3D Physics Engine for Elastic and Deformable Bodies

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December 2002

Abstract

The purpose of this project is to create 3D engine that displays the interaction of non-rigid bodies. As a part of our project we researched existing models for elastic and deformable bodies and algorithms for their collision detection and collision response. We have created a model of the object as a set of points connected by springs of given elasticity factor *k*. The model uses spring forces and damping to give elasticity to the objects. Object collisions are determined using our collision detection engine. After collision occurs the response is calculated using physics laws.

Model of a Single Object

Overview

The objects we are working with are elastic and deformable bodies. They change their shape under the influence of outside forces and then return to their original shapes. Considering gravity as an external force, in the real world situation, even in a state of rest, for example sitting on a table, this type of object will have a slight deformation of shape and due to it the springs will not be in equilibrium. This can be used to model objects made out of rubber, jell, metal or other similar substances.

These objects behave according to a set of rules commonly used in physics models. They maintain constant velocity and shape if no external forces are applied (Newton's First Law). Without deformation the object has six degrees of freedom (three for translation and three for rotation). If an external force is applied to some part of the object it deforms to find a state of rest where its internal energy is balanced by its external forces. If the influence of the force stops, the object returns to its previous shape, after any vibrations have dampened. We will assume that objects are non-breakable, do not change their elasticity over time, and do not deform permanently.

Prior Work

Over the past two decades, people in academia and industry have been working on simulating physically realistic elastic objects. Different models have been developed over time. Most of them use some kind of elasticity rule combined with different constraints Terzopoulos and Witkin presented the Hybrid model [4], where an object has a reference component, which represent shape and displacement components. These components represent a deformation from the initial shape. In later research other models and ideas were introduced, including the concept of local and global deformations [5]; using extra layer coatings [8]; using elastic grids with additional constraints. Recently, adaptive models for elastic and deformable bodies were developed; some of them use mass-spring system similar to the one we used for our project [6]. Compared to these models, our model is quite simple; however it includes all the main factors needed to animate and provide interaction between elastic and deformable bodies.

Description

For our models an object is represented as a mesh of polygons, namely triangles. The edges of the triangles possess the physical qualities of springs. Vertices have properties of rigid bodies that are connected by springs. Vertices have only three degrees of freedom – they can move in space but cannot rotate. If a distance between two adjacent vertices shortens, the spring which connects them forces them to move farther from each other and vice versa.

The principal idea behind our model is that each point behaves as an independent body, or *particle*, and only spring forces of its direct neighbors affect velocity and acceleration of this point. In our model we do not maintain information about linear and angular acceleration or the velocity of the object, and instead we only store the accelerations and velocities of each particle.

Physics Involved

As mentioned earlier, the main forces that move and deform the objects are the internal spring forces of is edges. The force applied on each vertex is calculated by the spring equation [1]:

$$F = \sum_{i=0}^{n} - k\Delta x$$

Where *k* is elasticity constant of the object and *Δx* is the displacement of the length of the edge, and *n* is number of direct neighbors of the vertex. Although we work in 3D, this force is calculated as projection on 1D space of each edge.

While working with springs the problem of damping arises. In a real world, springs do not oscillate forever because of the loss of internal energy. In graphics and mechanics the loss can be simulated by applying a damping on the spring. There are several ways to do damping: viscous damping, linear damping, or Rayleigh's damping [1]. For this project we have chosen the viscous damping. After including damping the formula for the force applied to each vertex changes to the following:

$$F = \sum_{i=o}^{n} - k\Delta x - cv$$

Where c is a damping constant and v is the velocity of a vertex.

The displacement of each vertex is calculated using Newton's Laws and basic formulas for the motion of the body [2]:

$$x = x_0 + vt + \frac{at^2}{2}$$

$$v = v_0 + at$$

$$a = \frac{F}{m}$$

To achieve the best performance, some assumptions should be made about the object. As each vertex of an object is assumed to have the same mass, the distances between adjacent vertices should be approximately equal to each other. So even if it is not needed for the appearance, the mesh of the object should be equally distributed over the object's surface, otherwise a more sophisticated algorithm is needed to compute mass of each vertex so that mass of the body is uniform.

Algorithms and Other Issues

After deriving the formulas for the vertex forces there are two problems that need to be solved: creating a data structure for the object and applying linear algebra for projection of 3D space to 2D.

The data structure of the model includes a set of vertices with velocities and accelerations for each vertex. Each vertex also holds a list of its direct neighbors as well as the initial (rest) distances to each of them. So in order to update the position of a vertex, we calculate the force applied (using the difference between the current and initial distances between the vertex and each neighbor), then update acceleration and velocity, and finally compute the displacement from previous position. There is also set of faces (triangles) and edges stored for each object and are used later for the collision detection and rendering.

The principal advantage of our model is that natural behavior of the elastic object can be achieved using a number of easily computed algebraic physics equations of degree at most two. The object mesh is easy to create using standard 3D graphics tool, for example 3D Studio Max

[13]. Note that our model does not necessarily preserve the volume of the body. If this is desired, additional constrains must be added. Also the elasticity constant depends on the complexity of the object and has to be calculated for each different object. One of the disadvantages of our model is that creating objects with no elasticity (rigid bodies) results in strong oscillation which damping cannot handle. For this reason, non-elastic objects are handled by a different method.

Mechanics behind Object Interaction

Overview

Given the object model presented in the previous section, the next building block to consider is how to combine them into a single world. One of the factors involved in this is updating movements between objects, namely applying the appropriate forces to each object and updating their coordinates over some time step. Following any type of non-predetermined movement, some sort of *collision detection* algorithm is run between all appropriate pairs of objects. If any contact is detected, all of the information regarding the collision must be extracted and the appropriate *collision response* mechanism is applied.

Typically in complex rendering programs or games, the objects in space would be contained in some type of data structure, such as an octree or kd-tree as proposed by Samet [11]. Such an implementation can provide several performance gains, including rendering of objects and limiting the pairs of objects to which the collision test must be applied. In the rendering process these data structures can help to determine whether an object needs to be drawn on the screen. For example the partitioning nature of these structures organizes spatial information such as objects in such a way that they can determine when other objects are very close to it or when one is occluded behind another. These properties help when trying to decide what objects need to be drawn or need to have complex operations applied to them such namely collision detection. Inaccuracies in the collision detection can arise when the time step between screen updates is large enough that the physical forces would place them on opposite sides of each other. To compensate for this scenario the objects typically require being sufficiently scaled in size or a smaller time step has to be used in the collision detection process.

Prior Work

There are many methods that have been proposed for collision detection. Generally all objects have some sort of boundary or more commonly a radius in which they are contained within, and whenever another object comes sufficiently near, a series of calculations are performed to see if there was an actual collision. When dealing with convex objects, this method works well because the object can be simplified to a sphere or ellipse and your chances of finding a collision are higher in an early time step. With concave objects there is a chance that the object could be very complex and a collision might not be found until several time steps later. To get around this problem this idea has been taken to another level with the use of hierarchal collision detection [12]. As the name suggests, there are layers of boundaries or radii that have to be penetrated before a collision is detected. In the case of concave objects this works well because, after the primary radius has been penetrated, the collision detection is done against the next set of radii and so forth, as necessary. This works well when the nature of the object is sparse or has convex substructures, because it increases the accuracy of the collision detection while reducing the need for computationally expensive algorithms.

When it is determined that the collision boundary has been penetrated, it is required to be known exactly if there was a collision and where. There are various algorithms that can calculate this but the overall method used by most of them is to compare all the faces or edges of one object and see if any of them lie within the boundaries of the other object. While simple in concept, most techniques require several floating-point calculations to check against many edges and points of every polygon in one object to the other. Typically there is a check to see if either point of any edge in one object penetrates any polygon in the other object. This procedure is run twice, reversing the roles of edges and polygons between the two objects. If this does not reveal an intersection, all the individual faces and edges are checked to see if they are coplanar and/or coincident. When naively implemented, this technique will still work but can be very expensive if the object consists of a large number of edges. In this instance some type of selection against the object is done in order to select a minimal set of edges and polygons to check against. For example, if the relative centers of two objects can be determined and the two points used as a vector and treated as the normal of a plane, then it suffices to test only points that lie on one side of that plane. In the situation where the objects are represented by polynomial equations, it is common to check if the surfaces defined by these equations intersect using any of several techniques based on integral calculus.

After it has been determined that a collision has occurred, we need to know where the collision has occurred and make an appropriate response to the point of intersection. In this stage, the need for accuracy in the location of the collision is the driving factor for what collision information should collected. In one case we can attempt to calculate the actual point of collision and try to isolate all the elements involved, such as the direction of the collision and the force being applied at that point. At the time of collision, if it is determined that the two objects have penetrated each other, somewhere between the previous time step and the current step there was a point in time when the collision first occurs. So in order to find the instance of collision, the collision data is recalculated using a time step that is a half of the current time step and the previous. This process is repeated until there is collision without penetration or until some threshold is met. While this solution provides accuracy in the collision data, it is computationally expensive to repeat several calculations, which can produce redundant information between iterations. What can happen instead is that all the information about the collision can be collected and then approximate what the real collision information data should be.

Algorithms Used

In our implementation we maintain a collection of objects, and then at arbitrary time intervals we update their positions in space, check for collisions and respond appropriately to them and repeat this process as necessary [10]. For the collision detection step, we used a variation of a ray to triangle intersection algorithm. For any two objects that we find to be within each other's collision boundary, we iterate over the edges of one object and check for any intersection with any of the planes of the triangles that make up the other object. If the edge has been found to be crossing or touching the plane, the point of intersection with the plane is then calculated. If that point is contained within the triangle on that plane then we have detected a collision. As we continue to iterate over the rest of the edges, we mark all the edges and points of one object that were found to have intersected the other object. Then with this set of edges, we run a depth-first search against the graph of the object's polygonal mesh to collect all the points that are contained within the other object. Once this set is complete, we apply our collision response system with the appropriate physics, as described in the previous section.

Implementation Details

In order to illustrate the models and algorithms we created and used, we developed an application that takes text file of meshes and their initial velocities as input and animates the behavior of these objects. This application was developed using C++ under the Microsoft Visual C++ .NET Compiler and the Standard C, OpenGL, STL libraries and the Win32 API. The program structure is intended to be cross platform compatible so there are areas where things such as the timing mechanism is abstracted away into its own object.

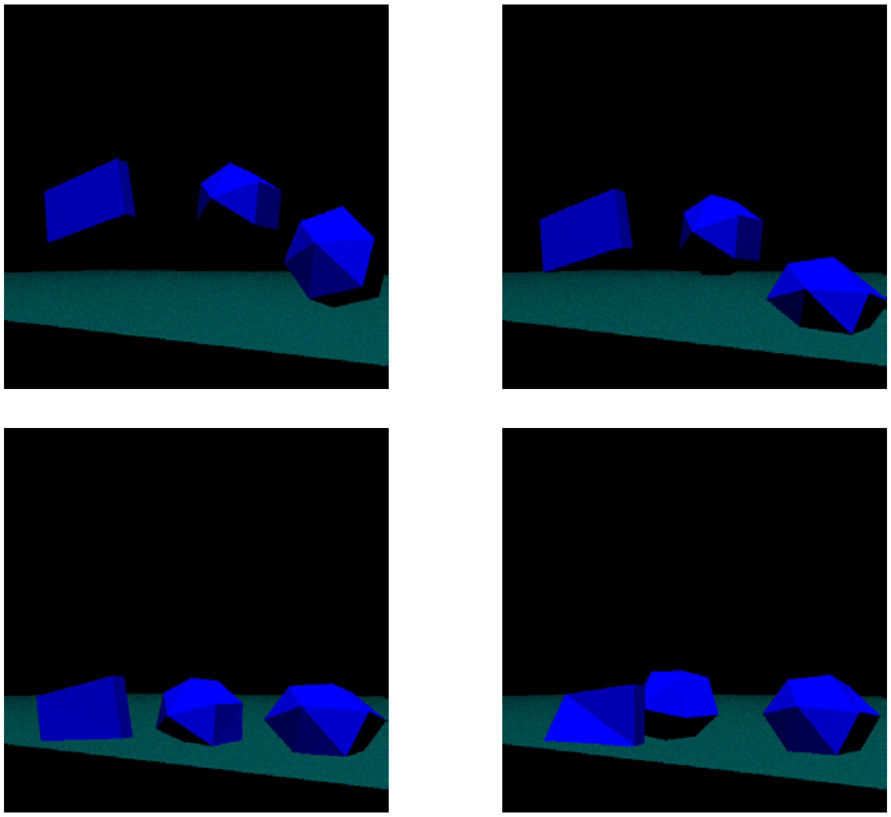
You can download the source code here.

The most general class in our program is *World*, which contains list of objects displayed on the screen (*EObject*). Each object has list of faces (*Triangle*), edges (*Edge*), and points (*GLPoint*). The principal functional elements of the program, including collision detection, collision response, and each point location update can be found in the source file EObject.cpp. In the main loop for our program, after all models have been loaded into memory and initialized, we iterate over our collection of objects calling an update on their movements using the time span between the last iteration and the current as the time step. After the updates, we check all appropriate objects for collisions against each other. If a collision is found, we apply the appropriate collision response mechanism for that collision.

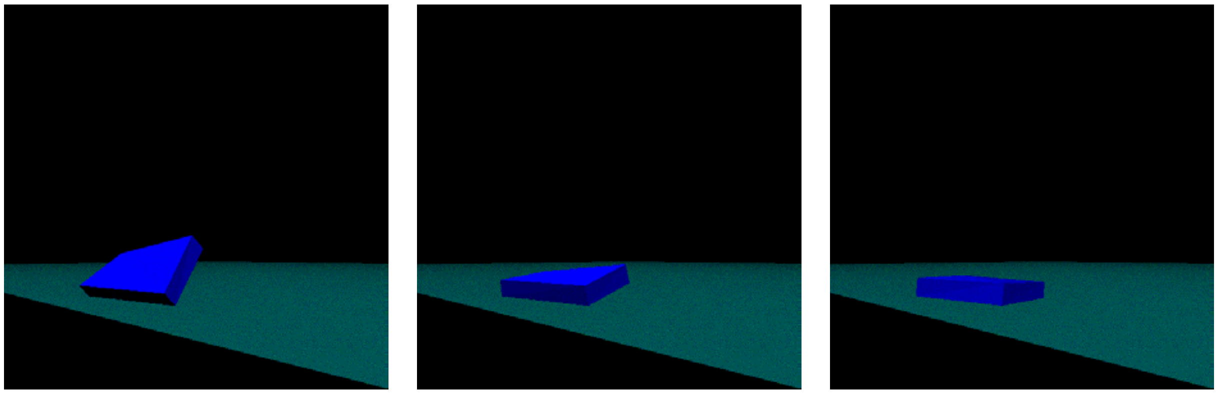
In Windows, the standard timing library did not allow for precision in timing beyond seconds so we had to use the WIN32 API to achieve greater precision. Our program uses a single thread for execution. Rather than using the timestamps from the system clock which would include time allocated to other programs by the processor, we used the timestamp for the lifetime of the thread.

Conclusions

In the project we presented a 3D engine for the animation of non-rigid bodies. We were able to achieve natural behavior of elastic bodies and their collisions. Here is set of screen shots which were taken from the engine:



Animation of multiple objects falling on the ground and interaction with each other.



A box falling on the ground and flipping over

Possible Future Work

There are several ways to extend this project. The first is to improve current engine. This might include adding global constraints such as preserving object volume; optimizing the collision detection algorithm by creating more sophisticated bounding boxes for each object, improving the algorithm for spring damping. The other possible direction is to use a similar system to create other types of flexible objects, for example cloth [9] or hair. As longer term work, it might be possible to extend our approach to create a model for much more general classes of substances. That would require adding more physically realistic elements into the model, creating uniform mesh over all the volume of the object, and finding specific constraints to satisfy properties of different types of the materials.

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