft brush (at the edge of the brush bristles). Using this method, the fingertip detected the brush when it came into contact with only two bristles after refinement.

**B. Rigid Object Perimeter Exploration**

While many modern approaches to rigid object shape exploration utilize partial tactile information to reconstruct a rigid object’s shape [5], [3], [20], we propose a more natural approach, where a robotic finger slides along an object’s perimeter (or traces the object’s perimeter), giving more complete information. This is similar to what a person or animal would do when exploring an object, running their fingers (or other members) along an object’s edge. This is especially true when searching for a small feature on the object [21].

The proposed robotic fingertips can be used in this way to map the surface of a planar, rigid object. To do this, there are two main stages: detection and tracing. In the detection stage, the fingertip must be moved in the assumed direction of the object, until it comes into contact with its perimeter. The linear rail is oriented in the direction of finger movement, so that any contact with an object is guaranteed to apply some force in the direction of the linear rail. This means that as soon as there is some force detected (relative movement between the linear rail components), the fingertip is in contact with the object, and a first contact point is established. A predefined constant force is then further applied to the object by the fingertip by moving the fingertip further in the same direction until the force is reached. As an example, humans typically apply forces of $1.54 \pm 0.5 \text{ N}$ when exploring surfaces with their fingertips [22]. The second stage is tracing, in this stage the constant force between the object and the fingertip is maintained, while the fingertip is moved parallel to the object’s surface at the contact point. The contact point and surface normal at the contact point is recorded at increments of distance passed, as determined by the turns of the roller. The tracing is terminated when the fingertip returns to the starting point. This process is detailed in Algorithm 1.

In Algorithm 1, $B$ represents the list of known perimeter points, $B'$ is the list of perimeter normals that corresponds to the points in $B$, $N$ is the sensed normal direction, $\delta$ is a user defined small increment of distance, $\text{Location}$ is the current sensed contact location, and $J = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$ is a simple rotation matrix.

**C. Object Stiffness Exploration**

If a point on the perimeter of a soft object is known, we can use this knowledge to gain additional information regarding the stiffness of the object at that point. The initial position of a point on the perimeter of a soft object can be attained using the method previously described in Section III-A. In this method, we bring the fingertip to the point on the perimeter, and apply a force in the direction assumed to be the normal direction to the object’s perimeter. The force exerted will cause the swivel mechanism to align normally to...
This stiffness can be expressed as:

\[ k(d_o) = \frac{F(d_r)}{d_o(d_r)} \]  

(8)

where \( k \) is the stiffness of the object at the probed point, \( F \) is the force applied and \( d_o \) is the displacement of the object’s perimeter (the penetration of the object in the normal direction of its surface). Both \( F \) and \( d_o \) are functions of the displacement of the linear rail \( d_r \). This type of stiffness probing can be used to palpate organic tissue at different points in order to detect sub-surface features with different stiffness’ than their surroundings, such as tumors or scar tissue. The palpation of a soft object (foam brick) is depicted in Fig. 6.

This palpation technique can be further advanced by applying a force on a soft object, and then moving the finger parallel to the object’s undistorted perimeter (which must be known). While moving the finger parallel to the object’s original perimeter, any changes in the deflection of the linear rail will indicate a change of stiffness at that point. It should be noted that this method requires full knowledge of the object’s perimeter without distortion by force, and does not provide a full stiffness function of the object, but rather indicates a general stiffness gradient along its perimeter.

### IV. Conclusion

In this paper we have introduced a novel tactile sensor that uses low-cost sensors and mechanical ingenuity in order to sense object properties at its surface. We described three main uses for the finger. Firstly, use of the finger to detect the edge of a soft or lightweight object, using extremely small tangential forces to detect the object without applying large forces upon it that may move or distort it. We show preliminary experimental data that proves the finger is capable of detecting hard and soft objects with high accuracy using very low force. Secondly, we described a method of “tracing” the perimeter of a rigid object, using the fingertips sensors to provide a complete map of the object’s perimeter, and the normal direction at any point. Lastly, we show how the finger can be used to palpate a soft object in order to learn the stiffness function of the object at any point, enabling it to detect stiffness anomalies that are not apparent by observing the object’s perimeter.

While tactile sensors that accomplish these tasks exist, the proposed robotic fingertips uses low-cost sensors, which are imperative to practical tactile sensing in industrial and consumer products. Furthermore, our fingertip provides a variety of different applications using the same sensors in different ways. The ability of the sensor to roll at the contact point allows it to move along an object’s perimeter without producing significant tangential force, which helps to prevent
tangential distortion, undesirable object movement, and shear stress (that could result in tearing) at the object’s surface. The proposed fingertip has the capability to measure a minimal travel distance of 0.153 mm with the encoder disk used in our experiments. The orientation of the swivel mechanism (and therefore the normal direction of a contacted surface) as well as the linear rail movement are measured by potentiometers, which are continuous sensors that provide essentially infinite accuracy. The practical limitations of the potentiometers are linearity errors (up to 2%) and microcontroller input resolution (10 bit). These limitations result in a realistic resolution of 3° for the normal direction. The linear rail can measure forces of 0.5-16 N with a resolution of 0.3 N. This force range is directly dependent on the spring stiffness can measure forces of 0.5-16 N with a resolution of 0.3 N.

We have also briefly discussed possible paths for probing soft or lightweight objects. We propose two types of paths, “lowering pendulum” and “zigzag”. Each of these path types are designed to ensure minimal normal velocity towards the object. Assuming the object is flat and directly beneath the robotic finger, the “lowering pendulum” type path has very low vertical velocity near its low points, and the finger is likely to make contact with the object near this low point due to its wide nature. However, if the object is not in the ideal position or is not flat, the finger may strike the object in the portions of the path that have greater vertical velocity, specifically the beginning of each “swing”, where the finger rapidly drops before losing vertical velocity. In the “zigzag” case, the vertical velocity is constant all along the path, therefore reducing the maximal value of vertical velocity, but also increasing the minimal velocity, giving a more predictable but non-ideal result. Each of these two paths have several parameters that change their characteristics, such as rate of descent and swing frequency. These parameters, as well as different path types should be further explored in order to improve the proposed fingertip’s accuracy and sensory robustness.

Future research will be focused on improving the design of the fingertip for minimization and accuracy, as well as determining optimal search paths for soft object detection. The natural progression of the design is a replacement of the roller mechanism with a rolling ball mechanism, so that forces and tangential rotations can be sensed in two dimensions, allowing sensation of 3D objects. Such a fingertip is currently being developed by our team, using similar principles as those shown in this paper, as well as adaptations for three-dimensional exploration. This low-cost sensor could provide many new uses for real object exploration. For instance, an array of 3D sensors could be used to quickly explore the stiffness map of organic tissue with a large surface area. We also intend to explore new uses for the fingertip, introduce haptic feedback mechanisms as well as consider using an array of these sensors to improve sensation speed and accuracy.

References


