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An extended bristle friction force model with experimental validation

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A R T I C L E I N F O

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A B S T R A C T

Bristle friction force models have been used by many as a preferred method for modeling friction forces. The original bristle friction force model is one-dimensional. It represents the physical reality for some practical application cases but does not accurately represent the friction phenomenon of a general contact between two 3D objects because the friction force vector is possibly rotating in the time-varying common tangential plane of the contacting surfaces. In this research the original integrated bristle friction model is extended to a 3-dimensional model. With such an extension, the resulting friction force model can be used to compute friction forces in both sticking and sliding regimes for general contact dynamics modeling. Simulation examples are presented to demonstrate the application of the model. Experiments were designed and performed to validate the new model. The presented validation exercise demonstrated that the extended bristle friction model can well duplicate experimental results including typical frictional behaviors such as sliding, sticking and stick-slip.

1. Introduction

Friction exists in almost all mechanical systems causing many unwanted effects such as wear, dynamic instabilities, tracking errors, limit cycles, stick-slip behavior, etc. It is a complicated phenomenon resulting from interactions between contacting surfaces, influenced by not only the motion state but also materials, geometry, temperature, moisture etc. Several effects have been observed with friction, such as Stribeck effect, viscous friction effect, time lag effect, and breakaway force dependence on force rate. Therefore, developing a complete friction model that can describe all the observed friction behaviors is a very challenging task. Tremendous efforts have been made to understand friction mechanism and predict frictional behaviors. Various friction force models have been introduced in the literature. Friction usually consists of two regimes, namely, the sticking regime and the sliding regime. The earliest friction models can only describe the friction behaviors in the sliding regime and are called static friction models (to distinguish from dynamic friction models). The most commonly seen static friction model is the Coulomb friction model, also known as classical model, which dated back to the work by Amontons in 1699 and Coulomb in 1785. The Coulomb friction model explains some friction phenomena such as that friction force is proportional to the normal load but independent of contacting area. The modeling method has been extensively studied and effectively applied to numerous engineering problems, such as those reported in [1–5]. However, the Coulomb friction law does not describe the friction phenomena happening at zero velocity. In fact, the static friction force is found to be more related to the displacement as opposed to the relative velocity between the contacting surfaces [6]. A few improvements were made to the classical friction models in the last century, such as those discussed in [7–9]. However, these improvements did not introduce a mechanism capturing the friction behaviors in the sticking regime.

Later on, dynamic friction models were introduced that model friction behaviors in both sliding and sticking regimes. Karnopp proposed a method of treating a static friction problem by introducing zero-velocity constraints into the equations of a dynamical system's motion [10]. Dupont [11] also solved for the static friction force from the system's dynamics equations. Such approaches can find the right static friction force (from the force equilibrium equations) but it is inconvenient in implementation (especially

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when dealing with a large multi-body system) because the friction force model is part of the entire system dynamics model as opposed to a standalone model. Dahl first developed a standalone model tackling the static friction problem in [12]. Dahl's model used an internal state to describe the dynamics nature of the friction phenomenon, which was used extensively for applications involving ball bearing friction. While Dahl's model accounts for the Coulomb friction and some static friction behaviors, it does not capture the Stribeck effect. Bliman [13] modified Dahl's model by extending it to a second-order state equation which can capture the Stribeck effect. Haessig and Friedland [14] developed a bristle friction model. It assumes that, between contact bodies, there are a lot of tiny, mass-less, and elastic elements, so called bristles. Friction force arises from the elasticity and deflection of these bristles. The model has gained a lot of popularity in practice because it is simple in concept and easy to implement. Based on the same idea, LuGre's model was proposed in [15].

Friction is an extremely complicated nonlinear phenomenon. Since the above-mentioned friction force models cannot accurately predict all of the experimentally observed friction behaviors, efforts of searching for more comprehensive and practical friction models persisted in the last decade. Some researchers focused on modifying the previous models to make them more accurately represent the experimentally observed frictional behaviors [16–19]. Others tried to develop new models for emerging applications. Some of the newer models are, for example, the elasto-plastic models [20–22], the Leuven model [23], the generalized Maxwell-slip model [24,25], the seven-parameter model [26], and the nano-scale friction model [27–29]. Ref. [30] extended the seven-parameter friction model using the idea of bristle friction modeling approach. This model is one of the most complete friction models in the sense that it takes the experimentally observed frictional phenomena into consideration. However, this also makes the model complicated and thus, difficult to implement.

Most of these models are defined in one-dimensional space, which have to be modified when they are applied to general contact situations like grasping an object and docking to a vehicle, where a contact can happen intermittently (on and off) in a time-varying location and direction. Some efforts have been made to extend the current dynamic friction models, especially the LuGre's model, to 2D or 3D models for tire-terrain applications where contacts happen between elastic/plastic bodies [31–34]. Ref. [31] presents a discrete scalar friction model in a vector form and Refs. [32–34] extend the longitudinal LuGre's friction model for modeling tire-road contact behavior.

The contact friction model introduced in this paper was aimed at general rigid or near-rigid body contact dynamics applications. It was developed based on the integrated bristle friction model introduced by Haessig and Friedland [14]. The original bristle model was developed for simulating the joint friction force or torque of a robot or other mechanisms. The model is defined only in a single dimensional space and thus, cannot be readily applied to a general contact dynamics problem where the friction force is a time-varying vector in 3D space (or in the 2D space constrained by the time-varying common tangential plane of the involved contacting surfaces). Although a preliminary extension of the bristle friction model to 3D case for general contact dynamics has been discussed in Ref. [35] with successful applications to several practical simulation cases for the space robotics applications, rigorous development of the model with direct experimental validation has not been done. This paper is aimed at filling the gap. In the paper, the extended bristle friction force model and its direct experimental validation results are presented.

Basically, the proposed friction force model treats the friction of each individual contact as a brush contacting the common tangential plane of the involved contacting surfaces. The motion state of the brush's bristles is represented by an effective bristle behaving like a linear spring which can stretch and rotate within the common tangential plane. The friction force is then computed as the force of this spring representing the average displacement of the brush in the common tangential plane. The bristle deflection vector is computed by integrating the relative tangential velocity between contacting surfaces at each simulation step. Multiple contact points are treated one by one independently in the same manner. The coupling of the multiple friction forces will be automatically accounted for when substituting these independently calculated friction forces into the system dynamics equations and solving for the system's motion state. The main advantages of the model are: 1) it describes both dynamic and static friction forces in the same model and can simulate usual friction behaviors, such as sliding, sticking, jamming, slip-slide, etc.; 2) it can be readily used for general contact dynamics modeling and simulation because the friction model is defined in the tangential plane of a 3D contact; 3) it, as a standalone model, can be very easily implemented and integrated into an existing general dynamics simulator for multi-body dynamical systems.

The rest of the paper is organized as follows: Section 2 describes the extended bristle friction model and the corresponding computational algorithm; it is followed by simulation examples in Section 3 and experimental validation cases in Section 4. The paper is concluded in Section 5.

2. The extended bristle friction model

The bristle friction model presented in this paper is an extension of the well-known 1D integrated bristle friction model [14] to the 3D space. The idea of the approach is illustrated in Fig. 1 where a "spring" is used to represent the average deflection of the bristles (i.e., the deflection of the effective bristle). Since the friction force is always constrained in the common tangential plane of the contacting surfaces of the two contact bodies, the spring is also constrained in this tangential plane. Shown in Fig. 1 is the tangential plane at time t and $t+\Delta t$ where Δt is a small time increment. The central points P_1 and P_2 represent the contact point (where the concentrated contact friction and normal forces are applied) at time t and $t+\Delta t$, respectively. This point is also assumed as where the bristle's stretch or deflection starts from. If the friction status remains in the static friction regime from time t to $t+\Delta t$, P_1 and P_2 are apparently the same point on the two contact bodies. If sliding happens between t and $t+\Delta t$, then P_1 and P_2 will be in two different locations on the contacting bodies.