An Interactive and Multi-sensory Learning Environment for Nano Education

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Abstract. Swift scientific advances in the area of nanoscience suggest that nanotechnology will play an increasingly important role in our everyday lives. Thus, knowledge of the principles underlying such technologies will inevitably be required to ensure a skilled industrial workforce. In this paper we describe the development of a virtual educational environment that allows for various direct interactive experiences and communication of nanophenomena to pupils and citizens, ranging from desktops to immersive and multi-sensory platforms. At the heart of the architecture is a nanoparticle simulator, which simulates effects such as short-range interaction, flexing of nanotubes and collisions with the solvent. The environment allows the user to interact with the particles to examine their behaviour related to fundamental science concepts.

Keywords: Learning Environment, Nanoscience concepts, Interaction, Multi-sensory, Haptics, Audio.

1 Introduction

Rapid scientific progress in nanoscience suggests that nanotechnology will play an increasingly prominent role in our everyday lives, so learning about phenomena at the nanoscale is becoming increasingly important[1]. Thus, knowledge of the principles underlying nanotechnologies will be required to be harnessed if we are to ensure a skilled industrial workforce. In addition, an awareness of 'nano' is critical for the public to make informed democratic decisions concerning the perceived benefits and risks associated with nanotechnology, as society adapts to the emerging nanorevolution. Research-based educational interventions for exposing learners to nano concepts are urgently required to meet these needs.

This paper describes the development of a virtual educational environment that allows pupils and citizens to directly experience different interactive nanophenomena, ranging from desktops to immersive and multi-sensory hardware platforms. The system includes a simulation of nanoparticles that runs at an interactive rate. Through computational steering, the simulation is connected to direct manipulation by the user allowing for instantaneous feedback about the behaviour and reaction to user input. The simulator includes interaction between nanoparticles as well as intermolecular interaction between nanoparticles and solvent molecules.

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There are three main contributions of this paper. Firstly, a description of an immersive, multi-sensory learning environment with inherent flexibility and portability between capabilities on different hardware platforms. This aims to provide support for different educational situations, ranging from classroom studies to public exhibitions. Secondly, we present approaches and methods for simulating nanoparticle behaviour at interactive rates. Thirdly, we provide links between the interactive environment and intended learning outcomes.

2 Nanoscience and Educational Perspectives

Nanoscience concerns structures that have at least one dimension in the range of 1–100 nm. At this level of scale, objects manifest radically different physical properties from the macroscopic scale of everyday life[9]. Examples of such contrasts are the inherent *stickiness* of molecules due to attractive intermolecular forces, the drastically reduced influence of gravity in comparison with other forces, and the constant random motion of nano-objects in solution.

2.1 Framing the Problem

The differences noted above are not intuitive for learners, and educational research suggests that pupils have difficulties in attempting to make transitions between different levels of scale, and in particular, grasp the specific scale at which nanophenomena occur[4]. A further obstacle for learning is that the nanoscale is inaccessible to our immediate senses. In addition, a lack of knowledge concerning the basis of nanotechnology has also been observed amongst the public[1].

Visualizations are often necessary for communicating the abstract and non-perceptual nanoscale ideas. Immersive multimodal systems have shown great potential as learning tools for nanotechnology concepts[4]. The notion that learning is connected to our bodily experiences[11] could be exploited by an immersive virtual representations of nanophenomena. Such a system could stimulate learners to integrate embodied knowledge in their construction of a scientific understanding concerning principles that govern the behavior of matter at the nanoscopic scale.

Recent work on learning in virtual environments in a nano-context has focused on letting users interact with simulations of advanced equipment such as atomic force microscopy[5,6]. However, apart from a few examples (e.g. [8]), there are not many available virtual learning environments that actually allow students to interact with representations of nanoscale objects.

For some concepts, we deem that the interactive, multimodal experience of nanoparticle behaviour is essential. However, for other concepts a subset of features may suffice. To facilitate an optimal balance between features and affordability for each purpose, the learning environment is designed to include a set of capabilities that include nanoparticle simulation, 3D computer graphics, interaction and sound, and a high level of portability between different hardware platforms. The interactive capabilities will then be enabled by the platform on which the system is executed. By supporting portability between different hardware platforms, we make it possible to choose between a variety of capabilities.

2.2 Educational Aspects

Key aspects in constructing the understanding necessary for an accurate assessment of both toxicicty and potential benefits of nanotechnology resides in considering the influence of inter-molecular forces, inter-molecular collisions, Brownian motion, as well as adhesion between nanoparticles into aggregates that may lead to sedimentation as gravity becomes the dominating force. To expose the learner to an environment that communicates these aspects, we define two contrasting scenarios: nano-tube aggregation which may be associated with potential toxicity, and nano-particle specificity and increased surface area which may have therapeutic applications. A learners' solving of these scenarios underlies being able to judge and make decisions about the hopes and fears that the nano-revolution brings with it.

At least four actors play a role in the design and implementation of the virtual environment as a platform for user interaction and learning, namely *scientific understanding*, *task scenarios*, *actual user interaction* and *interaction design theory*. Conceptualising the structural and interactive dimension of the multi-sensory virtual learning environment requires the simultaneous integration of each of these four components (figure 1).

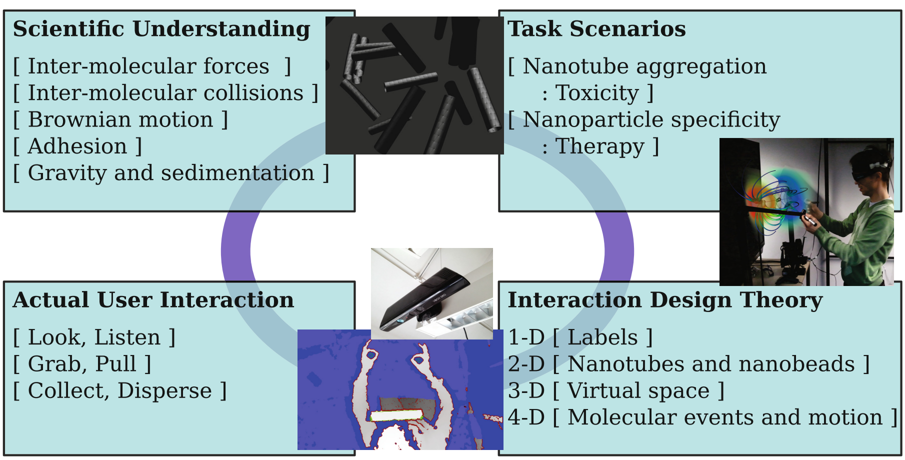


Fig. 1. Overview of four components underpinning the design and implementation of the multi-sensory nano-technology learning environment

3 Architecture and Core Capabilities

There are two aspects of the learning environment that place hard constraints on the design of the system: it must be flexible in that its core capabilities can be activated and deactivated depending on the hardware platform on which it is run, and all components must be updated at interactive rates. Therefore, multi-threading and modularity were two important design principles.

The learning environment is implemented in H3D API[3], which is a system for implementing multimodal applications with graphics, sound and haptics. The system runs at least two concurrent and asynchronous threads: one controlling the 3D environment, playing sound and displaying graphics, and the other running the nanoparticle simulator. The heart of the system and the most important core capability is the nano simulator displayed in a 3D environment, which is described in detail in section 4.

Other core capabilities are described below. Each defined capability may spawn a separate asynchronous thread that provides its specific functionality to the overall system.

3.1 Immersive 3D Technology

To enable an immersive experience for the learner, our system implements head tracking to calibrate and adjust user's view relative to the position of her/his eyes. This capability can be used together with a 3D TV to present computationally rendered objects in front of the user.

We have previously connected tracking with commercial equipment to H3D API and made the developed package publicly available as open source (H3D Candy/HVR). For the final system to be affordable for schools and other learning contexts, we have also implemented a Kinect-based head tracker for H3D API. This tracker uses the depth image from a downward facing Kinect mounted in the ceiling. The depth data from the Kinect are extracted using the Freenect library[2] that runs in a separate thread.

Some systems only use position tracking to view frustum configuration. However, to get a good immersive view, head orientation data are also required both to correctly direct the eye separation and to obtain the correct offset from tracked position to eye position. To enable high fidelity tracking of head position and orientation from the low quality Kinect data, the following techniques are applied: 3D glasses required for most 3D TVs are equipped with a rectangle geometry. The depth data is then used first to identify the rectangle and to subsequently determine its orientation which can be used as an estimation of the head pose, see figure 2.

3.2 Hand Detection and Interaction

An important feature of interactive learning environments is user action and subsequent system reaction that facilitates the understanding of complex behaviour. In our system, we allow the *grabbing* and *pulling* of nanoparticles so that the user can, for example, see how the particles adhere to each other with different intermolecular force strengths depending on surface area and shape.

We provide the opportunity to reach into the virtual environment by simply using the previously implemented tracking bridge for commercial tracking technology mentioned above, or the haptic hardware support readily available in H3D API. We have also implemented grabbing gestures together with the Kinect-based head tracking.

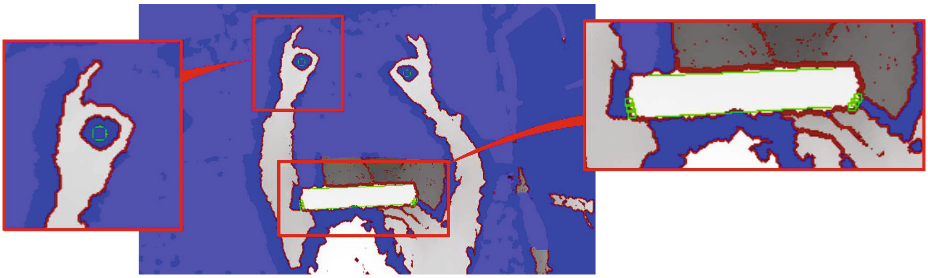


Fig. 2. The processed Kinect depth image showing simple hand gestures that represent a *grab* (green circles) and the rectangle geometry mounted to the 3D glasses, that provides both position and orientation information about the user's head (green lines)

Using techniques similar to those of [10] we detect a simple grasping gesture where thumb and index finger meet to form a circle, see figure 2. We anticipate that this gesture is simple and intuitive enough for use without much training, and at the same time,it is easy to robustly detect even with low quality data.

3.3 Haptic Technology

An important aspect of our learning environment is its multi-sensory feedback. When haptic technology is available on the hardware platform at hand, the device will be used as input for interaction and to provide force feedback from the simulation. The feedback directly reflects the force interactions between the grabbed particle and the surrounding environment in both inter-particle effects and the interactions with the solvent that give rise to the Brownian motion. Apart from seeing the behavioural response of the particle to the outer disturbance represented by the user action, by also feeling the strength and dynamics of the interacting force, the user will have a much better foundation from which to understand the relationship between the involved effects.

3.4 Audio Technology

Audio feedback is supported by the H3D API and when the underlying platform supports it, real 3D sound using generic Head-Related Transfer Functions (HRTF) will be applied to also give a sense of sound direction. The sound is generated by adding positional sound sources at positions and through parameters determined by the interaction points processed by the nanoparticle simulator.

The audio feedback can be activated to strengthen the sense of interactions provided between particles in the simulation. The sound feedback reflects interaction energy and interaction force. The *interaction energy* is zero when the particles are far apart and at a maximum at the optimal interaction distance. The *interaction force* is zero both when the particles are far apart and when they are at rest at the optimal interaction distance. Thus, the will reflect the restlessness of clusters emitting the sound.

4 Nanoparticle Simulator

The central core technology of the system is the nanoparticle simulator, an engine that simulates the time- and space-scaled behaviour of particles at the nanoscale. There are four main effects that the simulation enacts:

- motion of nanoparticles,
- flexing of nanotubes,
- short-range interactions between particles, and
- interaction with the solvent

4.1 Motion and Dynamics of Nanoparticles

Nanoparticle behaviour can be simulated using a rigid-body approach. However, due to the laws of physics at this scale, special collision and near-collision handling is required. The Open Dynamics Engine (ODE) is a powerful open source system for rigid-body simulation that allows for custom callbacks for collision detection and handling. This makes it possible to adapt to the required physics.

Rigid-body simulators distinguish the *body*, which is the dynamics representation of a particle, from its *shape*, which is its geometrical representation. In the ODE, one body can be assigned many shapes that can reside in different *spaces*. Three different shapes, in three different spaces, are used for each of the particle's bodies. These are explained further in sections 4.3 and 4.4.

The current implementation includes two particle types: nanobeads and nanotubes. The system defines nanobeads using simple spherical shapes, whereas nanotubes are defined by a chain of *capsules* consisting of cylinders with spherical caps. In this simulation we connect the nanotube segments into a chain using what are referred to as *universal joints*. This joint allows bending, but not twisting of the tube.

4.2 Flexing of Nanotubes

Nanotubes do not exhibit free flexing but are rather stiff. We chose to implement this effect by adding a rotational stiffness to all nanotube joints that adds a torque to the joint when its angle deviates for zero. This torque is controlled through a stiffness that is adjusted to allow the flexing behaviour to approximate the rigidity of real nanotubes.

4.3 Short-Range Inter-particle Interaction

We use a truncated Lennard-Jones (LJ) potential, a simple model that approximates the interaction between atoms or molecules, to estimate the inter-particle interactions. The cut-off distance, r_c , is typically set at $r = 2.5\sigma$, where σ can be considered the "size" of the particle. At this distance, the error resulting from the truncation is negligible.

The ODE is used to locate particles that are within the cut-off distance and thus are subject to the force resulting from the LJ potential. To do so, an *LJ cut-off shape* is assigned to each particle body, and set at 2.5 times larger than the size of the particle. The ODE uses space partitioning to speed up the search for these shapes, and subsequently triggers a callback for each intersecting pair of particles, or pair of segments in the case of nanotubes.

To reduce the risk of instability when the particles are in close proximity where the derivative of the LJ potential becomes large, we add a hard constraint so that if two particles come into close proximity, they will collide using the ODE's rigid-body surface collision handling. For this, a *hard LJ shape* is assigned to each particle body, set at the van der Waal surface of the particle. The ODE is then used to search for and apply rigid-body collisions between these shapes.

4.4 Solvent Interaction

Particles suspended in a solvent are constantly colliding with the surrounding solvent molecules. As a result of imbalances between collisions from different directions, the particles will move in a random pattern, known as Brownian motion. Consequently, three important effects must be exhibited by the simulation: 1) the particles must be transported through the solvent in a manner similar or identical to Brownian motion, 2) momentum only increases in a direction if the particle's current momentum in that direction is lower than the momentum of particles in the solvent, and 3) there must be an absense of collisions with solvent molecules in-between adjacent particles that are so close that no solvent molecules between the particles.

It would require a very large amount of processing power to interactively simulate the solvent as particles. Instead, we use a Monte-Carlo approach and simulate discrete collisions at random positions in space. Instead of solvent molecules, we use a single randomized ray, and instead of the particle's surface, we use a larger shape corresponding to the combined size of the particle and the solvent molecule. Although this approach provides us with the same effect, ray–shape intersection is much quicker to estimate than shape–shape intersection.

ODE is used to test the randomized ray against these *solvent collision shapes*. If positive, the ray's relative momentum is transferred to the particle upon collision. Each collision is applied over time to simulate the soft pushing of the solvent molecules.

4.5 Performance

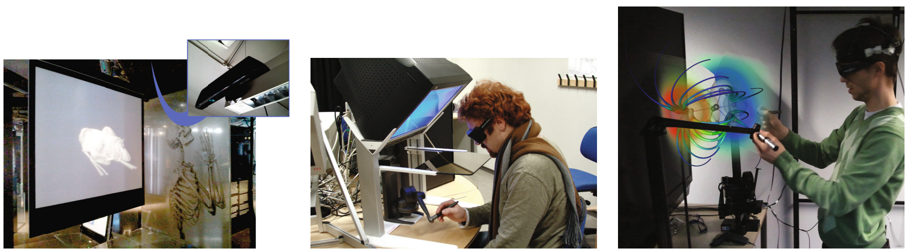
The current performance of the simulator is limited by ODE, which at this point, exhibits serial processing and cannot take advantage of the multi-core technologies. The simulation step used is 10 ms simulation step, so all the physical simulation needs to be performed within this time. To balance the computational requirements against power we adjust the number of rays used to simulate the solvent while maintaining the total amount of momentum.

On our current Intel Core 2 Duo E8500 platform, the simulation uses approximately 7000 rays for ten tubes of five segments each. Alternatively, it uses approximately 9000 rays for 20 beads.

5 Hardware Platforms

The system is designed for high portability and the selection of hardware platforms depending on the learning situation and target concepts. For example, a school scenario might adopt desktop computers for introductory principles and switch to more advanced hardware only for an advanced course on the topic.

We are currently investigating four different hardware platforms, three of which are shown in figure 3. The current focus is on the workbench environment.



(a) The Workbench (b) The Haptic Workstation (c) The Haptic Workbench

Fig. 3. Three of the target hardware platforms

The desktop environment (not shown) provides 2D graphics and a 2D input device without haptic feedback. This platform will allow for an entry level nano experience. The sound feedback can be rendered in 3D.

The workbench environment uses head tracking in combination with a stereo enabled display to provide an immersive sense of 3D. Our current implementation aims to provide a highly affordable immersive experience, using Kinect for tracking in conjunction with a commercial 3D TV. The interaction with the nanoparticles is colocated with the graphics representations, while the head tracking allows for accurate 3D sound directions.

The haptic workstation environment is a semi-immersive, 3D and haptics enabled version of the desktop environment, see figure 3(b). A stereo enabled screen displays 3D graphics through a mirror providing colocation with a haptic device and interaction. Although 3D sound is less effective in this platform, the haptic feedback provides the sense of intermolecular force dynamics when pulling nanotubes apart.

The haptic workbench environment is a workbench environment equipped with haptic device(s) for force feedback from the interaction with the nanoparticles, see figure 3(c). Here, we have colocated interaction, the haptic sense of forces as well as accurate 3D sound.

6 User Interaction and Learning

Describing the developed virtual environment by applying Crampton Smith's four "dimensions" [7] provides grounded points of departure for implementing the interaction design (see figure 1). With respect to 1-D, our design will use textual labels to denote the types of virtual objects displayed (e.g. "carbon nanotube") as well as textual descriptors of the task scenarios (e.g. "pull the carbon nanotubes apart"). Visual representation of the virtual objects (e.g. nanotubes and nanoparticles) will constitute the 2-D component. Representation of the volume wherein events such as nanotube aggregation in the form of the virtual space afforded to the user will establish the 3-D aspect of the interaction design. Application of the 4-D is manifested by simulating events such as intermolecular adhesion and collisions between nanotubes, in combination with auditory cues to depict aspects such as nanotube *stickiness*.

As exemplified in figure 1, interaction with the virtual environment will take the form of users' multi-sensory experience of performing two tasks related to the benefits and risks of nanotechnology. Performing the tasks requires behavioural and gestural interactions with the system such as looking, listening, grabbing and pulling virtual objects. The direct manipulation interface affords the construction of scientific understanding such as intermolecular forces and Brownian motion. The offered interactive multi-sensory experience might provide the conceptual basis for reasoning around the potential toxic and therapeutic implications of nano-materials.

7 Conclusions

The development of the described system is part of an ongoing project focussed on studying visual and interactive systems for nano education. For this purpose, we have developed a system with several important core capabilities: immersive 3D computer graphics with interactive simulation of nanoparticle behaviour, which is strengthened by audio and haptic feedback when available. This system takes advantage of modern multi-core processors by using asynchronous threads for CPU intensive processing, thereby allowing interactive update rates. It is also designed to run on several different platforms, which enables the utilization of different capabilities depending on the learning situation.

8 Future Work

In commencement of the user data collection phase, the system will be installed in a public arena where people of all ages will be able to explore the principles of nanotechnology. It is in this initial context that we plan to conduct the initial studies on the current qualities of the system and assess further needs by measuring variables such as patterns of user interaction, and any potential changes in the users' attitudes towards nanotechnology, as well as measuring the conceptual understanding related to nanophenomena.

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