Object Space Based Collision Detection for Cloth Simulation on the GPU

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Object Space Based Collision Detection for Cloth Simulation on the GPU: This paper presents an approach for cloth-body collision detection in computer graphics simulations of clothing. It is an object-space based algorithm implemented in OpenCL on the GPU. The underlying idea behind this work is to speed up the solution of the collision detection problem by utilizing the excessive computational capacity of contemporary GPUs. Results of the experiment are presented at the end of the paper.

Key words: Collision Detection, Object Space, GPU, Cloth Simulation

INTRODUCTION

The main objective of this work is to develop an efficient approach for collision detection (CD) in computer graphics simulations of clothing. Collision detection is the most time consuming stage in realistic cloth simulations. It is so due to a number of factors as: complexity of the CD problem; the deformable nature of cloth; cloth objects are usually situated near or on the same surface of other objects in the scene which results in multiple collisions in dynamic scenarios; achieving realism requires highly detailed object surfaces.

Over the past few years the continual progression of graphics processing unit (GPU) technology made these devices attractive for more than just rendering. The today's modern GPUs are very powerful computationally, capable of parallel processing. They outperform the modern central processing units (CPUs) in floating-point calculations. In addition GPUs have become more accessible programmwise which made them popular for speeding up all kinds of computational tasks.

The underlying idea behind the presented approach is to assist the CPU in solving the CD problem by utilizing the excessive computational GPU capacity. This will reduce the workload on the CPU and is expected to improve the simulation speed in general.

The rest of the paper is organized as follows. The next section reviews previous work on CD on GPUs. Section 3 describes the utilized cloth model and gives basic idea about the way a simulation is carried out. Section 4 presents the object space technique for CD on the GPU. Section 5 gives results of the experiment and Section 6 concludes the paper and gives ideas about future work.

PREVIOUS WORK ON COLLISION DETECTION ON GPUS

Due to the computational complexity of the CD task and its impact on the overall simulation speed in various computer graphics applications, significant research has been done on the topic by the Computer Graphics community. This resulted in wide variety of approaches and solutions. Initially, most of them ran on the CPU only. Later approaches involved the GPU implicitly (without direct GPU programming). In recent approaches it is common for the GPU to explicitly take part in or entirely solve the CD problem. Due to GPU's stream processing oriented architecture implementing an entire CD algorithm to run on the GPU only may not be always feasible. Thus, hybrid approaches that involve both the CPU and GPU in the CD process are quite common.

The techniques for CD could be divided in two major groups – based on geometrical interference tests in object-space and based on z-buffer interference tests in image-space. A common feature of the object-space approaches is the utilization of hierarchical structure(s) for reducing the complexity of the problem. There are two main strategies for building such hierarchies. The one is focused at space or voxel subdivision while the other is focused at the objects in the scene and relies on different types of bounding volumes and in particular bounding boxes.

In 2003 Knot et al [6] presented CInDeR – an image-space algorithm for CD on the

GPU. The GPU is used implicitly via hardware frame buffer operations which implement virtual ray-casting in order to detect static interference between solid objects. Kim et al [5] proposed hybrid parallel continuous CD method that takes advantage of hybrid multi-core architectures - using the general-purpose CPUs to perform bounding volume hierarchy (BVH) traversal and culling while GPUs are used to perform the actual tests for collisions which are reduced to solving cubic equations. Another hybrid approach is presented in the work of Georgii et al [1.2]. On the contrary of the work of Kim et al the GPU here is used to locate couples of possibly colliding polygons via ray tracing and depth peeling techniques. Afterwards, the actual tests for exact interaction are performed on the CPU. A hybrid object-space CD algorithm which mainly uses the GPU is developed by Zhang and Kim [10]. It is suitable for deformable polygonal objects. Given two objects the algorithm can detects all possible pairwise primitive-level intersections between them using two hierarchies of axis aligned bounding boxes (AABBs). The two balanced AABB trees are used as input streams over which the GPU performs tests for overlapping. An encoding / decoding strategy is also used to transfer only the list with possible collisions instead of the entire output streams which saves GPU - CPU communication bandwidth. Finally the tests for intersection between primitive-level elements (e.g. triangles) are implemented using the CPU. This approach is not capable of detecting self-collisions. Pabst et al [7] propose another hybrid CPU/GPU CD technique for rigid and deformable objects based on spatial subdivision. The algorithm is developed with scalability in mind on both the CPU and GPU sides and implements highly parallel spatial subdivision method to quickly prune away non colliding parts of the scene in a broad phase. Then a narrow phase with GPU-optimized exact collision tests follows. The CPU is used for BVH updates. A pure GPU based CD approach for rigid bodies is presented by Gress et al [3]. It operates in object-space and utilizes balanced AABB trees as BVH. The algorithm maps the AABB trees onto GPUs and performs a breadth-first search on the trees. During the traversal of hierarchy, occlusion query is used to count the number of overlapping AABB pairs and recursive AABB overlapping tests in object space is implemented using GPUs. In a later research the algorithm is modified and implemented for deformable parameterized surfaces [4]. The modifications include real-time generation of BVH on the GPU via stenciled geometry images representing the individual parameterized surfaces.

CLOTH MODEL

The elastic model of cloth, used in this work, is a mesh of $l \times n$ mass points, each of them being linked to its neighbours by massless springs of natural length greater than zero.



Fig. 1. Spring types in the cloth model

There are three different types of spring (Fig. 1):

- Springs linking vertices [*i*, *j*] with [*i*+1, *j*], and [*i*, *j*] with [*i*, *j*+1] are called "stretch" springs;
- Springs linking vertices [*i*, *j*] with [*i*+1, *j*+1], and [*i*+1, *j*] with [*i*, *j*+1] are called "shear" springs;
- Springs linking vertices [*i*, *j*] with [*i*+2, *j*], and [*i*, *j*] with [*i*, *j*+2] are called "bend" springs.

As the names indicate, the first type of spring implements resistance to stretching, the second – to shearing and the third – to bending.

Let $\mathbf{p}_{ij}(t)$, $\mathbf{v}_{ij}(t)$, $\mathbf{a}_{ij}(t)$, where i=1,...,l and j=1,...,n, be respectively the positions, velocities, and accelerations of the mass points at time *t*. The system is governed by the basic Newton's law:

$$\mathbf{f}_{ij} = m_{ij} \, \mathbf{a}_{ij},\tag{1}$$

where m_{ij} is the mass of point ij and f_{ij} is the sum of all forces applied at point ij. The force f_{ij} can be divided in two categories.

Internal forces arise from the tensions of the springs. The overall internal force applied at the point *ij* is a result of the stiffness of all springs linking this point to its neighbours:

$$\mathbf{f}_{int}(\mathbf{p}_{ij}) = -\sum_{k,l} k_{ijkl} \left((\mathbf{p}_{kl} - \mathbf{p}_{ij}) - I_{ijkl}^0 \frac{\mathbf{p}_{kl} - \mathbf{p}_{ij}}{\|\mathbf{p}_{kl} - \mathbf{p}_{ij}\|} \right),$$
(2)

where k_{ijkl} is the stiffness of the spring linking *ij* and *kl*, and I_{ijkl}^0 is the natural length of the same spring.

The **external forces** can differ in nature depending on what type of simulation we wish to make. The forces most frequently included are:

- Gravity: $\mathbf{f}_{ii}^{gr} = m\mathbf{g}$, where **g** is the gravity acceleration;
- Viscous damping: $\mathbf{f}_{ii}^{vd} = -C_{vd}(\mathbf{v}_i \mathbf{v}_j)$, where C_{vd} is a damping coefficient,
- Collision response.

From the above we may compute the force $\mathbf{f}_{ij}(t)$ applied to point *ij* at any time *t*. The fundamental equations of Newtonian dynamics can be integrated over time by a simple Euler method:

$$\mathbf{a}_{ij}(t + \Delta t) = \frac{1}{m_{ij}} \mathbf{f}_{ij}(t)$$

$$\mathbf{v}_{ij}(t + \Delta t) = \mathbf{v}_{ij}(t) + \Delta t \, \mathbf{a}_{ij}(t + \Delta t) , \qquad (3)$$

$$\mathbf{p}_{ij}(t + \Delta t) = \mathbf{p}_{ij}(t) + \Delta t \, \mathbf{v}_{ij}(t + \Delta t)$$

where Δt is a chosen time step. The Euler Equations 3 are known to be very fast and to give good results, provided the time step Δt is less than the natural period of the system $T_{_0} \approx \pi \sqrt{m/K}$, where *K* is the highest stiffness in the system. Numerous recent works in cloth simulation have shown that improvements in stability are possible by using implicit integration. However, for complex garments with mapping of Kawabata Evaluation System measurements to the spring properties, explicit integration still proved to be beneficial in terms of efficiency in our case [8]. The advantages of Euler integration became particularly apparent when computation of the collision detection and response, which require small time steps, were taken into consideration.

The implementation of this cloth model on the GPU is described in details in [9]. The collision detection and response is image-space based and is also implemented on the GPU. In this work we use a similar implementation but it is based on OpenCL. However, if

we want to animate a dressed body the image-based approach is not suitable, because of the arms moving in front and back of the body and in this way the body depth map is shadowed. This approach either has to be modified or a pure object space approach has to be developed.

OBJECT SPACE CD ON THE GPU

In this work we apply an object space collision detection algorithm implemented in OpenCL on the GPU. It is a brute force approach and checks for collisions between each cloth vertex and a face on the object. As on the GPU checks are performed in parallel, so the technique shows a relatively good speed on modern GPUs.

For this purpose we build an axis aligned bounding boxes (AABB) for each face of the objects colliding with the cloth. This requires two memory buffers; one for the (minx, miny, minz) and a second one for (maxx, maxy, maxz). Another buffer keeps the normal vectors of each face. The OpenCL kernel is executed for a rectangular grid of a size number_of_cloth_vertices x number_of_object_faces. It checks if the cloth vertex is inside the AABB and if so, it refines the check by computing the dot product of the face normal vector (**n**) and the vector from the cloth vertex (**cp**) to the object face vertex (**op**), i.e.:

$$\frac{\mathbf{cp} - \mathbf{op}}{|\mathbf{cp} - \mathbf{op}|} \bullet \mathbf{n} > 0.8 \tag{4}$$

If there is a collision the kernel writes to a collision buffer; XYZ components correspond to the face normal vector and W is one. Before the CD this buffer is cleared. The cloth simulation kernel checks the corresponding value of the collision buffer. If W=1 this means that there is a collision and the normal vector is used to apply an appropriate collision response. In OpenCL the programmer has control over the way parallelization is performed on the GPU. So the kernel is called with such values for the number of global and local threads, so that it is not possible to write to one and the same element of the collision buffer.

RESULTS

The algorithms were implemented in C++ under both Windows XP and Ubuntu Linux and were tested on a machine with a 2.8 GHz AMD processor, 4 GB RAM and NVidia GeForce GTX 260 graphics card. OpenCL was used to implement the parallel computation on the GPU. OpenGL and GLUT were utilized for rendering the images. The tests were performed for a table cloth draping on a sphere as shown in Fig. 2.



Fig. 2. Table cloth draping on a sphere

Times were measure for 2000 iteration steps. Fig. 3 compares three different implementations: pure CPU, GPU with object-space (OS) collision detection as described

in this paper and 576 faces on the sphere, GPU with image-space (IS) CD. As the results show the second approach is much faster than a pure CPU implementation and its performance is comparable with the IS CD.

Fig. 4 depicts how the speed of OS CD changes depending on the number of faces on the object. The simulation time increases almost linearly and up to 400-500 faces it is comparable with the IS CD. Moreover, if the number of faces is below 150, the OS CD performs better than the IS CD.



Fig. 3. Comparison of 3 implementations



Fig. 4. Performance vs the number of faces on the object

CONCLUSIONS AND FUTURE WORK

This paper presented an approach for object-space collision detection and response in cloth simulation, implemented on GPU. Its main advantage over the image-space based collision detection is that it can be applied for a dynamic simulation of garments on walking avatars. The following conclusions can be drawn:

- The OS CD for cloth simulation, described in this paper, can be used in real applications if the number of faces on the objects is not greater than 500-600;
- The OS CD shows better performance than IS CD for number of faces less than 150.

In order to speed up the current approach for greater number of faces we can implement a hierarchical approach, which reduces the number of checks. This will be explored in our future work.

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ДИПЛОМА

Програмният комитет на Научната конференция РУ&СУ'10 награждава с КРИСТАЛЕН ПРИЗ "THE BEST PAPER" Доц. ЦВЕТОМИР ВАСИЛЕВ И ВЛАДИМИР ДОЧЕВ автори на доклада Object Space Based Collision Detection

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DIPLOMA

The Programme Committee of the Scientific Conference RU&SU'10 Awards the Crystal Prize "THE BEST PAPER" to TZVETOMIR VASSILEV AND VLADIMIR DOCHEV authors of the paper "Object Space Based Collision Detection for Cloth Simulation on the GPU"

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