3-D Immersive Screen Experiments

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Abstract

We are currently piloting a range of computer simulated science experiments as 3-D virtual environments. These are rendered on a PC in 3-D and use photographs of specific parts of the actual apparatus as textures to add realism to the simulation. In particular, photographs are used to represent the consequential views of an experiment. These particular views may also be animated depending on the state of the experiment. The work combines the photographic approach of the Interactive Screen Experiments (ISEs) with the advantages of a fully simulated 3-D environment where the user can interact with the apparatus in a more natural and intuitive way. The potential advantages are that users can quickly adapt to the environment and in particular the controls. They gain realistic views of the physicality of the experiment as they are not just seeing it from a particular viewpoint, but from wherever they see fit to place themselves within the experiment's scene. They are immersed in the experiment in a way that mitigates some of the objections to online as opposed to real laboratory experimentation. Furthermore there is no need to represent scales, read-outs or controls as separate parts of the interface; these can all be rendered at their correct physical positions within the experiment. The first of these experiments based on the use of a diffraction grating has been fully implemented and has been evaluated with a Physics A' level class. The application and its evaluation will be presented. A more complicated experiment using a spectrometer has also been modelled which raises issues of complexity. These issues will also be discussed.

Introduction

2-D simulations are used extensively in Physics. From simple animations to complex simulations, we can find simulations of a simple pendulum or an atomic reaction. However, there are situations when 2-D is not enough and to gain a true insight into how something behaves we need 3-D. This is the case for the programs described below. The Celestial E-Sphere [8] was developed to help students understand celestial coordinates and various aspects of the motion of celestial bodies, and it is impossible to see how this could have ever worked as anything but a 3-D program.

The Meade Simulator [6] is used to help students studying the Open University course, Observing the Universe [3], gain familiarity with controlling a telescope. It simulates the night sky, a computer controlled telescope and its hand controller. It is the 3-D that gives this program the look and feel of the actual telescope and enables the students to come to terms with how to control it, enabling them to advance much more quickly when faced with the real thing.

The 3-D Immersive Screen Experiments are a natural progression from these. Having implemented these 3-D programs and then faced with the 2-D Interactive Screen Experiments it was at once obvious that the many difficulties that were inherent in the 2-D approach could be entirely avoided by rendering these experiments in their own 3-D virtual world.

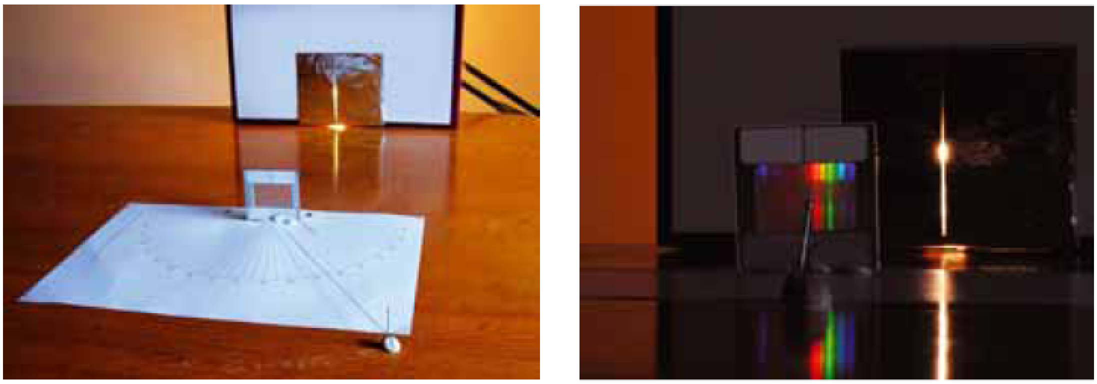
Styles of interactive experiment

Interactive Screen Experiments (ISE) [2,5] are the most common form of experiment that students can interact with on a personal computer. These use photographs to give 2-D views of the actual apparatus in use during an actual experiment. They are basically interactive movies and as such give a comforting feeling of reality. However, due to the combinatorial explosion of the necessary photographs there often needs to be compromises made in the degrees of freedom that the user can access. Despite this there have been many very successful implementations and the OU and other institutions are actively engaged in producing these.

3-D Immersive Screen Experiments still use photographs of a real experiment but these are reserved for consequential views such as a spectrum, rather than the mundane views, such as the back of a voltmeter. The apparatus of the experiment is reproduced as 3-D models. These models are animated to simulate their real-life behaviour. The user's eye is implemented as a software camera that can be positioned anywhere within the scene in exactly the same way that most computer games are programmed, indeed a games language is used as it provides many useful facilities such as collision detection. Clearly this approach is much more complicated to program than the 2-D ISE, in fact the modelling of the apparatus needs engineering accuracy so that all parts work properly together. This is where there is a large departure from the games approach, which mostly attempts to fool the user into believing that the operation of a device has realistic or even exaggerated behaviour, although there are an increasing number of games, particularly of the racing type, that strive to emulate the actual underlying physics.

Degrees of freedom

To demonstrate some of the challenges of reproducing an experiment on-screen, a concrete example of a simple experiment is used. Figure 1 shows the set-up for a diffraction grating experiment as used on the OU course, level one course, Exploring Science [4]. This experiment can be constructed by the student on a dining table and used to obtain the angles of various coloured light diffracted by the grating seen here mounted into a 35mm slide. A bedside or office light illuminates the inside of a shoebox. A slit in the shoebox allows light to reach the diffraction grating that then diffracts the different colours of the light into various directions. A paper protractor is used to measure angles. A pin and length of cotton is a sighting device that the user looks along when determining the direction of a particular colour. The angle of diffraction can then be read from the protractor by examining the pin's position. The diffraction pattern consists of a bright white central region with rainbow coloured regions on either side that repeat themselves several times. The white pattern in the centre is called the zero order and each rainbow of colours is called an order and they are counted outwards with the left and right ones next to the centre being the first order, the next pair moving outwards is the second order and so on.



(a)

Figure 1 The diffraction grating experiment

If this were to be faithfully reproduced by a set of photographs we would need to deal with all the possible configurations. For the sake of performing an experiment we will only consider those that directly bear on the experimental results that are to be obtained. For example, in reality it is always possible when performing an experiment to stand on our heads, but if this has no bearing on the useful visualisation of the experiment, the degree of freedom that allows us to perform such a manoeuvre will be excluded. One might imagine an experiment in which standing on one's head was useful. It is just a question of choosing those degrees of freedom that are of use for the experiment being considered. In reality and ignoring pointless degrees of motion there are three degrees of freedom for the user's eye, up/down, left/right, in/out. There is one degree of freedom in the shoebox that can move to the left or right to centre the zero order diffraction pattern so that its position reads zero on the paper protractor. Finally, the pin can be moved along the edge of the protractor adding one more degree of freedom. If we were to allow one hundred photographs for each degree of freedom we would need 10 billion photographs to represent the entire experiment in all its possible configurations. Note that the required number is the product of the number required for each degree of freedom. This perhaps is why we sometimes say '*the whole is more than the sum of its parts'* as in a very real sense the whole is the product of the parts. We can simplify this by not allowing the eye to move forward or backwards or up and down. A further simplification would be to have the experiment already calibrated.   So we are left with just the eye and pin moving in a plane. This would need 10,000 photographs and in practice this proves too many and the ISE that was actually produced combines the pin movement with the eye movement [5] See figure 2 where the image of the slide is superimposed onto an aerial photograph of the experiment's current configuration.

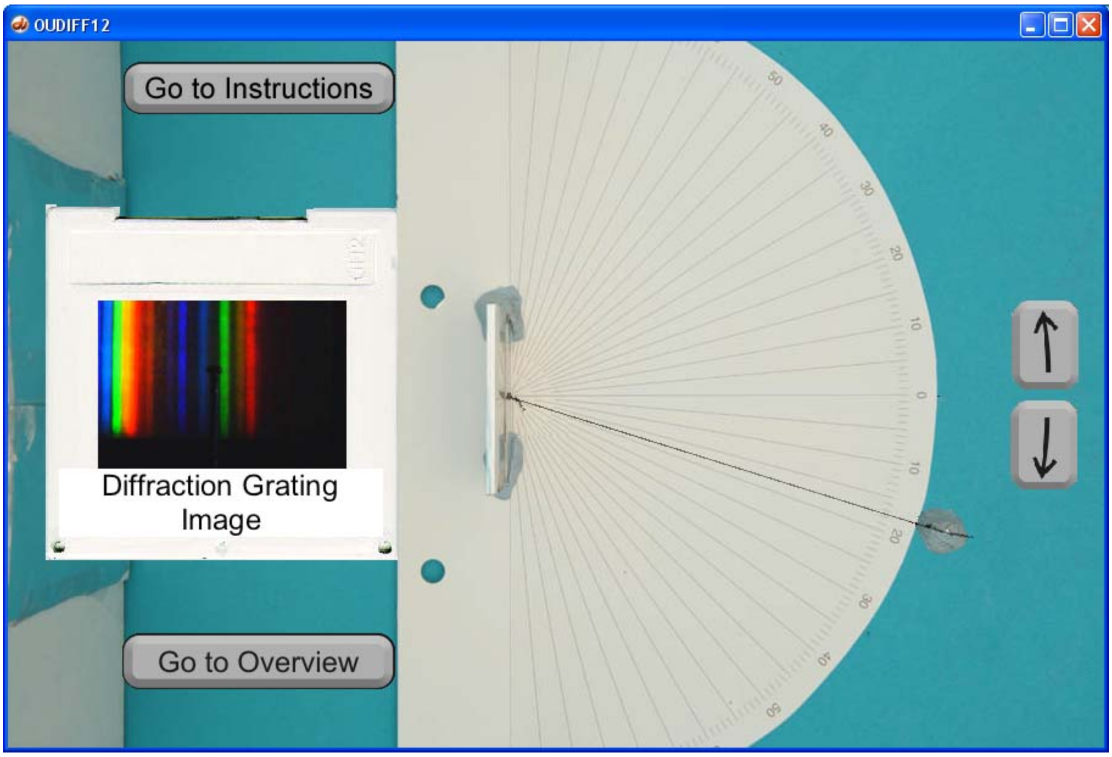


Figure 2 The diffraction grating ISE

This is perhaps one compromise too far, as we now have the diffraction pattern changing as the pin is moved which is emphatically not the case. The diffraction pattern seen depends only on where the eye or camera is. This is an example of how the combinatorial explosion at the heart of the ISE forces such compromises often with unfortunate effect. Some might say, and I have heard exactly this, that it is obvious that the viewpoint is along a line through the pin to the slide. The person saying this taught Physics at university level, so doubtless it was obvious to him. However, such assumptions should never be made of a student who potentially comes to this experiment with no expectations of its behaviour at all. Additionally, there is nothing intuitive about how the image on the diffraction grating appears to move as the viewpoint changes, if anything it is counter intuitive upon first viewing.

In practice the purely photographic approach of the ISE restricts us to reproducing just one degree of freedom at a time. Bronner [2]) states 'Obviously, it is not feasible to include all degrees of freedom in a single ISE', I suggest that this is an understatement and rarely more that one degree of freedom is seen in an ISE. Reproducing the experiment as a 3-D simulated environment allows us to keep all useful degrees of freedom but at the expense of a much more complicated simulation.

Figure 3 shows the same diffraction experiment rendered as a 3-D graphics simulation. Here the user can move his eye (the software camera) in all three directions. It is possible to move behind the shoebox and see what kind of light bulb is being used (the experiment is commonly performed with an ordinary tungsten filament and an energy saving bulb which produce quite different spectra). Note that there is no way of knowing what bulb is being used in the ISE other than reading the notes *which are not part of the* *simulation*. The pin can be moved independently and the shoebox can be moved left and right to perform the calibration. The final point is significant because the position of the zero order is one of the plotted points on a graph used to calculate the frequency of the various colours of light. And it is the accuracy of this point that needs to be taken account of when plotting a best-fit line. That there is an issue of accuracy concerning this point is very hard to appreciate if it is assumed that the apparatus has been set up with no possibility of moving this position.

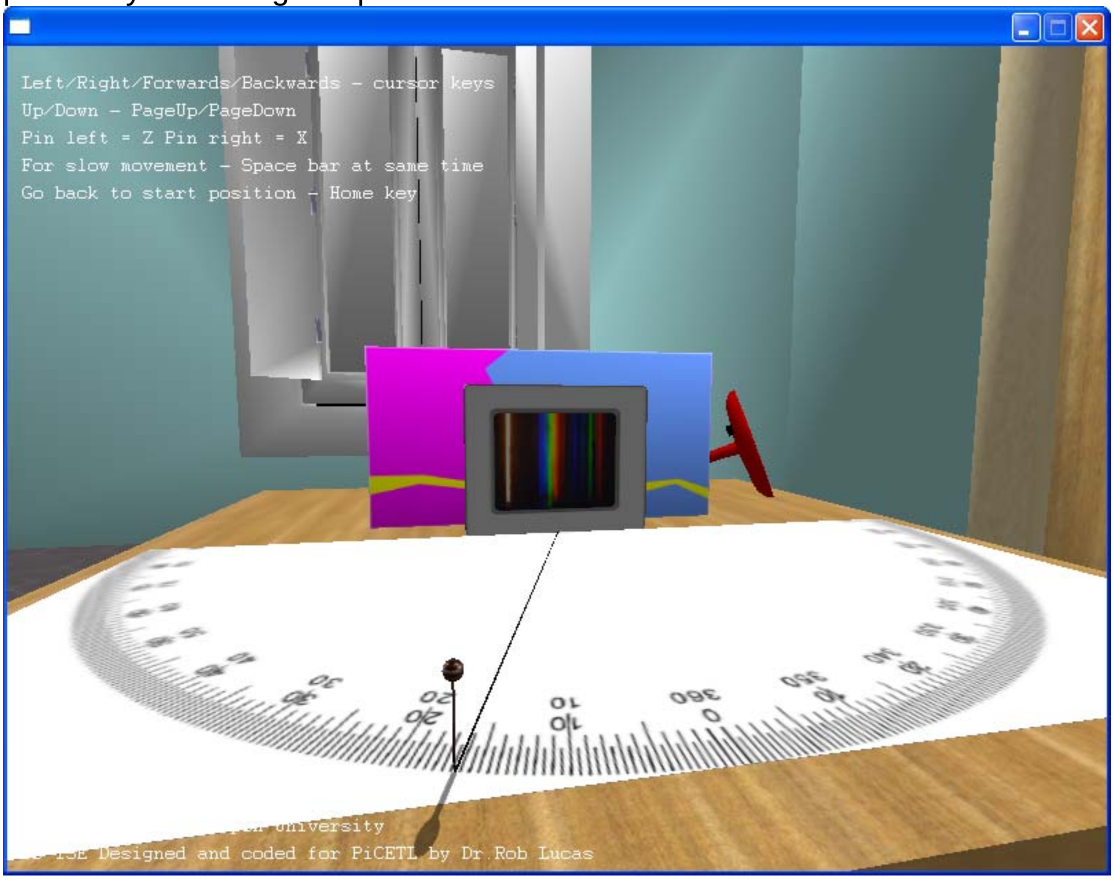


Figure 3 The diffraction grating 3D Immersive Screen Experiment

This ‘1-degree of freedom at a time’ often leads to a ‘flattening out’ of the experiment into a linear set of objectives where one degree of freedom is used to achieve the first goal and once achieved the experiment moves on the achieving a second goal using another degree of freedom now completely divorced from the first. Physics experiments are not like this, they are overwhelmingly built from many interacting facets. Figure 4 shows a spectrometer.

Figure 4 A commercially available spectrometer

The tube with the square appendage is the collimator used to produce a narrow beam of light. The other tube is a telescope with a reticle eyepiece used to accurately align on whatever image is produced by what is placed on the central platform. Commonly a prism or diffraction grating is placed on the table and the telescope is moved on the central vertical axis to view the spectrum. Essentially the spectrometer can be used to perform a very accurate version of the shoebox-and-protractor diffraction experiment described above. Performing the experiment with a spectrometer, however, means that the user must know how to use this piece of apparatus and be able to control it.

Before measurements can be made with the spectrometer it is important to focus the telescope on a distant object. In reality we point the telescope out of a window in the laboratory and focus on a distant tree or building.

The ISE of the spectrometer experiment requires that the user focus the telescope before being allowed to continue with the measurements. Once focused, the telescope is always focused. It is no longer possible to un-focus it. In reality it is the quality of the focus obtained by the student that has a direct bearing on the results he obtains. Part of the knowledge acquired by the student is how to deal with this parameter, the quality of the focus. He learns that a deal of care in performing the focus pays off in the result he gets. He may not learn this the first time he uses a spectrometer, but it is all part of the experience that he gains in a real laboratory. The ISE will always give him the results of a perfectly focused telescope, hence the user will have no experience of trying to garner readings from a less than perfectly focused instrument and is unlikely to learn either the significance of the focusing or the consequences of it. The user is simply being made to jump through a hoop to achieve the necessary focus to proceed.

Figure 5 shows the spectrometer experiment rendered as a 3-D graphics program. Here the telescope is being focused on a distant pylon visible through the window of the laboratory.

Figure 5 The Spectrometer 3D Immersive Screen Experiment

The user is able to move his eye/camera in all directions. The various parts of the spectrometer are moved by either dragging with the mouse, or using keys. The various knobs, such as the focus knob, can be turned by placing the mouse over them and then using the mouse wheel. This gives a very intuitive feeling for the focusing in particular and note that whatever focus is achieved is carried over into the experiment itself. If the telescope is poorly focused the user will find it difficult to obtain accurate readings as in the real experiment.

Another compromise that we find with the purely photographic ISE approach is that the view presented of the experiment will not necessarily yield a usable view of the scale that is being used for data collection. In the case of the spectrometer [5] it is necessary to represent the vernier that is used for measuring the angle of the telescope by a different window. This is an artifice that does not shed light on the workings of the spectrometer but obscures them. The student will almost certainly know how a vernier works but seeing it in its rightful place and being able to see its readings change when the telescope is moved gives the student a much better opportunity to understand it within the context of the experiment. Figure 6 shows how the vernier of the 3-D Immersive Screen Experiment is read by simply moving the eye/camera up to it.

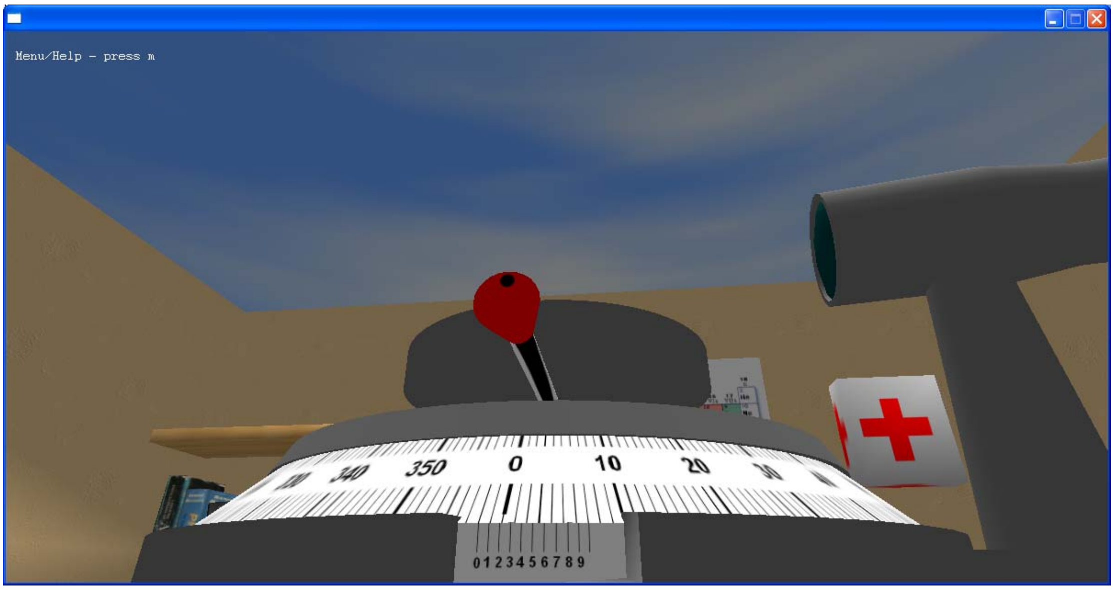


Figure 6 Reading the vernier scale

Implementation

The models used in the shoebox diffraction grating experiment were extremely easy to implement. However the spectroscope demanded some complex programming and modelling.

The spectroscope must be modelled as individual components that are assembled and animated by the program. Every moving part must be constructed as an individual 3-D model. Each component must accurately fit with all associated components so that they work together. For example, the main scale seen above, must be capable of moving accurately against the vernier scale which must give accurate results at all positions. This requires a high polygon count to achieve smoothness and a high degree of precision so that components fit together well. The spectroscope was created using a 3-D modelling program called Milkshape [7]. Figure 7 shows a view from within this program of the base and main scale. Construction of such a model is a painstaking business. This model took a total of about 30 hours to build and another 30 to animate correctly. The fixed base and scale account for over two thousand polygons. Although this may seem like a large amount, modern computers equipped with graphics cards can easily cope with an order of magnitude more than this. The knobs and the focus tubes are modelled separately so that turning the focus knob causes the focus tube to move in or out. This enables the student to understand how the focus is achieved and reinforce his understanding of the lens equation.

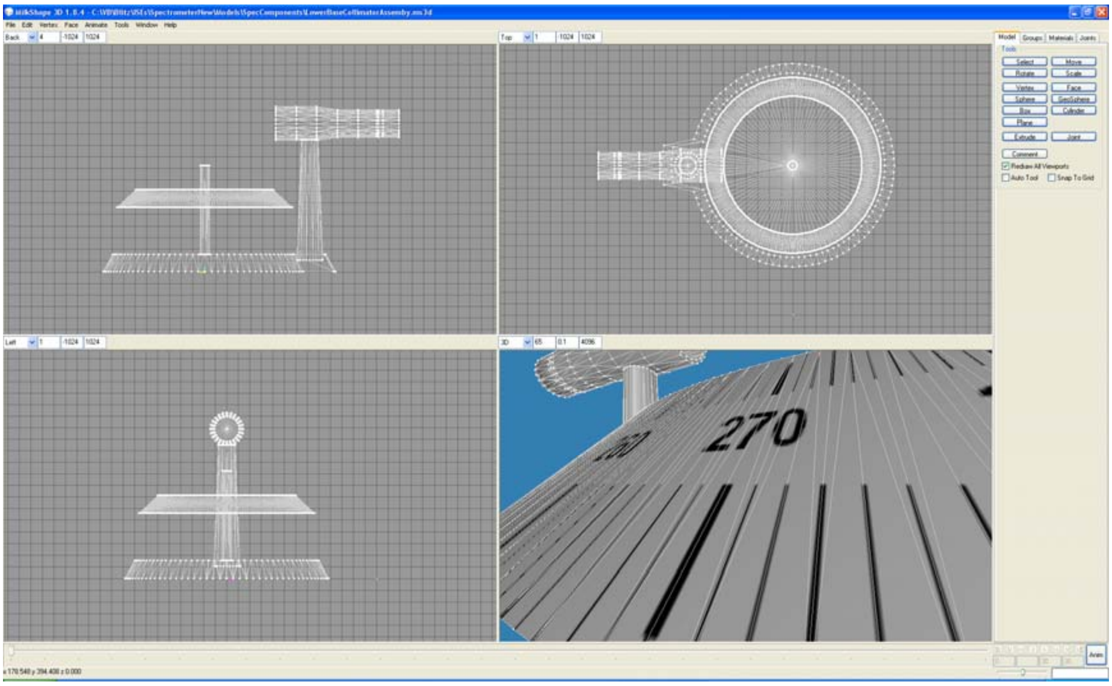


Figure 7 The Milkshape 3D modelling application

The telescope is modelled as a single lens magnifying glass. There is a second software camera (the first is the camera used for the user's eye) inside this telescope pointing towards the centre of the spectroscope. This camera copies its view to a buffer in memory. The lens equation is used to determine how the pixels of the telescope's memory buffer are to be dispersed over the eyepiece lens and it is this simulation that gives the focusing its realistic behaviour.

Figure 8 shows an exploded view of the spectroscope.

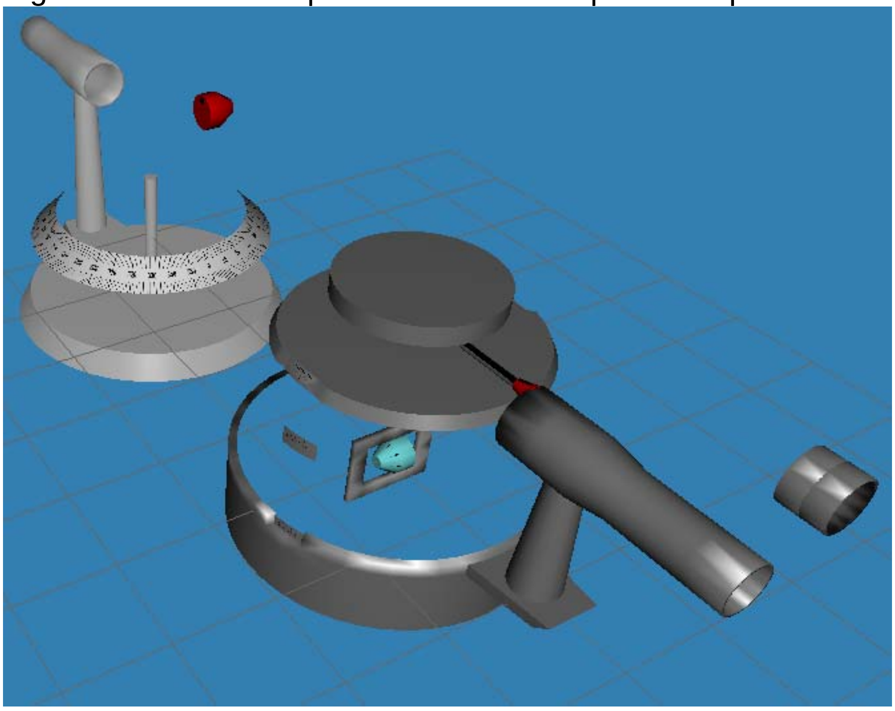


Figure 8 Exploded view of the spectrometer

The Blitz3D games language [1] is used to bring all the components together and simulate their behaviour.

In the classroom

We evaluated the 3-D Diffraction simulation with two lower sixth form physics classes consisting of a total of 22 students. All students successfully used the program to obtain the necessary readings that enabled them to plot the graphs and calculate the wavelengths of blue, red, and green light. They were given two sets of questions. The first set tested their understanding and the second set, asked for their views. The questions are given in appendix I and the results in appendix II. On ease of use the responses were extremely positive. On the idea of replacing real experiments with 3-D simulations they were rather negative which we expected and this was the same for whether they thought that they could learn as much from the simulation as a real experiment. On all the other questions they were very evenly split, but if we divide them into two groups, one that did well on the test and those that did not do so well, we get an interesting result. Those that did well are very positive about the use of the simulations for revision and preparation but do not rate the simulation as realistic as those that didn't do so well, and this group is less positive about the possible uses for revision and preparation. I would say this is quite logical, those who are very competent can perceive the weaknesses of the simulation but also understand its strengths too.

Conclusions

The crucial part of many physics experiments is how all the varying parameters interact. We are clearly able to reproduce this with the Immersive 3-D Screen Experiments that proves impossible with the ISE approach due to the combinatorial explosion of the necessary photographs. Furthermore, we do not need to create programming artefacts to represents scales or controls of any kind. These can be represented at the positions that they are found in reality. Classroom trials clearly show that students are receptive to this approach although healthily sceptical that such programs can replace the real thing.

References

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Appendix 1 Questionnaire

Questionnaire for evaluation of 3D-ISE Diffraction

(A) Understanding of the experiment

These questions should be answered with a Y for yes or a N for no.

(1) The zero order spectrum is visible at zero degrees from a line drawn from the diffraction grating at a right-angle.

(2) All the diffraction patterns occur in pairs.

(3) When sin(θ) is plotted against the order, the gradient gives the wavelength of the light?

(4) Moving the position of the eye (camera) alters the diffraction pattern that can be seen.

(5) Moving the position of the sighting pin alters the diffraction pattern that can be seen.

(6) The higher order diffraction patterns are brighter than the lower order ones.

(7) Each of a pair of diffraction patterns constituting an order occur at the same angle of view but on opposite sides of the zero line.

The following questions require more than just yes or no.

(8) At the zero order how are the various colours diffracted?

(9) List the sources of the uncertainties in your measurements.

(10) Why are the uncertainties not necessarily the same for all the measurements?

(B) Opinions about the experiment

These questions should be answered by circling one of the values given where 5 is ‘strongly agree’, 1 is ‘strongly disagree’.

(1) I found the controls easy to use. (5 4 3 2 1)

(2) The simulation was a realistic simulation of the real experiment. (5 4 3 2 1)

(3) Using the simulation improved my understanding of the experiment. (5 4 3 2 1)

(4) The simulation had the look and feel of the actual experiment. (5 4 3 2 1)

(5) I would find such simulations useful as a way of revising certain experiments. (5 4 3 2 1)

(6) Simulations like this could usefully replace actual experiments. (5 4 3 2 1)

(7) I would learn as much from this simulation as from the real experiment. (5 4 3 2 1)

(8) It would be useful to do this simulation before doing the actual experiment. (5 4 3 2 1)

Space for general comments

Please feel free to put any comments you like here. In particular we are keen to hear of any suggestions which will help us to improve the simulation.

Appendix 2 Results

Student who did well

Student	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	B1	B2	B3	B4	B5	B6	B7	B8
1	1	1	1	1	1	1	1	0	1	1	4	4	5	4	4	3	3	3
2	1	1	1	1	1	1	1	1	1	1	5	2	2	2	4	1	2	3
3	1	1	1	1	1	1	1	1	0	0	5	3	4	4	5	3	3	4
5	1	1	1	1	1	1	1	1	1	0	5	5	5	5	5	2	2	4
6	1	1	1	1	1	1	1	1	1	0	4	5	4	4	5	1	3	5
8	1	1	1	1	1	1	1	1	0	0	3	3	4	3	4	2	2	3
10	1	1	1	1	1	1	1	1	1	0	4	3	3	3	4	1	1	2
11	1	1	1	1	0	0	1	1	1	1	4	3	4	3	4	4	3	4
14	1	1	1	1	1	1	1	1	1	1	5	4	2	3	3	1	4	5
16	1	1	1	1	1	1	1	1	1	0	5	5	5	1	1	1	3	5
20	1	1	1	1	1	1	1	1	1	0	4	3	3	3	3	1	2	3
22	1	1	1	1	1	1	1	1	0	1	5	3	2	2	4	3	2	4

Students who did not so well

4	1	1	1	0	0	1	1	1	1	0	4	3	2	3	3	1	1	2
7	1	1	1	1	1	1	0	0	1	0	5	4	1	2	3	1	1	1
9	1	1	1	1	1	1	1	0	0	0	4	5	2	4	5	2	4	3
12	0	1	0	1	0	1	1	0	0	1	5	5	3	5	3	5	2	2
13	0	1	0	1	1	0	1	1	1	0	4	4	3	3	2	1	1	2
15	0	1	0	1	1	0	1	1	1	0	4	4	4	3	3	3	4	3
17	0	1	0	1	0	1	0	0	1	1	4	5	3	4	5	5	3	4
18	0	1	0	0	1	1	1	0	0	0	5	1	5	1	1	1	1	5
19	0	1	0	1	1	0	1	0	0	1	4	3	4	5	3	4	4	5
21	0	1	0	1	1	1	1	1	0	1	5	4	3	4	3	1	2	4