"Deep Cut": An all-in-one Geometric Algorithm for Unconstrained Cut, Tear and Drill of Soft-bodies in Mobile VR

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Figure 1: A linear-blend skinned 3D model (left), current state-of-the-art of predefined cut, tear and drill (center), our 'deep-cut' framework for unconstrained, arbitrary cuts, tears, drills with soft-body deformations in mobile VR (right)

ABSTRACT

In this work, we present an integrated geometric framework: "deep-cut" that enables for the first time a user to geometrically and algorithmically cut, tear and drill the surface of a skinned model without prior constraints, layered on top of a custom soft body mesh deformation algorithm. Both layered algorithms in this framework yield real-time results and are amenable for mobile Virtual Reality, in order to be utilized in a variety of interactive application scenarios. Our framework dramatically improves real-time user experience and task performance in VR, without pre-calculated or artificially designed cuts, tears, drills or surface deformations via predefined rigged animations, which is the current state-of-the-art in mobile VR. Thus our framework improves user experience on one hand, on the other hand saves both time and costs from expensive, manual, labour-intensive design pre-calculation stages.

CCS CONCEPTS
- Computing methodologies → Mesh geometry models; Virtual reality; • Mathematics of computing → Mesh generation.

KEYWORDS
Cutting Algorithm, Tear Algorithm, Drill Algorithm, Skinned Model, Soft-Body Deformation, Virtual Reality

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1 INTRODUCTION

Since their inception, rigged animated models [Magnenat-thalmann et al. 1988] have become a major research topic in real-time computer graphics. Experts have been experimenting with various animation and deformation techniques, pushing the boundaries of realism and real-time performance. As the industry of Virtual, Augmented Reality (VR, AR) rapidly grows, increasingly more complicated and optimized methods are being developed. An example of such tools in computer graphics involve the ability to perform cuts, tears and drills on the surface of a skinned model [Bruyns et al. 2002; Kamarianakis and Papagiannakis 2021]. Such algorithms are utilized with the aim to increase user immersion and be used as sub-modules of even more complex operations. However, their scale up for the extreme real-time conditions of virtual reality environments and the specifically mobile, all-in-one un-tethered VR computing environments, remains an active field of research.

The need to interact in a shared virtual world with other participants soon led to the need of more realistic deformation techniques and interaction paradigms. Certain rigid objects, e.g., a sponge, are expected to change in real world when external forces are applied on them. It feels natural to try and replicate this behavior in VR too [Macklin et al. 2014; Papagiannakis et al. 2018; Terzopoulos et al. 1987]. One way to accomplish this is via the so-called soft-body mesh deformation [Papagiannakis et al. 2020], an algorithm that essentially dictates how the vertices of a mesh should affect one another when an external force is applied somewhere on the surface of the model.

Performing interactive cuts on a model is not something new; current bibliography describes a great number of how one may accomplish this. However, most techniques cannot be applied in applications demanding a high frame rates, such as computer games or demanding VR applications. Moreover, if cuts are indeed implemented in such an application they are almost always constrained: camera, model or user degrees of freedom i.e. the user cannot freely cut anywhere on the model; a set of predefined cuts and their animations are usually created by VR designers or artists where each one of them is played/triggered by the user’s specific and constrained actions.

In this work, we propose a framework that allows the user to perform on a rigged soft-body mesh, actions such as cuts, tears and drills on the model’s skin surface, without any constraints. Our algorithms are based on pure geometric operations on the surface mesh, and therefore are amenable to yield real-time results, even in low-spec devices such as mobile VR Head Mounted Displays (HMDs). An offline pre-processing of the model’s mesh allows the creation of suitable data structures that store both vertex neighbours (used in cut/tear/drill) and a custom particles grid with weights assignment (used in soft-body deformations). This allows the effective, latency-free application of multiple consecutive actions as the data structures only need to be incrementally updated and not re-created from scratch. Our methods can be implemented in modern game engines such as Unity and Unreal Engine; convincing results are illustrated in the video accompanying this work.

The significance of our work lies on the fact that in the current state-of-the-art, cuts, tears and drills of a rigged 3D model in VR are predefined and require a VR designer to manually manipulate and rig the model for several labour-intensive hours, depending on the model complexity, to achieve a single operation of the above. Using our methods, the VR designer is removed from the loop, while similar results are obtained at a fraction of time (actually milliseconds). Moreover, in cases where a simple change on a cut, tear, or drill is needed, our proposed algorithms may be applied continuously and incrementally until a satisfying result is achieved, saving a lot of processing time.

Our work is organized as follows: first we provide an outline of our methodology (Section 2), we then present our results (Section 3) followed by our conclusions and future work (Section 4).

2 OUR METHODOLOGY

The key components of our proposed method are the Cut/Tear/Drill algorithms, described in Section 2.1, and the Soft Mesh Deformation algorithms, described in Section 2.2. To effectively combine these methods and achieve real-time performance, we used a variety of optimization techniques and tools; you may see Section 2.3 for more details.

2.1 Algorithms for Cut, Tear and Drill

The idea of performing cuts on a model’s skin has been a highly researched topic [Bruyns et al. 2002]. We may distinguish two main categories on how this may be achieved.

The first approach is via Finite Element Methods (FEM), which is mainly used to slice parts of concrete objects, using tetrahedral meshes [Wu et al. 2013]. This is a process requiring heavy pre-processing and near real-time results can only be achieved using powerful CPU/GPU machines.

The second approach utilizes elementary geometric subpredicates (e.g., intersection of a face with a given plane) on the model mesh. Such techniques require far less process power and therefore are suitable for VR environments, especially collaborative ones.

Below we provide an outline of how we perform cuts, tears and drills, following the second approach (see Figure 2). These algorithms are explained in detail in [Kamarianakis and Papagiannakis 2020] and [Kamarianakis and Papagiannakis 2021].

Cutting Algorithm. The user inputs a plane that intersects the model. The algorithm detects the intersection points of the mesh with the plane, re-triangulates the mesh and splits the original mesh into multiple models (usually two), that correspond to the submodels having vertices on each side of the plane only.

Tearing Algorithm. The user inputs the tearing tool’s (scalpel’s) starting and ending positions. Let P be the plane defined by the tool’s end position and the initial intersection point of the model with the scalpel. We evaluate the intersection points of P with the model that lie between the scalpel’s starting and ending position, and correspond them to the tear. These points are duplicated, re-triangulated and moved away from the plane by a fraction of its normal, forming a visible tear.

Drilling Algorithm. The user inputs the radius and the end points of the axis of a cyclical drill that intersects the model. The model’s mesh is up-projected to a plane P, perpendicular to the drill’s axis, and the mesh vertices intersected by the drill are detected. After removing all parts of the mesh “inside” the drill, we
re-triangulate the mesh on Π and down-project it to the original model.

After performing any of these actions, we assign weights to the newly introduced intersection points, using the update weight function described in [Kamarianakis and Papagiannakis 2021]. This allows the final model, or submodels in case of cut, to be (re)animated in an artifact-free way.

Details on the preprocessing of the model and the data-structures used to perform either of the methods are found in Section 2.3.

2.2 Soft Body Meshes

There are various methods to implement soft body mesh deformation for skinned models [Nealen et al. 2006]. In most methods, the vertices of the mesh are clustered into groups, called particles. A vertex can belong to multiple particles and a particle is centered at the average position of all vertices it contains. Deciding a suitable clustering is not an easy task; it depends on the topology of the model and the desired deformation behavior the user wants to achieve.

In our method, the clustering was determined by the following property: every particle may contain vertices within a range of 0.8 units, using the euclidean distance. This resulted in a total of 224 particles (see Figure 3). Notice that using a smaller range would result in more particles, and therefore more accurate deformations. However, this would impact performance by causing worse running-times during the deformation algorithm, as shown in Table 2.

When a user applies a force to a particle, its position changes and this movement affects the position of all vertices of the particle. The particle’s velocity is changed, proportionally to the displacement, always pointing to its initial position (simulating elasticity). For skinned models, the velocity and displacement of the particles are calculated based on the pose of the model at the existing time, similar to how the skinning algorithm works for the vertices. The physics part is natively handled by the game engine employed.

In order to apply soft-bodies clustering for cut, teared or drilled objects, we update the clustering map by adding or removing vertices, depending on the case. Simple rules allow fast updates without the need to add more particles. An example of such a rule is that, vertices belonging to opposite sides of a tear, although close enough, cannot belong to the same particle, as this would result to non-physically correct deformation results.

2.3 Optimization Techniques

To perform either of the three main algorithms (cut, tear or drill) in near real-time, we have created data structures containing, mainly, vertex neighbours and face neighbours. Currently, we maintain two adjacency data structures, tailored to optimize the running times of the tear and the drill algorithm respectively. When importing the model, we initially check and remove any duplicate vertices that may occur as they cause artifacts in our algorithms. Then the data structures are populated; this is the most time-consuming part of the preprocessing. After the initialization is complete, the data structures are updated every time the user performs one of the algorithms. The time required to update them is miniscule compared to the initialization time and is a fraction of the time required to perform the algorithm itself. A summary of the running times for the preprocessing and the main algorithms can be found in Table 1.

The visualization quality of the drilling algorithm was also optimized. Specifically, if one drills the model in an area and the number of the edges on the contour of the hole drops below a user-defined threshold (e.g., 10), then the drilled part looks more like a polygon rather than a circle. In this case, we split each face involved into 4 subtriangles by introducing new edges that connect the mid points of their edges. This is done recursively until the number of intersection points with the updated mesh are above the threshold. Of course, for each introduced vertex, we assign weights to allow subsequent model deformation.

Important under-the-hood optimizations regard the (re)design of the algorithms described in [Kamarianakis and Papagiannakis 2021] to take advantage of multi-threaded or parallel processing allowed by modern game engines such as Unity and Unreal Engine. Since basic geometric subpredicates such as the intersection of a face of the mesh with a plane (used multiple times when cutting or tearing) can be done in parallel, we have carefully structured our
Table 1: Running times regarding the cactus model. The model optimization time corresponds to the time we need to detect and delete duplicate vertices of the mesh. The preprocessing times required for the tear, drill and clustering are only performed during the initial import and can be done in parallel in different threads. The running times of cut, tear and drill grow linearly with respect to the number of intersection points and include the time required to update the data structure that was initialized during the model preprocessing.

| Procedure                | Running time |
|--------------------------|--------------|
| Model Optimization       | 0.005 sec    |
| Preprocess for Tear      | 13.620 sec   |
| Preprocess for Drill     | 0.876 sec    |
| Soft Body Clustering     | 41.279 sec   |
| Cut                      | 0.440 sec    |
| (156 intersection points)|              |
| Tear                     | 0.095 sec    |
| (26 intersection points) |              |
| Drill                    | 0.201 sec    |
| (27 intersection points) |              |

Table 2: Running times for the soft body deformation for the cactus model. As expected, the running times are proportional to the number of the particles.

| Particles number | Running time min-max |
|------------------|----------------------|
| 224              | 1.5 msec - 3.7 msec  |
| 452              | 1.6 msec - 4.2 msec  |
| 863              | 2.0 msec - 6.7 msec  |

3 RESULTS

The results of our methods are depicted in Figure 1 and are further illustrated in the video accompanying this work. We depict a cactus model of 15819 vertices and 25267 triangles that is getting cut, teared and/or drilled. In all cases, further soft-body deformations and/or model animation are possible. Our methods are also partially implemented in a VR medical training application [Zikas et al. 2021], running on a modern game engine.

Table 1 contains the time required to perform the model preprocessing and individually apply one of the algorithms for cut, tear or drill. In Table 2, we describe the time required to evaluate the soft body deformation depending on the number of the particles. All running times were obtained using an Intel core i7 7700HQ at 2.8GHZ with an Nvidia GTX 1050ti m (8GB RAM) graphics card.

4 CONCLUSIONS & FUTURE WORK

We have presented an algorithm that allows a user to perform unconstrained cuts, tears and drills on a rigged model in VR, while preserving its ability to be deformed as a soft-body. Since our method is geometry-based, it does not require significant GPU/CPU resources, it is amenable to work in real-time VR for even low-spc devices, making it ideal for mobile VR. We expect that it will eventually pave the way to alter the modern landscape of such VR interactions, where similar operations are mostly predefined and most state-of-the-art expensive, physically-correct methods (e.g. Finite Element Methods) cannot be used as they require significant computing resources and/or produce low fps results unsuitable for mobile VR applications. In an area of the 3D model that the surface triangles are larger in comparison to the drilling diameter and not particularly dense, the resulting hole looks more like a polygon than a drilled circle. That’s due to the low number of the intersection points of the circle with the triangles in the drilling area. In the current state of our drilling algorithm, when we increase the model density the texture coordinates are showing some artifacts due to non-proper UV recalculation. In the future, we will be addressing this artifact.

In the future, we also intend to optimize further our ‘deep-cut’ framework so that they can achieve higher frame-rates with compute and geometry shaders for the pre-processing stage; so far, we have minimum latency after applying any algorithm that in some cases is negligible as the user usually takes some time for mental preparation between actions. However, we are planning to support consecutive tears, something that is not possible at this stage.

As cuts, tears and drills are especially useful for VR medical training scenarios, we would like to explore how our framework could adapt to the collaborative needs of such applications. Lastly, we would like to see how deep learning could be used to help identify which type of clustering is best suited, based on the model and the action(s) the user would like to perform.

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