Presented at the 1995 IEEE/RSJ International Conference on Intelligent Robots and Systems, Pittsburgh, PA, August 5-9, 1995.

Rolling with Deformable Fingertips

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Abstract

The superiority of deformable human fingertips as compared to hard robot gripper fingers for grasping and manipulation has lead to a number of investigations with robot hands employing elastomers or materials such as fluids or powders beneath a membrane at the fingertips. When using such materials, it is important to account for their properties during manipulation. The rigid-body rolling kinematic equations developed and applied in previous investigations do not consider load- and object-dependent fingertip deformations. This paper is concerned with determining the kinematic effects of soft fingertips during manipulation with rolling. The long-term goal of this work is to produce a model of rolling with soft fingertips that can be incorporated into a real-time control system to produce current best estimates of contact locations and velocities when planning and executing rolling maneuvers.

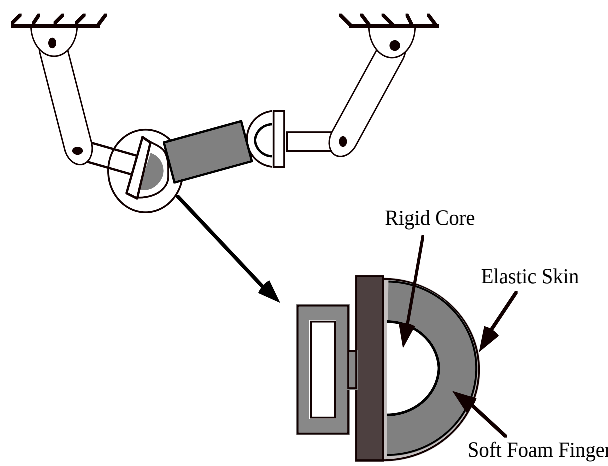

Figure 1: Planar Manipulator with Soft Foam-Backed Fingers [2][3]

1. Introduction

Human fingertips are fleshy, soft, and deformable. They locally mold to the shape of a touched or grasped object, and for these reasons, are capable of extremely dextrous manipulation tasks. Until recently, most robot fingers have been crude and pincer-like, and therefore rather limited in capability. This realization has led to the investigation of robotic manipulation with soft, human-like fingers. For example, Son and Howe[1], Tremblay and Cutkosky[2], Howe and Cutkosky[3], Russell and Parkinson[4], Nowlin[5], Clark[6], Brockett[7] and Shimoga and Goldenberg[8] report on experiments in which either foam-backed or fluid-filled fingers successfully enhanced dextrous capability (see Figure 1).

However, employing these types of compliant fingers introduces an added complexity. Grasp conditions causing significant deformations of the fingertips will affect the kinematics of the finger/object contact. We address the problem of determining these load- and object-dependent effects during manipulation with rolling. After reviewing previous rolling work, we will present and discuss some two-dimensional rolling experimental results that illustrate the significance of the kinematic effects.

2. Previous Work

There has been extensive work in rigid body rolling manipulation. Cai and Roth[9] and Montana[10] articulated the kinematic contact constraint equations to provide input/output relationships between relative velocities of two rolling bodies and the velocity of the contact point over the surface of the two bodies. Kumar et al[11] examined the same problem with dynamics and derived a set equations that describe the acceleration of the contact point. Kumar et al[12] and Choi et al[13] applied the kinematic relationships to coordinated manipulation simulation and control with rolling. Sastry et al[14][15]and Li and Canny[16] examined reachability of locations and feasibility of paths in planning of rolling motions. Hemami et al[17] incorporated information from a tactile array into control of rolling. As mentioned, these works have all been exclusively rigid body analyses. Kao and Cutkosky[18] and Montana[19] considered small adjustments to the rigid body Jacobian matrices and kinematics of contact equations to account for compliant fingertips, but they did not comprehensively examine the significant effects of deformable fingertips.

3. Kinematic Effects of Rolling with Soft Fingers

We wish to consider the rolling kinematics problem with the additional consideration that a grasp force is exerted between the finger and the object and that the finger is compressible. To simplify the analysis, we limited our study to pure rolling without sliding in two dimensions. The experiments involved rolling deformable cylindrical fingertips against a rigid cylindrical object. Given identical rotations of the fingertips, we wanted to measure the differences in the imparted motions on the object due to fingertip deformations. The deformations are functions both of loading and finger/object geometry.

A rigid cylinder 25.4mm in radius representing a rigid object and soft cylindrical fingertips of various radii from 6.4mm to 25.4mm and of various materials were tested using the fixture shown in Figure 2. The fingertips and cylinder were mounted onto shafts with low-friction bearings. The cylinder was mounted to a linear ball slide and held against the fingertips using weights. Optical encoders mounted to the shafts measured how far the cylinder and fingertips rotated. A third optical encoder mounted to the linear slide measured deflection of the soft fingertip. In these experiments the soft fingertips were used to drive the rigid cylinder through several revolutions. The rotations of the rigid cylinder were recorded after each revolution of the fingertip and averaged. Deflections of the soft cylindrical fingertips were also recorded. This procedure was repeated for each soft finger over a wide range of grasp forces: 0.10N, 0.20N, 0.34N, 0.49N, 0.74N, 0.98N, 1.47N, 1.96N, 2.94N, 4.91N, 6.87N, 9.81N.

Table 1 shows the modulus of elasticity, E, and the coefficient of friction, μ, of the various soft fingertips, which included two types of rubber, closed-cell foam, and an air-filled rubber membrane (like a small pneumatic tire), all of varying radii. All fingertips had a rigid 12.7mm radius shaft at the core. The foam fingertips had an additional rigid, cylindrical hub for support, with core radii as shown in Table 1. For comparison, both the foam and the rubber cylinders were also tested with comparatively inelastic cellophane tape wrapped around the perimeter to prevent circumferential strains. The rubbers used were Dow Corning's Silastic T RTV silicone rubber and Hardman's DPR 4280-LV depolymerized latex rubber.

Figure 3 summarizes our findings for these experiments. The numbers labelling each trace correspond to the numbers of the fingertips in Table 1. As the soft fingertip rotates through one revolution, it rolls along the rigid cylinder a distance equal to the rigid cylinder's radius

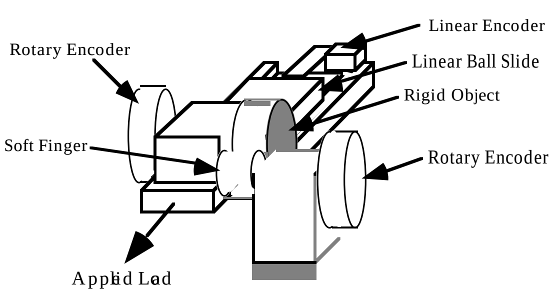

Figure 2: Setup for Rolling Experiment

#	material	radius (mm)	core radius (mm)	E (N/m^2)	fric. coeff, μ
1	foam	25.4	12.7	5.9e5	0.2
2	foam	22.2	12.7	5.9e5	0.2
3	foam	19.1	9.5	5.9e5	0.2
4	silastic	25.4	3.2	1.19e6	0.5
5	silastic	12.7	3.2	1.19e6	0.5
6	silastic	6.4	3.2	1.19e6	0.5
7	dpr	25.4	3.2	2.5e5	0.5
8	dpr	12.7	3.2	2.5e5	0.5
9	dpr	6.4	3.2	2.5e5	0.5
10	air-filled	25.4	9.5	6.0e5	0.5
11	foam/tape	25.4	12.7	5.9e5	0.2
12	foam/tape	22.2	12.7	5.9e5	0.2
13	foam/tape	19.1	9.5	5.9e5	0.2
14	dpr/tape	12.7	3.2	2.5e5	0.5
15	silastic/tape	6.4	3.2	1.19e6	0.5
16	dpr/tape	6.4	3.2	2.5e5	0.5

Table 1: Properties of soft cylinders tested

multiplied by the rigid cylinder's angle of rotation. If the fingertip is rigid or undeformed, we call this distance the nominal rolling distance. Since the fingertip is soft, the rolling distance may be different. The y-axis shows the distance rolled along the rigid cylinder as a ratio of the nominal rolling distance. The x-axis shows how much the soft fingertip deformed as a fraction of its undeformed radius. For example, a point at (0.10,0.95) means that for a finger deflection equal to 10% of the undeformed finger radius, the finger rolled along the object 95% of the distance that it would have rolled if it were undeformed. The distance/deflection relations shown in Figure 3 are over the full range of grasp forces listed earlier, with the right-most point of each trace corresponding to the deflection ratio at the maximum 9.81N load.

4. Results and Discussion

4.1 Results

The soft fingertips in Figure 3 fall into three general groups. The foam and air-filled rubber cylinders have a linearly decreasing relationship between the rolling distance ratio and the deflection ratio. The graph shows that the different radius foam and the air-filled rubber membranes have almost identical distance/deflection relations. Therefore, the behavior of a foam cylinder seems to be independent of its radius. At the largest load of 9.81N, deflections of 5-10% of the radius cause roughly a 5% reduction in rolling distance. The 19.1mm radius foam cylinder shows the same general relationship, but it has a smaller rigid core than the larger foam cylinders.

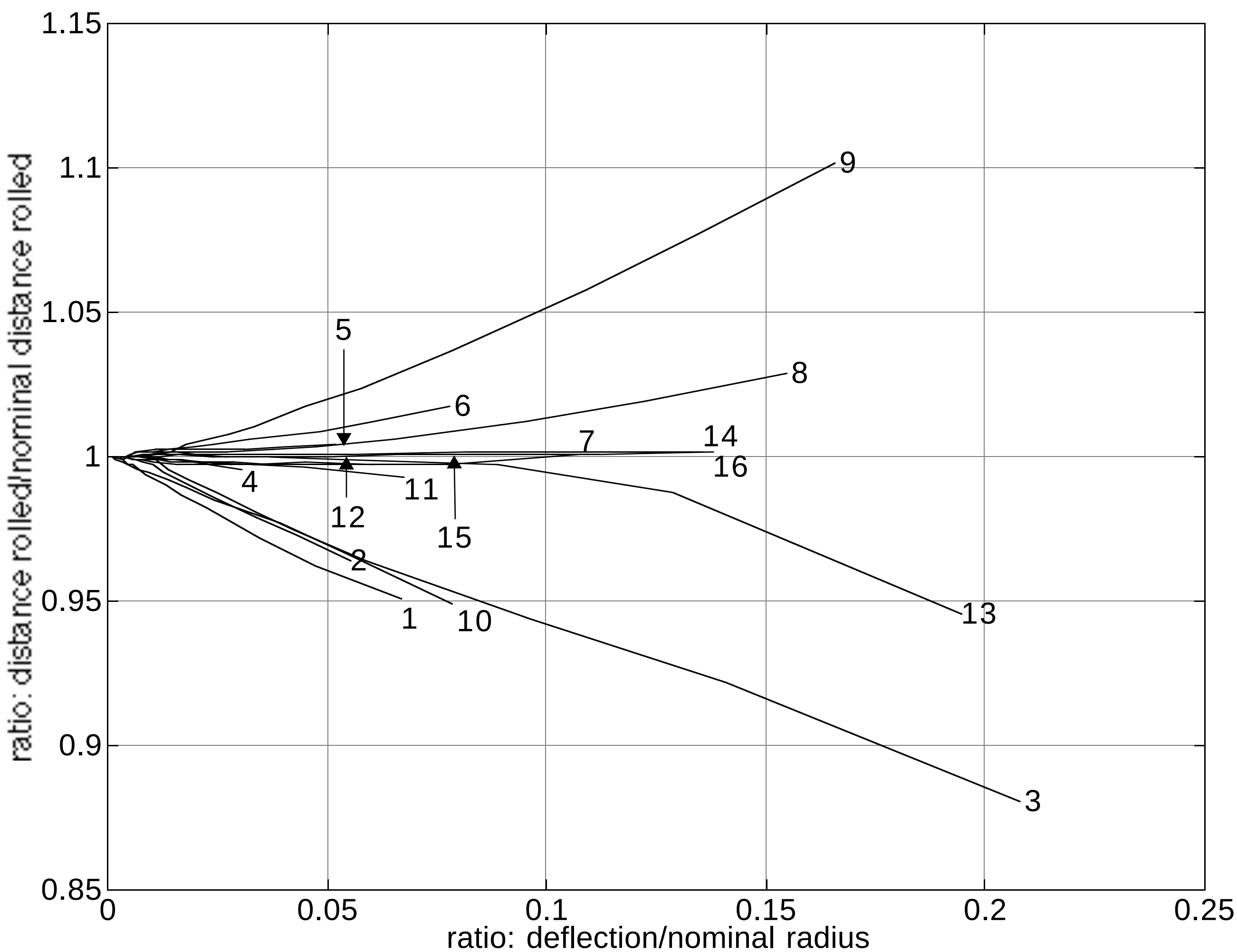

Figure 3: Normalized rolling distance versus finger deflection as ratio of radius (Numbers correspond to Table 1)

Therefore, the same 9.81N load causes a larger deflection (about 20% of the radius) and about a 12% reduction in rolling distance.

Unlike the first group, the Silastic and DPR rubber cylinders have a distance/deflection relation that is dependent on the relative finger/object geometry. Both types of 25.4mm radius cylinders show less than 1% reduction in rolling distance for the entire range of loads. However, with a modulus of elasticity significantly lower than the Silastic, the DPR cylinders all show much higher deflections for the same loads. The two types of 12.7mm radius cylinders have almost identical distance/deflection relations. As the deflection increases in the 12.7mm radius cylinders, the rolling distance becomes *greater* than the nominal rolling distance. The effect is nonlinear and becomes more significant for higher deflections. The increase in rolling distance and non linearity are even more evident in the traces of the 6.4mm radius cylinders. At the largest load of 9.81N, the DPR cylinder shows about a 16% deflection and about a 10% increase in rolling distance.

The third group of curves includes cylinders with thin, comparatively inelastic cellophane bands wrapped around the circumference. These fingers all behave alike and roll approximately the nominal rolling distance independent of deformation. The reduction in rolling distance for the 19.1mm foam cylinder above deflections of 10% was due to the cellophane tape buckling and separating from the cylinder at the high loads.

4.2 Discussion

How do we explain the three different behaviors? Increasing deflection caused rolling distances to increase in rubber cylinders (6.4mm and 12.7 mm) and to decrease in foam cylinders. Yet, when cellophane tape was wrapped around the these same cylinders, increasing deflection had no significant effect on the rolling distance.

The answer lies in circumferential strain. When the cellophane tape was wrapped around the cylinders, the perimeter was constrained to remain unchanged. One revolution of the cylinder rolled a distance exactly equal to the perimeter length, regardless of how the cylinder deformed. Without the cellophane tape, the soft cylinders undergo circumferential strain in the contact patch. If the circumferential strain is tensile, the effect is to stretch and lengthen the cylinder's perimeter and thereby increase the rolling distance (Johnson[18]). Conversely, a compressive circumferential strain decreases the rolling distance.

The next question is “Why do the foam and the air-filled rubber membrane experience compressive circumferential strain while the rubber experiences tensile strain?” The difference is due to compressibility of the material. Both the foam and the air-filled membrane fingertips are extremely compressible. Pressing a rigid cylinder against the foam cylinder causes the foam to locally compact in the contact patch into an effectively smaller radius cylinder, (i.e., the compacted cylinder acts like it has a smaller circumference).

On the other hand, rubber is incompressible (Poisson's ratio = 0.5), so no compaction occurs. Any deformation of the rubber cylinder causes the cylinder to bulge out in unloaded directions. Therefore, the rigid cylinder causes the contact patch to expand tangentially, lengthening the perimeter and rolling distance.

4.3 Hertzian Analysis

Our finding that rubber cylinders experience tensile circumferential strain seems to contradict Hertzian contact mechanics, which states that if two cylinders exert only an opposing normal force in a static, non-conforming contact, they will experience compressive circumferential strain (Johnson[20]). However, Hertzian analysis does not pertain to our experiments because the Hertzian assumptions are not satisfied. The assumptions are, first, that the contact area should be small relative to the size of the bodies. Second, the contact area should be small relative to the radii of curvature of the bodies. Finally, Hertzian theory assumes any tangential stresses present are very small and can be neglected when computing the normal pressure distribution.

In our experiments, at very light loads, the soft finger/rigid object contact area is initially small relative to the cylinders' sizes and radii. Indeed for small loads, the silastic rubber fingertips do exhibit the load/deflection behavior predicted by a Hertzian analysis. However, as the load increases, the soft nature of the fingers causes the contact area to quickly grow so large as to clearly violate Hertzian assumptions. Furthermore, as loads increase, tangential stresses quickly become non-negligible as they resist deformation of the cylinder as it turns. Therefore, a Hertzian analysis can not be applied to our experiments.

5. Conclusions

When performing rolling manipulations with soft, deformable fingers, how the object moves is dependent on the grasp force as well as the finger material and geometry. A rigid body rolling model does not account for finger deformation, so planned trajectories can differ from actual trajectories, depending on the grasp force and the finger properties. We conducted experiments with a variety of soft materials including rubber, foams and membrane fingertips and found that in most cases, for modest deformations on the order of 10% of the undeformed fingertip radius, the change in rolling distance or speed is small but noticeable and can be either positive or negative depending on the fingertip material.

The principal cause for differences in expected and actual trajectories is circumferential strain. Adding a thin, inelastic band around the finger prevents circumferential strain and results in object rolling motions almost exactly identical to those predicted with rigid body rolling kinematics. Without such an inelastic band, fingers of very compressive materials, such as foam and air-filled membranes, cause the object to roll less than a rigid finger of identical dimensions would by an amount determined solely by the finger deflection. Fingers of rubber, an incompressible material, can cause the object to roll more than a rigid finger would, but the amount is dependent on the finger radius and the rubber properties, as well as the finger deflection.

6. Future Work

As mentioned, the long-term goal of this work is to produce a model of rolling with soft fingertips that can be incorporated into a real-time control system to produce current best estimates of contact locations and velocities when planning and executing rolling maneuvers.

By examining two-dimensional rolling of soft cylinders, we have begun to determine the kinematic effects of soft fingertips during manipulation with rolling. When planning extended rolling manipulations, the difference between expected and actual rolling distances may be significant. The kinematic effects of three dimensional rolling with general-profile soft fingers can be extrapolated from our findings for the two-dimensional problem. We note that for the case of fingertips with two principal radii of curvature, the differences between expected and actual rolling velocities about different axes will cause contact trajectories to deviate from the expected paths. This effect is illustrated in Figure 4, for the case of an ellipsoidal fingertip rolling over a spherical object. Montana's rolling equations [10] are used for the case of a rigid or undeformed fingertip and for the case of a deformed fingertip for which rolling velocities are decreased by an amount approximately equal to the changes in the principal radii of curvature. The result is that the deformed fingertip follows a trajectory that diverges from the trajectory predicted by rigid body rolling equations. The validity of such extrapolations should be tested experimentally in future work.

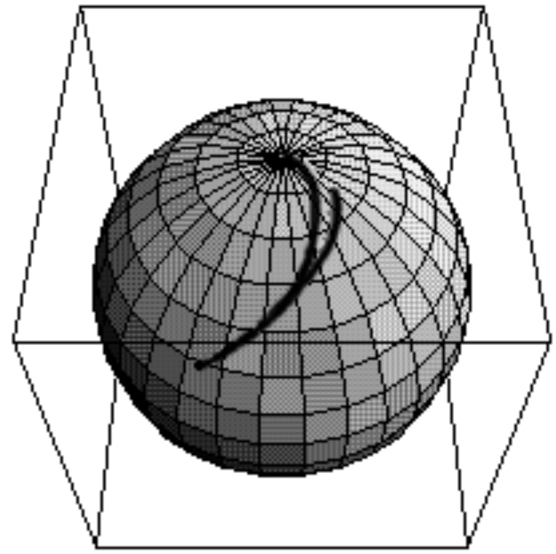

Figure 4: Predicted and actual rolling trajectories diverging on spherical object

Acknowledgments

The authors would like to thank Marc Tremblay, Jim Hyde, and Jae Son for their insights and contributions to this work. This work was supported by the ONR contract N00014-92-J-1887 and the Air Force Office of Scientific Research Laboratory Graduate Fellowship Program.

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