Force Sensing with Compliant Joints

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ABSTRACT

Compliance provides many advantages for the grasping performance of robotic hands. However, it also enables new approaches to tactile sensing – compliance makes simple sensors smart. Compliance simplifies the control of contact interactions during tactile sensing operations, and compliant joints with joint-angle sensors are a powerful, simple sensor that can be used to determine important information without damaging the sensors or target object. In this study, we present a sensor for measuring the angles across compliant flexure joints, and methods to use this sensor to measure contact forces and determine contact locations.

1. INTRODUCTION

Object geometry, surface friction, and contact force are important properties for grasping and manipulating objects. Historically, however, it has been difficult to use tactile sensors to measure these properties due to the cost, fragility, and complexity of sensor hardware. Unstructured environments such as peoples' houses contain many obstacles and sensors must withstand unexpected collisions.

Recently, however, there has been a trend towards using compliance in grasper design [3, 6, 2]. In previous work, we have developed a hand that uses compliant flexure joints and passive mechanics to achieve stable grasps on a wide range of objects in the presence of uncertainty about object position and shape without active sensing and control [2].

While compliance provides advantages for grasping, it also gives significant advantages for tactile sensing. Soft joints provide "built-in" impedance control so that a position- controlled hand can interact gently with objects that it contacts without the need for high-speed force feedback loops. Additionally, the deflection of soft joints provides important information and can serve as a useful tactile sensing modality itself [5, 4].

In this abstract, we present a way to measure this deflection in flexure joints with multiple degrees of freedom (DOFs), and a way to use compliant joints together with contact location sensing to determine contact forces without expensive, fragile force-torque sensors. Finally, we present ongoing work in our lab to use compliant fingers to determine contact location and object geometry.

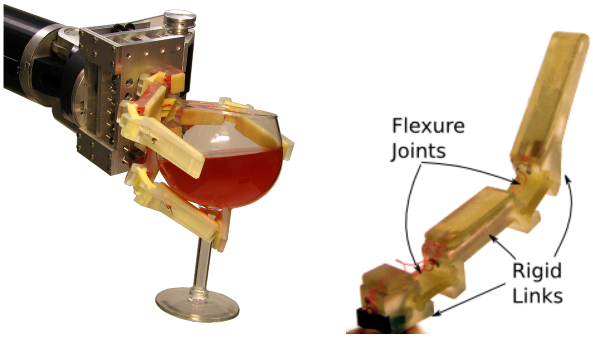

Figure 1: The SDM Hand (left) uses fingers with flexure joints (right) to provide a strong, stable grasp that passively adapts to the shape of objects without feedback control. When equipped with joint angle sensors and contact location sensors, such compliant fingers can be used to measure contact forces and determine object geometry.

2. FLEXURE JOINT-ANGLE SENSORS

Although many methods exist to measure the position of rotary joints (e.g. encoders, potentiometers), there is little work on measuring the deflection of flexure joints that have no fixed mechanical center of rotation, and to the authors' knowledge there is no existing literature about measuring deflection of flexures that deform in multiple degrees of freedom. The problem is challenging for several reasons: the continuous deflection in the flexure makes it difficult to separate different DOFs (large rotations are not commutative), and the large scale of deflection puts the behavior outside the range of linear beam-mode models.

To address this problem, a novel sensor was developed. It consists of four modules that measure the local angle deflection at each corner of the joint as shown in Fig. 2. In each module, an optical fiber shines onto a pair of phototransistors that measure the angle of this light beam, which changes as the flexure bends. The effects of any variation in the light intensity are minimized by taking the ratio of the difference of the voltages to the sum of the voltages

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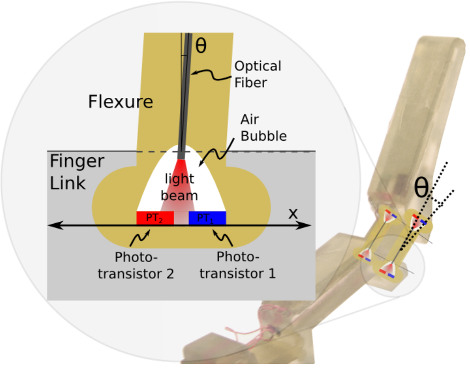


Figure 2: A joint-angle sensor. At each of the four corners of the joint, an optical fiber shines onto a pair of phototransistors. As the flexure bends, these measure the angle of the light beam to give a local measure of flexure deformation.

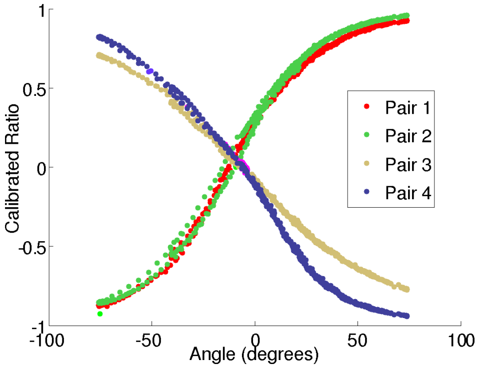


Figure 3: Response of the optical fiber units as the joint is flexed. These measurements are combined to produce measurements of the flexion and twist at both ends of the joint.

$\theta = (v_1 - v_2)/(v_1 + v_2)$. Each end of the joint has two such optical fiber units. The performance of this sensor hardware is shown in Fig. 3.

To convert the readings from these four modules to a measurement of the total deflection of the joint, we first assume that the instantaneous rotation at any point along the joint is primarily around the two softest directions – flexion θ (as the finger closes towards the palm) and twist ϕ (around the axis of the finger). To the first order, we can measure these at each end of the joint by taking the sum of the readings from the units to give flexion, and the difference to give twist.

Using a linear interpolation between the two ends, we can then get a measures of the flexion, θ_i, and curvature, ϕ_i, at any point along the length of the joint. We break up the total rotation of the joint into a series of smaller rotations in series (moving along the length of the joint) because the rotation so far affects the axes of the rotation at the next point ($\mathbf{R}(\theta)$ is not commutative with $\mathbf{R}(\phi)$ for large angles). Thus, we can compute the net rotation of the full joint as the following product:

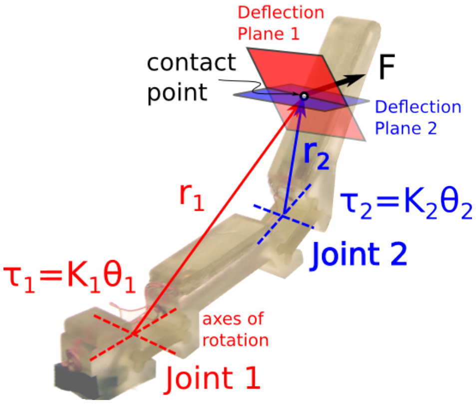


Figure 4: Contact force can be calculated by projecting torques from joint stiffness out to the contact location. Several joints are needed to span the full space.

$$\mathbf{R}(s) = \prod_{i=0}^{i=N} \mathbf{R}(\phi_i)\mathbf{R}(\theta_i)ds \tag{1}$$

3. MEASURING CONTACT FORCE

3.1 Contact Force

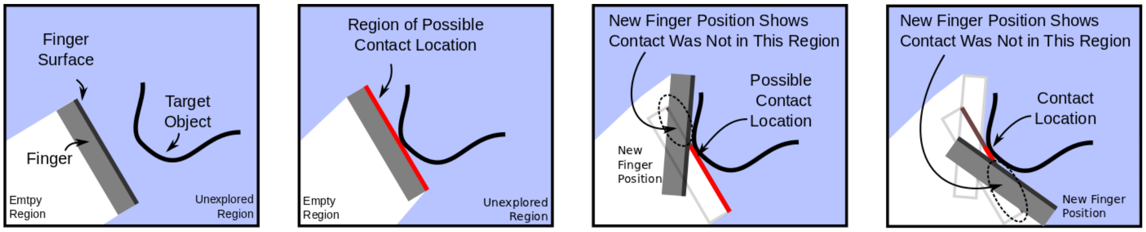
In our proposed scheme, we take advantage of the finger's compliance to enable force sensing using only joint angle and contact location sensing. We model the joints as spring-loaded spherical joints. Thus, any contact point can move around center of the joint on a spherical path that is locally approximated by a plane perpendicular to the vector $\vec{r}$ between the joint center and contact location as shown in Fig. 4.

The deflection of the joint $\Delta\vec{\theta}$ and the joint stiffness $\mathbf{K}$ give the torque around the joint $\vec{\tau} = \Delta\mathbf{K}\vec{\theta}$. This will cause a force at the contact point in the plane of motion, which can be calculated by multiplying the torque by the joint Jacobian matrix $\mathbf{J}$. The Jacobian matrix $\mathbf{J}$ of each spherical joint is a diagonal matrix with each element $j_{ii} = 1/r_i$ where $\vec{r}$ is the vector from the joint center to the contact location. Thus, the projection of the contact force $\vec{F}$ onto the plane of deflection is given by

$$\mathbf{T}\vec{F} = \mathbf{J}\mathbf{K}\Delta\vec{\theta} \tag{2}$$

where $\mathbf{T}$ is a projection matrix onto the plane perpendicular to $\vec{r}$. Note that because a single joint cannot deflect in all directions (it is not compliant in the axis of the link), several joints in series are required to measure the force between the finger and object. Each joint will then give a projection of $\vec{F}$ onto a different plane of motion. Provided these planes span the space, they can then be integrated into a single system of equations and solved using a pseudoinverse.

$$\vec{F} = \begin{bmatrix} \mathbf{T}_1 \\ \mathbf{T}_2 \\ \dots \\ \mathbf{T}_N \end{bmatrix}^+ \begin{bmatrix} \mathbf{J}_1\mathbf{K}_1\Delta\vec{\theta}_1 \\ \mathbf{J}_2\mathbf{K}_2\Delta\vec{\theta}_2 \end{bmatrix} \tag{3}$$



Approach

Contact with Object

Move Finger

Contact Localization

Figure 5: With compliant joints and joint-angle sensors, it is also possible to determine object geometry by "sweeping" through the space around an object [4].

This can then be used to compare normal and tangential forces while stroking an object to determine friction, or measure object compliance by comparing force to deflection. Note that measuring forces does not require the computation of the full stiffness ellipsoid at the contact point.

3.2 Sensitivity

The error in each planar measurement of force is a function of the precision of the joint-angle sensors, the spring stiffness measurement, and the measurement of the contact location. In the one-dimensional case,

$$f_i = \frac{1}{r + \epsilon_r}(k + \epsilon_k)\Delta(\theta + \epsilon_\theta) \tag{4}$$

From this, it is clear that an error in joint-angle measurement ϵ_θ has a proportional effect on the total force measurement, as does an error in spring stiffness ϵ_k. The effects of a given noise level in the radius measurement depends on the magnitude of the radius $F_{meas} = \frac{1}{1+\frac{\epsilon}{r}} F_{act}$. If the finger is actuated, the spring deflection alone is no longer sufficient to determine the torque around the joint; however, the method can be extended by including a cable tension sensor or other similar device.

4. CONTACT LOCATION

The preceding method requires an estimate of the contact location. Traditionally this would come from a tactile array. Once again, however, we can take advantage of the compliance of the finger together with carefully designed sensing actions to enable simple contact location detection using only joint angles [4] as shown in Fig. 5.

Traditional methods to sense contact location have revolved around tactile arrays or internal force-torque sensors[1] mounted on stiff fingers; while they provide certain advantages during manipulation, these are poorly suited to exploration. In contrast, compliant joints with angle sensors are mechanically robust, avoid exerting large forces on the object, and have few blind spots since the entire finger serves as the sensing surface.

We assume the object does not move under low forces; then, the object and finger cannot interpenetrate. When contact is detected between a finger and a static object, the current finger surface defines a set of potential locations for this contact. If we assume the object is rigid and unmoving, the location of the contact cannot lie in any region that is subsequently occupied by the finger, and finger motion narrows the contact location.

5. CONCLUSION

Compliant joints provide significant advantages for tactile sensing: soft fingers allow hands with basic position controllers to interact gently with objects, and the deflection of soft joints can be used to determine key information for grasping and manipulation. We present a novel sensor to measure the deflection of compliant flexure joints with multiple DOFs. Additionally, we present a method to use compliant joints to measure contact forces without the need for fragile force-torque sensors, and a method to use compliant joints to determine contact location without tactile arrays.

6. ACKNOWLEDGMENTS

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