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The Compliance of an Object in Tactile Sensing

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Abstract

Using a tactile sensor to detect the hardness of an object is discussed in the report. The hardness of an object can be represented by its compliance measurement. A softer object has a greater compliance value than a harder object. An algorithm for computing the compliance of objects by a tactile sensor is presented. The algorithm was tested on a wide range of different objects. The results show that the algorithm is very promising.

1. Introduction

Recently, the tactile perception has received increasing attention in robotics research. Robotics systems are being built to perform complex tasks such as object recognition, grasping, manipulation and assembly. Robots which are to operate in an unknown or a partially specified environment will require sophisticated perceptual abilities. The most concerted effort in machine perception to date has been in machine vision. Research into the integration of vision and touch has shown that the accuracy and efficiency of machine vision can be greatly improved by adding touch as a verifier [1,2,3]. Psychological experiments suggest that the human tactile system is both fast and accurate to recognize real world objects. A robotics tactile perception system will be an important component in an integrated robotics system and a concentrated effort in the development of robot tactile perception is warranted.

Tactile sensing is a good choice for a complementary sensor to vision in a generalized robotics environment for a number of reasons. It has the following advantages over visual techniques [4]:

(1) They do not suffer from perspective distortion and most of the other difficulties associated with visual data. Vision is often affected by imaging geometry, surface reflectance, lighting and some other environmental conditions.

(2) Tactile sensors are relatively small and light so that they do not interfere with the operation of the robot.

(3) Tactile sensors do not have the problem of being obscured by the robot arm or other objects in the workspace.

The active tactile sensing acquires the information by touching the surface of an object directly. It is capable of detecting the texture, compliance, temperature and slippage of a grasped object [5,6,7]. Such information is useful for locating, identifying and handling objects.

The Tactile sensing has some limitations. It is low resolution and can only be applied locally.

This report presents our research result on computing the compliance of an object through a tactile sensor system. The hardness of the surface of an object can be measured by its compliance. The compliance of a harder object is expected to be smaller than a softer object. Comparing the compliance values of objects, we are able to determine the types of the material of the objects. Stanfield in University of Pennsylvania introduced an approach for computing the compliance of an object. His approach is very simple, but, it does not work in many situations. [7] The work we presented here is part of the ongoing sensor integration project at the Robotics Research Laboratory in The University of Michigan.

2. Sensor Environment

The tactile sensor used in our Robotics Research Laboratory is the LTS-200 from Lord Corporation. This device contains both a tactile sensor array and a gross load sensor. The tactile sensor array is composed of 160 sensitive sites. The sites are organized as a 10x16 orthogonal array with 0.071 inches center-to-center spacing between each site. Each site monitors the deflection of a small portion of the touch surface. The gross load sensor measures the forces and torques being applied to the touch surface.

The force and torque are measured along X, Y and Z axes. The load capacity is no more than 160 lbs at the center of the touch surface and 40lbs at the edge. The LTS-200 tactile sensor system has a microprocessor based data acquisition system to support the sensors. It accepts the simplified commands from the host and takes the necessary step to complete the desired operation. The sensor is capable of the following commands:

Scan Array: to measure the deflection of the tactile surface at each sensitive site.

Scan vector: to measure the forces and torques acting on the tactile surface.

Scan site: to measure the deflection of a single site on the tactile surface.

Vector thresholding: to scan the vector continuously until the force components reach the specified threshold. It returns the current value of the vector.

The tactile sensor is mounted on one of the two fingers of a gripper on a PUMA robot arm. An interface between the sensor and the Apollo work station is available. All data processing and high level computation can be done in C under UNIX operating system on Apollo. The sensor interface program on Apollo provides user all the sensor commands and gives user the control of the motion of the gripper on the PUMA robot arm. The gripper can open up to 4.5 inches wide. The current opening distance of the gripper can be read directly from the sensor interface. There is a pressure control applied on the gripper. The pressure is controlled manually.

3. The Compliance of an Object

The hardness of an object can be measured by its compliance. The compliance of a harder object is expected to be smaller than a softer object. In the tactile sensor application, we can measure the deflection at each sensitive site of the touching surface of the sensor, the gross forces and the torques over the touching surface of the sensor. Because of the inaccuracy of the hardware environment, the deflection, the forces and torques read at a different time for the same object surface may not have the same value. Hence, a tactile sensing based method for computing the compliance value of an object bears the following problems:

1. a tactile sensing based method for computing compliance can't give a constant compliance value to the same object at every measuring;

2. for the two objects with the same surface material, a tactile sensing based method may not give the same compliance value to these two objects.

However in robotics environment, we only want to know the hardness of an object in comparison with a set of other objects. Even in the human environment, human touching can only sense one object being harder(softer) than others. We want to design an algorithm which computes the compliance values for all objects in a set. By comparing the compliance values of the objects, we are able to rank the hardness of these objects. The algorithm should satisfy the following two criteria:

1. The rank of the hardness of the objects in the set should coincide with human touching sense.

2. We should get the consistent result from the different runs on the same set of object.

Let O = { O_1, O_2, ..., O_k } be a set of objects with different surface materials, C(O_i) be the compliance value of object O_i, i=1,...,k. Criterion 1 tells us that if we have C(O_{j1}) > C(O_{j2}) > ... > C(O_{jk}), then object $O_{j\,i-1}$ should be softer than O_{ji}, where 2≤i≤k. Criterion 2 assures that when the algorithm runs on the same set of objects repeatedly, or a set of objects with the same surface material as the other set, we should have the consistent result from the algorithm. In another words, let O^1 = { O_1^1, O_2^1, ..., O_k^1 } be another set of objects where O_i^1 has the same surface material as O_i,where $1 \le i \le k$. If the algorithm produces the result on O as

$$C(O_{j1}) > C(O_{j2}) > \dots > C(O_{jk}),$$

then the algorithm should produce the following result on O^1

$$C(O_{j1}^1) > C(O_{j2}^1) > \dots > C(O_{jk}^1).$$

From the study of many experimental results, we have found some factors which are influenced strongly by the hardness of an object. These factors constitute our measurement of the compliance for an object. We shall start with the analysis of these components. The complete algorithm for computing the compliance for an object based on a set of objects will be presented.

The relaxation component C_1.

For every object, we define an initial distance, d_0, and a stablized distance, d_s. d_0 is defined as the greatest opening distance of the gripper that it touches more than

50% of the object surface. When the opening distance of the two fingers of the gripper decreases, the gripper holds the object tighter, and more pressure is applied on the object. In general the force we read from the sensor increases with the applied pressure. When the gripper reaches a certain opening distance, the force will stop increasing. This opening distance of the gripper is the stablized distance, d_s, of the object. The relaxation component, C_1, is defined as the difference of d_s and d_0,

$$C_1 = d_0 - d_s.$$

If an object has a harder surface, it has a smaller value of C_1; a softer object has a greater value of C_1. We use this fact to recognize the material of an object.

If the hardness of two different materials are close, C_1 is not able to give a good measurement. When two objects have different thickness, C_1 alone sometime cannot give us an accurate measurement on the hardness of the surface. But C_1 can be considered as an important component for measuring the compliance of an object.

The force component C_2.

Let F_0 indicate the force we read from the initial opening distance of the two fingers d_0, and F_s indicate the force we read from the stablized distance d_s. F_0 and F_s may also be referred to as initial force and stablized force correspondingly. We define the force component C_2 as the difference of F_s and F_0,

$$C_2 = F_s - F_0.$$

Many experimental results show that usually the initial force of an harder object is closer to its stablized force, hence an softer object has a greater C_2 value than a harder object. C_2 is not much effected by the thickness of an object.

The force and relaxation component C_{12}.

The force and relaxation component is a combination of C_1 and C_2. We define C_{12} as follows:

$$C_{12} = w_{12}C_1 + C_2,$$

where w_{12} is a weight and can be computed in the the following way:

$$w_{12} = \frac{C_2^{\min}}{C_1^{\min}},$$

where $C_2^{\min}$ is the minimal value of C_2 and $C_1^{\min}$ is the minimal value of C_1.

The initial force component C_3.

Many experimental data indicate that the initial force, F_0, is a very good measurement for the hardness of an object. The initial force for a softer object is smaller than a harder object. The initial force component C_3 is defined as the reciprocal of F_0:

$$C_3 = \frac{1}{F_0}.$$

The compliance C

Both C_{12} and C_3 are good components for measuring the hardness of an object. We can define the compliance of an object by these two components. But we notice that the difference between the magnitude of C_{12} and C_3 is very large, a standard normalization is required. Let $C_{12}^{\min}$ be the minimal value of C_{12} obtained in the experiment, $C_3^{\min}$ be the minimal value of C_3 obtained in the experiment, n_1 and n_2 are the two integers such that

$$1 < C_{12}^{\min} * 10^{n_1} < 10,$$

$$1 < C_3^{\min} * 10^{n_2} < 10.$$

The compliance of an object can be defined as:

$$C = 10^{n_1} C_{12} + 10^{n_2} C_3$$

4. An algorithm for computing the compliance of an object

The following algorithm computes the values of the compliance for a set of objects. The output of the algorithm are the compliance values of all the objects in the set and the weights, W_{12}, n_1 and n_2, which are used in the computation. The compliance values rank the hardness of the objects in the set. An object has a smaller compliance value has a harder surface. The weights, W_{12}, n_1 and n_2 can be used late to compute the compliance value of a new object. Let's call the object set from which we computed these weights as the base object set. When we want to compare the hardness of an unknown object with the objects in the base object set, we can use the tactile sensor to get d_0, d_s, F_0 and F_s values of the unknown object. From d_0, d_s, F_0, F_s and the weights, W_{12}, n_1 and n_2, from the base object set. From these data, we are able to compute the compliance of the unknown object. We can determine the hardness of the unknown object by comparing its compliance value with the compliance value of each object in the base object set.

The algorithm

Input: A set of objects, O = $\{o_1, o_2, ..., o_k\}$

Output: weights: W_{12}, n1 and n2; the compliance of each object o_i.

Step 1. [Compute d_0^i and d_s^i, F_0^i and F_s^i for each object o_i.]

For each object o_i, do the following steps:

Step 1.1. Open the two fingers of the gripper to its maximum distance and initialize the sensor.

Step 1.2. Close the gripper gradually until the sensor touches more than 50% of the object surface. Copy this distance as d_0^i and the force as F_0^i.

Step 1.3. Close the gripper again until it reaches a distance that the force does not increase any more. Copy this distance as d_s^i and the force as F_s^i.

Step 2. [Compute the relaxation component C_1^i and the force component C_2^i for each object o_i.]

For i=1 to k compute:

$$C_1^i = d_0^i - d_s^i,$$

$$C_2^i = F_s^i - F_0^i,$$

Step 3. [Compute the weight W_{12}.]

Step 3.1. For i=1 to k : search the minimum value in C_1^i and store it in $C_1^{\min}$; search the minimum value in C_2^i and store it in $C_2^{\min}$

Step 3.2. $W_{12} = \dfrac{C_2^{\min}}{C_1^{\min}}$

Step 4. [Compute C_{12}^i for each object o_i.]

For i=1 to k compute:

$$C_{12}^i = W_{12}C_1^i + C_2^i$$

Step 5. [Compute C_3^i for each object o_i.]

For i=1 to k compute:

$$C_3^i = \frac{1}{F_0^i} .$$

Step 6. [Compute weights n1 and n2.]

Step 6.1. For i=1 to k search for the minimum value in C_{12}^i and store it in C_{12}^{min}; search for the minimum value in C_3^i and store it in C_3^{min}.

Step 6.1. Compute n1 and n2 such that:

$$1 < C_{12}^{min} * 10^{n1} < 10,$$

$$1 < C_3^{min} * 10^{n2} < 10.$$

Step 7. [Compute the compliance C^i for each object o_i.]

For i=1 to k compute

$$C^i = 10^{n1} * C_{12} + 10^{n2} * C_3.$$

Step 8. Print out the weights, W_{12}, n1 and n2.

Step 9. Print out every C^i value of object o_i in the decreasing order.

A discussion on the implementation of the algorithm.

The force we read from the tactile sensor is a vector with X, Y and Z components. In the implementation of the algorithm, we compute the force by averaging the absolute values of the three force components.

We use the deflection array to determine the initialized distance d_0. The fingers of the gripper initially is at its maximum distance and then they close to each other gradually. Before the sensor touches the surface of the object, every element in the deflection array is 0. When more than 50% elements in the deflection array are greater 1, we define this distance of the two fingers as the initial distance d_0. The stablized distance is a little more complicated. Since the measurement of the force is coarse, sometimes the force at distance d_i smaller than the force at d_{i+1}; but at distance d_{i+k}, the force may jump to a much greater value, where $d_i > d_{i+1} > d_{i+k}$. Such situation happens particularly when the object is soft and F_i is close to F_0. One example is the sponge in experiment 2 in Fig. 2. Our experiments show that we always have F_s - F_0 > 200. So we compute the d_s by the following statements: if $(F_{i+1}$-$F_i)$<3 and $(F_i$-$F_0)$ > 200, then the distance at F_i is d_s and store this F_i as F_s.

5. Experiments and discussion

We have performed some experiments on the following objects: a sponge, a folded towel, an eraser, a hard cover book(h-book), the same book without the hard cover(book), a piece of wood and a piece of metal. All these objects have flat surface and the surface is bigger than the sensor surface. The algorithm has been applied on this set of objects twice. The results are shown in the tables of Appendix 1, 2, 3 and 4. Appendix 1 and Appendix 2 show the force measurement for each object from the first and second run respectively. In these tables, d_i is the opening distance of the two fingers of the gripper and $d_s \le d_i \le d_0$, and F_i is the force read at d_i, and $F_0 \le F_i \le F_s$. Appendix 3 and Appendix 4 show the results of each components of the compliance and the compliance for each object from the first run and second run respectively.

In the first run of the algorithm, we have weights, $W_{12} = \frac{350}{15} \approx 23$, $10^{n_1} = 10^{-2}$, $10^{n_2} = 10^3$. In the second run of the algorithm, we have weights, $W_{12} = \frac{429}{15} \approx 28$, $10^{n_1} = 10^{-2}$, $10^{n_2} = 10^3$. The tables in Appendix 3 and Appendix 4 give the values of the different compliance components and the compliance from the two runs. If component C_1 is used to measure the hardness of the object, we will get the following result from the first run:

C_1[sponge]>C_1[towel]>C_1[eraser]=C_1[h-book]>C_1[book]>C_1[wood]>C_1[metal].

From the second run, we have:

C_1[sponge]>C_1[towel]>C_1[eraser]>C_1[book]=C_1[h-book]>C_1[metal]>C_1[wood].

From the results of the two experiments, component C_1 alone tells us that metal and wood are the harder than the rest of the objects; book and eraser are harder than folded towel and sponge and sponge is the softest object. C_1 can't tell any further information, so it is not a sufficient measurement. Upon the values of component C_2, we can tell metal is the hardest object, h-book is harder than the book, metal, h-book and the book are harder than eraser, sponge and towel. C_2 alone is not a good measurement for the hardness of an object. The force and relaxation component gives us a satisfactory result. The results from both run show:

C_{12}[sponge]>C_{12}[towel]>C_3[eraser]>C_3[book]>C_3[h-book]>C_3[wood]>C_3[metal];

at the second run,

C_3[sponge]>C_3[towel]>C_3[eraser]>C_3[book]>C_3[wood]>C_3[h-book]>C_3[metal];

On the whole, C_3 does give us quite good result except the little confusion between 'wood' and 'h-book'.

The results from both runs show that compliance C is a good measurement for the hardness of an object. The results are consistent in both runs and coincide with human sense:

C[sponge]>C[towel]>C[eraser]>C[book]>C[h-book]>C[wood]>C[metal].

6. Conclusion

This report has given a detailed analysis on the measurements of the hardness of objects and presented an algorithm for measuring the compliance values for a set of objects by the tactile sensing data. The experimental results show that the algorithm works well over a wide range of various objects and it meets the criteria proposed in section 3.

Frequently in robotics environment, we have a set of objects as the models in the system. By applying the proposed algorithm, We can achieve the compliance values of the system models along with the weights W_{12}, n1 and n2. We can use these weights and perform Step 1.1, 1.2, 1.3, Step 2, Step 4, Step 5 and Step 7 to get the compliance value for an unknown object. By comparing the compliance value of the unknown object with the compliance values of the system models, we can determine the hardness of this unknown object.

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Appendix 1. The result of experiment 1

Object : metal					
Position di	100	95	90	85	80
Force Fi	519	752	819	869	873

Object : wood						
Position di	200	195	190	185	180	175
Force Fi	415	943	1064	1091	1101	1098

Object : h-book									
Position di	195	190	185	180	175	170	165	160	155
Force Fi	362	633	859	969	1016	1021	1029	1034	1033

Object : book							
Position di	175	170	165	160	155	150	145
Force Fi	98	354	697	919	957	968	972

Object : eraser									
Position di	145	140	135	130	125	120	115	110	105
Force Fi	52	210	383	591	795	898	926	934	936

Object : towel										
Position di	160	155	150	145	140	135	130	125	120	115
Force Fi	49	36	61	82	114	162	220	309	419	565
Position di	110	105	100	95	90					
Force Fi	725	864	912	924	927					

Object : sponge										
Position di	130	125	120	115	110	105	100	95	90	85
Force Fi	16	34	34	37	37	59	68	66	73	86
Position di	80	75	70	65	60	55	50			

Appendix 2. The result of experiment 2

Object : metal						
Position di	100	95	90	85	80	75
Force Fi	459	817	870	879	888	887

Object : wood					
Position di	200	195	190	185	180
Force Fi	329	943	1116	1153	1157

Object : h-book								
Position di	195	190	185	180	175	170	165	160
Force Fi	395	703	902	962	979	986	996	997

Object : book								
Position di	180	175	170	165	160	155	150	145
Force Fi	156	309	623	871	930	943	950	950

Object : eraser									
Position di	145	140	135	130	125	120	115	110	105
Force Fi	74	253	424	622	784	881	902	910	910

Object : towel										
Position di	150	145	140	135	130	125	120	115	110	105
Force Fi	33	45	74	116	168	250	361	500	677	840
Position di	100	95	90	85						
Force Fi	909	930	938	939						

Object : sponge											
Position di	135	130	125	120	115	110	105	100	95	90	85
Force Fi	19	30	29	33	45	41	59	55	62	62	99
Position di	80	75	70	65	60	55	50	45			

Appendix 3 C1, C2, C12, C3 and C from experiment 1.

Pressure=40	metal	wood	towel	eraser	sponge	h-book	book
C1	15	20	65	35	75	35	25
C2	350	686	875	882	803	672	870
C12	710	1166	2435	1722	2603	1512	1470
C3	0.00193	0.00241	0.02041	0.01923	0.0625	0.00276	0.0102
C	9.03	14.07	44.76	36.45	88.53	17.88	24.9

Appendix 4 C1, C2, C12, C3 and C from experiment 2.

Pressure=40	metal	wood	towel	eraser	sponge	h-book	book
C1	20	15	60	35	85	30	30
C2	429	824	905	836	814	601	794
C12	909	1184	2345	1676	2854	1321	1514
C3	0.002179	0.00304	0.0303	0.0135	0.05263	0.00253	0.00641
C	11.27	14.88	53.75	30.27	81.17	15.74	21.55

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