Realistic Simulation of Environmental Phenomena – Snow Fall and Accumulation

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ABSTRACT
One particular case of the intersection between the photorealistic presentation and the dynamics of 3D scene of objects is snow in nature, which presents behavioral aspects of the environment such as accumulation, particle movement, and redistribution, with the added time element that allows change and progress analysis. Due to the complexity of the phenomenon, little to no attention has been given to the realism of the interaction, the attention being channeled only on the visual aspects of it. The focus of this paper is to analyze different approaches of representing snow fall and accumulation effects in real time in such a digital ensemble in order to add a layer of realism and accurately reflect natural processes. The emphasis is put on the actual manifestations that take place in nature and the micro physics that pertain to the processes. Comparisons are made between different existing approaches to snow accumulation and a new particle hierarchy is imposed to suit both the technological requirements and to maintain the realism of scenes.

Author Keywords
Photorealistic Presentation; Environmental Phenomena; Snowing Phenomenon; Snow Fall; Snow Accumulation.

ACM Classification Keywords
H.5.2 User Interfaces, I.3.7 Three-Dimensional Graphics and Realism, I.6.8 Types of Simulation.

INTRODUCTION

Virtual environments are digitally generated mediums that represent settings which contain 3D visualization support. Their use is wide spread in today's applications, bringing diversity in domains such as games, physics simulation software, tourism applications. Their intended purpose is to depict the world as we perceive it, and, as such contains 3 critical dimensions: visual, temporal and behavioral.

The visual dimension is generally achieved from detailed models representing entities, complex textures and application positions, and, of course, the most crucial aspects for realism in visualization, lights and shadows. While the visual aspect has been thoroughly dissected throughout the years, minimal consideration has been given to the plane created by the relation between behavior and time.

One particular case of the intersection between the last two dimensions is snow in nature: it presents behavioral aspects of the environment (accumulation, particle movement, redistribution) with the added time element that allows change and progress analysis. Due to the complexity of the phenomenon, little to no attention has been given to the realism of the interaction, the attention being channeled only on the visual aspects of it.

The focus of this paper is to analyze different approaches of representing snow fall and accumulation effects in real time in such a digital ensemble in order to accurately reflect natural processes. The emphasis is put on the actual manifestations that take place in nature and the micro physics that pertain to the processes. Comparisons are made between different existing approaches to snow accumulation and a new particle hierarchy is imposed to suit both the technological requirements and to maintain the realism of scenes. The micro physics element is completely new to the scene and provides a needed layer of realism to better emulate the real world.

The paper is structured as follows. The Related Works section presents an overview of the sources of the research foundations for this study and a comparison to the current approaches. The next section presents the theoretical analysis, complete explanations of choices, algorithms and mathematical models used to develop the solution and the main contributions. The testing and evaluation section presents metrics and the final experimental results. Finally, the paper concludes on the main contributions, and future research directions.

RELATED WORKS

This section is a quick overview of the research in the related domains such as computer graphics and interactive systems, 3D environmental practices, project management and elaboration, microphysics, snow fall in real time and accumulation techniques. It is meant as a discussion covering the major inspirations on which the premise of the project has been centered.

In nature, snow accumulation on a surface implies a great deal of factors. Snow usually reaches surfaces that are directly visible from an aerial view. This is not universally true however, given the disturbances in motion created by wind currents of different intensities. That is why, snow can actually reach surfaces that are hidden or partially covered by other objects. The difficulty arises, not only in the motion, but also in the way the particles are laid out and the manner in which they interact once they reach the ground/a snow patch. Having relatively small masses, ice crystals are not as stable as ice would be, but not as volatile as any liquid. Such a conglomeration of micro particles presents varying behaviors depending on the current state of the surroundings.

Snow collection on surfaces is the predominant theme of discussion in natural phenomenon modelling for virtual worlds. It is complex in the sense that it depends on a great number of factors and that is has a great impact on the speed of any application.

Willmore and Fermeglia present in [1] all the relevant aspects of wind influence and snowflake motion, accumulation of snow corresponding to the amount fallen as indicated by the snowflake weight, and finally, redistribution of snow.

Wind influence in [1] is modelled by a force or impulse that is applied to the snowflake which gains a velocity according to its weight in the direction specified by the wind. The main observation here is that there is no concern for altitude in this approach causing a diminished behavioral realism. Wind can be present at one altitude and be completely changed in direction or intensity or even absent at another. This not only gives liveliness to the scene but also allows modelling of actual current behaviors and snow distribution accordingly.

Snowflake motion depends on the wind and mass [1]. The approach was the fact that the mass of a snowflake was a predefined value, whereas in nature, mass is directly influenced by pressure, supersaturation with respect to water of the air and creation time from the vapor stage. Modelling these factors has the effect of making an environment that can be easily customized and that can support variation of any kind.

Visually, [1] states that a 3D representation is the best method to portray individual snowflakes. This is indeed true, but due to the fact that having 3D objects involves visibility calculations for each polygon and that typical particle systems contain thousands of such models, another technique was chosen. Partly inspired by the simplicity of particle system [2], the approach is to have a plane consisting of four vertices with a texture representing a cross section of a snowflake. This plane is always oriented according to the camera view direction, and, as such, the GPU is less strained than in the case of full 3D objects rendering. The disadvantages described in [2] apply here as well: unfortunately there is no influence of the medium reflected on the snowflake: the lighting, no shadows portrayed and the colors are not altered under any circumstances. Such a compromise was found small in comparison to the great benefit of speed.

The paper also proposes individual collisions per particle. This means that in a bigger system each snowflake will check for collisions with each other object. While this presents many disadvantages in regards to speed and can produce a bottleneck in large test scenes with millions of particles, the approach is not fundamentally flawed. An adaptation of it has been made in order to reduce collision numbers but maintain an even higher number of particles. As such, quanta entities are introduced that contain exactly what their names hint at: a quanta or measure of snowflakes. It is a point in space having tied to a particle system that acts as a single individual when it comes to colliding with other objects. While the actual collision with the fallen snow surface may not be as smooth as in Willmore and Fermeglia’s case, the particle numbers increase dramatically.

The height at each point in [1] is determined by the density of the snow. Again, the problem of mass arises, the approach developed considering, other than density, the volume of snow by being directly influenced by the size and weight of ice crystals.

Redistribution of snow has been modelled as closely possible to the approach presented in [1]. Although more intuitive than practical, the model proposes a threshold that has to be respected by the Laplacian of each point. While the modelled snow surfaces are not the same in representation (height maps as images versus adjacency list of mesh vertices in 3D models), the same principle can be easily applied. The drawback of this is that that threshold has absolutely no connection to the actual parametric representation of the climate.

The aspects presented encapsulate the main features analyzed and adapted from [1], while the next big influence in the accumulation approach is taken from Festenberg’s famous research paper [3], detailing a diffusive manner to snow cover creation. Concepts introduced by Festenberg have a high level of detail: the snow is presented in the most realistic manner, treating cases such as snow bridges, different approaches to texturing per location in patch, accumulation on surfaces that are not visible from the top view approach, snowflake dusting and flutter. While these techniques present a great naturalness to the digital medium, they utilize slow algorithms that use a lot of memory and cannot be used in vast stages. The scenes are all static, and presented as snapshots rather than interactive media. That is why, for the purpose of real time simulations, the proposed representation algorithms could not be used.

This experiment does however focus mostly on the behavioral realism, so a technique from [3] was adapted in our research, and that is snow distribution according to the diffusive coefficient. Festenberg explains the fact that there was a need to replace snow recursive redistribution for stability measures and depth buffer displacement techniques. This statement is what drove the project in the search for the optimal solution.

Paper [3] proposes that the snow profile change its steepness according to the quality of the snow: whether snowflakes accumulate water between ice crystals or have a higher ice to water ratio. As such, this aspect ties in very well with the proposed climate modelling scheme, where the entire purpose is to actually see the impact the temperature and water levels have on the resulting scenery. The explanations regarding the efficiency of this method in contrast to the recursive accumulation have not been expanded upon.

Snow falls in form of snowflakes: a collection of ice crystals formed through aggregation or condensation The difficult part is not modelling how snowflakes fall or positioning them, but actually simulating exactly how they come to be as they are, how they gain their mass and shape. The studies presented in [4], entitled „Cloud Microphysics", not only explain the exact implications of cloud types, atmospheric density, and altitude, but also present different growth patterns in snowflakes and shape modifications according to each formation process.

The most important benefit of [4] is the understanding of how an ice crystal is affected by the temperature and water saturation. It also presents calculation methods in order to determine mass and radius for ice crystals, general snowflake densities and a broad overview of the actual ice crystal fusion into a large – snowflake – structure.

SNOW NATURAL PHENOMENON

Snowing Phases

Snow behavior as a natural phenomenon contains three major phases: (1) creation or snowflake composition process according to the atmospherically conditions/ parameters; (2) fall or particle motion; and (3) accumulation or distribution of snow on surfaces in relation to external forces. These are the constituents of the research and the main results that should take part in completing all milestones for the entire system. There are the following requirements regarding each phase of the snowing phenomenon.

Snow Creation

The system has to create and render snowflakes in each particle system of size and weight corresponding to the atmospheric conditions at the time of its creation.

Snow Fall and Motion

The system has to begin the simulation and correspondingly the fluid motion of the snowflakes in the 3D environment without interruptions or visible stuttering. Moreover the motion of the snowflake is influenced by the wind currents defined by the user, the gravitational force, and the mass of the snowflakes.

Snow Accumulation

The system has to animate the entire process of snow surface growth in real time at a speed perceivable by the human eye, the volume of fallen snow on a surface has to be equal to the volume of deposited snow, and the accumulation shape is in accordance to the atmospherically conditions.

Parameters of Snow Phenomenon

Particle System Model

The snowflakes particles are defined by the following parameters, as in [5]:

- *Temperature* expressed in degrees Celsius at the location and moment of snowflake creation;
- *Density* or number of units of snowflakes per particle system size;
- *Formation Time* or the time taken in seconds to develop ice crystals from the vapor stage;
- *Position* or initial location of the entire particle system expressed in centimeters and relative to the scene origin point.

Wind Model

The following parameters describe the wind model:

- *Direction* expressed as a unit vector that aims to portray the general movement of the wind current;
- *Speed* expressed in meters per second that defines the intensity of the wind current;
- *Minimum Altitude* expressed in meters, portrays the minimal height relative to the ground at which the wind current stops affecting objects;
- *Maximum Altitude* expressed in meters, portrays the maximal height relative to the ground at which the wind current stops affecting objects.

Accumulation Phenomenon

The snow redistribution over the upper surface of 3D objects is described by the concept of *Laplacian Threshold*.

External forces

There are two main driving forces for such a system:

- *Gravity* in physics can be defined as the attraction between all material objects. The most visible manifestation of it can be viewed between items in the scene and the earth [6].
- *Wind* is an air transition described by speed and direction. Wind is an impulse that is applied on a force in a specific direction with a degree of intensity to it [7]. The idea when using wind, given the fact that the system already has an attached mass to it, was to apply a force on an object for every frame that it is in the wind altitude range.

Critical Situations

Different environmental states produce dissimilar particles, collisions have an impact on the future locations of snowflakes and wind can alter the expected location for any entity. These are just a few of the circumstances that have to be considered while approaching such a theme. They are critical not because they represent an exception, but because they encompass the most common occurrences that are also the most difficult to portray.

In order to depict the behavioral aspects of this specific environment, a number of situations have been foreseen and treated. These are the main cases to be evaluated in order to convey a complete image of a dynamic winter landscape:

- Particle differentiation according to parameters;
- Collision detection between appropriate object types;
- Particle system decomposition and regrouping at collision;
- Modification of snow surfaces at collision;
- Appropriate redistribution of snow surfaces after collision and certain conditions are met;
- Trajectory change of particle systems when external forces are applied;
- Accumulation beneath obstacles;
- Atmospheric changes according to wind influences.

These will be further expanded later on, but it is important to take note of them for now.

SYSTEM COMPONENTS AND CONCEPTUAL MODELS

Objects in 3D Virtual Environment

In order to populate the scene of objects to portray a realistic medium for snow to fall in, modelling and use of polygonal meshes has been employed. Meshes are structures that represent 3 dimensional objects containing the information necessary to accurately depict real world entities: vertices, faces and edges, [**Error! Reference source not found.**]. Each object in the created scene has been built from primitive shapes (cones, cubes and spheres) welded together, while others (the particles for example) are simply planes.

Snowflake Considerations

A snowflake begins as a collection of water molecules that freeze into ice crystals if a particle of matter is present in the cloud atmosphere and later aggregate together to form a larger entity. That is why, when modelling the process of their creation the following phases have been considered: (a) Vapor phase; (b) Individual crystal phase; and (c) Aggregated phase.

In the vapor phase, the most relevant aspects in order to determine the supersaturation with respect to water are the temperature and pressure of the cloud location. These factors later influence how „wet” the snow is, and as a result, the final section shape of the accumulation on surfaces. Supersaturation influences mass, shape and radius as well. The growth in mass over time influence the way snowflakes interact with the medium: how they are affected by the gravitational force, the speed of their fall, the way they respond to external influences such as wind.

Snowflakes Quanta

The entire collection of snowflakes is contained inside a volume, which in these particular research cases is a cube. The center point of the „quanta” represents the ‚parent’ node for each and every instance in the particle system: once the parent node translates, or rotates, so do each of the snowflakes. Although not as dynamical, it permits the system to manipulate a greater number of particles because of the way collisions are handled.

Decomposition of Quanta

Snowy scenes typically contain obstacles under which snow cannot be accumulated. This is caused by the fact that the objects block the path of the snowflake, which can no longer reach its corresponding ground location. The experiments consider four cases of relationships between quanta and the obstacle (Figure 1).

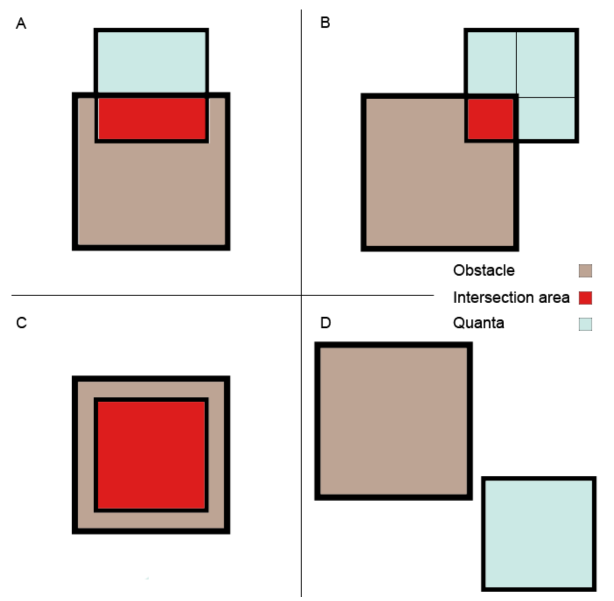

Figure 1. Cases of relationship between quanta and obstacles: A - quanta is separated into two parts, B - quanta is decomposed into four parts, C - quanta completely included on the obstacle surface, D - no interactions occur.

Snowflake and Quanta Formation

While the shapes of the ice crystals differ, their inherent volume can be constrained by a cylinder. The mass of a snow crystal can be computed from density and volume of the crystal. The computation of the mass takes also in consideration the vapor phase, the time factor [4]. The quanta are formed by spawning a set of particles at random positions enclosed in the volume attached to it (i.e. cube).

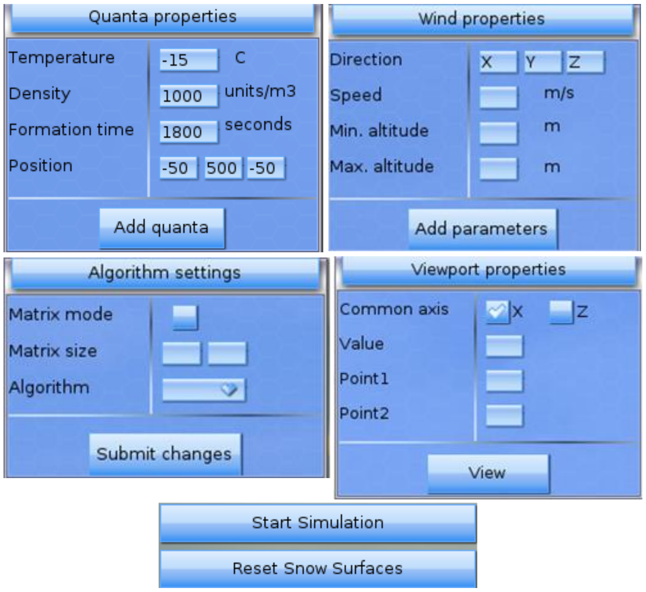

Figure 2. Application user interfaces for editing sessions for Quanta properties, Wind properties, Algorithm settings, Viewport properties, and Control options.

The volume is determined by getting the bounding box center, width and height and extracting the limits in world coordinates by mathematically deducing the half extents. The spawn positions are completely random inside the boundaries and do not conform to any rules. The snowflakes can spawn one on top of the other, as it actually happens in nature in case of the aggregation formation process.

Snow Accumulation

Snow accumulation is the most complex process of the entire system. It should accurately portray the growth of a surface according to the quantity of snow fallen. There are four primary steps in which the process can be decomposed: collision detection, mapping, growth calculations and animation.

Shaping the snow surface is done through either of two methods (according to user choice of algorithm): diffusive or recursive accumulation.

Diffusive accumulation takes all the points included on the mapped surface, one at a time. The diffusion coefficient is linked directly to the supersaturating of air with respect to water. It computes the corresponding vertex's Laplacian by calculating the mean value of all the adjacent vertices. The diffusion coefficient is multiplied by the computed mean value of vertices related to distance.

Recursive accumulation, while not directly linked to the climate, proposes a way to redistribute the snow surface in order to prevent surface spikiness and resemble the phenomenon. Due to the fact that it has no actual scientific

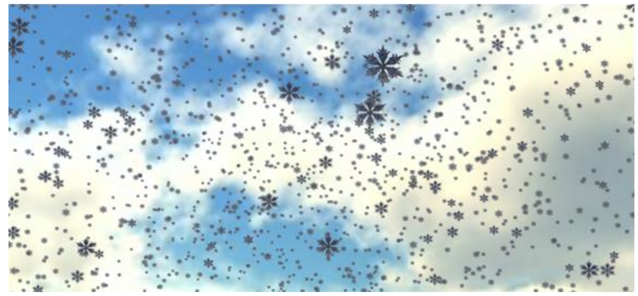

Figure 3. Particle system with varying levels of details.

basis, most of its underlying fundamental values can be tweaked by the user in order to study different effects.

EXPERIMENTAL EVALUATION

The experiments have used the following software configuration: the code has been developed in C++ under Windows 7 operating system, Ogre3D SDK 1.9 for graphics modeling and visualization [9] and [10], Bullet Physics 2.82 as physics engine [11], and MyGUI 3.2 for graphical user interface development.

Parameter Setting

There are a few parameters by which the user controls the experiments (Figure 2). They address the definition of quanta and wind, setting of the algorithms, definition of the viewport, and the options for controlling the snow simulation.

Snowflakes Visualization

Figure 3 presents the particle system with various levels of details for the snowflakes.

Visualization Modes

There are three visualization modes: (a) wireframe; (b) textures and colors, no lights but polygonal mesh; and (c) photorealism with lights and shadows.

The first of three visualization modes for the scene is the wireframe mode. While it does not portray lights, shadows, textures or any kind of colors it helps to better observe the vertices and the edges of the snow surface in order to properly study the accumulation behavior.

The second visualization viewed retains the textures and colors but disables lighting and maintains the vertices and edges on display. This has been the visualization mode that has been used for the majority of the development phase, because, contrary to the wireframe mode, it does not display hidden lines and points so it displays fewer details while retaining the useful information where the user can observe them.

The last mode and the most visually appealing is the realistic approach that has lighting and shadows enabled. Though not as relevant when checking for behavioral

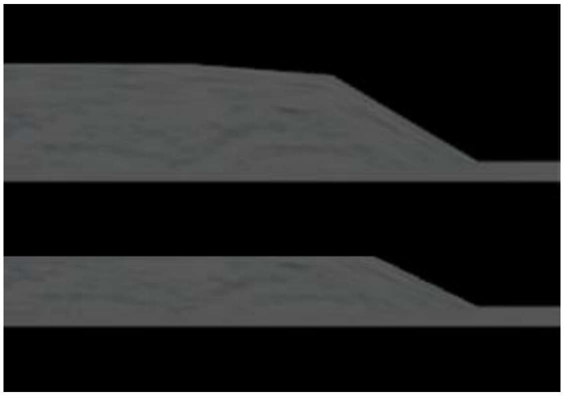

Figure 4. Snow accumulation at -15 degrees Celsius (top) and -5 degrees Celsius (bottom).

correctness, it does help to construct a parallel to the real world.

Temperature Impact

The next experiment focuses on the difference brought about by temperature. Figure 4 shows a comparison of the materialization of the theoretical concept, where 8 quantas have fallen in the same surface area. Because of the fact that the temperature of -15 degrees gives the highest super-saturation, it has the biggest snowflakes, so, in theory it should give a bigger growth while the slope should be a bit leaner because of the fact that snowflakes have more water between ice crystals. The other chosen value for temperature is -5 degrees Celsius, a choice that should result in rougher edges since the snow is ‚drier' and less volume to it because of the smaller snowflakes.

Diffuse Versus Recursive Algorithms

For the next experiment the long awaited comparison of the two snow accumulation algorithms has been sought out. The climate conditions are at -5 degrees with a formation time of half an hour. Each of the following scenes has 8 quantas deposited, with the recursive algorithm setting a threshold of 20 centimeters.

Figure 5. Snow accumulation by the diffuse (top) and recursive (bottom) algorithms.

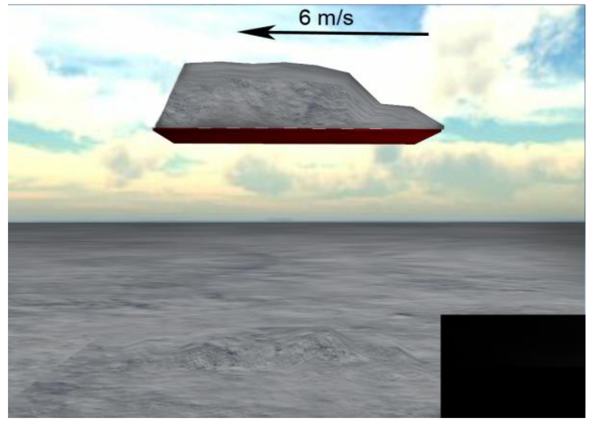

Figure 6. Windy snow accumulation of 8 quantas.

Though the recursive method does not depend on the water content of the snowflakes and chooses to portray the scene with less physics background information, it is quite obvious that it looks a lot more natural than the roughness of the diffusive method. The threshold is also quite an important factor of the recursive algorithm, but has no actual corresponding microphysics formula, so the results can greatly vary from one choice of a value to another.

Windy Snow Accumulation under Obstacle

The experiments consider the windy snow falling and accumulation under obstacles.

There are 8 quantas with a density of 1000 snowflakes, formation time is half an hour, at the temperature of -15 degrees Celsius, and the wind speed is 6 m/s toward direction specified in the Figure 6. The upper piece of snow represents just the snow accumulated and blown by the wind to the left.

Figure 7 shows the initial position of a group of quantas relative to the obstacle. The obstacle is located at 3 m above the terrain, and the wind is limited between 0.5 and 2.5 m relative to the ground.

Figure 8 presents the snow accumulation after all 8 quantas arrive on to the soil.

CONCLUSIONS

Contributions

Most of the concepts discussed in this paper have been used before in many other works. This is not the first time vertex morphing is employed or the discovery of the combination between a graphics and a rendering engine is made. The novelty of it all is the method in which they were all integrated together with the added novelties brought by the new quanta concept, decomposition technique idea and micro physics calculations. To have an application that can

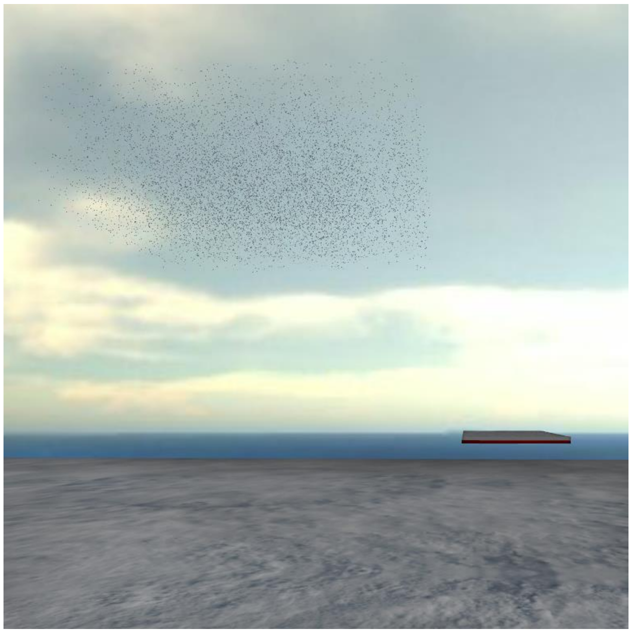

Figure 7. Initial position of a group of quantas relative to the right side obstacle.

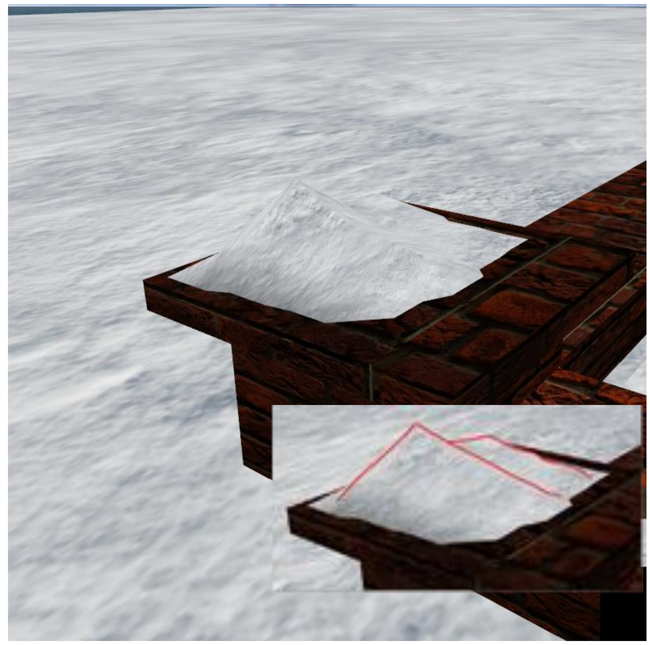

Figure 8. Result of snow accumulation after all 8 quantas arrive on to the soil.

help study the downsides or benefits of a certain implementation can speed up the process of deciding upon a case that yields fast results and can be applied universally.

The quanta decomposition method was not inspired by any algorithm, so it can be said that even though primitive, it is one of this paper's completely original contribution. A combination of methods that pertain to both statically accumulation and real time snow rendering for winter sceneries have been employed in order to test their likeliness to reality.

Another major contribution brought about was the inclusion of concepts found in microphysics to the process of forming appropriate sizes and weights for snowflakes. This not only helps keeping the climate under strict rules (e.g. temperatures of -1 degrees cannot produce snowflakes of great sizes), but also adds the benefit of practicality that can be applied to programs that model real world simulations in fields like architecture or civil engineering.

Critical Analysis of Results

Most of the objectives described at the beginning of the research work have been achieved. For the first part, there is no jitter or waiting time for particle system creation. The process runs fast independently of the actual parameters provided. Once the simulation has started, addition of particle systems does not cause any kind of problem or program interruption. All particle system properties are modelled exactly in the way that the user has specified and the difference between results can be observed as easily as visually analyzing the scene. The mass and radius for each snowflake is calculated through specialized formulas taken from scientific literature, so that particular objective is met throughout. Whenever the user starts the simulation all quanta's begin to move and their motion is constant over time. Due to the utilization of a physics engine, this motion environment (i.e. gravitation, wind) so it is as accurately portrayed as the implementation of the software integrated has allowed. Another purpose is fulfilled through the last statement, the one considering the motion in accordance to the wind parameters that are defined by the user. The movement of the particle system is heavily reliant on the properties of each snowflake, defining an added dimension of realism.

The predominant problem of the current state of the application is that no definition has been found yet for the programmed in margin, so while it is a great thing that it isn't hardcoded, the user has no actual basis on which to select this value. Furthermore, the threshold does not have any real world correspondence. The problem brought about by the diffusive method is that it does not yield realistic looking results in a dynamic environment (as can be seen in the figures from the testing chapter) and continues to accumulate on the same patch if the snow falls only on that portion. Also, the obstacle shapes have to be rather primitive in order for the decomposition to work. Because of the fact that the entire concept works on the presumption that the shape is encompassed by its bounding box, the method would not give realistic results for any shape that contains curved surfaces. The accumulation in concave shapes has to be developed as well.

Further Developments

From an implementation point of view the most important aspect would be to change from a bounding box approach to a rigid body check for quanta decomposition. While the technique would be altered a bit, the significant aspects of the algorithm would still remain.

Another development would be to include vertical accumulation, as can be seen on house walls in snowstorms or when the intensity and inclination of snow fall is greater than usual. This implies modelling the adherence to surfaces, and going into much more detail on the less insisted upon snow surface properties. So far, the quanta is the only one that has been fully parameterized. The actual melting factor has not been taken into account as well, and would be a great addition. Even though the difference between wet/dry snow and different temperatures is made, after creation there is no further impact of the atmospheric factors on the surface of the snow. This new feature would also help transition between snow and water and make it possible to increase the temperature range already available to house the creation of rain droplets and water flow.

There are two ways in which this application can be further developed from a strict usability point of view. Initially the idea of the study came about when planning for the development of a 3D application directed at the tourism field which aimed to portray Cluj-Napoca in the Middle Ages. Somewhere in the midst of development, the idea to actually alter the state of the city and be able to visualize it throughout the seasons surfaced, and with it, a dilemma arose. The fact that there was no way to realistically portray the scenery during winter was what drove the project to take shape. This project is the first path mentioned that the thesis can be integrated in.

A future expansion would consists of a complex scene , on the scale of representing a historical city center with details such as arcs or sculptures included, with the polished version of the algorithms implemented such that people can take advantage of technology in order to marvel at the lost times of the middle ages (e.g. visualization of Cluj-Napoca downtown).

The second research idea was to create an application that uses the developed algorithms in order to calculate structure resistance. Given the fact that the physics engine already supports mass and joints, all structures could be portrayed through the light of their respective materials. This could result in an interesting approach to modelling and designing constructions such as buildings or heavier formations. The experts would not have to calculate all the possible factors that come into play, but rather simply provide a set of parameters and see how the scene responds to them. It would test the points that are the most susceptible to fissures and tears and make sure that all buildings are solid and can withstand harsher environmental conditions. Again, the idea of melting the snow would be extremely helpful in this context, since it would deal with the problem of design that permits leakages to occur.

These are just a few of the directions that come to mind, both from an implementation and project purpose point of view. Due to the vastness of the virtual environments domain and its many uses in applications, many other uses could be found for the project at hand.

ACKNOWLEDGMENTS

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