Implementation of a Soft-Rigid Collision Algorithm in an Open-Source Engine for Surgery Realistic Simulation

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INTRODUCTION

The aim of this work is to integrate a soft-rigid collision algorithm proposed by Fukuhara [1] in an open source physics engine, Bullet Physics [2]. In surgical applications this can be the case of a clamp grabbing deformable organic materials or of a spatula opening a brain fissure. The default soft-rigid collision algorithm proposed in Bullet is not very effective in the case of thin tools interacting with deformable objects. In particular, if the rigid body (surgical tool) moves slowly, i.e. its displacement covers a small distance compared to the simulation step size, the collision is detected regularly, otherwise the default algorithm does not recognize the collision. As a consequence, the object penetrates into the soft body. Besides the implementation in [2] of the soft-rigid collision algorithm in [1], the new contribution consists on generalizing the algorithm to different shaped rigid object such as convex rigid bodies with thin thickness along one of the three main directions. Moreover, the haptic rendering has been realized by controlling the spatula in the 3D virtual space with the Novint Falcon 3D Haptic Controller. The default linear elastic model of the interaction force has been replaced with a more realistic and physical consistent non-linear viscoelastic model [3]. As a second step, the algorithm has been further extended to a clamp constituted by two rigid colliding objects grabbing deformable materials.

MATERIALS AND METHODS

The Scene

In the first step, a single rigid object (like a spatula) interacting with a deformable sphere has been considered. The sphere is composed by a 128 triangular meshes, and is placed on a ground plane. The position of the spatula in the 3D space is given by the Novint Falcon 3D Haptic Controller. The visual rendering has been realized using OpenGL. In the second step, the scene is constituted of a clamp realized with two collidable rigid objects and a handle not collidable but with solely aesthetic functions. The haptic interface allows three degrees of freedom (DoFs) for the controlled object motion. However, the clamp requires one DoF for closing and opening. Therfore for simulation purpose, the motion of the clamp has been limited to a plane and the extra DoF has been used to control the closing/opening on different object shapes, such as a sphere and an elongated object shape, that simulate more realistically vessel and in general organic tissues.

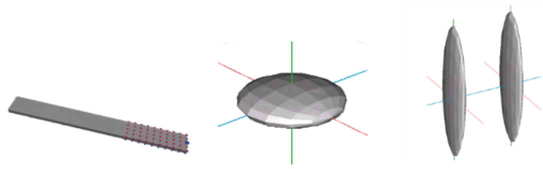

Figure. 1. Example of a spatula and nodes displacement in [1] (left image). 3D Model of the convex rigid body (middle image). The two collidable bodies of the clam (right image).

Extension of the algorithm to convex thin bodies

The rigid body used in [1] is a parallelepiped and the nodes used for collision detection are placed only on the two larger surfaces. The symmetrical shape of the body allows an easy placement of the nodes by defining the resolution along the planar directions of the two surfaces, see Fig. 1 (left image). In this work, the proposed algorithm has been extended from rigid boxes to generic convex objects modelled with triangular meshes. The algorithm in [1] requires that nodes on parallel surfaces are associated in pairs that belongs to the same surface normal. For convex objects, as in Fig. 1 (middle image), the nodes association is realized by placing a node in the centroid of each triangle mesh and by associating it to a node that belongs to the triangle intersected by the ray casting. The ray source is the node itself and the direction is the opposite of the normal to the triangle to which the nodes belongs. In this way each triangle finds its opposite pair. With respect to [1] where if a node x is associated to a node y also the vice-versa holds, in this case the nodes are not always mutual associated. This is not intrinsically critical for the algorithm application, nevertheless some problems arise. The rigid object represented in Fig. 1 (left image) presents triangular faces in close proximity to the side edge, thus, very close to one another. Indeed, the distance between two triangles on the side edge may be of two orders of magnitude smaller than the thickness of the object, as in Fig. 2 (left side). Moreover, as an effect of triangle orientation, if a node on the top left, that belongs to a triangle in proximity to the edge side, casts a ray in the opposite direction of its normal, a node on the bottom right can be associated, as represented in Fig. 2 (right side). This can be critical for the proper application of the algorithm. Indeed, when the symmetrical arrangement of the associated nodes is lost, the wrong triangle associations can cause unfeasible deformations. To solve the problems arising for these critical nodes,

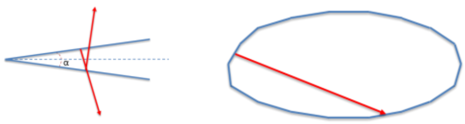

Figure. 2. Triangular faces in close proximity to the side edge.

the ray casted has no more infinite extension but limited according to the dimensions of the scene and especially of the colliding soft bodies. In this way infeasible collisions are highly reduced. Moreover, since there is no mutual association between the nodes, it is no possible to study the state of a node by verifying only the state of the opposite one. When a node belongs to an infeasible pair, the associated index is stored in a vector collecting all the indices of the nodes that cannot collide in the current simulation step. Thus, a cross-check is necessary at each step.

The interaction force model

In order to improve the sense of realism during the simulation, the contact force has been modeled using the Hunt Crossley model [3]. The model incorporates a non linear spring in parallel with a non-linear damper to model the viscoelastic dynamics:

$$F(t) = \begin{cases} kx^n(t) + \lambda x^n(t)\dot{x}(t) & x(t) \geq 0 \\ 0 & x(t) < 0 \end{cases}$$

where x is the deformation, k and λ are the elastic and viscous parameters of the model, and n is a real number (usually close to one), that takes into account the geometry of contact surfaces. At each time step, the deformation x is the distance between the current centroid of a triangle and the centroid of the same triangle at time zero. For this purpose, during the object initialization, the original position of each triangle vertices is stored. Obviously, the calculation of x is executed if and only if at least one of the nodes belonging to the triangle is in a colliding state. The total force is computed by adding the components related to each deformed triangle involved in the collision.

RESULTS AND FUTURE WORKS

By applying the default collision detection method proposed by Bullet Physics, it follows that the spatula collides with the soft body in a consistent way only for small displacements and slow motion. Fast displacement of the spatula can cause a complete penetration into the soft body surface without further collision, see Fig. 3 (left image).

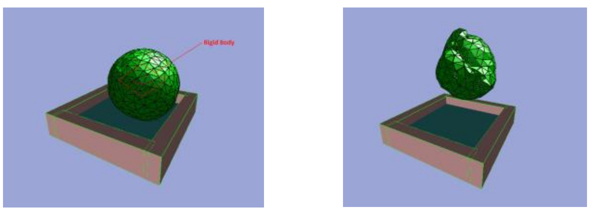

Figure. 3. Soft-rigid collision Bullet default algorithm.

Moreover, the application of only the ray casting method without node association (second step of the algorithm) causes drawbacks if the dimension of the rigid body along the collision direction is not large enough. The collision appears unstable, as in Fig. 3 (right image), when both the nodes belonging to opposite surfaces apply collision forces to the soft body even if they are unfeasible. This drawback is overcome by applying also the second step of the algorithm, that detects the unfeasible collisions and excludes them from the study at the current simulation step. The algorithm has been extended to convex rigid objects and to a clamp grabbing deformable objects, see Fig.4. The results are realistic both in terms of visual rendering and in terms of force feedback, Fig. 5.

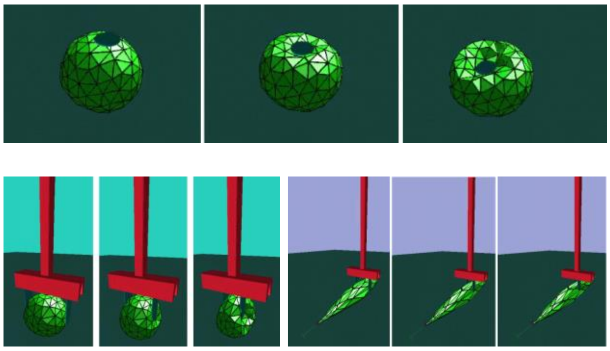

Figure. 4. Simulation results of the collision algorithm extended to different object shapes and to a clamp.

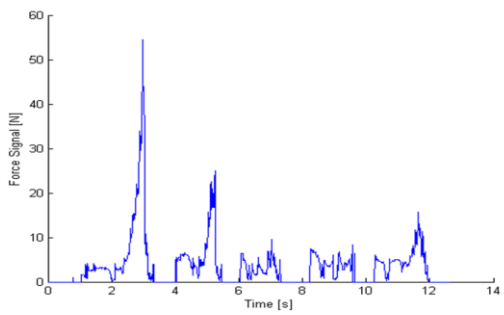

Figure. 5. Resultant force on the sphere grabbed by the clamp.

Since the promising results w.r.t the Bullet default collision algorithm, for future works is worth continuing to investigate toward improved solutions, such as for concave objects, friction models for the interaction force and future integration within different engines such as SOFA [4].

REFERENCES

[1] A. Fukuhara et al., ROBOMECH Journal, 2014.
[2] http://bulletphysics.org/wordpress/.
[3] F. Ficuciello et al., IROS, 2010.
[4] https://www.sofa-framework.org/.