Resolving Cloth Penetrations with Discrete Collision Detection

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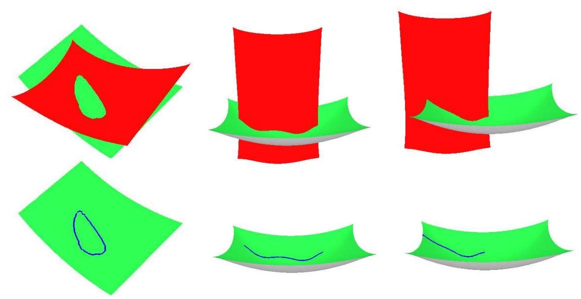
***Abstract*—We present a new method for resolving some of the most frequently occurring penetration configurations in cloth simulation, with a history-free discrete collision detection (DCD). To be adapted to a wide range of applications, this method is also orientation-free as no inside/outside surface setting is assumed. Our method relies on a heuristic paradigm "small region is illegal" to identify penetrating (illegal) regions whenever possible. First, intersection contours are constructed and classified, followed by a global analysis of the collision configurations. Then for those surfaces having identifiable illegal regions, we use *dynamic repulsive normal* (DRN) to compute proper displacements to relocate incorrectly configured vertices to be intersection-free. For those configurations that do not clearly define legal/illegal regions, displacements are designed to push one mesh to the boundary of the other. The proposed method can also be used in the context of time-dependent simulation of complex deformable surfaces, making it an competitive alternative to the popular CCD-based approach.**

***Keywords*-cloth simulation; collision detection; penetration resolving; untangling;**

I. Introduction

The majority of cloth modeling systems adopt *continuous collision detection* (CCD) to predict impending collisions, then attempt to prevent them from happening by altering the particles' velocities. The success of CCD-based response relies on a hard constraint: an intersection-free state for not only the initial configuration but also the starting of every time interval in the simulation. There are applications in which an intersection-free initial state is impossible, or the simulation context is subject to external constraints forcing the cloth into illegal states for a number of consecutive steps.

We envision a DCD-based collision correction framework, not only for untangling penetrations, but also as an alternative to the popular CCD-based approaches. However, designing a purely history-free and orientation-free response algorithm is often an ambiguous and ill-defined problem. In a simulation context with modest to moderate collision complexity, three types of configurations, as shown in Fig 1, constitute almost all collision cases. The objective of our paper is to resolve these three types collision with DCD. As history information is either unavailable or not helpful in DCD, heuristic has to be resorted to identify the penetration regions. Instead of imposing a hard constraints as in CCD,



(a) Case I (b) Case II (c) Case III

Figure 1. The configurations of intersection contours. (a) CL/CL pair. (b) BB/II pair. (c) BI/BI pair.

we only make an assumption which is easily satisfied: most of a surface is of legal status at any time of the simulation.

II. Determining Legal/illegal Regions from Intersection Contours

As some previous work, our algorithm also uses global intersection analysis to determine which parts of the cloth have crossed over to the wrong side. The success of the analysis depends on the classification of the contour. There are four types of contours as shown in Figure 1:

- **CL:** closed curve; no loop-vertex.
- **BB:** open; both ends on boundary; no loop-vertex.
- **BI:** one end on boundary, the other inside; no loop-vertex.
- **II:** open; both ends inside; no loop-vertex.

In a collision configuration, a BB contour usually comes along with an II contour. CL and BB were defined in [2] as *partitioning* contours, i.e. they partition a mesh into two components. However, we find it is true for BB contour only if the mesh has one boundary. BB contours in multi-boundary meshes (e.g. cylindrical surface) are more complicated to handle. For now, we assume the mesh has at most one boundary. Type II always corresponds to BB in which the illegal region can be identified, then II contour will diminish automatically along with the diminishing of BB. BI always corresponds to BI, and the BI/BI configuration is resolved by pushing one mesh to the boundary of another

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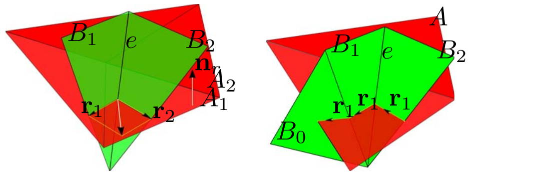

(a) (b)

Figure 2. (a) BB/II configuration. The DRN $\mathbf{n}_r$ is up for face A_1. (b) BI/BI configuration.

mesh. With the paradigm “small is illegal”, the small region delimited by CL or BB is regarded as on the wrong side.

III. Untangling with Position Displacement

In dynamics simulation, surface normals play a very important role in bouncing back the colliding geometric primitives. In that sense, they can be called *repulsive normals*. A polygonal mesh, with clearly defined normal directions to denote inside/outside, can be called *oriented surface*. For untangling two oriented surfaces, two factors are considered in developing a scheme. First, one mesh ought to be pushed along the “outside-pointing” normal direction of the other mesh. Second, the length of the intersection contour should be reduced, ultimately leading to a complete disappearance. For un-oriented surfaces, the directions of repulsive normals have to be determined on-the-fly, leading to the concept of *dynamic repulsive normals* (DRN).

The task of untangling two intersecting meshes can be broken down into separating a series of E-F intersections. In a collision configuration shown in Figure 2, edge e, shared by two green triangles, intersects a red triangle in mesh A. We denote $\hat{\mathbf{r}}_1$ and $\hat{\mathbf{r}}_2$ two unit vectors on the intersection contour, originated from the intersection point. Let us temporarily suppose that the normal vector $\mathbf{n}_r$ unambiguously designates the outside direction of mesh A. According to the above discussion, the displacement applied to e for separation has two components: one along $\mathbf{n}_r$ to push it outside of mesh A, and the other within the plane of A to shorten the length of the contour. The direction of the displacement is thus defined as

$$\mathbf{d}_e = \hat{\mathbf{n}}_r + \lambda(\hat{\mathbf{r}}_1 + \hat{\mathbf{r}}_2). \tag{1}$$

$\mathbf{n}_r$ is the repulsive normal. The effect of $\lambda(\hat{\mathbf{r}}_1 + \hat{\mathbf{r}}_2)$ is to straighten the contour until $\hat{\mathbf{r}}_1$ and $\hat{\mathbf{r}}_2$ become collinear. To avoid over-shooting, we choose small value: $\lambda = 0.1$, for the in-plane component. The small λ also decreases the possibility of moving the contour to be stuck at a local minima in the case of concave surfaces.

Equ. 1 works for type CL/CL and BB/II contours. If a contour pair is of type BI/BI, as shown in Figure 2(b), no mesh is partitioned and the DRN is defined to be zero vector, contributing nothing to the displacement vector $\mathbf{d}_e$. To resolve the E-F intersection, the edge is pushed towards the boundary of the other mesh. Of the two in-plane vectors $\hat{\mathbf{r}}_1$ and $\hat{\mathbf{r}}_2$ for an intersecting edge, from a bookkeeping point of view $\hat{\mathbf{r}}_1$ is picked this way: traveling in the direction of every $\hat{\mathbf{r}}_1$ along the contour will arrive at the boundary of the other mesh. Then Equ.1 degenerates to $\mathbf{d}_e = \hat{\mathbf{r}}_1$. To conserve the momentum of the whole system, once a vector $\mathbf{d}_e$ is computed, -$\mathbf{d}_e$ is introduced and applied to the corresponding face. This works as a pair of action and reaction forces which are equal but opposite.

IV. Applications and Results

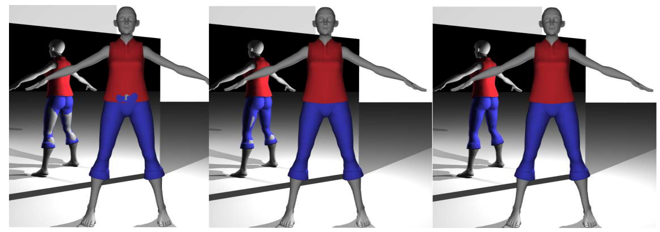

Figure 3. Garment fitting starts with an initial penetration state.

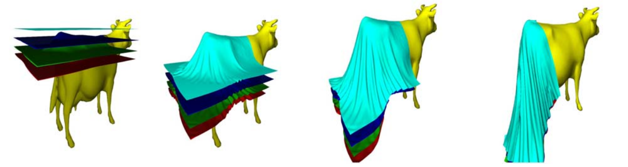

Figure 4. Four sheets of 6,561 particles each, fall on a cow model.

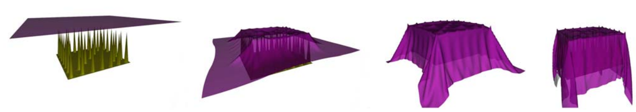

Figure 5. Simulation of a sheet of 6,561 particles falling on spikes.

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