Gecko-inspired synthetic adhesives - a smooth particle hydrodynamics simulation approach

Jane Doe and Bob Smith [1]

Baskin School of Engineering, UC Santa Cruz

Abstract

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1. Introduction

The ability of certain species (insects, geckos etc.) to climb or cling to surfaces has been observed for many years. However, the underlying physics, leading to this ability, start being understood only recently. Time, habitat and evolution have yielded in different solutions for adhesive ability of the various species, where the complexity of the mechanism seems to be directly proportional to the size of the creature. Since the heaviest of these species is the family of gecko lizards, most research has been directed towards understanding their adhesive ability. It has been shown that the principal mechanism responsible is a very skillful use of "directional friction" between nano-scale structures occurring on the gecko toe skin and the environment. Recent analytical work has shown that the spatula-like structure at the end of the natural gecko nanofibers is a critical element in the gecko adhesive system. This provides the ability to get intimate contact with rough surfaces, significantly increases the effective contact area and therefore the adhesive properties of the gecko foot. **???**.

When a GSAs nanofibrillar array is adhering to a surface, fibers undergo non-linear deformation of both the stems and the tip. The polymers used for manufacturing the fibers display plastic creep even at relatively low strain rates and stresses below plastic yield. Therefore, a suitable numerical solution, which predicts the optimal fiber geometry, must consider not only the initial shape of the fiber, but also the fiber progressive deformation (local and global) and the influence this has on the local mechanical properties (elastic, viscoelastic, strain hardening/softening and plastic flow). Modeling all these analytically is impossible and using traditional modeling techniques (e.g. finite element methods) could be prohibitive due to the nonlinear nature of the phenomena (e.g. viscoelastic behavior and creep) and the continuously changing boundary conditions (e.g. material relocation). A suitable modeling technique is the Smoothed-Particle Hydrodynamics (SPH). This is a mesh free Lagrange method that considers a particle array, which interact based on predefined

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[1]*Corresponding author's email address : BobSmith@ucsc.edu*

local potentials, accounting for the continuously evolving shape (e.g. creep or plastic flow) and material properties (e.g. strain softening) much more easily than the FEM does

The current paper is a parametric study of realistic (modeling existing GSAs) arrays of soft compressible viscoelastic polymer fibers. The deformation, adhesion and shear/friction resistance will be predicted using SPH as a function of the polymer constitutive model (describing different polymers) fiber geometry (different manufacturing techniques and/or shapes) and loading conditions (adhesion on different media and/or loading cycles).

1.1. FEM vs. Meshfree

The Finite Element Method (FEM) represents the traditional approach of predicting the stresses, strains and deformations in an elastic solid.

1. Mesh distortion. This could either terminate the simulation of result in significant errors. The solution: re-meshing.
2. High gradient or distinct local character: very fine mesh = computationally expensive. The solution: adaptive FEM.
3. Cracks, fragmentations, explosions, impact/penetration: the problems are not only with re-meshing, but the also with mapping the state variables (e.g. thermodynamics variables)
4. Failure mechanics: in FEM simulated material material disintegration is in fact disintegration of the FEM subdivision. therefore, the simulated disintegration pattern was integrated in the model before the simulation ever started (e.g mesh sensitivity in crack growth simulations).

1.2. SPH

- Meshfree methods are a natural extension of the FEM. However: It cold be computationally efficient and physically more accurate to discretize a continuum by only a set of nodal points (particles) without adding mesh constraints.
- Smoothed particle hydrodynamics (SPH) is a gridless Lagrangian particle method which replaces the continuum equations of fluid dynamics with particle equations.
- The interactions between the particles are determined by interpolation from information at the SPH particles.
- When SPH is applied to solids the SPH particles mimic the behavior of the atoms: If the solid is compressed the atoms repel each other. If it is stretched the atoms attract each other and oppose the stretch **?**.

2. Formulation of the problem

SPH is a mesh free Lagrange method that starts with the creation of a particle array and is governed by momentum equations, which determine change in density and viscosity. The kernel function W_{ab} is a function of the distance r_{ab} between particle a and b.

The interaction between the particle a and the neighboring particles is considered through a smoothening kernel function. In the current paper we used cubic spline kernel .... (see equation 1), where h is the... and $q = r_{ab}/h$ represents the normalized distance between the particle a and b. Figure show a schematic representation of the kernel function.....

(a) We should redraw this

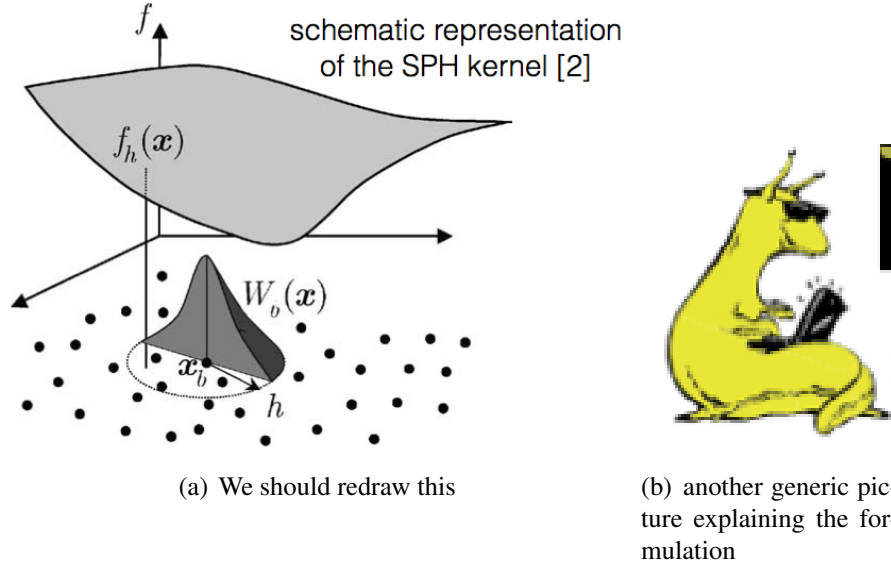(b) another generic picture explaining the formulation

Figure 1: array of soft compressible viscoelastic polymer fibers compressed by an elastic wall the colors represent non-dimensional particle density, where 1 is the density of the undeformed fibers

$$W(r,h) = \begin{cases} \frac{10}{7\pi h^2} \left(1 - \frac{3}{2}q^2 + \frac{3}{4}q^3\right), & q < 1, \\ \frac{5}{14\pi h^2} (2-q)^3, & 1 < q < 2, \\ 0, & 2 < q \end{cases} \tag{1}$$

$$\frac{\partial \rho_a}{\partial t} = \sum_{b=1}^{N} m_b \left(\vec{v}_b - \vec{v}_a\right) \nabla_a W_{ab}, \tag{2a}$$

$$\frac{\vec{v}_a}{\partial t} = -\sum_{b=1}^{N} m_b \left(\frac{p_a}{\rho_a^2} + \frac{p_b}{\rho_b^2}\right) \nabla_a W_{ab}, \tag{2b}$$

$$\frac{\vec{x}_a}{\partial t} = \vec{v}_a, \tag{2c}$$

where N is the total number of particles at distance $|\vec{x}_a - \vec{x}_b| < h$, ρ_i is the density, m_i the mass and $\vec{v}_i$ the velocity of a particle $i \in \{a,b\}$. ∇W is the gradient of a smoothing kernel function, p is the pressure applied on a particle, which is obtained from the energy equation. If the SPH method is used to model a fluid, this is given by Tait equation. If, however, a solid is modeled, the pressure is predicted by teh material constitutive model.

Therefore, for an elastic solid, equation 2b could be rewritten as:

$$\frac{\partial v_a^i}{\partial t} = \sum_{b=1}^{N} m_b \left(\frac{\sigma_a^{ij}}{\rho_a^2} + \frac{\sigma_b^{ij}}{\rho_b^2} + \Pi_{ab}\delta^{ij}\right) \frac{\partial W_{ab}}{\partial x_a^i} + g^i, \tag{3}$$

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where σ^{ij} is teh stress tensor, the term $\Pi_{ab}\delta^{ij}$ represents teh shear bulk viscosity and g^i is the ith component of teh body force per unit mass.

3. Method of solution

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4. Implementation
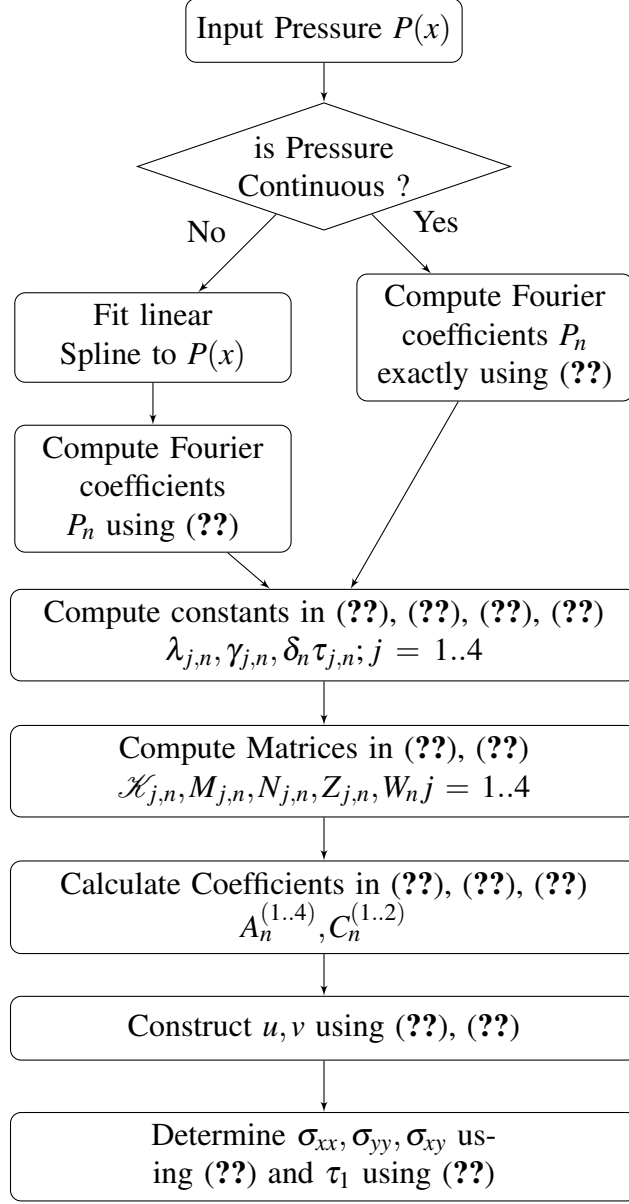
The algorithm, the numerical solution etc.

Figure 2: Example of a chart

5. Numerical results and discussions

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(a) undeformed array of fibers   (b) deformed array of fibers
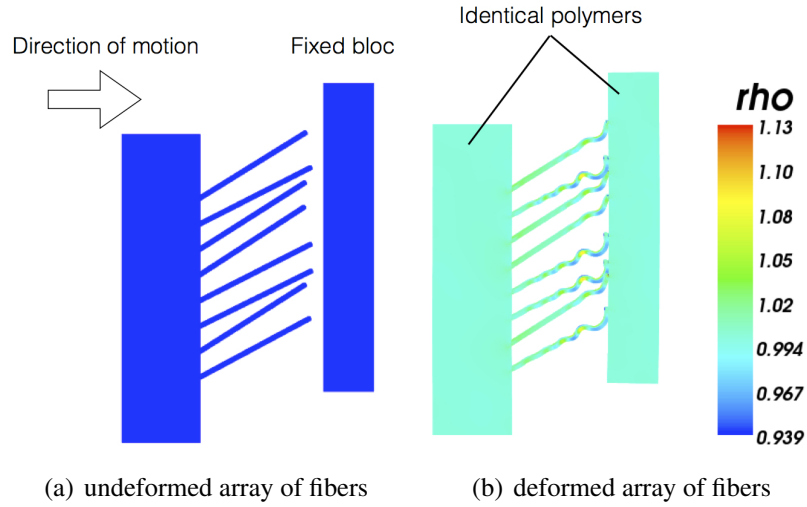
Figure 3: array of soft compressible viscoelastic polymer fibers compressed by an elastic wall the colors represent non-dimensional particle density, where 1 is the density of the undeformed fibers

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Acknowledgement

References