Estimation of Friction Characteristics with Haptic Vision

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Abstract Virtual reality technologies are increasingly being applied to various fields. Recently, from the importance of the sense of touch for human-computer interaction, the force feedback devices have been developed and put into practical use. For high fidelity simulation of phenomena in real-world, the haptic information such as weight, friction, and elasticity etc., are important. In this paper we propose a method for automatic extraction of friction characteristic based on Haptic Vision; we estimate the parameters of the conventional friction models from by analyzing observed shape and force data obtained by Haptic Vision and then evaluate the performance of each friction model.

1 Introduction

Virtual reality technologies are increasingly being applied to various fields as a human interface technology. Recently, from the importance of the sense of touch for human-computer interaction, the force feedback devices which enable user to grasp and manipulating virtual objects in a natural manner have been developed and put into practical use. For high fidelity simulation of phenomena in real-world, not only the visual information such as texture, shape, form of the objects but also the haptic information such as weight, friction, and elasticity etc., are important.

Acquiring the haptic information requires a huge amount of time and manpower. We have proposed a vision-based haptic exploration approach called Haptic Vision toward an automatic construction of reality-based virtual environment simulator, by augmenting active vision with active touch. The proposed system automatically extracts and describes both geometrical and physical properties of a real object, through the observation of interactions of “active vision” and “active touch” using robot hands, CCD cameras, range cameras and force-feedback sensors.

We have applied the proposed technique for exploration of shape and volume[1], mass[2], relational constrains[3], viscoelasticity[4], function[5], and have also used the results to construct virtual object manipulation simulator. However, the problem on extracting the friction characteristic has not been addressed yet.

Friction is important factor for operating objects in virtual environments. Many numerical computing friction models [6][7][8] have been proposed for animation, haptic rendering and machine simulation when the friction characteristics are given However, there are no researches on automatic extraction of friction parameter from observed data for reality-based virtual environment simulation.

In this paper we propose a observation-based automatic method for extracting the friction characteristic based on Haptic Vision; we estimate the parameters of the three conventional friction models; Coulomb, Dahl, LuGre models, Then we discuss the performance of each model from experimental results obtained with Haptic Vision.

2 Related Works

Science and technology of friction and lubrication is called "tribology". Friction is difficult to model, because it is a phenomenon depending on many variable factors such as micro forms or states of surfaces, etc.

Friction is a universal phenomenon that exists in all the mechanical systems and between all objects in daily life, the study of friction has a long history, which dates back to Aristotle and Leonardo. After Leonardo, Coulomb proposed the friction law with the coefficient of friction, and this experience-based law has been used widely. A turning point toward realistic friction modeling was the observations of Stribeck. He showed the dependence of the friction coefficient on the relative sliding velocity of two contacting bodies by performing experiments on sliding bearings.

More recently, dynamic friction models has been developed, where the dependence of friction on the relative sliding velocity is modeled using a differential equation. These dynamic models use the regime, known as presliding, extending over several microns of motion in contacts before the object begins to slip.

The first dynamic model proposed by Dahl[6] and represented by the stress-strain curve of classic solid mechanics. This has been later modified and improved by the LuGre (Lund-Grenoble) model [7] corresponded to the Stribeck effect and the viscous friction. Moreover, to avoid a nonphysical drift artifact that affects the LuGre model,

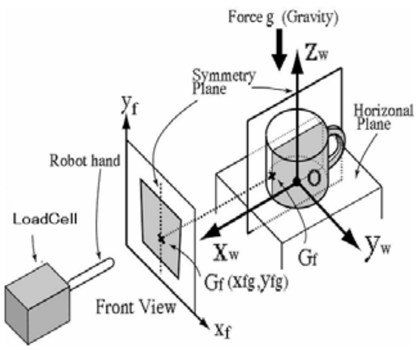

Fig. 1: Contact for friction characteristic estimation

elasto-plastic model [8], etc. have been proposed. Though these dynamic models can declare truly friction phenomenon in theory, those parameters cannot be acquired easily. In other words because of complicated microscopic features of frictional surfaces, it is not simple to model friction phenomena in general.

3 Friction Characteristic Estimation

A. Proposal method

Modeling of friction force is important for realistic haptic interaction in virtual environments. Our approach to friction characteristic estimation is as follows.

Step1: The object is put in a horizontal supporting plane. We first observe the object to extract and model its geometrical properties such as 3D shape, surface texture, posture by using our haptic vision sensor.

Step2: As shown in Fig.1, we estimate a symmetric plane *S* passing through the center of gravity, from a set of principal views acquired by our active vision system. We design a point *Gf* of the intersection of its surface and *S* as contact point. The contact point *Gf* is a point to cause a pilot event for friction characteristic extraction where an object moves straight in the direction of

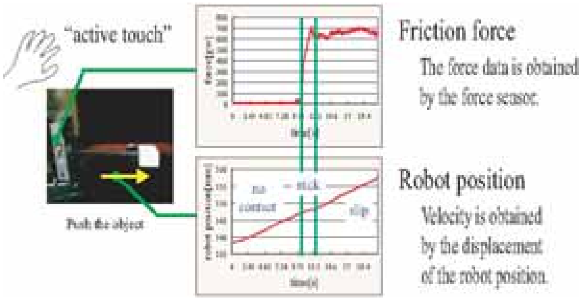

Fig. 2: Contact for friction characteristic estimation

a contact force *F* with no rotation and with no change in its posture when robot hand push this point

Step3: we make a contact by "Push" operation by a robot hand, at a point *Gf* with the direction of *F* parallel to the horizontal plane and also included in the plane of symmetry.

Step4: we measure the displacement of *F* during "Push" contact using a force-feedback sensor mounted on the robot hand and estimate a velocity v with respect to the fixed surface by the displacement of the robot hand position (Fig.2).

Step5: we estimate the friction characteristic between the object and the supporting plane by estimating the parameter of the conventional friction models (Coulomb, Dahl, LuGre) by analyzing the observational data obtained by a force-feedback sensor and the displacement of the robot hand position.

Because of easy acquisition of parameters, we consider the Coulomb, Dahl, and LuGre friction models in **Step5.**

B. Friction models

As previously stated, though several models such as Coulomb friction model, Dahl model, LuGre model, and elasto-plastic model, etc. have been proposed, the acquisition of parameters of these models is difficult. In this paper, these parameters

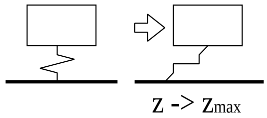

Fig. 3: Dahl model

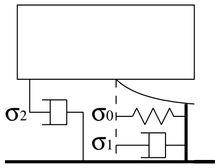

Fig. 4: LuGre model

are estimated from the observation of objects with the Haptic Vision system. We investigate and compare the models to find proper one.

1) Coulomb Model

The algorithm for estimating parameters of Coulomb friction model is described as follows.

The measured maximum static friction force is F_1 [gw]. When robot hand moves the object while suppressing it on by already-known force W [gw], the measured maximum static friction force is F_2 [gw]. As a result, with the Coulomb friction law, F_1 and F_2 are as follows.

$$F_1 = \mu Mg \qquad (1)$$
$$F_2 = \mu(Mg + W) \qquad (2)$$

Where M is a mass, μ is static friction coefficients, g is gravity force. From (1) and (2), μ is estimated as follows.

$$\mu = (F_2 - F_1)/W \qquad (3)$$

The dynamic friction coefficient is similarly estimated.

2) Dahl Model

Next, the algorithm for estimating parameters of the Dahl model is described as follows.

It is supposed in Dahl model that there is a spring between the object and the supporting plane, and the object begins to slip when the elasticity displacement z becomes z_{max} as shown in Fig.3.

The model can be shown by the following expressions.

$$f = kz,\ k > 0 \qquad (4)$$

$$\frac{d}{dt}z = v\left(1 - \frac{z}{z_{\max}}\operatorname{sgn}(v)\right) \qquad (5)$$

Where f is friction force, k is spring constant, v is velocity of the object. Here, unknown values of (4) are k and z. z is the variable which takes real values in the interval [0,1]. Since we have $z_{\max} = 1$, the differential equation of (5) is solved, and z is substituted for (4). A result frictional force f can be shown as follows.

$$f = k\operatorname{sgn}(v)\left(1 - e^{-\operatorname{sgn}(v)vt}\right),\quad k > 0 \qquad (6)$$

In (6) t is sampling time while the object is slipping. As a result, the constant value k is estimated from the observed values f, v, t.

3) LuGre Model

The LuGre model presents the asperities of two surfaces as elastic blastles and is modeled by

$$\frac{d}{dt}z = v\left(1 - \frac{\sigma_0 z}{g(v)}\operatorname{sgn}(v)\right) \qquad (7)$$

$$f = \sigma_0 z + \sigma_1\frac{dz}{dt} + \sigma_2 v \qquad (8)$$

where z is the average deflection of the bristles, v is the relative velocity between the two surfaces and f is the friction force. As shown in Fig.4, σ_0, σ_1 and σ_2 show stiffness, damping, and viscous friction coefficients respectively. $g(v)$ represents the Stribeck friction and is defined by

$$g(v) = F_c + (F_s - F_c)\exp[-(\frac{v}{Vs})]^2 \qquad (9)$$

where F_c is the Coulomb friction force, F_s is the stiction force, and Vs is the Stribeck velocity, which is a parameter based on the experiment. the constant value σ_0, σ_1, σ_2 are estimated from the observed values f, v, F_c, F_s.

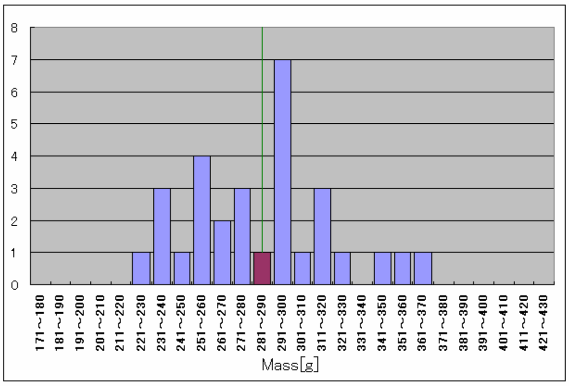

Fig. 5: Histogram of the estimated weighs.

4 Experiment Results

The objects used in our experiment are man-made solid object that satisfies the following conditions: (1) They can be placed stably on the horizontal supporting plane; (2) They have at least one vertical symmetric plane; (3) Their density are uniform.

We carried out an experiment using Haptic Vision system, which consist of vision and haptic robots. The vision robot is Mitsubishi Electric's robot manipulator RV-E4N equipped with Cubix's range finder and Toshiba's CCD camera. The haptic robot is Mitsubishi Electric's robot manipulator RV-E2 equipped with A&D's force sensor (LC-4102-K1.5). The weight sensor can give us weight data of 0.2 *gw* unit (one count) every 0.1 seconds.

We used an aluminum block (281 *g*) as the object and a cardboard as the supporting plane.

The coefficient of friction is estimated 30 times with Coulomb friction model. From these friction coefficients we estimate the corresponding weighs by the expression $Mg = F / \mu$. Fig. 5 is the histogram that shows what proportion of case fall into many ranges of estimated weighs. The range of weigh of the red bar is the range including the real weight. The mean of estimated weights is shown by the vertical line. The mean of estimated weights is close to the real weight. This means that the corresponding friction coefficient is close

Table 1: Example of estimated friction model parameter values

Friction data	**Fs**	**889.2**
	Fc	**680.243**
Coulomb	**μs**	**0.329**
	μd	**0.252**
Dahl	**K**	**699.2**
LuGre	**σ0**	**4531.24**
	σ1	**4054.11**
	σ2	**0.0**

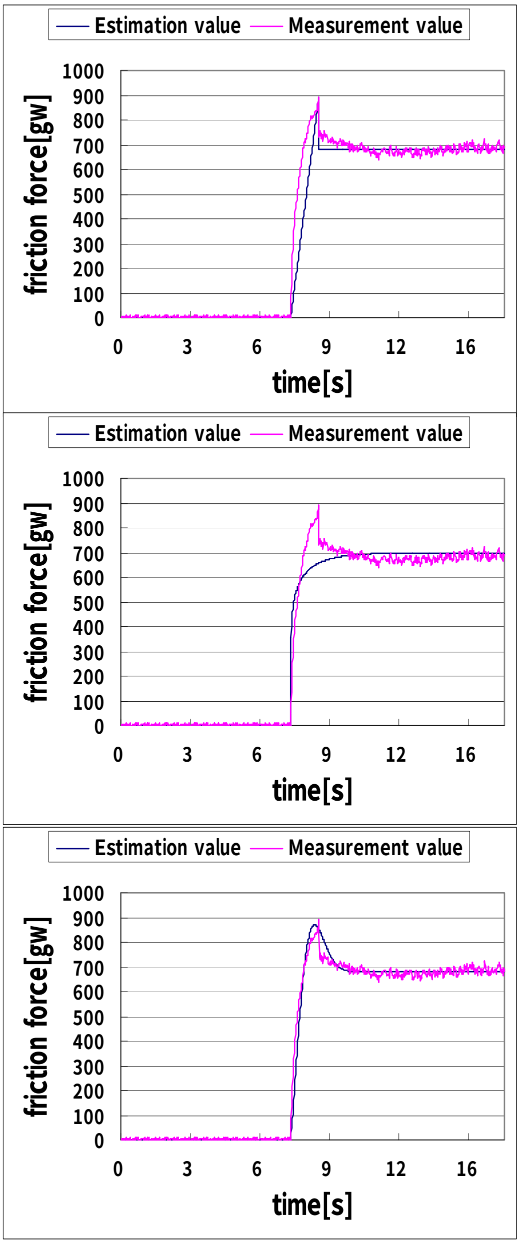

Fig. 6: Estimation value and measurement value of Coulomb, Dahl, and LuGre model

velocity		Coulomb	Dahl	LuGre
1mm/s	1	81.6	79.2	**36.3**
	2	77.7	54.5	**44.1**
	3	80.5	56.8	**44.7**
0.5mm/s	1	80.9	61.3	**31.1**
	2	95.4	77.4	**45.9**
	3	63.4	75.8	**31.8**
0.1mm/s	1	**32.4**	54.7	35.8
	2	28.2	33.8	**22.1**
	3	39.4	40.6	**31.9**

Table 2: RMS (Root Mean Square) friction error

to the real friction coefficient.

As shown in Table 1, we estimated the parameters of Coulomb, Dahl, LuGre friction models, where μ_s is the static friction coefficient and μ_d is the dynamic friction coefficient, using aluminum block (2500 *g*) as the object and a cardboard as the supporting plane. Because the dry friction is considered, $\sigma_2 = 0$.

Then, as shown in Fig.6, the friction force was estimated by each friction models.

Coulomb model corresponds to estimated friction coefficients are close to the real friction coefficients as Fig. 5. However, because this model cannot represent dependency between friction force and velocity, it is insufficient to express the phenomenon dynamically. In other words, Coulomb model doesn't consider Stribeck effect.

Dahl model can express dependency between friction force and velocity. However, this model cannot represent the moment when the object begins to move, and so have a large error in neighborhood of the maximum static friction force. In other words, Dahl model doesn't also consider Stribeck effect.

LuGre model can represent Stribeck effect and viscous friction.

Moreover, RMS friction error between the measured friction force and the estimated friction force by each model was shown in Table 2.

5 Conclusions

We proposed the automatic estimation method of the parameter of Coulomb, Dahl, and LuGre friction models from the observe shape and force data obtained by Haptic Vision. Then we gave the comparison results of the performance of each friction model. Coulomb friction model give values close to the actual friction coefficient, but is insufficient to express the friction phenomenon dynamically. Dahl model expresses the transition of a continuous frictional force, but give large error in neighborhood of the maximum static friction force. LuGre model considers the Stribeck effect, therefore, overcome the fault of Coulomb and Dahl model.

As a result, LuGre model demonstrated better performance than the others in representation of friction phenomenon.

In future works, we will construct the simulation in virtual environment.

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